Twin-Horizontal Downhole Water Loop Production System

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ABSTRACT

Water-coning is a severe problem in bottom-water-drive reservoirs, especially for those having thin oil bearing layer and strong aquifer. Effectively developing these kinds of reservoirs is always an engineering challenge. Water-coning causes water influx to oil producers which leads to high water-cut and early shut-down of wells without sufficient recovery of hydrocarbon in place. The mechanics of water-coning and significant concepts dealing with water-coning problem have been stated and analyzed in this paper.

Numerous technologies have been invented to develop water-drive reservoir efficiently and economically. Downhole water sink (DWS) and downhole water loop (DWL) are attractive alternatives to conventional water-coning attenuation technologies. They are proven to be effective theoretically, numerically and by field application. This study evaluated production performance of DWS and DWL production systems using CMG® IMEX simulator, and conceptual designs for both systems have been presented according to evaluation results. However, simulation results revealed that both DWS and DWL production systems suffer from serious drawbacks. Herewith, an innovative water-coning suppressing technology is offered in this paper on the basis of DWS and DWL system, which is referred to as twin-horizontal downhole water loop production system. THDWL production system has a water drainage interval below oil-water-contact and two symmetric horizontal wells for drainage water re-injection. Through simulation results, design criterion for THDWL production system was conducted and a conceptual design case was provided. THDWL production system was proven to be potential and valuable by the reason of positive simulation result.
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NOMENKLATURES

Abbreviations
DWS: Downhole water sink well
DWL: Downhole water loop well
THDWL: Twin-horizontal downhole water loop well
WC: Water cut
WDI: Water drainage interval
WRI: Water re-injection interval

Latin
\( B_o \): Oil formation factor, dimensionless
\( B_w \): Water formation factor, dimensionless
\( h_{ap} \): Oil column height above oil production completion, m
\( h_o \): Oil zone thickness, m
\( h_p \): Length of oil production completion, m
\( h_i \): Cone height, m
\( H_{DV} \): Dimensionless cone height, dimensionless
\( h_{aWDI} \): Water column height above water drainage interval, m
\( h_{WDI} \): Length of water drainage interval, m
\( h_i \): Length of water re-injection interval, m
\( h_{id} \): Distance between water re-injection interval to free-water-level, m
\( k_h \): Horizontal permeability, mD
\( k_v \): Vertical permeability, mD
\( k_r \): Permeability in radial direction, mD
\( k_{ro} \): Oil relative permeability, dimensionless
\( k_{rw} \): Water relative permeability, dimensionless
\( L_o \): Distance between top of pay and top of perforated interval, m
\( L_w \): Distance between oil-water-contact and bottom of perforated interval, m

\( L_i \): Length of horizontal well for drainage water re-injection, m

\( M \): Mobility ratio, dimensionless

\( P_e \): Pressure at external boundary, Pa

\( P_w \): Bottom hole pressure, Pa

\( \Delta P_{\text{skin}} \): Pressure drop due to skin factor, Pa

\( q_{\text{oc}} \): Critical oil production rate, \( \text{m}^3/\text{d} \)

\( q_{\text{ow}} \): Critical rate at oil-water system, \( \text{m}^3/\text{d} \)

\( q_{\text{og}} \): Critical rate at oil-gas system, \( \text{m}^3/\text{d} \)

\( q_{\text{cd}} \): Dimensionless critical rate, dimensionless

\( q_{\text{wi}} \): Bottom water influx rate, \( \text{m}^3/\text{d} \)

\( R_d \): Ratio between the external aquifer radius and the reservoir external radius

\( r_d \): Drainage radius, m

\( r_w \): Well radius, m

\( r \): Radius, m

\( r_D \): Dimensionless radius, dimensionless

\( S_w \): Water saturation, dimensionless

\( S_{\text{wc}} \): Connate water saturation, dimensionless

\( S_{\text{or}} \): Residual oil saturation, dimensionless

\( S_{\text{geo}} \): Geometric skin factor, dimensionless

\( t \): Time, s

\( t_{\text{BT}} \): Water breakthrough time, day

\( t_D \): Dimensionless time, dimensionless

**Greek**

\( \mu_o \): Oil viscosity, mPa.s

\( \mu_w \): Water viscosity, mPa.s
\( \rho_o \): Oil density, \( \text{kg/m}^3 \)

\( \rho_w \): Water density, \( \text{kg/m}^3 \)
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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATIONS

Reservoirs which are bound by and in communication with active aquifers are referred to as water-drive reservoirs. If active aquifer is located at the bottom of the reservoir, then these reservoirs can be called bottom-water-drive reservoirs. During production, active aquifer is a natural and effective energy, water from aquifer gradually invades into the reservoir, pressure of reservoir is thus maintained at relative high level, and sufficient flow to the producer can be ensured.

Production of oil through a well that partially penetrates an oil reservoir with aquifer underlain is challenging. Vertical pressure gradient beneath well bottom and viscosity contrast between oil and water lead to a rise of oil-water-contact, changing oil-water-contact from a flat surface into the shape of cone. As production rate increasing, height of the cone above the original oil-water-contact also increases. Above a certain production rate the cone becomes unstable and keeps increasing. Bottom water infiltrates the perforation zone at the near-wellbore area, resulting in rapid water cut increasing and high water-cut. This phenomenon is defined as water-coning. At bottom-water-drive reservoirs, more severe water-coning problems occur. Invade water from bottom can easily lead to an unstable water-coning and higher rising rate of oil-water-contact.

For bottom-water-drive reservoir with thin oil bearing layer, the presence of water coning hampers oil production severely. Although many wells can produce economically even at the situation that water-cut is above 98% using conventional production method, the great majority of the wells become uneconomical at high water-cut (>90%) stage due to lifting and water handling cost. Thus attenuation of water-coning at bottom-water-drive reservoir is crucial.

Numerous methods have been proposed to solve the water-coning problem. Downhole water loop (DWL) and downhole water sink (DWS) technologies are potential and effective methods. These two technologies are developed since 1991. Comparing to conventional method used to attenuate water-coning, DWS technology directly controls water-coning employs in-situ water drainage at oil wells with a downhole water drainage completion (Swisher et al. 1995; Bowlin et al. 1997; Shirman et al. 2000; Ould-Amer et al. 2004). DWL can be seen as a natural extension of the downhole water sink technology: by returning the drainage water back to the same aquifer using a triple-completed well (Jin et al. 2010, 2011). DWL has the advantage of dewatering the near-well zone as DWS technology. Besides, DWL has certain characters which demonstrate superiority compared to other methods of water-coning attenuation: DWL eliminates disposal cost of producer water; reduces
energy consumption and cost of water pumping; provides an in-situ separation method to prevent environmental pollution (Wojtanowic et al. 1995); prevents excessive water drainage which depresses bottom-water-drive, especially for reservoirs with weak aquifer.

Although DWL technology has unique advantages, several studies reveal that for most cases, under same production condition, DWL well has higher water cut than DWS well which results in less hydrocarbon recovered at the surface (Lin et al. 2010). Oil reservoir simulation in our study reflects the same condition. With the intention of combining the advantage of downhole water sink technology and downhole loop technology, according to our simulation result, we propose an innovative technology called twin-horizontal downhole water loop (THDWL).

Twin-horizontal downhole water loop well is a quadruple-completed well. A THDWL well has five packers and separate the system into three part: the top part contains oil production interval located at the upper side of oil zone which is used for oil production; the second part includes water drainage completion (WDI) just below oil-water-contact and used for water drainage; the third part consists of two water re-injection interval (WRI) at the tail of two symmetric horizontal sections for drained water re-injection.

1.2 PURPOSE OF STUDY

The objective of this study was to investigate the principle and design criteria of THDWL well by numerical simulation. Meanwhile, the feasibility of THDWL well need to be proven by comparison of production performances between conventional well, DWS well, DWL well and THDWL well.

The remainder of this thesis is organized in four chapters. The second chapter presents the theoretical study of water-coning, recent research status of DWS and DWL well and idea of THDWL well. The third chapter provides details of numerical model built for THDWL well study. Chapter four presents conceptual designs for DWS well, DWL well and THDWL well respectively based on design parameters analysis. Chapter five evaluates production performance of THDWL well and provides some further discussions.
CHAPTER 2 THEORY OF WATER-CONING AND WATER-CONING ATTENUATION TECHNOLOGIES

This chapter reviews the basic theory of water-coning and the current research statues of downhole water sink and downhole water loop technology. In order to solve certain limitations of the current water-coning attenuation technology, a new oil production method developed for bottom-water-drive reservoir has been presented. The basic theory of this production technology was described, enclosed with a schematic of the whole system.

2.1 WATER CONING AT OIL RESERVOIRS

Water-coning is a production problem for partial perforated wells which only penetrates upper part of the reservoir. During production, the pressure drop at oil production interval tends to “suck” water up towards the lowest perforation in the down-dip wells. Bottom water flows to the perforated zone in the near-wellbore area and reduces oil production.

Water-coning is caused by potential distribution near wellbore. Since the moment producer starts producing, water-cone is formed. The upward speed of the water-cone depends upon vertical potential gradient $\frac{\partial \Phi}{\partial z}$, activity of aquifer, vertical permeability, fractional well penetration, drainage radius, well radius, as well as water-oil density contrast. At most cases, water is more mobile than oil. When applying the same potential gradient, velocity of water is larger than that of oil, oil-water-contact below oil production interval rises as a consequent. When aquifer is not active and reservoir has infinite supply, this upward force can be offset by gravity.
contrast of water and oil if production rate is sufficiently low. At this condition, water-cone becomes stable and stops rising. When the production rate increases, the cone height above the original oil-water-contact (WOC) also increases until at certain moment, gravity contrast of water and oil cannot offset their mobility contrast. Water-cone becomes unstable and keeps rising. As a consequence, water breakthrough is unavoidable. Thus a maximum water-free production rate existed which is then defined as critical oil production rate. (Figure 3, Figure 4)

Figure 2 Potential distribution of partial perforated well

Figure 3 Oil-water-contact (production rate is lower than critical rate)
However, study of water-coning in strong-bottom-water-drive reservoir is very difficult. Strictly speaking, the concept of critical rate cannot be applied in strong-bottom-water-drive reservoirs. Because material balance implies that as water invades to reservoir from bottom and oil is displaced by invaded water, there must be upward movement of the oil-water-contact. Due to the development of reservoir simulation, simulating anticline bottom-water-drive reservoir becomes possible. In order to precisely simulate this type of reservoirs, the numerical model need to contain a close outer boundary and assume an active aquifer underneath. Under this boundary condition, classical critical rate is no longer exists, and theoretical predicting of oil production performance is significantly complex. First, oil-water two-phase flow is involved in bottom-water-drive reservoirs. It is very hard to get analytical solution based on differential equation of two-phase flow. Secondly, water influx from active aquifer is a dynamic process, which includes time dependence, making boundary condition even more complicated. Thus dynamic production process of bottom-water-drive reservoir can only be studied numerically and bases on reservoir engineering method. Critical oil production rate for bottom-water-reservoir is expressed as a function time.

Due to the existence of more severe water-coning, bottom-water-drive reservoirs always have earlier water breakthrough time and shorter water-free production period than edge-water-drive reservoirs or the reservoirs with inactive aquifer underneath. At bottom-water-drive reservoirs, most oil is recovered at high water-cut condition which leads to relative high unit production cost (UPC). As water-coning causes severe oil production decline during production, several ways have been developed by
petroleum engineers to handle water-coning:

1. Producing below critical production rate
2. Perforating far from oil-water-contact
3. Total penetration (perforation interval covers the entire oil zone and extended some distance below OWC into the water layer)
4. Vertical well gel treatments (numerous gel treatments have been conducted to create vertical artificial impermeable barriers to suppress coning)
5. Fracture completion (create propped fracture to alleviate pressure draw down, hence to mitigate the effect of coning)
6. Downhole water sink (DWS) and downhole water loop technology (DWL)
7. Use of horizontal wells
8. Dual horizontal well completion (Bilateral water sink technology)

2.2 CRITICAL RATE

2.2.1 Theory of critical rate

Critical rate was firstly put forward by French engineer Dupuit (1863) when dealing with groundwater engineering problems. Then this idea was extended to petroleum engineering field by Muskat and Wyckoff (1935). As water-coning is sensitive to production rate, the term critical production rate is defined as the maximum water-free production rate for reservoirs are underlain by water. Numerous methods have been developed to predict the critical production rate.

