A New Method for Predicting Water Breakthrough Time in the Edge Water Condensate Gas Reservoir

Quanhua Huang¹, Xingyu Lin¹*, Qinglong Xu², Yunjun He³

College of petroleum y and natural gas engineering, Southwest petroleum university, Sichuan, chengdu, 610500, china
Natural gas laboratory, Daqing oilfield exploration and development research institute, Heilongjiang, daqing, 16300, china
*Corresponding author’s e-mail: 364520856@qq.com

Abstract: The influence of condensate oil is often ignored when people predict the water breakthrough time of condensate gas reservoirs, leading to a certain difference between the prediction and the actual results. In order to efficiently and scientifically develop the edge water condensate gas reservoir, it is necessary to consider the influence of the precipitated condensate oil when making reasonable predictions on the water breakthrough time. Based on the basic law of gas-water two-phase percolation, this paper simplified the water inlet process as the migration of water particles to the well bottom, with the influence of condensate oil precipitation taken into consideration. In this meantime, this paper derived a new model for predicting the breakthrough time of the edge water condensate gas reservoir based on the idea that the change of condensate saturation varies with time and the distance from well bottom. Case studies show that the lower the permeability, the greater the influence of condensate oil precipitation on water breakthrough time; the farther the well bottom is from the initial gas-water boundary, the longer the water breakthrough time; the effect of condensate oil cannot be ignored during the prediction of the water breakthrough time in the edge water condensate gas reservoir. The new model considers the dual effects of time and location on the condensate saturation, which is more in line with the actual situation of the change of condensate saturation in the formation.

1. Introduction

Edge water tonguing causes water intrusion in the gas reservoir, reducing the recovery rate. With the development of gas reservoirs, condensate gas reservoirs produce condensate oil, which will be adsorbed in the formation before it reaches the critical flow saturation. Therefore, when predicting the water breakthrough time of the edge water condensate gas reservoir, we shall not neglect the impact of retrograde condensation damage. At present, there are many studies on the prediction of water breakthrough time of conventional oil and gas reservoirs and condensate gas reservoirs at home and abroad. Muskat [1-2] put forward the calculation formula of condensate oil saturation, the formula shows that the condensate oil saturation is related to the distance and time from the bottom of the well. Hu [3] derived the blockage radius calculation method when reaching the critical condensate oil flow saturation on the basis of the Muskat formula. He et al. [4-6] studied the development mode, water invasion characteristics and gas-water distribution characteristics of condensate gas reservoirs. Wang et al. [7-11] explored the method for predicting the water breakthrough time, with gas-water interface propulsion and retrograde condensation damage taken into consideration. Shi et al. [12] used numerical
simulation to study the law of edge water propulsion. Liu et al. [13] predicted the water breakthrough time in the edge water reservoir. Wu et al. [14] derived an edge water condensate gas reservoir method with approximately straight boundary supply by taking retrograde condensation damage into consideration. Wang et al. [15-19] considered the non-Darcy effect and gravity when conducting an edge water breakthrough study. Li et al. [20] established the flow partition in model with the retrograde condensation damage taken into consideration based on the difference in over-fluidity ratio. Ming et al. [21] derived the formula for predicting the water breakthrough time in the edge water condensate gas reservoir with the non-Darcy effect taken into consideration. Part of the present studies on the prediction of water breakthrough time in edge water condensate gas reservoirs used Hu's formula and Muskat's formula when considering retrograde condensation damage for simplification. In this way, the blocking radius in the condensate saturation formula is considered as that of condensate oil saturation, and condensate saturation is ultimately only related to time, leading to some deficiencies. This paper makes corresponding improvements on that basis and establishes the prediction model of the water breakthrough time in the edge water condensate gas reservoir.

2. Model building
It is assumed that there exists an edge water condensate gas reservoir and that the distance between the production well B and the original gas-water interface is \( r' \). A water particle A makes a flat radial flow to the bottom B of the well, and reaches it after the time \( t \). The formula for the increase rate of condensate saturation derived by Muskat shows that the condensate saturation changes with time and distance from the bottom of the well. Therefore, the following assumptions are made for the gas reservoir: 1) the reservoir is a homogeneous reservoir; 2) residual gas is formed in the water intrusion area after water flooding (see Figure 1); 3) the radius of the bottom hole is ignored; 4) the flow is controlled by the viscous force while neglecting the capillary force; 5) the viscosity and density of gas and water are constant; 6) the flow of gas and water satisfies the Darcy's law; 7) the condensate oil saturation in the condensate area changes continuously with time and distance (see Figure 2), without considering the condensate oil flow.

