Attenuation of water coning using dual completion technology

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Abstract

Water coning causes a reduction of oil production and an increase of production costs. Dual completion (downhole water sink) is one of the methods adopted to attenuate water coning. This work describes numerical results associated with this completion technique. The water cone shape and water breakthrough time are investigated to define the mechanism and performance of this technical procedure. The numerical results show that dual completion deforms the shape of the cone. For instance, the top of the water–oil interface is shifted away from the well yielding (under high water production rates) oil breakthrough into water perforations. The water breakthrough is proportional to dimensionless density difference and horizontal permeability and inversely proportional to oil production rate, mobility, and anisotropy ratios. High oil production rates yield elevation of water coning height that intercepts oil flow. Paradoxically, high production rate at water sink is not recommended, the improvement of water breakthrough begins when dimensionless density difference is greater than 0.05. The dual completion technique delays water breakthrough time (BT\textsuperscript{*}). In general, the BT\textsuperscript{*} is delayed by two times that of single completion and critical oil rate is augmented compared to single completion.

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1. Introduction

Oil reservoirs with bottom water drive exhibit high oil recovery due to supplemental energy imparted by the aquifer. A large oil production rate may cause water to be produced by upward flow mixed with oil. This phenomenon is known as water coning and refers to the deformation of water–oil interface which was initially horizontal.

Water coning has been a serious problem in managing reservoir recoveries; numerous authors addressed this phenomenon (Muskat and Wyckoff, 1935; Muskat, 1949; Elkins, 1958; Karp et al., 1962; Fortunati, 1962; Smith and Pirson, 1963; Chierici et al., 1964; Outmans, 1964; Romero-Juarez, 1964; Blake and Kucera, 1988; Ould-amer and Chikh, 2002). Their research investigated several issues such as critical rate and/or breakthrough time calculations. It was found that the maximum water-free oil production rate corresponds to the critical rate.
and the breakthrough time which represents the period required by bottom water to reach the well’s oil perforations. If oil production rate is above this critical value, water breakthrough occurs. After breakthrough, the water phase may dominate the total production rate to the extent that further operation of the well becomes economically not valuable and the well must be shut down (Muskat and Wyckoff, 1935; Meyer and Garder, 1954; Chaney et al., 1956; Schols, 1972; Kuo and Debrisisay, 1983; Hoyland et al., 1986; Chaperon, 1986; Abass and Bass, 1988; Giger, 1989; Papatzacos et al., 1989; Yang and Wattenbarger, 1991; Suprunowicz and Butler, 1992; Yang, 1992; Guo and Lee, 1993; Menouar and Hakim, 1995; Ould-amer and Chikh, 2003).

Several solutions have been developed to minimise the impact of unwanted water in oil wells. These methods are: (1) keeping production rate below the critical value; (2) perforating far away from the initial water–oil contact; and (3) creating a water blocking zone around the well by injecting cross-linking polymers or gels. Unfortunately, none of these conventional methods are able to solve the water breakthrough problem. Horizontal wells also are used to minimise water coning. However, horizontal wells are themselves not free of water influx problems. Like the vertical wells, typical critical oil rates for avoiding water influx into horizontal wells are too low for any economic recovery. A detailed investigation of the cost and profits of horizontal wells reveals several disadvantages for their use: vulnerability to poor cementing, limited re-completion potential, and design constraints imposed by drilling technology (Chugbo et al., 1989; Irrgang, 1994).

Downhole water sink technology (DWS) is one of the solutions developed to reduce water coning in vertical oil completions. This technique requires a dually completed well in the oil and water zones. The oil and water perforations are separated by a packer. As a result, the produced oil is water-free. DWS technology has been investigated theoretically (Wojtanowicz et al., 1991; Swisher and Wojtanowicz, 1995a,b) and experimentally (Shirman and Wojtanowicz, 1997a,b).