Muskat and Wyckoff et al. (1935) firstly made substantial contribution to this concept of critical production rate. They suggested that if production rate is lower than certain value, which is then defined as critical rate, increasing of water cone due to viscous contrast of oil and water might be offset by gravity force. In such case, oil-water-contact is hydrostatic equilibrium below the region of oil flow; bottom water from aquifer cannot break into well bore.

Mayer and Garder (1956) pointed out that the formation of water-coning is the result of pressure drawdown near wellbore due to radial flow of oil phase. They developed an equation to calculate critical rate based on continuity equation, Darcy’s law and following assumptions: Homogeneous and isotropic reservoir; flow of oil and gas to the wellbore is strict radial flow; flow of water from oil-water-contact to wellbore is strict vertical flow; pressure gradient due to the flow of fluid is balanced by gravity force.

Mayer and Garder presented an equation for critical rate calculation based on the
results of their theoretical analysis:

\[
q_{\infty} = \frac{2.63 \times 10^{-6} k_s (\rho_w - \rho_o) (h_o^2 - h_p^2)}{B_o \mu_o \ln \frac{r_c}{r_w}}
\]  

(2-1)

Chaney et al. (1956) developed a method for critical rate calculation which is an extension of Muskat’s method. This method took mathematical and potentiometric analysis of water-coning into account. Based on certain reservoir geometrical morphology and rock-fluid property, Chaney et al developed a set of curves, from which critical rates can be determined at various values of perforation length. The obtained results were then fitted by using the least square method. They thought that if geometrical morphology of reservoir was unchanged, critical rate obtained from these curves could be corrected by actual reservoir rock-fluid properties.

\[
q_{\text{curve}} = 0.225 \left( h_o^2 - h_p^2 \right) - 3.69
\]

(2-2)

Where 

\( q_{\text{curve}} \) is critical rate obtained from Chaney’s curve

Following reservoir geometrical morphology and rock-fluid properties data were applied to obtain Chaney’s curve for critical rate calculation: Drainage radius=305m, well radius=0.0762m, oil zone thickness=3.81m, 7.62m, 15.24m, 22.86m and 30.48m individually, permeability=1mPa.s, oil-water density contrast=300kg/m³. When predicting critical rate for real case through Chaney’s method, calculated \( q_{\text{curve}} \) should be corrected by equation below:

\[
q_{\infty} = \frac{3.33 \times 10^{-6} k_s (\rho_w - \rho_o) q_{\text{curve}}}{\mu_o B_o}
\]

(2-3)

Chierici et al. (1964) did research based on Muskat’s theory of water and gas coning. They used potentiometric model to determine maximum oil production rates without water and/or free-gas production. They assumed that the reservoir is homogeneous (either isotropic or anisotropic); the volume of aquifer is very small that cannot contribute to energy supply; the gas cap is assumed to be in quasi-static condition. They plotted their experiment result in a dimensionless diagram which can be applied to solve two types of problems: determination of the maximum oil production rate without water and/or free gas production while giving the reservoir, fluids and perforated interval data; optimization of the position and length of the perforated interval.

\[
q_{\infty} = \frac{5.256 \times 10^{-7} h_o^2 (\rho_w - \rho_o) (k_r k_o) \Psi_w (r_{De}, \epsilon, \delta_w)}{B_o \mu_o}
\]

(2-4)
\[ q_{og} = \frac{5.256 \times 10^{-6} h^2 (\rho_o - \rho_g) (k_{ro} k_h)}{B_o \mu_o} \Psi (r_{De}, \varepsilon, \delta_g) \] (2-5)

Where

\( h \) is the thickness of the oil bearing formation (include the thickness of gas cap and small aquifer)

\[ 5 \leq r_{De} = \frac{r_o}{h} \sqrt{\frac{k_v}{k_h}} \leq 80 \]

\[ 5 \leq r_{De} = \frac{r_o}{h} \sqrt{\frac{k_v}{k_h}} \leq 80 \]

\[ 0 \leq \varepsilon = \frac{h_p}{h} \leq 0.75 \]

\[ 0.07 \leq \delta_g = \frac{L_k}{h} \leq 0.9 \]

\[ 0.07 \leq \delta_w = \frac{L_w}{h} \leq 0.9 \]

\( \Psi \) is function, can be get from dimensionless diagram

MacDonald and Coats et al. (1970) develop a numerical model to simulate water-coning and investigated several ways to mitigating the effect of coning, which include gas injection, polymer injection, etc.

Schols (1972) conducted numerous water-coning experiments using Hele-Shaw model. He presented two empirical equations to calculate critical rate which are suitable for isotropy and anisotropy reservoirs respectively.

For homogeneous and isotropic reservoir:

\[ q_{\infty} = 8.36 \times 10^{-7} \left[ \frac{k_v (\rho_w - \rho_o)(h_o^2 - h_g^2)}{B_o \mu_o} \right] 0.432 + \frac{\pi}{\ln \frac{r_e}{r_w}} \left( \frac{h}{r_e} \right)^{0.14} \] (2-6)

For homogeneous and anisotropic reservoir:

\[ q_{\infty} = 8.63 \times 10^{-7} \left[ \frac{k_v (\rho_w - \rho_o)(h_o^2 - h_g^2)}{B_o \mu_o (k_v / k_h)^{0.07}} \right] 0.432 + \frac{\pi}{\ln \frac{r_e}{r_w}} \left( \frac{h}{r_e} \right)^{0.14} \] (2-7)

Chaperon (1986) analyzed critical rate of vertical wells and horizontal wells theoretically. He found out that for vertical wells, critical production rate increases
with the decrease of vertical permeability. He also pointed out that unless vertical permeability is far greater than horizontal permeability, critical rate of horizontal wells is larger than vertical wells. Chaperon presented an equation to calculate critical rate at homogeneous and anisotropic reservoirs. This equation takes the distance between reservoir boundary and production well into consideration.

\[
q_{oc} = 8.63 \times 10^{-7} \left[ \frac{k_h (\rho_w - \rho_o) (h_o - h_p - h_{wp})}{B_o \mu_o} \right] \times q_c^* \quad (2-8)
\]

Joshi correlated the value of \( q_c^* \) by \( a^\prime \)

\[
q_c^* = 0.7311 + (1.943 / a^\prime)
\]

\[
a^\prime = (\frac{r_c}{h_o}) \sqrt{k_e / k_h}
\]

**Abbas and Bass (1988)** considered that location and length of perforated interval has influence on critical production rate. They used analytical method, numerical method and experimental method to study dynamical property of water-coning under different boundary conditions. They built a fully implicit, strong coupling mathematical model to handle rapid pressure-saturation changes. On the other hand, they constructed a plexiglass model to obtain a qualitative and quantitative description of water-coning problem. Finally, they presented analytical solutions for critical rate calculations under steady-state flow condition and unsteady-state flow condition individually. They neglected vertical pressure gradient, limited entry and skin effect.

**Critical rate for steady state flow condition:**

\[
q_{oc} = \frac{5.25 \times 10^{-6} \times k_h h_p (\rho_w - \rho_o) (h_o - h_p - h_{wp})}{\mu_o B_o \left( \frac{r_c^2}{r_w^2} \ln \frac{r_c}{r_w} - \frac{1}{2} \right)}
\]

**Critical rate for unsteady state flow conditions:**

\[
q_{oc} = \frac{5.25 \times 10^{-6} \times k_h h_p (\rho_w - \rho_o) (h_o - h_p - h_{wp})}{\mu_o B_o \left( \frac{r_c^2}{r_w^2} \ln \frac{r_c}{r_w} + \frac{r_c^2 + r_w^2}{4r_c^2} - \frac{1}{2} \right)}
\]

**Høyland et al. (1989)** applied analytical and numerical methods to analyze critical rate in isotropy reservoirs and anisotropy reservoirs. For anisotropic reservoirs, they conducted a general correlation to predict critical rate based on the results of large number of simulations. For isotropic reservoirs, this correlation can be formulated as an equation. As for their analytical approach of study, they extended Muskat and Wyckoff’s theory developed in 1935 based on the following assumptions: flow in reservoir is single-phase flow; the fluid is compressible; wellbore has infinite conductivity. They drew a conclusion that the critical rate has a linear relationship
with oil formation volume factor and a nonlinear relationship with well perforation length, reservoir radius, height of oil zone and vertical/horizontal permeability ratio. The boundary condition of Høyland’s numerical model is specified in Figure 5.

![Figure 5 Høyland's numerical model to critical rate calculation](image)

Based on the results of reservoir simulations in combination with analytical analysis, Høyland derived a general correlation to determine critical rate:

$$q_{oc} = 2.63 \times 10^{-6} \times \frac{h^2 (\rho_o - \rho_w) k_h}{B_o \mu_o} q_{cd}$$

(2-11)

Where

$q_{cd}$ is dimensionless critical rate obtain from Figure 2-6 as a function of dimensionless radius $r_D$, $r_D = \frac{r_e}{h} \sqrt{\frac{k_w}{k_h}}$

![Figure 2-6 Dimensionless critical rate curves by Hoyland et al.](image)
Guo and Lee (1993) carried out a simple analysis of the mechanism of water-coning. They defined unstable coning as: vertical pressure gradient beneath the well bottom is higher than water hydrostatic pressure gradient. The following assumptions are made: oil reservoir is homogeneous and steady-state flow prevails; flow in reservoir can be separated into two patterns (radial-flow pattern and spherical-flow pattern). They derived potential functions for radial-flow pattern and spherical-flow pattern individually. In combination with Darcy’s law and their definition of unstable water-coning, they solved these potential equations analytically to calculate the critical rate that takes the effect of limited wellbore penetration into consideration. Through the equation they presented for critical calculation, they further calculated the optimum wellbore-penetration-interval length, which should be smaller than one third of the oil zone height.

\[
q_{cc} = 1.68 \times 10^{-5} \times \frac{k_r (\rho_w - \rho_o)}{\mu_o} \times \left[ r_e - \sqrt{r_e^2 - r_o (h_o - h_p)} \right]^2 \times \left[ \frac{k_r}{\sqrt{k_h^2 + k_r^2}} + \frac{h_p (\frac{1}{r_w} - \frac{1}{r_e})}{\ln(\frac{r_e}{r_w})} \right]
\]

(2-12)

Yang (1993) used numerical simulation method in combination with reservoir engineering method to investigate the phenomenon of water-coning. According to his simulation result, he presented several equations to calculate critical rate and water breakthrough time for vertical wells and horizontal wells.