3. Equation derivation
The gas phase velocity under formation conditions is:

\[
v_g = \frac{q_g B_g}{2\pi r h}
\]

The gas-water two-phase seepage equation is:
The junction between gas and liquid meets:

\[
\left( \frac{dp_g}{dr} \right)_{r=r_0} = \left( \frac{dp_w}{dr} \right)_{r=r_0}
\]

From the above, the liquid phase velocity can be expressed as:

\[v_{wg} = \frac{v_g}{M_{wg}}\]

The mobility ratio is defined as:

\[M_{wg} = \frac{k_w}{\mu_w}/\frac{k_g}{\mu_g}\]

Muskat's formula for the increase rate of condensate saturation \([1-2]\) shall be:

\[
\frac{dS_o}{dt} = \frac{q_B B_g}{2\pi r h} \frac{dc}{dr}
\]

After the integral transformation, it can be seen that the saturation of condensate oil changes continuously with time \(t\) and the radius \(r\) from the bottom of the well:

\[S_o = \left( \frac{q_B B_g}{2\pi r h} \right)^2 \frac{\mu_g}{k_g} t\]

Present prediction of the water breakthrough time in the edge water condensate gas reservoirs \([14,20,21]\) often adopts Hu's formula based on the Muskat's formula of condensate saturation change to derive the blocking radius of condensate critical flow saturation near the well bottom. It is necessary to pay attention to the following two points: 1) unify the unit of daily gas production and that used for calculating the gas flow rate; 2) the formula can only be used in the situation where the boundary direction of the condensate oil that has reached the critical saturation diffuses towards the formation, but not in the all situation in the condensate gas reservoir, therefore should be used with caution.

When the water particles move to any position \(r\) at time \(t\), with the influence of the irreducible water saturation \(S_{wi}\), residual gas saturation \(S_{gr}\) and condensate oil saturation \(S_o\) at this point taken into consideration, we can obtain the corresponding equation of water particle movement. At the same time, we cannot ignore that the condensate oil saturation changes with the distance, as shown in the following figure:

![Figure 3 Water quality migration in the micro-element](image)

Therefore, the movement equation of water particles in this micro-element is as follows:

\[
\frac{d\phi}{dt} = \frac{\phi \left( 1 - S_{wi} - S_{gr} - S_o \right)}{v_{wg}} dr
\]

Substitute it in (8), we can have:
After solving the equation, we can obtain the water breakthrough time in the condensate gas reservoir when the retrograde condensation damage is considered:

\[ t = \frac{Ar^2}{2 - B} \]

If the retrograde condensation damage is neglected, the water seeing time is:

\[ t = \frac{Ar^2}{2} = \frac{\pi h r^2 \phi(1 - S_{wi} - S_{gr})}{q_g B_g M_{wg}} \]

The parameter B reflects the effect of condensate oil on the water breakthrough time in the condensate gas reservoir, including gas viscosity, daily gas production, porosity, permeability, gas layer thickness and fluidity ratio. There are many influencing factors, indicating the complexity of the situation where condensate precipitation is taken into account.

4. Instance Computation

A well in \( H \), a low-permeability condensate gas field, is used as an example to calculate the breakthrough time of the edge water. The relevant parameters of the well are shown in the table below:

| Parameter | \( \phi \) | \( K \) | \( K_{\text{gwi}} \) | \( K_{\text{wgr}} \) | \( \mu_w \) | \( \mu_g \) | \( S_{wi} \) |
|-----------|---------|-------|----------------|----------------|---------|---------|---------|
| Unit      | mD     | mD    | mD            | mD            | mPa.s   | mPa.s   |         |
| Value     | 0.06   | 0.34  | 0.61          | 0.39          | 0.24    | 0.035   | 0.43    |

| Parameter | \( S_{gr} \) | \( Y \) | \( q_g \) | \( B_g \) | \( h \) | \( r \) | \( S_{or} \) |
|-----------|-------------|-------|---------|---------|------|------|-----------|
| Unit      | m\(^3\)/d\/(m\(^3\)·MPa) | m\(^3\)/d | m      | m      |      |      |          |
| Value     | 0.20       | 0.0000435 | 130000 | 0.0045 | 10   | 450  | 0.31     |

The well was put into production on April 27, 2018. On April 20, 2015, the water-gas ratio increased sharply, the Cl- content increased, and the wellhead pressure decreased, indicating the edge water breakthrough since this time point and that the actual edge water breakthrough time is 2,549 days. According to the actual production data (see Figure 4), the average daily gas production before the edge water breakthrough is 130,000 m\(^3\)/d.
Substitute the relevant parameters into the formula, and we can see that the water breakthrough time with and without taking into consideration the condensate pollution is 2588 days and 2,572 days, respectively.

Figure 5 is the water seepage time under different permeability conditions. It can be seen from the figure that when considering retrograde condensation damage, the greater the permeability, the shorter the water breakthrough time. The lower the permeability, the greater the impact on water seepage time. In conventional gas reservoirs, since condensate pollution is not considered, the relationship between water breakthrough time and permeability is mainly related to the gas-water mobility ratio, but not to permeability.

Fig. 6 shows the relationship between the distance between the gas-water boundary the bottom of the well and the water breakthrough time with different initial gas-water boundaries. It can be seen that the greater the distance, the longer the water seepage time.
Figure 6 Relationship between water breakthrough time and the distance between the well bottom and the initial gas-water boundary

5. Conclusion
1. The main factors affecting the water breakthrough time in the condensate gas reservoirs include daily gas production, gas viscosity, porosity, permeability, gas-water mobility ratio, gas layer thickness, and the distance between the initial gas-water boundary and the bottom of the well.