Shirman and Wojtanowicz (1997a,b) conducted a model DWS completion investigation using a transparent Hele–Shaw model. Their results indicate that oil production from wells with DWS completion may have high economic merit and is technically feasible. Coning in dually completed wells also has been investigated by Gunning et al. (1999). A simple model for dual completion similar to that of Wojtanowicz and Bassiouni (1994) was proposed. A sharp interface is used between the fluids, across which no fluid may flow. An analytical solution is proposed for low flow rates where gravity has a dominant effect. In order to overcome this limitation (low flow rates), a numerical model was used by Gunning et al. In both numerical models, the ratio of the distances between the initial water–oil interface and the water and oil completions was introduced. Their results indicate that in a symmetric configuration corresponding to the ratio of distances between the initial water–oil interface and the lower water and upper oil completions, water-free oil production is possible at rates up to five times greater than those available with single completions. Less improvement is obtained in asymmetric situations where the ratio is different from unity.

Several parameters affect water coning in vertical oil producing wells: (1) oil production rate, (2) mobility ratio, (3) density difference between fluids, (4) anisotropy, and (5) porosity. Our present parametric study simulated numerically the behaviour of the water–oil interface and computed water breakthrough time for a wide range of the cited parameters. This analysis allows us to obtain a detailed and precise answer of dual completion performance in a vertical well.

2. Formulation

A single well model (Azziz and Settari, 1986) is used to evaluate the performance of the DWS completion in the control of water coning in vertical wells. The physical model and co-ordinate system are shown in Fig. 1. The well is dually completed in the oil and water zones (Fig. 2). The two completions are separated by a packer set inside the well at the water–oil contact and the two fluids are considered incompressible and immiscible with constant properties. The porous medium is homogeneous and
anisotropic (the vertical permeability is less or greater than the horizontal permeability).

Darcy’s law and the continuity equation describe the flow of the two fluids.

Continuity:

\[ - \nabla \cdot \left( \bar{V}_l \right) = \frac{\partial}{\partial t} (\phi S_l) + \bar{Q}_{la} \quad (1) \]

Darcy’s law:

\[ \bar{V}_l = -\bar{K} \frac{kr_l}{\mu_l} (\nabla P_l + \rho_l g) \quad (2) \]

The subscript \((l)\) indicates either the water (w) or oil (o) phase and the subscript \((a)\) can indicate either oil completion (oc) or water completion (wc).

Substituting the Darcy velocity in Eq. (2) into Eq. (1), the following equation is obtained:

\[ \nabla \cdot \left[ \bar{K} \frac{kr_l}{\mu_l} (\nabla P_l + \rho_l g) \right] = \frac{\partial}{\partial t} (\phi S_l) + \bar{Q}_{la} \quad (3) \]

For each fluid phase, Eq. (3) is then written as

\[ \nabla \cdot \left[ \bar{K} \frac{kr_o}{\mu_o} (\nabla P_o + \rho_o g) \right] = \frac{\partial}{\partial t} (\phi S_o) + \bar{Q}_{oa} \quad (4) \]

\[ \nabla \cdot \left[ \bar{K} \frac{kr_w}{\mu_w} (\nabla P_w + \rho_w g) \right] = \frac{\partial}{\partial t} (\phi S_w) + \bar{Q}_{wa} \quad (5) \]

Adding Eqs. (4) and (5), and assuming that the porous medium is completely saturated by the fluids, then

\[ \nabla \cdot \left[ \bar{K} \frac{kr_o}{\mu_o} (\nabla P_o + \rho_o g) \right] + \nabla \cdot \left[ \bar{K} \frac{kr_w}{\mu_w} (\nabla P_w + \rho_w g) \right] = \bar{Q}_a \quad (6) \]

where

\[ \bar{Q}_a = \bar{Q}_{oa} + \bar{Q}_{wa} \quad (7) \]

Additional equations closing the system are given below

\[ S_w + S_o = 1 \quad (8) \]

\[ P_c = P_o - P_w \quad (9) \]

The capillary pressure \(P_c\) depends on water saturation and is given by Eq. (25).
Substituting Eq. (9) into Eq. (6), yields the water pressure equation

$$\nabla \cdot \left[ K \frac{kr_o}{\mu_o} (\nabla P_w + \nabla P_z + \rho_o g) \right] + \nabla \cdot \left[ \frac{kr_w}{\mu_w} (\nabla P_w + \rho_w g) \right] = \tilde{Q}_a$$

(10)

No flow boundary conditions are imposed on a closed boundary. A constant pressure of the bottom aquifer is used. These conditions are mathematically written as

$$\vec{V}_w \cdot \vec{n} = 0 \text{ at closed boundary or}$$

$$\nabla (P_w + \rho_o g) \cdot \vec{n} = 0$$

(11)

$$P_w = P_{aq} \text{ at } z = 0 \text{ and } r_w < r < r_c$$

(12)

$$\vec{n}$$ is the unit vector normal to the closed boundary.