Previously, calculation of critical rate is based on the assumption of steady-state flow or pseudo-steady-state flow conditions. Instead, Yang made an alternative assumption that outer boundary is close and aquifer underlain by reservoir is active. He further proposed a new idea that as water-cone moves up, critical rate gradually decreases. Therefore, he thought critical rate is a dynamic factor which is a function of \(h_{bp}\) (average oil column height below perforation). He defined and calculated a new parameter \(h_{wb}\) (average oil column height at water breakthrough time) as a function of production rate. Assuming that a well is produced at the rate \(q_t\), when \(h_{bp}\) is equal to the corresponding \(h_{wp}\) of \(q_t\), water breaks into well. In another word, at this moment, if production rate is lower than \(q_t\), the well does not produce water. So \(q_t\) is the critical rate at this moment. Through a series of simulations cases and related correlations, Yang presented an equation to calculate \(h_{wb}\):

\[
\left( \frac{h - h_p - h_{wp}}{h_{wb}} \right)^2 = 1 + 39.0633 \times 10^{-4} \left( \frac{1}{r_{De}} \right)^0.6 \left( \frac{1}{q_D} \right) \frac{1}{1 + M^{0.7} (1 - \delta)^{0.4}}
\]

(2-13)

Where
\[
q_D = \frac{q_i \mu_o}{0.742 k_h k_{ro} (S_{wo}) \Delta \rho h^2}
\]

\[
r_{De} = \frac{r_c}{h} \sqrt{\frac{k_v}{k_h}}
\]

\[
\lambda = \frac{h_{wp}}{h_o}
\]

\[
\delta = \frac{h_p}{h}
\]

\[
M = \frac{\mu_o k_{ro} (1 - S_{ao})}{\mu_w k_{ro} (S_{wc})}
\]

From equation (2-13), critical rate can be solved:

\[
q_{cD} = 39.0633 \times 10^{-4} \left( \frac{1}{r_{De}} \right)^{0.6} \left( 1 - \lambda \right)^{0.4} \frac{h_{wp}^2}{1 + M^{0.7} \left( 1 - \delta \right)^{0.4} (h - h_p - h_{wp})^2 - h_{wp}^2}
\]  \hspace{1cm} (2-14)

\[
q_{wc} = \frac{0.742 k_h k_{ro} (S_{wc}) \Delta \rho}{\mu_o} q_{cD}
\]  \hspace{1cm} (2-15)

### 2.2.2 Case study and conclusion of the presented theories

**Case:** A cylindrical reservoir has infinite oil/water supplies at outer boundary and an inactive aquifer underneath. This reservoir has an oil zone of 40 meters and a water zone of 20 meters. A vertical well is located in the center of the reservoir, which has a radius of 0.18 meters and a drainage radius of 300 meters. Rock fluid properties of this reservoir are: porosity=0.1, horizontal permeability=400mD, vertical permeability=80mD, Oil density=825kg/m^3, water density=1055 kg/m^3, oil viscosity=1.4mPa.s, water viscosity=0.4mPa.s, oil formation factor=1. Critical rates are plotted at Figure 7 as a function of fraction wellbore penetration (the ratio between wellbore penetration length at oil zone and oil zone height) based on several critical rate calculation methods presented in Chapter 2.2.1.
Equations for critical rate calculation are derived based on certain assumptions. These assumptions result in the limitation when applying these equations. From Figure 7, calculated critical rates according to different methods have dramatic difference. Method of Chaney, Schols, Chaperon, and Meyer & Garder don’t consider that limited wellbore penetration having an effect on oil productivity of the well. Corresponding curves of these methods show that critical rates decrease as the increase of fractional wellbore penetration. Maximum water-free oil production rates are obtained when fractional wellbore penetration is equal to zero, which is physically impossible. The curves of Guo & Lee’s method and Abbas & Bass’s method show similar trend, however the values are significantly different. Optimal fractional wellbore penetration of Abbas & Bass’s method is 0.5, for Guo & Lee’s method, this number is 0.32. The difference mainly results from the fact that Abbas & Bass assumed pure radial oil flow toward perforation interval, whereas Guo & Lee assumed that oil flow toward perforation interval is a combination of radial flow and spherical flow.

At the situation when aquifer is active and bottom water drives oil upward, all the methods shown at Figure 7 cannot be employed anymore. In this situation, flow of oil and water to wellbore is two-phase flow which strongly conflicts with the assumption of single-phase flow in these methods.
In conclusion, rigorous analysis of well production condition is a necessity before using these methods for critical rate calculation. Choosing the best-fit method is the key to get relatively reliable result. However, for all these methods, calculated critical rate is too low to be economically applicable. Thus water breakthrough time calculation and prediction of water cut after water breakthrough become crucial.

2.3 WATER BREAKTHROUGH TIME PREDICTION UNDER WATER-CONING CONDITION

Sobocinski and Cornelius (1965) developed a numerical model to simulate water-coning at the condition that production rate is larger than the critical rate. Meanwhile, they carried out a series of experiments using a fan-shaped organic glass with sand filled. Based on their laboratory experimental data and computer program results, they presented a correlation to predict the water breakthrough time.

Dimensionless cone height $H_{DV}$:

$$H_{DV} = \frac{2\pi gh_o^2 (\rho_w - \rho_o) k_r}{q_o B_o \mu_o} h_{DV}$$

(2-16)

Where

$$h_{DV} = \frac{h_w}{h_o}$$

Dimensionless time $t_D$:

$$t_D = \frac{g (\rho_w - \rho_o) k_r \left(1 + M^\alpha\right)}{2\mu_o \phi h_o} t$$

(2-17)

Where

$$M = \frac{k_{rw} \left(S_{rw}\right) \mu_o}{k_{rw} \left(S_{rw}\right) \mu_w}$$

$\alpha$ is a factor, when $M \leq 1$, $\alpha = 0.5$; when $1 < M \leq 10$, $\alpha = 0.6$.

At the water breakthrough time:

$$(h_{DV})_{BT} = 1 - \frac{h_p}{h_o}$$

(2-18)

Thus dimensionless cone height at water breakthrough can be derived:

$$(H_{DV})_{BT} = \frac{2\pi gh_o^2 (\rho_w - \rho_o) k_r}{q_o B_o \mu_o} \left(1 - \frac{h_p}{h_o}\right)$$

(2-19)
Dimensionless breakthrough time:

\[
(t_D)_{BT} = \frac{g (\rho_w - \rho_o) k_v (1 + M^\alpha)}{2 \mu_o \phi h_o} t_{BT}
\]  

(2-20)

A correlation was made which can accurately fit the relationship between dimensionless water breakthrough time and dimensionless cone height:

\[
(t_D)_{BT} = \frac{(H_{DV})_{BT} 16 + 7(H_{DV})_{BT} - 3(H_{DV})_{BT}^2}{7 - 2(H_{DV})_{BT}}
\]  

(2-21)

Using SI unit:

\[
(H_{DV})_{BT} = 5.256 \times 10^4 \frac{h_o^2 (\rho_w - \rho_o) k_v}{q_o B_o \mu_o} \left(1 - \frac{h_p}{h_o}\right)
\]  

(2-22)

The calculated \((H_{DV})_{BT}\) can be used to calculate \((t_D)_{BT}\) based on equation (2-19).

\[
t_{BT} = 2.392 \times 10^6 \frac{\mu_o \phi h_o}{(\rho_w - \rho_o) k_v (1 + M^\alpha)} (t_D)_{BT}
\]  

(2-23)

Joshi (1991) found in equation (2-19), when \((H_{DV})_{BT} \geq 3.5\), water would not break into production well. Taking \((H_{DV})_{BT} = 3.5\) into equation (2-20), thus critical rate can be obtained:

\[
Q_{oc} = 1.23 \times 10^{-6} \frac{k_v (\rho_w - \rho_o) (h - h_p)}{B_o \mu_o}
\]  

(2-24)

**Bournazel and Jeanson (1971)** applied the same dimensionless factors as Sobocinski-Cornelius method to calculate water breakthrough time on the foundation of experimental data and field data. They found that water breakthrough time measured in their study is lower than which predicted by Sobocinski and Cornelius’s method. Thus they presented a new equation to represent the relationship of dimensionless cone height and water breakthrough time based on their data. Furthermore, they pointed out that when \(0.14 < M \leq 7.3\), the value of \(\alpha\) should be modified to 0.7.

\((H_{DV})_{BT}\) can be calculated from equation (2-19).

Calculation of dimensionless water breakthrough time:

\[
(t_D)_{BT} = \frac{(H_{DV})_{BT}}{3 - 0.7(H_{DV})_{BT}}
\]  

(2-25)

Then water breakthrough time can be calculated according to equation (2-21).

**Yang (1993)** presented an equation to calculate water breakthrough time based on the theory stated at Chapter 2.2.1.
For a cylindrical oil reservoir, average oil column height below perforation \( h_{bp} \) has a linear relation with cumulative oil production rate \( N_p \). According to Yang’s theory, average oil column height at water breakthrough time \( h_{wb} \) is function of \( q_t \). At the production rate of \( q_t \), when \( h_{bp} \) is equal to corresponding \( h_{wb} \) of \( q_t \), water breaks into producer. Cumulative water-free oil production rate \( (N_p)_{bt} \) and water breakthrough time can be calculated on the basis of \( h_{wp} \) and \( q_t \).

\[
(N_p)_{bt} = A\phi(1 - S_{wc} - S_{wr}) (h_b - h_{wp} - h_p - h_{wp}) \tag{2-26}
\]

Where

\( h_{wp} \) can be solved from equation (2-13)

If production well is producing at constant rate:

\[
t_{BT} = \frac{(N_p)_{BT}}{q_t}
\]

### 2.4 PRODUCTION PERFORMANCE AFTER WATER BREAKTHROUGH

Kuo and DesBrisay (1983) investigated the effect that various reservoir parameters have on water-coning development through numerical simulations. They developed a simplified correlation to predict water cut after water breakthrough, which is valid for most reservoirs.

Water breakthrough time \( t_{BT} \) can be obtained through Sobocinski-Cornelius method or Bournazel-Jeanson method.

Normalization of their simulation results:

\[
t_D = \frac{t}{t_{BT}}
\]

\[
WC_D = \frac{WC}{(WC)}_{\text{limit}} \tag{2-24}
\]

\[
(WC)_{\text{limit}} = \frac{Mh_w}{Mh_w + h}
\]

Where

\( t = \) certain time after water breakthrough, days

The correction can be represented by the following equations

\[
(WC)_{D} = 0 \quad t_D < 0.5
\]

\[
(WC)_{D} = 0.94\log t_D + 0.29 \quad 0.5 \leq t_D \leq 5.7
\]

\[
(WC)_{D} = 1.0 \quad t_D > 5.7
\]

From this correlation, water cut can be calculated from equation (2-24).
Yang (1993) found that after water breakthrough, water-oil ratio (WOR) at the producer has a linear relationship with $h_{bp}$ on semi-log scale. It is in accord with the finding of Addington (1981) when he studied the phenomenon of gas-coning. The relationship of WOR and $h_{bp}$ can be used to forecast WOR after water breakthrough.

$$WOR = 0 \text{ when } h_{bp} > h_{wp} \quad (2-25)$$

$$\log(WOR + 0.02) = m(h_{bp} - h_{wp}) + \log(0.02) \text{ when } h_{bp} \leq h_{wp} \quad (2-26)$$

Where

$m$ is the slope of the linear relationship. The value of $m$ can be obtained from the correlation of Yang’s simulation results:

$$m = -0.015 \left[ 1 + 485.7757 \left( \frac{1}{r_{Dw}} \right)^{0.5} \left( \frac{1}{q_D} \right)^{0.5} \frac{1}{1 + \delta} \frac{(1 - \delta)(1 - \lambda)}{h_{wp}^{1.7}} \right] \quad (2-27)$$

### 2.5 DOWNHOLE WATER SINK TECHNOLOGY

The downhole water sink is a completion/production technique in production hydrocarbons from reservoirs with bottom-water-drive and strong tendency to water-coning. DWS provides an innovate solution for coning control which can reduce water cut significantly. Basically, DWS requires a dual-completion well with one completion at oil zone for oil production and one completion at water zone for water drainage near oil-water-contact. In conventional well, the upward force of water-cone can only be balanced by gravity contrast of oil and water. In DWS well, water drainage interval provides an extra pressure drop below oil-water-contact which can balance the rising force of the interface. As a result, water-coning is considerably attenuated and leads to better water cut control after water breakthrough. DWS technology has been investigated theoretically (Wojtanowicz et al. 1991; Swisher and Wojtanowicz, 1995a, b), numerically (Kurban et al. 1999; Inikori, 2002) and experimentally (Shirman and Wojtanowicz, 1997a,b). Numerical simulation study (Ould-amer et al. 2004) and field application (Swisher and Wojtanowicz, 1995) has justified the feasibility of DWS: the critical rate is improved compared to conventional vertical well and water breakthrough time delays. At the first glance, for DWS well, the total amount of water produced at the surface could be even more than conventional well, because drainage water would be lifted to the surface. However, drainage water doesn’t need to be treated since it is oil free. Therefore, water disposal cost would not increase as a consequence.