Initially the oil zone is saturated with oil at irreducible water saturation ($S_{wi}$) and the water zone is free of oil.

$$S_o = 1 - S_{wi} \text{ and } S_w = S_{wi} \text{ at } h_w < z < h,$$

$$r_w < r < r_c$$

(13)

$$S_o = 0 \text{ and } S_w = 1 \text{ at } 0 < z < h_w, \text{ } r_w < r < r_c$$

(14)

The introduction of dimensionless parameters related to rock characteristics, fluid properties, and production (defined in the nomenclature) allows us to rewrite Eqs. (5) and (10) as

$$\left[ \frac{1}{r^*} \frac{\partial}{\partial z^*} \left( Ra kr_w \frac{\partial P_w^*}{\partial z^*} \right) + \frac{r^*}{r^*} \frac{\partial}{\partial r^*} \left( kr^* \frac{\partial P_w^*}{\partial r^*} \right) \right]$$

$$\times \left( ND \rho \right) \left( N \rho_w \right) = \frac{1}{Da_H} \left( \frac{\partial}{\partial r^*} (\phi S_w) + Q_{wa}^* \right)$$

(15)

and

$$\left\{ \begin{array}{l}
Ra \frac{\partial}{\partial z^*} \left[ \frac{kr_o}{M} + kr_w \frac{\partial P_w^*}{\partial z^*} \right] + \frac{kr_o}{M} \frac{\partial P_w^*}{\partial z^*} + \frac{kr_o}{M} \frac{\partial P_w^*}{\partial z^*} \\
+ r^* \left( kr^* \frac{\partial P_w^*}{\partial r^*} \right) \end{array} \right\} \left( ND \rho \right) \left( N \rho_w \right) \frac{\tilde{Q}_a^*}{Da_H}$$

(16)

The set of equations to be solved consists of the dimensionless pressure Eq. (16), the water saturation Eq. (15), and the total saturation Eq. (8).

In the oil completion (until water breakthrough) only oil is produced and $Q_{wa}^*$ is zero; however, after breakthrough, $Q_{wa}^*$ decreases while $Q_{wa}^*$ increases. In the water completion, oil breakthrough may or may not take place. When oil breakthrough into the water perforations occurs, $Q_{wa}^*$ does not increase continuously.

The boundary and initial conditions written in dimensionless form, are

$$\nabla (P_w^*) \cdot \vec{n} = 0 \text{ at a closed boundary}$$

(17)

$$P_w^* = P_{aq}^* \text{ at } z = 0 \text{ and } r_w^* < r^* < r_c^*$$

(18)

$$S_o = 1 - S_{wi} \text{ and}$$

$$S_w = S_{wi} \text{ at } h_w^* < z < h^*, \text{ } r_w^* < r^* < r_c^*$$

(19)

$$S_o = 0 \text{ and}$$

$$S_w = 1 \text{ at } 0 < z^* < h_w^*, \text{ } r_w^* < r^* < r_c^*$$

(20)

3. Numerical simulation

The governing equations are transformed into algebraic equations by using the control volume method (Patankar, 1980, 1981). The fully implicit scheme is used and the relative permeabilities at the block interfaces are evaluated using an asymmetric second-order approximation that considers two upstream points (Azziz and Settari, 1986). The set of algebraic equations is solved by a block-iterative method. The iterative procedure is stopped at each time step when a convergence criterion is met between two consecutive iterations, and it is set on the maximum relative error of pressure less than 1%. A non-uniform grid of 40 × 24 nodes in r and z direction, respectively, with a dimensionless time step of $\Delta t^* = 72 \times 10^{11}$ are used to conduct the computations, with a finer mesh grid near the well. The grid choice is based on grid sensitivity analysis (Table 1).
The code was validated by reconsidering the work of Yang (1992), who studied, analytically, water coning in vertical and horizontal wells. Fig. 3 illustrates the excellent agreement between our results and those of Yang for water breakthrough time prediction versus production rate.