Although DWS technology shows great advantage and potential, it requires a large amount of water to be pumped to the surface. This implies large lifting costs. Meanwhile, for reservoirs with relative small aquifer, draining of too much water
results in large pressure drawdown and hampers oil production.

2.6 **DOWNHOLE WATER LOOP TECHNOLOGY**

Due to the drawbacks of DWS technology, DWL technology was developed on the basis of DWS well. A DWL well is a triple-completion well. One perforation locates at oil zone; the other two locate at water zone. These three completions are separated by two packers. Similar to DWS, the top most completion at oil zone is used for oil production and the second completion is used to produce water simultaneously near oil-water-contact to stabilize the interface. With a submersible pump installed, the function of lowest completion is to re-inject the water produced at WDI into the same aquifer. DWL technology has the following distinct advantages over other methods of coning control:

1. Increase of critical rate and decrease of water cut
2. Reduce the amount of produced water, which is environmental friendly and economical
3. Drainage water of DWL well would not be lifted to the surface. Comparing to DWS well, DWL well has better performance at reservoir pressure maintenance, especially for reservoirs with weak bottom-water-drive.

As water-coning is a complex and dynamic process, DWL production system need to be carefully designed. Several well and reservoir properties are considered to have potential effect on the performance of DWL well: DI spacing, vertical/horizontal permeability anisotropy ratio, penetration length, top and bottom rate, perforation length, formation damage effect, oil/water viscosity ratio etc (Jin et al. 2010).

2.7 **IDEA OF TWIN-HORIZONTAL WATER LOOP TECHNOLOGY**

In the previous study of water-coning, two situations have been studied by scholars: reservoirs are underlain by inactive aquifer and underlain by active aquifer. When reservoir has constant pressure at outer boundary with an inactive aquifer underneath, DWL well is found to be effective through numerical simulation (Jin et al. 2010). At the situation of active aquifer and limited oil reserve, we found DWL well is not effective comparing to DWS well based on the result of our reservoir simulation (Figure 8). In order to further improve the performance of DWL at bottom-water-drive reservoir, we introduce the concept of twin-horizontal water loop technology.
When simulating the performance of DWS and DWL well at bottom-drive-reservoir, we found that when choosing a reservoir model with a small finite numerical aquifer comparing to oil zone size (an infinite analytical aquifer is set underneath the reservoir model for energy supply), DWS well is much more effective than DWL well. At first instance we thought that short distance between water drainage interval and drainage water re-injection interval (DI spacing) led to a highly ineffective loop (i.e., much of the re-injected water was drained again by the WDI). Further scrutiny of results revealed that pressure distribution also played a significant role on the production efficiency. In commercial reservoir simulator, more invaded bottom water from active aquifer flows into the reservoir close to the outer boundary. This is the realistic situation in real world. When numerical aquifer is relative thin, influx water from infinite analytical aquifer has great influence on pressure distribution at the oil zone. As stated at chapter 2, water-coning is caused by potential distribution near wellbore. Right beneath wellbore, vertical pressure gradient is the maximum and decreasing gradually along radial direction, that’s the reason why water is sucked up below well bottom of a partial-perforated well. When applying DWS technology, vertical pressure gradient along wellbore direction is reduced due to WDI. Meanwhile, bottom water influx from the outer side of model increases vertical pressure gradient at far-wellbore-zone. Both of these reasons lead to a flatter oil-water-contact, mitigate the effect of water-coning and enhance oil recovery factor dramatically.
Inspired by this finding, it is a logical thinking that if vertical pressure gradient at near-wellbore area can be diminished while artificially growing vertical pressure gradient at area close to outer boundary, water-coning can be effective controlled; the oil-water-contact moves up more flatly. Twin-horizontal downhole water loop (THDWL) technology is put forward based on this idea. Twin-horizontal downhole water loop well is a quadruple-completed well. Comparing to DWL well, THDWL well has two symmetric horizontal sections for drainage water re-injection below WDI instead of a simple extension of vertical well. These two horizontal sections should be placed close to oil-water-contact to maximum pressure influence at oil zone. In the meantime, WRI should be extended to the outer boundary of the reservoir. Besides attenuating the effect of water-coning, THDWL well adds two additional “injectors” to displace oil, which could be very helpful to increase displacement factor. Simulation result proves that THDWL production system has a better performance than conventional well, DWS well and DWL well while producing much less water at the surface.
Figure 10 THDWL production system
CHAPTER 3 NUMERICAL MODEL

As already mentioned, many numerical studies of water-coning have been reported in the literature (MacDonald and Coats et al. 1970; Kuo and DesBrisay 1983; Høyland 1989; Yang et al. 1991). Among these numerical studies, only that of Yang assumes: (a) no-flow across the outer boundary and (b) formation is underlain by a recharged bottom aquifer. Other numerical and analytical studies assume a constant pressure at outer boundary and steady state flow condition (Figure 5), which is only valid for very large reservoirs. In this study we adopted the approach of Yang et al. As this model is more suitable for investigating reservoir performance due to depletion effects, in terms of water cut development and recover factor.

3.1 FORMULATION OF THDWL PRODUCTION SYSTEM

Schematic drawing of THDWL well is presented at Figure 10.

Continuity equation:

\[-\nabla \left( \rho_i \bar{V}_i \right) = \frac{\partial}{\partial t} \left( \rho_i \phi_i S_i \right) + \rho_i q_i \] (3-1)

Darcy’s law:

\[\bar{V}_i = -K_i \frac{k_i}{\mu_i} (\nabla P_i + \rho_i g) \] (3-2)

The subscript \(i\) indicates for either oil or water phases in two phase flow condition.

Substituting the velocity equation based on Darcy’s law (3-2) into equation (3-1), the following equation is thus obtained

\[\nabla \left( \rho_o K \frac{k_w}{\mu_o} (\nabla P_o + \rho_o g) \right) = \frac{\partial}{\partial t} \left( \rho_o \phi S_o \right) + \rho_o q_o \] (3-3)

\[\nabla \left( \rho_w K \frac{k_w}{\mu_w} (\nabla P_w + \rho_w g) \right) = \frac{\partial}{\partial t} \left( \rho_w \phi S_w \right) + \rho_w q_w \] (3-4)

At oil production interval, \(q_o=\)oil production rate, \(q_w=\)water production rate

At WDI, \(q_w=\)water drainage rate

At WRI, \(q_w=\)water re-injection rate, which is half of water drainage rate

\(S_w + S_o = 1\)

\(P_o = P_o - P_w\)

The capillary pressure depends on water saturation \(S_w\).
It is assumed no flow across the outer boundary of the cylinder model.

\[
\frac{\partial P}{\partial r} = 0 \quad \text{when} \quad r = r_c
\]

At the bottom side of the cell, the boundary condition can be expressed as:

\[
K \frac{k_w}{\mu_w} \left[ \frac{\partial P}{\partial z} + \rho_w g \right] \mid_{z=0} = -\frac{q_w}{\pi r_c^2}
\]  

(3-5)

Due to the existence of capillary pressure, an oil-water transition zone would be formed in the reservoir. A relationship between height above free-water-level and capillary pressure is derived from consideration of the gravity-capillary pressure force equilibrium and is expressed in SI unit as (Archer and Wall, 1986):

\[
P_c(S_w) = \frac{H(S_u)(\rho_w - \rho_o)}{102}
\]  

(3-6)

Oil zone above transition zone:

\[ S_o = 1 - S_{wc} \quad \text{and} \quad S_w = S_{wc} \]

Water zone below free-water-level:

\[ S_o = 0 \quad \text{and} \quad S_w = 1 \]

It is not feasible to solve these equations analytically. Two-phase flow in three dimension system can only be solved numerically, even if some assumptions are used to simplify the problem. Numerically solving these equations can be completed by a black oil simulator, which is a mature technology in petroleum industry and widely used by petroleum engineers.

### 3.2 DESCRIPTION

A commercial black oil simulator CMG® IMEX was used in this work to study oil production performance of conventional well, DWS well, DWL well, THDWL well. The bottom-water-drive reservoir model is a radial numerical model comprises 100 layers at z-direction, 6 radial subdivisions and a certain number of grids in the radial direction (to be determined by numerical sensitivity analysis). Along radial direction, grid size is gradually increasing based on geometric progression. At oil zone, height of grid at z-direction is half of the height at water zone (oil zone: 40×0.5m, water zone: 60×1m). The following assumptions are made in the simulation (Figure 11).

1. No-flow at the outer and top boundary of the model
2. Oil zone is underlain by a strong and rechargeable aquifer
3. Reservoir is homogeneous but anisotropic
4. Only oil phase and water phase existed in the model
5. Capillary is not negligible

Attention need to be paid that capillary pressure is taken into account in this study, thus we use free-water-level to describe oil-water-contact due to the existence of oil-water transient zone.

Figure 11 Radial reservoir model (3D)

Figure 12 Areal view of radial reservoir model
### Table 1 Reservoir property

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage radius, m</td>
<td>1000</td>
</tr>
<tr>
<td>Wellbore radius, m</td>
<td>0.18</td>
</tr>
<tr>
<td>Oil Zone thickness, m</td>
<td>20</td>
</tr>
<tr>
<td>Numerical Water Zone thickness, m</td>
<td>60</td>
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<tr>
<td>Horizontal permeability, mD</td>
<td>400</td>
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<tr>
<td>Vertical permeability, mD</td>
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<tr>
<td>Length of top completion, m</td>
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</tr>
<tr>
<td>Length of oil column above top completion, m</td>
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</tr>
<tr>
<td>Porosity</td>
<td>0.1</td>
</tr>
<tr>
<td>Depth of oil-water-contact, m</td>
<td>3040</td>
</tr>
<tr>
<td>Depth of reservoir top, m</td>
<td>3020</td>
</tr>
</tbody>
</table>

### Table 2 Fluid property

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil density, kg/ m³</td>
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</tr>
<tr>
<td>Water density, kg/ m³</td>
<td>1055</td>
</tr>
<tr>
<td>Oil viscosity, mPa.s</td>
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<tr>
<td>Water viscosity, mPa.s</td>
<td>0.4</td>
</tr>
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<tr>
<td>Water formation volume factor</td>
<td>1.03</td>
</tr>
<tr>
<td>Oil compressibility, MPa⁻¹</td>
<td>2*10⁻³</td>
</tr>
<tr>
<td>Water compressibility, MPa⁻¹</td>
<td>4*10⁻⁴</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.1</td>
</tr>
<tr>
<td>Depth of oil-water-contact, m</td>
<td>3040</td>
</tr>
</tbody>
</table>

### Table 3 Production constraints

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production surface liquid rate, m³/d</td>
<td>300</td>
</tr>
<tr>
<td>Water cut</td>
<td>&lt;98%</td>
</tr>
<tr>
<td>Oil production rate, m³/d</td>
<td>&gt;4.45</td>
</tr>
</tbody>
</table>
Figure 13 Relative permeability

Figure 14 Capillary pressure curve
3.3 BOTTOM WATER INFLUX MODEL

Aquifer plays an important role in bottom-water-drive reservoir: it supplies energy to the connected reservoir in the form of water influx which helps maintaining reservoir pressure. In reservoir simulation studies, aquifers can be represented either as numerical aquifers (additional grid blocks added) or analytical aquifers. In this study, both of the methods are used. 150×6×60 grids are located below free-water-level which is referred to as numerical aquifer, and an infinite analytical aquifer is added below the it.

Basically, numerical aquifer is convenient and accurate, since it provides exact geometrical and probable geological description of the phenomenon. Aquifer properties can be easily modified by changing grid properties. Numerical aquifer can be useful for a relatively small aquifer or an aquifer with small volume of oil or dissolved gas contained. However, the disadvantage of numerical aquifer is increasing the number of blocks would results in increasing computing time and storage space. For very large aquifers, an equally large number of grids are needed to represent the aquifer correctly, with the risk of converging problem in addition. As this study is based on the condition of strong aquifer, besides a finite numerical aquifer added for drainage water reinjection, an infinite analytical aquifer is added as well. The parameters of the numerical aquifer are shown at Table 2 and Table 3.

Analytical aquifer means the calculation of this aquifer is solved analytically instead of numerically. There are two famous analytical methods: Fetkovich aquifer (1971) and Carter-Tracy aquifer (1960).

Fetkovich aquifer is based on pseudo-steady-state aquifer productivity index and an aquifer material balance to represent a finite compressible aquifer system. This kind of aquifer is easy to define and has fast calculation speed. It assumes that water flows from the aquifer to reservoir is in similar manner to the flow from reservoir to wellbore, which is valid for an oil reservoir underlain by a much larger aquifer. Fetkovich aquifer is the simplest way to represent an analytical aquifer. It is applicable for finite aquifers and infinite aquifers. The Fetkovich aquifer model in CMG® requires the following 6 input parameters: aquifer thickness, aquifer porosity, aquifer permeability, effective reservoir external radius, reservoir/aquifer contact angle and ratio between the external aquifer radius and the reservoir external radius (Rd).

In this study, we have chosen the Carter-Tracy aquifer which is based on van Everdingen-Hurst method (1949). The Carter-Tracy method eliminates superposition calculation and gives results close to the results given by van Everdingen-Hurst method. They assumed constant water influx rate for finite period of time. In combination with material balance and flow equation, an equation is given for the explicit step-wise calculation of pressure history for a prescribed oil-production history. Since
Carter-Tracy method is based on the solution of radial flow equation, it is a rigorous mathematic solution and provides accurate result. Carter-Tracy method can simulate all kinds of aquifers with quick calculation speed; however, the definition of Carter-Tracy method is more complicated than Fetkovich method. For Carter-Tracy method, it requires different table entry (include dimensionless time $t_D$ and $P(t_D)$) to simulate a given aquifer extent (value of $R_d$). As the value of $R_d$ changes, the entry table needs to be adjusted as well. For infinite aquifer, which is the default setting of CMG®, table entry doesn’t need to be input manually. Aquifer thickness, aquifer porosity, aquifer permeability, effective reservoir eternal radius, reservoir/aquifer contact angle are the only parameters need to be input. As for finite aquifer with finite $R_d$, the user needs to enter the correct table for a pre-determined value of $R_d$.

<table>
<thead>
<tr>
<th>Table 4 Analytical aquifer properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical aquifer type</td>
</tr>
<tr>
<td>Aquifer thickness, m</td>
</tr>
<tr>
<td>Aquifer porosity</td>
</tr>
<tr>
<td>Aquifer permeability, mD</td>
</tr>
<tr>
<td>Effective reservoir eternal radius, m</td>
</tr>
<tr>
<td>Contact angle, radians</td>
</tr>
</tbody>
</table>

### 3.4 NUMERICAL SENSITIVITY

Figure 15 and 16 show schematically the radial reservoir models used for the numerical simulation of water-coning. The grid size along radial direction increases according to a geometric progression. This radial grid pattern can effectively capture the variations of pressure along the radial direction, especially for radial flow of single-phase fluid.

Pressure distribution for radial flow of single-phase fluid in cylindrical models:

$$P = P_e - \frac{P_e - P_w}{\ln \frac{r_w}{r}} \ln \frac{r}{r_w}$$

Equation (3-7) indicates that the pressure from external boundary to wellbore has a logarithmic relationship with radius. During production, pressure gradient along radial direction is large at near-wellbore area, while being insignificant at the area near external boundary. This phenomenon is referred to as pressure drop funnel. Grid size following geometric progression results in small grid size at near-wellbore area and much larger grid size at the area near external boundary, which is very appropriate for representing this logarithmic relationship between pressure and radius. As for two-phase flow in cylindrical model, similar trend can be found that pressure gradient
at near-wellbore area is much greater than that at far-wellbore area. This geometric-progression-grid-partition is still suitable for simulating two-phase flow in cylindrical model. However, two-phase flow is a dynamic process; oil is displaced by water gradually as time goes by. Besides pressure distribution, saturation profile should also be taken into account when deciding grid partition. Grid size must be fine enough to accurately capture the change of water/oil saturation at each time step, which would have relatively huge effect on the simulation result.

A sensitivity analysis of grid size was carried out in order to determine the optimum grid size. A series of radial models with different grid sizes in the radial direction were built and run for 15 years. For all the models, grid size along radial direction increases according to a geometric progression, however, the number of grid is different. A conventional well is located at the center of the models with identical completion for oil production. Production rate and other rock-fluid properties are kept the same. Cumulative oil production data was collected for grid size sensitivity analysis.

Figure 15 Areal view of the geometric-progression-grid-partition along radial direction (25 grids at radial direction)
Figure 16 Areal view of the geometric-progression-grid-partition along radial direction (160 grids at the radial direction)

At Figure 17, cumulative oil productions of each model are plotted as a function of grid-number at radial direction. Shown at Figure 17, as the number of grid increases, cumulative oil production follows the trend of decline. This decreasing trend starts to be mitigated when grid number is larger than 60. When grid number is higher than 140, cumulative oil production curve is relatively stable with negligible error. Based on this sensitivity analysis, we choose 150 grid blocks in radial direction. We believe this grid pattern along radial direction is sufficient to obtain relative accurate simulation results while having acceptable CPU time. Reservoir simulation result reveals that this fine geometric-progress-grid-pattern can precisely represent the change of free-water-level (shown at Figure 18).
Figure 17 Relation of cumulative oil production and grid-size

Figure 18 Water saturation profile of model has 150 grids at radial direction (half of radial-cross-section)
CHAPTER 4 CONCEPTUAL DESIGN OF DES, DWL AND THDWL WELL

DWS, DWL and THDWL well are sophisticated production systems including several parameters can be controlled manually. In this chapter, conceptual designs of DWS, DWL and THDWL wells have been presented after careful analysis of the effects these parameters have on production performance.

4.1 CONCEPTUAL DESIGN OF DWS WELL

A schematic drawing of DWS well is presented at Figure 19. In DWS system, length/position of oil production completion, total production rate, length/position of water drainage interval (WDI), water drainage rate are parameters need to be designed and optimized by petroleum engineers. In our study, we only focused on the parameters related to water drainage interval. Since oil production interval and water drainage interval are two relatively isolated systems with different functions. Under any oil production conditions, better design of WDI would have more enhanced water-coning attenuation effect and a better oil production performance accordingly. Design and operation constrains of oil production interval are presented at Table 1 and Table 3 in Chapter 3.

![Figure 19 DWS production system](image)

Under the same oil production condition, water-coning attenuation and water cut reduction effect of DWS system is evaluated by oil recovery factor after 15 years of production.

The first parameter investigated is water drainage interval length (h_{WDI}). The WDI
starts from 2 meters below free-water-level (i.e., $h_{WDI}=2m$), the water drainage rate maintains to be 300 m$^3$/d which is equal to production rate.

![Figure 20 Recovery factor of DWS production system as a function of $h_{WDI}$](image)

Figure 20 shows that the recovery factor (after 15 years) decreases steadily when $h_{WDI}$ increases, although the amount of decrease is negligible. The increase of geometric skin attributes to this decline of recovery factor.

In order to achieve its function of water-coning control, water drainage completion doesn’t perforate the whole reservoir and aquifer interval. The flow to WDI is a combination of radial flow and spherical flow. The spherical flow causes more pressure drop than radial flow at the same flow rate, and this addition pressure drop due to spherical flow is defined as geometric skin. The shorter completion interval is, spherical flow would be more dominated, which would results in a larger geometric skin and more pressure drop. At the same production condition, BHP (bottom hole pressure) at WDI is lower in this condition.

$$\Delta P_{skin} = \frac{Q_l B_o \mu_w}{2\pi k_a h_{WDI}} S_{geo} \quad (4-1)$$

The main principal of DWS technology is that addition pressure drawdown provided by WDI can counteract the upward force of free-water-level. With more pressure drawdown provide, the upward velocity of free-water-level is slower. Even though at bottom-water-drive reservoirs, the upward force cannot be completely offset. However, lower BHP means a larger pumping capacity is needed for lifting drainage water to the surface. When reservoir pressure is high enough and a high BHP corresponding, this drawback is negligible. Furthermore, shorter perforation interval
implies high water inflow velocity at the same water drainage rate. Sand production could be a severe problem at this condition for some reservoirs. In conclusion, it is recommended to take the shortest possible WDI length. The choice of WDI length needs to take reservoir pressure and sand production into consideration. Figure 21 indicates that BHP is lower when $h_{WDI}$ is shorter, which is in coincide with our judgment.

It is found a small amount of oil would be “drained” by WDI at the first year of production (Figure 22). This is because that at free-water-level, mobility contrast and gravity contrast of oil and water cannot offset the pressure gradient generated by WDI when free-water-level and WDI are very close. Free-water-level shifts downside toward WDI at near-wellbore area, oil is “drained” accordingly. As free-water-level gradually moving up due to the effect of bottom-water-drive, distance between oil zone and WDI goes up as well. Oil flows down to WDI need a larger energy consumption. At the same time, pressure gradient imposed on oil generated by WDI decreases as the increase of distance. Effect of mobility contrast and gravity contrast of oil and water overwhelms the effect of pressure drop at WDI, pure water flows to WDI. At Figure 21, a clear fluctuation of BHP at WDI can be witnessed at the first year of production due to the effect of “drained” oil. After the first production year, curve of BHP at WDI become flat and steady state flow condition reaches, which implies two facts: the flow to WDI is single phase flow (i.e., pure water flow), and it is justified by Figure 22; aquifer is very strong to maintain the reservoir pressure constant.

![Figure 21 Well bottom hole pressure at WDI at different $h_{WDI}$ value](image)

Figure 21 Well bottom hole pressure at WDI at different $h_{WDI}$ value
The second and third parameters researched are water drainage rate and WDI location ($h_{\text{WDI}}$). We set a series of water drainage rates and $h_{\text{WDI}}$ values to investigate the influence of these two parameters have on production performance while keeping $h_{\text{WDI}}=2\text{m}$. The simulation results are shown in Figure 23.

![Figure 22 Oil drainage rate at different $h_{\text{WDI}}$ value](image)

![Figure 23 Recovery factor of DWS production system at a series of water drainage rates and water drainage interval locations](image)
Figure 22 indicates that water drainage rate plays a dominant role for oil production enhancement. The recovery factor after 15 years rises linearly as the increase of water drainage rate. According to simple Darcy’s law, pressure drop has a linear relationship with flow rate. A larger water drainage rate mains a larger pressure drop at WDI, which is beneficial for water coning attenuation. Meanwhile, after water breakthrough, a larger water drainage rate at WDI implies higher water flow rate from water-cone to WDI. In another word, the water flow from water-cone to oil production interval is lower as a consequence. Water cut at oil production interval decreases consequently, more oil is produced at the same liquid production rate.

Figure 23 Water cut at oil production interval for DWS well (h\text{WDI}=2 m, h\text{aWDI}=2m)

As for the influence of h\text{aWDI}, it can be observed from Figure 23 that oil recovery factor is the maximum when water drainage interval is just below free-water-level. The impact of h\text{aWDI} is more significant than h\text{WDI}. However, at the same water drainage rate, the maximum recovery factor difference we observed in our simulation due to the effect of h\text{WDI} is 0.68%, which is relatively unimportant. Under further scrutiny, we think two reasons contribute to effect of h\text{aWDI} has on production performance: BHP at WDI and imposing pressure gradient on free-water-level generated by WDI.

As stated before, if WDI is placed near free-water-level, oil “drained” by WDI is unavoidable at the early stage of production. Oil flows to WDI only need to compensate a little energy, which is provided by pressure drop at WDI. Shown at Figure 25, when h\text{aWDI} is large enough (e.g., h\text{aWDI}=10m and h\text{aWDI}=20m), no water
been “drained” by WDI. The amount of “drained” oil increases as the decrease of $h_{aWDI}$ under the condition of same water drainage rate. Since oil is less mobile than water, according to Darcy’s law, at the same flow rate, a larger pressure drop is needed for oil flow comparing to water flow. Therefore, at the equal drainage rate, more oil included in drainage liquid would results in a larger pressure drop and lower BHP, which is proved by Figure 25 and Figure 26.