4. Results and discussion

Three groups of dimensionless parameters were distinguished and considered: (1) total dimensionless production rates at oil and water completions; (2) fluid properties (mobility ratio and dimensionless density difference); and (3) rock characteristics (anisotropy ratio, horizontal Darcy number and porosity). These parameters vary in the following ranges: $10^{-10} \leq Q_w^* \leq 25 \times 10^{-10}$, $0 \leq Q_o^* \leq 1.5$, $0.1 \leq M \leq 20$, $0 \leq ND \leq 0.4$, $0 < Ra \leq 1.4$, $0 < Da_H \leq 8 \times 10^{-16}$, $0.1 \leq \phi \leq 0.4$, which illustrate practical situations.

The total dimensionless production rates are given by

$$Q_o^* = 2\pi r_w^* \int_{h_o}^{h_*} Q_o^* dz^*$$  

$$Q_w^* = 2\pi r_w^* \int_{h_w}^{h_*} Q_w^* dz^*$$  

No general forms exist for the capillary pressure and relative permeability functions, there are several commonly used empirical functions or data (Russel et al., 2002). The Abass and Bass (1988) data which provide capillary pressure are considered in the present work. Their data was correlated using the following expressions:

$$k_r = 0.97/[1 + \exp((S_w - 0.33)/0.11)] - 0.02$$  

$$k_r = -1.90/[1 + \exp((S_w - 0.91)/0.26)] + 1.80$$  

$$P_c = 2.09 \times 10^6/[1 + \exp((S_w - 0.09)/0.02)] + 3190.60$$

The shape of water–oil interface for single completion is considered as a reference for comparison. In the plots (Figs. 5–9), the dual completion is referenced with $Q_w^* = 1.5$ and the single completion with $Q_w^* = 0$. High values of oil production rates are considered with water production rates within the water perforations being less or equal to $1.5 \times Q_o^*$. This choice is justified by the fact that higher values could be harmful to the hydraulic performance of well completion.

To clarify the position of well perforations in the plots, two dashed rectangles are added and they represent the limits of the oil and water completions. The use of DWS technology deforms the cone profile shape, as illustrated in Fig. 4, at different times of production. The top of water–

![Fig. 3. Comparison of numerical simulations with published results from Yang (1992).](image-url)
oil interface is shifted to the right (away from the well) yielding, in certain situations, oil breakthrough into the water sink.

Fig. 5 shows the development of water–oil interface profiles for two values of oil production rate with and without dual completion at \( t^* = 0.95 \times 10^{18} \). In the single completion case, the water–oil interface develops as a classical cone which is very sensitive to production rate. At \( Q_{oc}^* = 20 \times 10^{-10} \) which corresponds to a very high value of the production rate, the water invades rapidly in a wide region of the oil zone affecting the oil production performance. The water intercepts the oil flow into well perforations. The well perforations in the water zone constitute a water sink affecting considerably the shape of the cone. Not only is water retained, but the top of the cone is shifted to the right and is located at approximately \( r^* = 1.5 \). At \( Q_{oc}^* = 10 \times 10^{-10} \), the dual completion technique retains the rapidly upcoming water coning. Indeed, for a same period of production, water has broken through into oil perforations for the single completion; whereas, in dual completion
case, the top of water–oil interface is located at a dimensionless distance of 0.5 below the oil well. At a $Q_{oc}^* = 20 \times 10^{-10}$, which corresponds to a very high value of oil production rate (Fig. 5), even if water has not broken through oil perforations at this stage of production, the development of the cone is important. Indeed, its tendency to be higher and to move away from the well could intercept the oil flow. It is evident from these plots that multiplying oil production rate by a factor 2, in dual completion, causes development of a cone and the position of its top is raised by twice as much. Physically, the water sink alters the flow potential field around the well so that the water–oil interface is retained. At each point, the upward vertical component of viscous force generated by the flow into the oil perforations is reduced by the downward vertical component of the second viscous force generated by the flow into the water sink.

The effect of mobility ratio on water–oil interface development is illustrated in Fig. 6. With a single completion, the water cone expands vertically towards...
the well rather than outward radially. The use of a dual completion deforms the classical cone shape. The top of the cone is shifted to the right. At this stage of production, the oil breakthrough into water sink is still taking place for $M = 2$, whereas for $M = 6$, oil stops flowing into the water perforations. During the first stage of production, the viscous force, generated by the flow into the water sink, overcomes the viscous force generated by the flow into oil perforations. The inverse behaviour occurred at this stage of production ($t^* = 0.70 \times 10^{18}$). When viscous forces arise due to the resistance of the flow they are important and prevail, the oil mobility is reduced, this situation accelerates the upward motion of water into oil perforations.