![Figure 25 Cumulative amount of oil “drained” by WDI at a series of water drainage rates and values of $h_{aWDI}$](image-url)
As for imposing pressure gradient on free-water-level generated by WDI, flow of water and oil above WDI to this drainage completion can evaluated as spherical flow. For single-phase-spherical flow at steady state condition, pressure gradient at certain location of sphere can be calculated by:

$$\frac{dp}{dr} = \frac{p_e - p_w}{\frac{1}{R_w} - \frac{1}{r^2}}$$

(4-2)

From equation 4-2, it is clear that pressure gradient descends when radius of sphere ascends. For two-phase flow at transient flow condition or steady-state-flow conditions, the relationship between pressure gradient and spherical radius is not strictly coincident with equation 4-2. However, similar trend can be found. If distance between free-water-level and WDI is longer, the pressure gradient imposing on free-water-level is weaker. The effect of WDI has on stabilizing free-water-level is worse in this case.

From previous analysis in this chapter, it seems to be a paradox that more oil is “drained” by WDI is preferred, since a lower BHP is achieved as a consequence, which contributes to water-coning control. On the other hand, drainage water which would be lifted to the surface needs to be treated when it is mixed with oil. Treatment of oil-water mixture is costly. Furthermore, two-phase flow reduced the efficiency of pump. However, shown at Figure 22, the phenomenon of oil drainage only exists at
the first year of production. Secondly, only a little amount of oil is “drained”, and it is still true at very large water drainage rate. Thus we believe oil “drained” by WDI is not a severe problem. Choosing of $h_{aWDI}$ need to take water drainage rate, water treatment cost and pump capacity into consideration. This choice needs to be relied by actual field data. Principally, it is recommended to choose a relative long $h_{aWDI}$ OWC under high water drainage rate.

Our study provides a conceptual design for DWS well. A $9 \frac{5}{8}$ inch casing is used with a $5 \frac{1}{2}$ inch liner installed at the tail of casing for WDI. Two parallel $2 \frac{7}{8}$ inch tubing are set, both are permanently constrained by two sets of hydraulic packer. For each tubing, an electric submersible pump (ESP) is installed, one for oil production, one for water drainage. There are different series of ESP which are designed for different case size and liquid capacity. According to analysis in this chapter, we want to use the largest water drainage rate possible for the best water-coning attenuation and water reduction effect. From APPENDIX A, the ESP can be installed in $5 \frac{1}{2}$ inch liner that has largest liquid capacity is D5800N. This series of ESP has recommended liquid capacity from 699.54 to 1112.91 m$^3$/d, which means the maximum water drainage rate can be achieved is 1112.91 m$^3$/d if this type of ESP is installed. Since the exact field data is not provided, choosing for the optimized value of $h_{WDI}$ and $h_{aWDI}$ could be difficult. We simply take comprise values which have been investigated: choosing $h_{WDI}=2$ m and $h_{aWDI}=2$ m.

<table>
<thead>
<tr>
<th>Table 5 Conceptual design parameters for DWS production system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of water drainage interval ($h_{WDI}$), m</td>
</tr>
<tr>
<td>Water column height above water drainage interval ($h_{aWDI}$), m</td>
</tr>
<tr>
<td>Water drainage rate, m$^3$/d</td>
</tr>
</tbody>
</table>
Figure 27 Conceptual design of DWS production system for bottom water-drive-reservoir model

4.2 CONCEPTUAL DESIGN OF DWL WELL

A schematic drawing of DWL well is presented at Figure 28. Similar to DWS production system, several design parameters of DWL well can be controlled manually: length/position of oil production completion, total production rate, length/position of water drainage interval (WDI), water loop rate, length of water re-injection interval (h) and drainage-injection spacing (DI spacing). In DWL well, oil production interval, water drainage interval and water re-injection interval (WRI) are three comparatively isolated systems. The design parameters related to WDI have been evaluated thoroughly at chapter 4.1. Therefore, in this chapter, we only focus on water loop rate and the parameters related to water re-injection section (DI spacing)
and \( h_i \). Parameters of WDI section we simply take the values chosen for conceptual design of DWS well \( (h_{WDI}=2\text{m}, h_{aWDI}=2\text{m}) \). Design and operation constrains of oil production interval are presented at Table 1 and Table 3 in Chapter 3.

![Diagram of DWL production system](image)

**Figure 28 DWL production system**

Similar to chapter 4.1, under the same oil production condition, water-coning attenuation and water cut reduction effect of DWL system is evaluated by oil recovery factor after 15 years of production.

The first parameters been evaluated is water re-injection interval length \( (h_i) \). Other control variables are maintained constant \( (\text{DI spacing}=44\text{m}, \text{water loop rate}=300 \text{ m}^3/\text{d}) \).
Figure 29 Recovery factor of DWL production system as a function of $h_i$

From Figure 31, an ascend trend of recovery factor can be observed, although the value of $h_i$ seems to have very little effect on recovery factor. Obviously, WRI has a side effect at water-coning control. In order to re-inject drainage water to the aquifer, BHP at WRI is high. Therefore, an additional upward pressure gradient would be imposed at free-water consequently, which counteracts water-coning suppression effect of WDI. Similar to the analysis of $h_{WDI}$, a shorter completion interval means a larger geometric skin factor. Re-injecting water at larger geometric skin factor needs to overcome more resistance, which would result in a higher BHP at WRI. Since the distance between original free-water-level and WRI is constant in this series of simulations, a higher BHP means a higher upward pressure gradient would be imposed at free-water-level, and a worse water-coning control as a consequence (Figure 30). Therefore, the longer water re-injection interval length is a better design for DWL well.
DI spacing and water loop rate are believed to have important influence on water-coning control and water cut reduction after water breakthrough (Lin et al. 2010). A series value of DI spacing and water loop rate have been set to instigate of these two parameters. Value of $h_i$ is maintained to be 2 meters.

According to simple Darcy’s law, pressure drop has a linear relationship with flow...
rate. A larger water loop rate means a larger pressure drop at WDI, which is good for water coning; however, it also means a higher pressure increment at WRI, which would accelerate the moving up of free-water-level. Meanwhile, after water breakthrough, a larger water loop rate implies more water could be drained from water cone to WDI; but it also implies a higher water re-injection rate at WRI. At this condition, re-injected water is more likely to be sucked by WDI again, which could reduce the ability of WDI at water cut control. Therefore, it is a paradox that a large water loop works better if we only focus on WDI. But the disadvantage of high water loop rate at WRI counteract its advantage at WDI. Figure 31 shows that the recovery factor of DWL production system increases as the increase of water loop rate. So the benefit of high water loop rate overwhelms its drawback. The increment of the recovery factor due to the increase of water loop rate slows down at high water loop rate.

Figure 31 also indicates that larger DI spacing leads to a better production performance. The flow of re-injected water toward free-water-level can be regarded as single-phase-spherical flow. According to equation 4-2, as the distance between free-water-level and WRI increases, upward pressure gradient imposed on free-water-level would decrease. Meanwhile, water flow from WRI to WDI decreases. The side effect of WRI mitigates at larger DI spacing. Hence, it is recommended to choose a long DI spacing. Even though drilling cost would increase slightly for a longer DI spacing.

Attention need to be paid that a little amount oil would be drained by WDI when it is placed close to free-water-level, which is the same as DWS well. The volume of “drained” oil increases with water loop rate. Unlike DWS well, “drained” oil would not be lifted to the surface for DWL well. Therefore, we think the disadvantage of “drained” oil is negligible at DWL production system.

A conceptual design for DWL well is presented based on previous analysis in this chapter. A $\frac{5}{8}$ inch casing is used with a $\frac{7}{8}$ inch liner installed at the tail of casing for WDI and WRI. Two parallel 2$\frac{7}{8}$ inch tubing are set, both are permanently constrained by two sets of hydraulic packer. For each tubing, an ESP is installed, one for oil production, one for water looping. The same as DWS well, D5800N series of pump is chosen to achieve largest possible water loop rate (1112.91 m$^3$/d) in $\frac{5}{2}$ inch liner. The ESP installed in DWL well for water loop needs much fewer stages and electricity consumption comparing to ESP installed in DWS well for water drainage and lifting. In the process the water loop, water would be lifted to the surface and gravity assists water re-injection. To maximum the water-coning attenuation effect, we choose the longest possible DI spacing in our model: 54 meters. The value of $h_i$ is
proved to be insignificant, we simply choose $h_i=2m$ in this conceptual design. Design of WDI is the same as conceptual design for DWS well.

Table 6 Conceptual design parameters for DWL production system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of water drainage completion ($h_{WDI}$), m</td>
<td>2</td>
</tr>
<tr>
<td>Water column height above water drainage interval ($h_{aWDI}$), m</td>
<td>2</td>
</tr>
<tr>
<td>Length of water drainage re-injection completion ($h_i$), m</td>
<td>2</td>
</tr>
<tr>
<td>Water loop rate, m$^3$/d</td>
<td>1100</td>
</tr>
<tr>
<td>DI spacing, m</td>
<td>54</td>
</tr>
</tbody>
</table>

Figure 32 Conceptual design of DWL production system for bottom-water-drive reservoir model
4.3 CONCEPTUAL DESIGN OF THDWL WELL

Schematic drawing of THDWL is shown at Figure 10 in Chapter 2.7. In THDWL production system, water re-injection intervals are placed at the end at two symmetric horizontal sections. For THDWL well, length/position of oil production interval, total production rate, length position of water drainage interval (WDI), water loop rate, length of horizontal section for drainage water re-injection (L_d), length of water re-injection interval (h_i), and distance between water re-injection interval to free-water-level (h_ai) can be controlled manually. In THDWL well, oil production interval, water drainage interval and water re-injection interval are three relatively isolated systems, which is the same as DWL well. In this chapter, we only investigate the parameters related to WRI: water loop rate, L_d, h_i, and h_ai. Parameters of WDI section we simply take the values chosen for conceptual design of DWS well (h_WDI=2m, h_aWDL=2m). Design and operation constrains of oil production interval are presented at Table 1 and Table 3 in Chapter 3.

Under the same oil production condition, water-coning attenuation and water cut reduction effect of THDWL system is evaluated by oil recovery factor after 15 years of production.

The effect of water re-injection interval length (h_i) has been investigated carefully at DWL well which is evaluated to be negligible. As for THDWL well, we found the same conclusion can be drawn. Therefore, the effect h_i would not be specifically analyzed in this chapter.

As for the effect of distance between water re-injection intervals and free-water-level (h_ai), we found at different value of L_d, this parameter has diverse influent on production performance. At the condition of large L_d (horizontal well is longer than 500 meters), a small value of h_ai would be preferred. But at the condition of small L_d (horizontal well is shorter than 300 meters), a large value of h_ai would be more beneficial to oil production enhancement (Figure 33).
When the value of $L_i$ is small, the performance of THDWL well is very similar to DWL well. If a smaller value of $h_{ai}$ is chosen at this condition, at near-wellbore-zone, WRI would impose a larger upward pressure gradient at free-water-level. This effect is not good for water-coning control. At the same time, re-injected water is more likely to be drained by WDI again. A large value of $h_{ai}$ can mitigate the effect of WRI has on free-water-level. When the value of $L_i$ is large enough and horizontal well for drainage water re-injection extends to far-wellbore-zone, upward pressure gradient generated by WRI mainly affect free-water-level at far-wellbore-zone. Stated at Chapter 2, water-coning is a phenomenon occurred at near-wellbore-zone due to potential distribution, upward pressure gradient imposed at far-well-zone would not contribute to water-coning development and the re-injected water is less likely to be drained by WDI again. Furthermore, the upward pressure gradient generated by WRIs (two water re-injection intervals are include in THDWL well) can “push” oil above them aside. In another word, at far-well-zone, WRIs can be regarded as injectors. In this situation, a higher upward pressure gradient imposed on free-water-level would be preferred. If a smaller $h_{ai}$ is chosen, a higher upward pressure gradient at free-water-level can be obtained. More oil would be “pushed” to producer from far-wellbore-zone consequently, even though the increment of oil production is negligible.

The most crucial parameters for THDWL production system are water loop rates and length of horizontal section for drainage water re-injection ($L_i$).

Figure 33 Recovery factor of THDWL production system at a series of $L_i$ and $h_{ai}$ value ($h_i=32.6$ m, water loop rate=300 m$^3$/d)
Oil recovery factor increases as the increase of $L_i$. However, when the length of the horizontal well for drainage water re-injection exceeds 700 meters, further increasing oil recovery factor is not that obvious.

It has already been stated that WRIs of THDWL well can be regarded as injectors if they are located at far-wellbore-zone. Precisely interpreting the effect of $L_i$ could be challenged, since the flow pattern of THDWL well is too complicated: flow of invaded bottom-water, flow of water to WDI, flow of water from WRI and flow of oil and water to producer. Currently, no flow theory can accurately describe such complex flow pattern. Therefore, an approximate theory is developed which only focuses on the oil flow to producer due to re-injected water displacement. The process that re-injected water displaces oil to producer can be estimated as Buckley-Leverett approach. If WRI are placed at the outer boundary of reservoir, re-injected water can effectively displace oil of the whole reservoir, which results in a large cross-section of water-oil displacement front. Conversely, if WRI are placed at near-wellbore-zone, only a little amount of oil can be “pushed” by re-injected water, which leads to a small cross-section of displacing front.

If liquid production rate and injection rate are constant, a larger cross-section of water-oil displacement front means a slower moving speed of this front. Figure 35 indicates that after 15 years of production, displacing front of re-injected water and oil reaches producer when $L_i=500m$. If $L_i$ extends to 700 meters, after 15 years of production, the displacement front still does not reach the producer.
production, displacing front still has a distance away from the producer (Figure 36).

According to Buckley-Leverett theory, before the moment that displacing front reaches producer, producer should produce pure oil. When displacing front reaches producer,
water cut at producer immediately increases to so-called “shock saturation” at the displacing front. After water breakthrough, water cut gradually increase until the moment water cut=100%. We assume that flow of oil and water to producer due to other factors (e.g., invaded bottom-water displacement, water flow from water cone) are equal at all values of $L_i$ along time. Therefore, at constant production rate and injection rate, before the moment that displacement front of re-injected water and oil reaches producer, water cut of produced liquid should equal for all value of $L_i$ along time. However, small value of $L_i$ would result in earlier moment that displacing front reaches the producer; water cut of producer immediately increases accordingly. Comparing to whose displacing front is still away from producer; production performance is poorer in this case. Therefore, when $L_i$ is smaller than 700 m, as the increase of $L_i$, the arrival time of displacement front of re-injected water and oil increases, more oil can be produced. For all values of $L_i$ larger than 700 m, after 15 years of production, displacing fronts don’t reach producer, oil production performances are similar in these cases. This can roughly interpret when $L_i$ exceeds 700 meters, further increasing of $L_i$ doesn’t has obvious effect on oil recovery factor enhancement.

High water loop rate results in a massive oil production increment. Two reasons results in this increment: first, as specified at chapter 4.2, higher water loop rate attribute to lower BHP at WDI, which has positive effect on water-coning attenuation (Figure 37); Secondly, after water breakthrough, higher water rate reduces water flow from water cone to oil production interval; Thirdly, as analyzed in this chapter, the process that re-injected water at WRIs displaces oil to producer can be estimated as a Buckley-Leverett approach. Comparing to oil driven by bottom-water, oil displaced by WRIs leads to lower water cut at producer. At larger water loop rate, the effect of re-injected water becomes more dominated. Oil flows to producer mainly due to the displacement effect of re-injected water. As a consequence, producer produces oil at lower water cut and more oil is recovered at the surface.
A little amount oil would be drained by WDI when it is placed close to free-water-level. The volume of “drained” oil increases with water loop rate. The same as DWL well, “drained” oil would not be lifted to the surface. Therefore, we think the drawback of “drained” oil is negligible at THDWL production system.

A conceptual design for THDWL well is presented based on previous analysis in this chapter. A 9\(\frac{5}{8}\) inch casing is used at vertical section of well. 5\(\frac{1}{2}\) inch liners are installed at the tail of casing for WDI section and twin-horizontal wells. Two parallel 2\(\frac{7}{8}\) inch tubing are set, both are permanently constrained by two sets of hydraulic packer. For each tubing, an ESP is installed, one for oil production, one for water loop. At WDI, D5800N series of pump is chosen for largest possible water loop rate (1112.91\(m^3/d\)) in 5\(\frac{1}{2}\) inch liner. The ESP installed in THDWL well for water loop needs more stages and electricity consumption than ESP installed in DWL well for the same function, but much fewer stages than that in DWS well for water drainage and lifting. Design of WDI is the same as conceptual design for DWS well: \(h_{WDI}=2m\) and \(h_{WDF}=2m\). Two flexible pipes are connected to ESP D5800N and extend to WRI for drainage water injection. Analysis in this chapter reveals that when \(L_i\) is larger 700 meter, further increasing \(L_i\) doesn’t contribute a lot to final recovery factor after 15 years of production, thus we choose \(L_i=700m\) in the conceptual design. Attention need to be paid that although a small value for \(h_{ai}\) is preferred at the condition that \(L_i=700m\).
Value of $h_{ai}$ has to be longer than the summation of WDI length (4 meters) and ESP length (approximately 10 meters). As a result, we choose the minimum possible value of $h_{ai}$: $h_{ai}=14$ m.

Table 7 Conceptual design parameters for THDWL production system

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Length of water drainage interval ($h_{WDI}$), m</td>
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<td>Water column height above water drainage interval ($h_{aWDI}$), m</td>
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<td>Length of water drainage re-injection completion ($h_{i}$), m</td>
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<td>Water loop rate, $m^3/d$</td>
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<td>length of horizontal section for drainage water re-injection ($L_i$)</td>
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<td>Distance between water re-injection interval to free-water-level ($h_{ai}$)</td>
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Figure 38 Conceptual design of THDWL production system for bottom-water-drive reservoir model
CHAPTER 5 EVALUATION AND FURTHER DISCUSSION OF THDWL PRODUCTION SYSTEM

In this chapter, we evaluate production performance and potential of THDWL well. The following simulations cases were conducted: (a) conventional well, (b) DWS well, (c) DWL well and (d) THDWL well. Design of conventional well is presented at Table 3 in Chapter 3.2. Conceptual design of DWS well, DWL well and THDWL well presented in Chapter 4 are used in this series of simulations. In order to make comparison fair, production constrains and design of oil production interval are maintained constant for all simulation cases (Table 3).

The simulation runs for 15 years.

5.1 SATURATION PROFILE ANALYSIS OF THDWL WELL

THDWL is a complicated production system includes several flow patterns. Analysis of saturation profile change during production can contribute to the understanding of the whole system. First, we focused on the radial-cross-section of the reservoir where horizontal wells for water re-injection locate.

Figure 39 Saturation profile of THDWL (half of the radial-cross-section, 1 month after production)

Figure 39 indicates that at the first stage, WDI considerably affects the shape of water cone. Not only is water retained, but the top of water cone is shifted to the right and is located at approximately r=30m.
Figure 40 indicates at the certain moment, WDI cannot retain water anymore, water breaks into the producer. This can be defined as the second stage of production.

Figure 41 indicates that after water breakthrough, a stable water cone would be formed below the oil production interval. Oil flows to producer at the side of water cone, which can be estimated as partial-spherical flow in combination with radial flow.
The effect of WRIs become obvious and they are important forces driving oil from reservoir to producer. A clear displacement front of re-injected water and oil becomes visible. This stage is defined as the third stage.

At the third stage, displacement front of re-injected water and oil gradually moves to production, at certain moment, this displacing front reaches producer. The production of oil after this moment can be defined as the fourth stage of production. In our simulation, this stage hasn’t been observed due to simulation time.

Simulation results prove that at the radial-cross-section where WRIs locate, THDWL successfully flattens free-water-level during production, even though water-coning is unavoidable. Saturation profile changes of THDWL well and conventional well are shown in APPENDIX B.

However, the reservoir model is a cylinder. At the radial-cross-section away from WRI, the effect of WRI is not that obvious. At the radial-cross-section which is perpendicular to the radial-cross-section where WRIs locate, WRIs have weakest effect at free-water-level. The detail of this phenomenon is shown at APPENDIX C. The only way to solve this problem is increasing WRIs at different directions, which could be very costly. If THDWL wells are placed in 5-spot well pattern, we think a modified THDWL production system can solve part of the problem.
Shown at Figure 43, a 500m*500m well pattern is used. As for modified THDWL production system, only one horizontal well is needed for drainage water re-injection. In this condition, three WRIs can react on one production interval. Comparing to two WRIs, we expect for better production performance.

5.2 PRODUCTION PERFORMANCE COMPARISON OF CONVENTIONAL WELL, DWS WELL AND THDWL WELL

DWS and DWL well share similar theoretical foundation, which mainly focus water-coning attenuation and water flow reduction from water cone to production interval. THDWL well can be described as an extension of DWL well; however, the principle of THDWL well is significantly different from DWL well. Besides the benefits of DWS well and DWL well, THDWL well can also effectively displace oil from WRIs to producer. Simulation results prove that THDWL well has the best production performance. Although DWS well has less production enhancement effect comparing to THDWL well, the performance of DWS well still can be judged as good. However, the performance of DWL well is unacceptable according to simulation results.
Oil production performance of conventional, DWS, DWL, and THDWL well

<table>
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<tr>
<th></th>
<th>Oil production performance of conventional, DWS, DWL, and THDWL well</th>
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<tr>
<td>Oil recovery factor of conventional well after 15 years of production, %</td>
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<td>Oil recovery factor of DWS well after 15 years of production, %</td>
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<td>Oil recovery factor of DWL well after 15 years of production, %</td>
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<td>Oil recovery factor of THDWL well after 15 years of production, %</td>
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<tr>
<td>DWS well: Increment in oil recovery factor comparing to conventional well, %</td>
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<td>DWL well: Increment in oil recovery factor comparing to conventional well, %</td>
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<td>THDWL well: Increment in oil recovery factor comparing to conventional well, %</td>
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In Figure 44, trends of oil production rate curves and water cut curves can help us roughly separate the production into two stages which are suitable for all wells: early stage and stable stage. At the early stage, water cone is forming and unstable. After water breakthrough, at constant liquid production rate, oil rate decreases rapidly while water cut increases fast. At the stable stage, a stable water cone is formed, oil production rate and water cut has much less change comparing to the early stage.
As for the convention well, just 7 days after production, water breaks into producer. Figure 44 indicates for conventional well, water cut grows fastest at the early stage with severe decline of oil production rate. Water cut rises to 90% before it becomes stable. For DWS and THDWS well, water-coning have been controlled successfully. Comparing to conventional well, we got later water breakthrough time; slower water cut increasing speeds at the early stage and smaller values of water cut when the curves become stable. This finding implies that although the forming of water cone at DWS well and THDWL well is unavoidable. The existence of WDI can significantly reduce water-coning development speed and the amount of water flows from water cone to oil production interval after the moment that a stable cone is formed. At the same liquid production rate, water cut is reduced expressively. THDWL well has two additional “injectors”, which help it becomes a better production system than DWS.

From Figure 44 and Table 8, we think previous studies (Lin et al. 2010, 2011) have seriously underestimated the influence of WRI at DWL well. Figure 44 indicates that DWL well contributes to slow down water cut increasing speed at the early of production, even though it is not as good as DWS well and THDWL well. However, after the moment that a stable water cone is formed, the existence of WRI below water cone increases the water flow from water cone to oil production interval. Therefore, a much higher value of water cut is obtained at the stable stage. Meanwhile, we found that re-injected water at WRI can even be sucked by oil production interval (Figure 45).

As a result, when applying DWL technology, oil recovery factor after 15 years of
production can only increases from 5.42% to 7.57%. However, DWS well and THDWL well have oil recovery increments of 15.23% and 16.31% respectively.