The gravity force (dimensionless density difference) represents an important parameter that can affect the cone profile considerably. When the viscous force resulting from natural drive due to oil perforations overcomes the gravitational force induced by difference in fluid densities, water coning occurs. As shown in Fig. 7, the cone is very developed in both directions (horizontal and vertical) and reaches the oil perforations for a single completion and at low values of dimensionless density difference ($ND\rho = 0.05$ for example). At a dimensionless density difference ($ND\rho = 0.2$) four times greater than the previous value, the water cone profile is less developed and is located at about a dimensionless distance of 0.5 below the bottom of the oil perforations. With dual completion, the water–oil interface behaves differently and the top of the cone is kept away from the well. High values of $ND\rho$ means that water arrival at oil perforations is more delayed, yet the duration of oil flow into the water sink is longer. From these plots, the gravity force, aided by viscous force generated by the flow into the water sink, allows retention of rapid upward flow of water into oil perforations.

Another parameter affecting the water coning behaviour is the ratio of vertical to horizontal permeability, also termed as anisotropy ratio ($Ra$). Low values of this ratio result in a very dumped upward motion of the water–oil interface in single completion as shown in Fig. 8. In dual completion situations, the cone shape is greatly affected at low values of $Ra$. The water–oil interface motion is reversed and oil breakthrough takes place. The top of the cone in this case is shifted to the right and is located at a dimensionless radial distance of approximately 3. At high values of $Ra$, the cone shape is not affected; however, its motion toward oil perforations is decreased compared to the single completion. With a dual completion, and at high anisotropy ratio, the upward flow of water into oil perforations is delayed by viscous force due to the
flow into the water sink. At a low anisotropy ratio, the downward vertical component of viscous force generated by the flow to water perforations overcomes the upward vertical component of viscous force due to the flow into oil perforations. This situation causes oil to break into water perforations. Nevertheless, this case may easily be avoided by reducing the water production rate.

Oil recovery from the well is principally radial, indicating the important role played by the horizontal permeability. The placement of perforations in the water zone in order to drain the water phase, deforms the cone shape and causes the motion of its top away from the well (Fig. 9). The radial location of this top is proportional to the permeability. The water–oil interface motion is faster for less permeable reservoirs. Physically, this situation results from slower flow in the radial direction for the less permeable rocks.

From this analysis of the cone shape, it is apparent that oil breaks into water perforations in certain situations. The simulation results indicate that there exists a critical flow rate in the water sink which should not be exceeded in order to avoid oil breakthrough. In fact, there is competition between two forces (upward and downward) owing to the dual sink. For instance, one should optimise both oil and water production so that the interface is always maintained in between oil and water perforations. Fig. 10 is a graph that provides the oil breakthrough time $B_{T_{oil}^*}$ versus water production rate. When water production rate ($Q_{wc}^*$) in the water sink is less or equal to approximately $2 \times 10^{-10}$ the oil breakthrough does not occur.

The previous analysis of the water–oil interface behaviour provides an answer to the cone shape when dual completion is used. It is shown by our data that the interface is not stable for all ranges of parameters.

![Fig. 8. Shape of the water–oil interface in single and dual completions for two values of anisotropy ratio for $M=2$, $ND\rho =0.1$, $Da_H=4 \times 10^{-16}$, $\phi =0.2$, $Q_{dc}^*=10 \times 10^{-10}$, $r^*=0.69 \times 10^{18}$.](image1)

![Fig. 9. Shape of the water–oil interface in single and dual completions for two values of horizontal permeability $M=2$, $ND\rho =0.1$, $\phi =0.2$, $Q_{wc}^*=10 \times 10^{-10}$, $Da_V=8 \times 10^{-17}$, $r^*=0.40 \times 10^{18}$.](image2)

![Fig. 10. Influence of water production rate (in water sink) on oil breakthrough time $B\_T_{oil}^*$ in dual completion for $M=2$, $ND\rho =0.1$, $Da_H=4 \times 10^{-16}$, $Ra =0.2$, $\phi =0.2$, $Q_{oc}^*=10 \times 10^{-10}$.](image3)
investigated and water can break into oil perforations. Thus, other results on water breakthrough time are documented and discussed.