5.3 FURTHER DISCUSSION OF THDWL PRODUCTION SYSTEM

In this chapter, three water-coning attenuation methods are evaluated at bottom-water-drive reservoir. Basically, THDWL production system has the best performance. After 15 years of production, recovery factor of THDWL well is 3 times higher than that of conventional well while keeping the same liquid production rate at surface. THDWL overcomes the drawbacks of DWS wells, it reduces water disposal and lifting cost and can be used in weak bottom-water-drive reservoir. Meanwhile, THDWL well has much better water cut control than DWL well.

The main concern for applying THDWL well is the cost. Comparing to conventional well, more investment is needed on drilling two horizontal sections for drainage water re-injection. However, the drilling cost of horizontal well decreases year by year. Kharus (1991) pointed out that the drilling cost of horizontal well is just 30% more than vertical well of the same length. Since THDWL well has dramatic effect on production enhancement in bottom-water-drive reservoir, we believe applying THDWL well would result in good economic performance.

The main bottleneck of THDWL production system is the characteristic of current electrical submersible pump. The performance of THDWL well would be considerably improved at higher water loop rate. In THDWL well, ESP installed for water loop doesn’t need to provide much water head, since drainage water would not be lifted the surface. If a new kind of ESP can be invented, which provides less water head but has larger liquid capacity, the advantage of THDWL well would be more significant.

Ehlig-Economides et al. (1996) found that horizontal well completion can enhance oil recovery at bottom-water-drive reservoir. Therefore, it seems a better recovery factor can be obtained by simply drilling a horizontal well at the top of oil zone for oil production. However, for reservoirs with thin oil zone, drilling a horizontal well at the top oil zone could be very difficult. Instead, two horizontal sections in THDWL well are drilled at water zone, which is of much less technical challenge.

In conclusion, THDWL production system is an innovative and smart technology can be used to develop bottom-water-drive reservoir much more effectively. It deserves further study and development.
CONCLUSION

1. Early water breakthrough and rapid increase of water cut after water breakthrough are the main problems hamper oil production at bottom-water-drive reservoirs.

2. Only a few theories for water coning study are valid at bottom-water-drive reservoirs.

3. Water drainage rate is the main parameter affecting the performance of DWS well. DI spacing and water loop rate play dominant roles at DWL well performance. Water loop rate and length of horizontal section for drainage water re-injection are most crucial design parameters for THDWL well.

4. For bottom-water-drive reservoir with relative large effective radius (1000 m in this study), DWL production system is proven to be less effective.

5. DWS well and THDWL well are proven to be very efficient in this study. After 15 years of production, recovery factor of THDWL well is 3 times higher than that of conventional well under the same liquid production rate.

6. THDWL is an innovative and smart production technology can be used to develop bottom-water-drive reservoir effectively. Although THDWL well need more investment, the potential of the system has been proved and it deserves a further analysis and development.
REFERENCE


Dupuit, J. (1863). Etudes theoriques et pratiques sur le mouvement des eaux dans les canaux decouverts et a travers les terrains permeables avec des considerations relatives au regime des grandes eaux, au debouche a leur donner et a la marche des alluvions dans les rivières a fond mobile. Dunod.


Chaperon, I. (1986). Theoretical study of coning toward horizontal and vertical wells in anisotropic formations: subcritical and critical rates (No. CONF-861080-). TOTAL-CFP.


# APPENDIX A

Contains dimensional data and recommended capacities for REDA submersible centrifugal pumps

<table>
<thead>
<tr>
<th>Pump Series</th>
<th>Nominal OD (in.)</th>
<th>Minimum casing (in.)</th>
<th>Pump Designation</th>
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<th>Recommended liquid capacity m³/d</th>
<th>Shaft HP</th>
<th>Shaft diameter (in.)</th>
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| HN21000 | 17500-24000 | 2782.28-3815.70 | 637 | 1019 | 1.188 |
| H28000N | 28000-36000 | 4451.64-5723.54 | 637 | 1019 | 1.188 |

| 675 | 6.75 | 8.625 |   |   |
| J700N | 4500-9000 | 715.44-1430.89 | 637 | 1019 | 1.188 |
| J1200N | 8000-18500 | 1271.90-2941.27 | 637 | 1019 | 1.188 |
| JN16000 | 12800-19500 | 2035.04-3100.25 | 637 | 1019 | 1.188 |
| JN21000 | 16000-25000 | 2543.80-3974.68 | 637 | 1019 | 1.188 |

| 725 | 7.25 | 9.625 |   |   |
| L16000N | 11000-20000 | 1748.86-3179.75 | 637 | 1019 | 1.188 |
| L43000N | 36000-54000 | 5723.54-8585.31 | 1000 | 1600 | 1.500 |

| 862 | 8.63 | 10.75 |   |   |
| M520A | 12000-24000 | 1907.85-3815.70 | 637 | 1019 | 1.188 |
| M520B | 12000-23000 | 1907.85-3656.71 | 637 | 1019 | 1.188 |
| M520C | 12000-22000 | 1907.85-3497.72 | 637 | 1019 | 1.188 |
| M675A | 19000-32500 | 3020.76-5167.09 | 637 | 1019 | 1.188 |
| M675B | 19000-29000 | 3020.76-4610.63 | 637 | 1019 | 1.188 |
| M675C | 19000-28000 | 3020.76-4451.64 | 637 | 1019 | 1.188 |

| 1000 | 10.00 | 11.75 |   |   |
| N1050 | 35000-64000 | 5564.56-9539.24 | 1500 | 2400 | 1.188 |
| N1400NA | 35000-64000 | 5564.56-9539.24 | 1500 | 2400 | 1.750 |
| N1400NB | 35000-60000 | 5564.56-10175.19 | 1500 | 2400 | 1.750 |
APPENDIX B

Saturation profile evolution process of THDWL well (optimized design) and conventional well

Figure 46 Initial saturation profile for THDWL well and conventional well

Figure 47 Saturation profile for THDWL well and conventional well (1 month)
Figure 48 Saturation profile of THDWL well and conventional well (2 month)

Figure 49 Saturation profile of THDWL well and conventional well (half year)

Figure 50 Saturation profile of THDWL well and conventional well (1 year)
Figure 51 Saturation profile of THDWL well and conventional well (2 year)

Figure 52 Saturation profile of THDWL well and conventional well (5 year)

Figure 53 Saturation profile of THDWL well and conventional well (10 year)
Figure 54 Saturation profile of THDWL well and conventional well (15 year)
APPENDIX C

Figure 55 Saturation profile of THDWL well at the radial-cross-section where horizontal wells locate (15 years)

Figure 56 Saturation profile of THDWL well at the radial-cross-section 45 degree apart from the radial-cross-section horizontal wells locate (15 years)
Figure 57 Saturation profile of THDWL well at the radial-cross-section 90 degree apart from the radial-cross-section horizontal wells locate (15 year)
APPENDIX D

CMG data file for optimized design of THDWL production system

RESULTS SIMULATOR IMEX 201401

*TITLE1 'Twin horizontal downhole water loop'
*TITLE2 'Twin horizontal downhole water loop'
*CASEID 'THDW 1100 L700'

*INUNIT *SI

*WPRN *WELL *TIME
*WPRN *GRID *TIME
*OUTPRN *GRID *SW *PRES
*OUTPRN *TABLES *NONE
*OUTPRN *WELL *ALL
*OUTPRN *RES *NONE
*WSRF *WELL *TIME
*WSRF *GRID *TIME
*OUTSRF *GRID *SW *PRES *FLUXSC *VELOSC *WINFLUX

***********************************************************************
** RESERVOIR DESCRIPTION SECTION
***********************************************************************

*GRID *RADIAL 150 6 100 *RW 0.18
*KDIR *DOWN
*DEPTH 1 1 1 3020
** 0 = null block, 1 = active block
NULL CON 1
*DI *IVAR
0.0471 0.0494 0.0517 0.0541 0.0567 0.0593 0.0621 0.0651 0.0681 0.0713
0.0747 0.0782 0.0819 0.0858 0.0898 0.0940 0.0985 0.1031 0.1080 0.1131
0.1184 0.1240 0.1298 0.1359 0.1423 0.1490 0.1561 0.1634 0.1711 0.1792
0.1876 0.1965 0.2057 0.2154 0.2256 0.2362 0.2474 0.2590 0.2712 0.2840
0.2974 0.3114 0.3261 0.3414 0.3575 0.3744 0.3920 0.4105 0.4299 0.4501
0.4713 0.4935 0.5168 0.5412 0.5667 0.5934 0.6213 0.6506 0.6813 0.7134
0.7470 0.7822 0.8191 0.8577 0.8981 0.9405 0.9848 1.0312 1.0798 1.1307
1.1840 1.2398 1.2982 1.3594 1.4234 1.4905 1.5608 1.6343 1.7114 1.7920
1.8765 1.9649 2.0575 2.1545 2.2560 2.3624 2.4737 2.5903 2.7124 2.8402
AQUIFER *BOTTOM
** h phi perm radius angle
*AQPROP 60 0.1 400 1000 0

****************************************************************************************

**COMPONENT PROPERTIES SECTION
****************************************************************************************

MODEL OILWATER
** PB RS BO I/Bg VISO VISG CO
PVT EG 1
** p Rs Bo Eg viso visg co
2433.85 13.53 1.1136 211.86 1.4 0.0228 2e-6
24497.07 17.891814 1.1336 213.64 1.4 0.0238 2e-6

BWI 1.03
CVO 3.60e-5
CVW 0.0
CW 4e-7 **water compressibility
DENSITY OIL 825
DENSITY WATER 1055
REFPW 33000
VWI 0.4
DENSITY GAS 1.12
PTYPE CON 1
**Rock-Fluid Property Section**

*ROCKFLUID
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**Initial Conditions Section**

*INITIAL
*VERTICAL *BLOCK_CENTER *WATER_OIL
*PB  *CON  2433.9
*REFDEPTH 3040
*REFPRES 33000
*DWOC 3039.5

** Numerical Control Section**

*NUMERICAL
*DTMAX    10.0
*DTMIN    0.001
*NORM *PRESS  3447.5
*NORM *SATUR  0.20
*AIM    *OFF

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**    Well Data Section
****************************************

*RUN
*DATE    1994  06  08
*DTWELL  0.025
**
** *WELL 1 'Producer' *VERT    1  1
**
WELL 'Producer' VERT 1 1
PRODUCER 'Producer'
OPERATE MAX STL 300 CONT
MONITOR MIN STO 4.45 STOP
MONITOR WCUT 0.98 STOP
**         rad geofac wfrac skin
GEOMETRY K 0.18 0.5 1.0 0.0
PERF GEO 'Producer'
** uba   ff   Status
     1 1 5  1.0 OPEN
     1 1 6  1.0 OPEN
     1 1 7  1.0 OPEN
     1 1 8  1.0 OPEN
     1 1 9  1.0 OPEN
     1 1 10 1.0 OPEN
     1 1 11 1.0 OPEN
     1 1 12 1.0 OPEN

WELL 'sink' VERT 1 1
PRODUCER 'sink'
OPERATE MAX STL 1100.0 CONT
**         rad geofac wfrac skin
GEOMETRY K 0.18 0.5 1.0 0.0
PERF GEO 'sink'
** uba   ff   Status
WELL  're-inj 1'
INJECTOR *MOBWEIGHT 're-inj 1'
INCOMP *WATER
OPERATE MAX STW 550.0 CONT
** rad geofac wfrac skin
GEOMETRY K 0.18 0.5 1.0 0.0
PERF GEO 're-inj 1'
** UBA ff Status
143 1 54 1.0 OPEN

WELL  're-inj 2'
INJECTOR *MOBWEIGHT 're-inj 2'
INCOMP *WATER
OPERATE MAX STW 550.0 CONT
** rad geofac wfrac skin
GEOMETRY K 0.18 0.5 1.0 0.0
PERF GEO 're-inj 2'
** UBA ff Status
143 4 54 1.0 OPEN

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