For all of the parameters, three cases of water production rate ($Q_{wc}^*$) in the water sink were examined: $Q_{wc}^* = 0$ that corresponds to single completion, $Q_{wc}^* = 0.8 \times Q_{oc}^*$ and $Q_{wc}^* = 1.5 \times Q_{oc}^*$ in dually completed wells.

Fig. 11 shows a decrease of water breakthrough time ($BT^*$) when the production rate increases in both single or dual completions. The use of DWS completion allows a delay of the water breakthrough for a period of time that is not different for two values of water production rate. In a dually completed well, the $BT^*$ is improved by approximately a factor of two compared to single completion. Also the analysis of $BT^*$ in single completion shows that for an oil production rate less than about $2.5 \times 10^{-10}$, water does not break into oil perforations, i.e., this value corresponds to the critical oil rate. Dual completion yields an increase in the critical oil production rate, which goes from $2.5 \times 10^{-10}$ in single completion to $5 \times 10^{-10}$ in dual completion. As explained previously in the cone analysis, the upward vertical component of the viscous force due to oil perforations is reduced by the downward vertical component of the second viscous force due to the water sink.

The mobility ratio affects oil recovery. The higher the mobility ratio ($M$), the faster the water breakthrough occurs, as shown in Fig. 12. For values of $M$ greater than 10, water coning is delayed only for a short period of time by the use of DWS technology. As explained in the cone profile analysis, when viscous forces are important and predominate, the oil mobility is reduced yielding faster upward motion of the water–oil interface. The $BT^*$ is slightly greater at $Q_{wc}^*/Q_{oc}^* = 1.5$ compared to $BT^*$ at $Q_{wc}^*/Q_{oc}^* = 0.8$, only for the range of $M$ between 2.5 and 10. An asymptotic behaviour of $BT^*$ is observed in single or dual completions for values of $M$ less than a certain critical value. It is an indication of critical oil rate. It starts from values of $M$ less than 0.25 in single completion and less than 1 for a dually completed well.

Fig. 13 shows the effect of the dimensionless density difference ($ND\rho$) on $BT^*$. For the most part, use of a
dual completion considerably delays the water coning at high values of ND\(q\). The improvement due to DWS yields a BT* at least two times greater when ND\(q\) is increased from 0.1 to 0.2. Increasing water production allows delay of water arrival at the oil perforations for values of \(Q_{wc}/Q_{oc} = 1.5\) and 0.8, owing to the stabilising effect of gravity at high values of ND\(q\) (Fig. 13). The gravitational force, induced by the difference in fluid densities, add to the downward vertical component of viscous force due to the water sink, hindering water breakthrough. For ND\(q\) < 0.05, the effect of DWS on BT* is still sensitive. Nevertheless, the effect of water production rate on BT* seems to be negligible.

The effects of the rock characteristics on BT* are shown in Figs. 14–16 through the anisotropy ratio (Ra), the horizontal permeability (\(D_{\text{H}}\)) and the porosity (\(\phi\)). An improvement of BT* is recorded when the well is dually completed. The augmentation of water production rate from \(Q_{wc}/Q_{oc} = 0.8\) to \(Q_{wc}/Q_{oc} = 1.5\) does not significantly improve the delay of water into oil perforations. It is noticed that for good rock characteristics (low values of Ra, high \(D_{\text{H}}\) and \(\phi\)) a better enhancement is reached. An asymptotic behaviour of BT* versus \(Ra\) is shown in Fig. 14, it corresponds to a critical oil production rate.

5. Conclusions and remarks

Results of numerical simulations related to water–oil interface behaviour and BT* were analysed and documented for single and dual completions. With a parametric study of dual completion technology, the cone profile shape and the performance of this technique were discussed arriving at the following conclusions:

(a) The use of dual completion deforms the cone profile shape in most cases. The top of water–oil interface moves away from the well.

(b) The use of high oil production rates yields an elevation of water coning height that would intercept oil flow.
For dimensionless water production rates greater than $2 \times 10^{-10}$, the oil breaks into water perforations. The water breakthrough time is proportional to dimensionless density difference and horizontal permeability and inversely proportional to oil production rate, mobility, and anisotropy ratios.

For rock reservoir with high anisotropy ratio, the cone shape, induced by DWS technology, takes the classical behaviour occurring in single completion after a short period of production.

At low ND$q$ numbers, the values of BT* for $Q_{wc*}^*/Q_{oc*}^* = 0.8$ and $Q_{wc*}^*/Q_{oc*}^* = 1.5$ are not too different, thus the use of high production rate at water sink is not recommended. The improvement begins when dimensionless density difference is greater than 0.05.

Using the dual completion, water breakthrough is delayed. In general, the BT* is doubly delayed compared to single completion situation.

The critical oil production rate is improved compared to a single completion.

**Nomenclature**

- $Da_H$: radial Darcy number ($Da_H = k_H/h_o^2$)
- $Da_V$: vertical Darcy number ($Da_V = k_V/h_o^2$)
- $Dp$: density difference ($Dp = \rho_w - \rho_o$)
- DWS: downhole water sink
- $g$: gravity acceleration ($m/s^2$)
- $h$: total height of the physical domain ($h = h_o + h_w$, m)
- $h^*$: dimensionless total height of the physical domain
- $h_o$: oil zone height (m)
- $h_o^*$: dimensionless oil zone height
- $h_p$: oil perforation height (m)
- $h_p^*$: dimensionless oil perforation height
- $h_w$: water zone height (m)
- $h_w^*$: dimensionless water zone height
- $h_{wp}$: water perforation height (m)
- $h_{wp}^*$: dimensionless water perforations height
- $K$: permeability tensor
- $k_H$: horizontal permeability ($m^2$)
- $kr_l$: relative permeability to phase $l$
- $kr_{oilw}$: relative permeability to oil at irreducible water saturation
- $kr_{wor}$: relative permeability to water at residual oil saturation
- $k_V$: vertical permeability ($m^2$)
- $M$: mobility ratio ($M = Rkr_{oilw}/\mu_o$)
- $n$: normal vector to boundary
- ND$p$: dimensionless density difference ($NDp = (\rho_w - \rho_o)/\rho_w$)
- $Np_w$: dimensionless expression ($Np_w = \rho_w gh_o/P_{woc}$)
- $P_{aq}$: pressure at bottom aquifer (Pa)
- $P_c$: capillary pressure (Pa)
- $P_c^*$: dimensionless capillary pressure ($P_c^* = (P_c - Dpgh_o)/(Dpgh_o)$)
- $P_i$: phase pressure (Pa)
- $P_{woc}^*$: total dimensionless production rate (Eq. (21))
- $Q_{a}$: total production rate ($m^3/s$)
- $Q_{a}^*$: total dimensionless production rate
- $Q_{la}$: total production rate by unit reservoir volume ($s^{-1}$)
- $Q_{wc*}^*$: dimensionless water production rate in water sink
- $Q_{wc}^*$: dimensionless water production rate
- $r$: radial co-ordinate (m)
- $r^*$: dimensionless radial co-ordinate ($r^* = r/h_o$)
- $Ra$: anisotropy ratio, $Ra = Da_V/Da_H$
- $r_e$: total radius of the physical domain (m)
- $r_e^*$: total dimensionless radius
- $Rkr$: relative permeability ratio ($Rkr = kr_{wor}/kr_{oilw}$)
- $r_{w^*}^*$: dimensionless well radius
- $r_w$: well radius (m)
- $S_l$: phase saturation
- $S_{or}$: residual oil saturation
- $S_{wi}$: irreducible water saturation
- $t$: time (s)
- $t^*$: dimensionless time ($t^* = P_{woc} t/\mu_w$)
- $V_l$: phase filtration vector ($m/s$)
- $z$: vertical co-ordinate (m)
- $z^*$: dimensionless vertical co-ordinate ($z^* = z/h_o$)

**Greek symbols**

- $\rho_l$: fluid phase density ($kg/m^3$)
- $\phi$: porosity
\[ \mu \quad \text{dynamic viscosity (Pa.s)} \]
\[ \nabla \quad \text{gradient operator} \]

**Subscripts**

- \( a \) zone completion (\( a = o_c, w_c \))
- \( l \) phase (\( l = o, w \))
- \(*\) dimensionless

**References**