2. The determination of the condensate saturation with retrograde condensation damage taken into consideration shall not only consider the relationship between condensate saturation and time, but also the dual effects of condensate saturation and time and radius. Hu's formula is essentially the same as Muskat's formula, which cannot be applied repeatedly.

3. The method for predicting the water breakthrough time in the gas reservoir with retrograde condensation damage taken into account delivers the result more consistent with the actual situation and is more in line with the characteristics of retrograde condensation.

Symbol Description: $\phi$: Porosity; $K$: Effective permeability of the reservoir, mD; $K_{gwi}$: Relative permeability of gas phase under original conditions, mD; $K_{wgr}$: Relative permeability of the water phase in the retrograde condensation area, mD; $\mu_w$: Viscosity of water phase, mPa.s; $\mu_g$: Gas phase viscosity, mPa.s; $t$: Time, d; $S_{wi}$: Irreducible water saturation; $S_{gr}$: Residual gas saturation; $d_c$: Condensate oil change per unit volume, m$^3$/m$^3$; $Y$: Retrograde condensation factor, m$^3$/m$^3$.MPa; $q_g$: Daily gas production of condensate gas wells, m$^3$/d; $B_g$: Gas volume coefficient; $h$: Thickness of gas layer, m; $r$: Distance between the initial gas-water boundary and the bottom of the well, m; $M_{wg}$: Water flow ratio.

References
[1] MUSKAT,M,WYCOKOFF ,R D.(1935)An approximate theory of water-coning in oil production. Transactions of the Aime, 114(1):144-163.
[2] MUSKAT,M.(1949)Physical principles of oil production. New York: Mc Graw-Hill11:93-126.
[3] Hu ,Y L.(1996)Analysis of retrograde condensate phenomenon in condensate well test. Oil and gas well test,5(1):21-25.
[4] Wang,H Q, Li X P, et al. Prediction (2007)method of water breakthrough time in bottom water reservoirs. Petroleum geology of xinjiang, 28 (1) : 92-93.
[5] Huang,Q H, Lu ,Y , et al.(2016) Prediction method of water breakthrough time for bottom water reservoirs considering non-darcy effect. Science & technology & engineering, 16 (14) : 137-140.
[6] Zhu, W Y, Huang, X H, Yue, M. (2014) Study on water breakthrough time of horizontal well in bottom water reservoir. Science and technology guide, 32(08): 27-31.

[7] Ming, R Q, He, H Q, Hu, Q F. (2018) A new method for prediction of water breakthrough time in bottom water condensate reservoirs. Special oil & gas reservoirs, 2018(05): 1-7.

[8] Zhang, L H, et al. (2004) A new method for predicting the water breakthrough time of bottom water condensate gas reservoirs considering the precipitation of condensate oil. Natural gas industry, 24 (7): 74-75.

[9] He, X D, Zou, S L, Lu, X M. (2006) Identification and mechanism of water intrusion in marginal water reservoirs. Natural gas industry, 2006 (3): 87-89.

[10] Xiong, Y, Chen, Y, et al. (2009) Gas-water distribution characteristics of kmiqiao main buried hill condensate gas reservoir. Special reservoirs, 16 (6): 48-51.

[11] Zheng, X M, et al. (2008) A brief analysis on the development mode of condensate gas reservoirs. Special oil and gas reservoirs, 15 (6): 59-63.

[12] Shi, G Z, Feng, G Q, Zhang, L H. (2006) Numerical simulation study on development of a marginal water reservoir. Natural gas exploration and development, 29 (2): 21-24.

[13] Liu, G W, Jiang, H Q, Li, L Y, et al. (2014) A new method for predicting water breakthrough time in horizontal Wells in marginal water reservoirs. Science & technology & engineering, 14 (2): 84-86.

[14] Wu, K I, Li, X F, Zhang, G T, et al. (2011) A new method for predicting water breakthrough time in boundary water condensate gas reservoirs with retrograde condensate. Science & technology & engineering, 19 (11): 4574-4577.

[15] Wang, Z H, Wang, Z D, et al. (2016) Prediction model of boundary water breakthrough time in edge water gas reservoirs with gravity and non-darcy effect. Oil drilling and production technology, 38 (2): 210-215.

[16] Wang, H Q, Li, X P, et al. (2008) Prediction method of well water breakthrough time in boundary water reservoirs. Special oil & gas reservoirs, 15 (4): 73-74.

[17] Li, Z J, Qi, Z L, et al. (2014) Prediction model of boundary water gas reservoir performance based on early warning of water invasion. Journal of southwest petroleum university, 36 (3): 87-92.

[18] Huang, Q H, Lin, X Y, Tong, K, et al. (2019) Prediction of water breakthrough time in horizontal Wells of fida percolation marginal water reservoir. Lithologic reservoirs, 31 (01): 147-152.

[19] Yang, F R, Fan, P T, He, J, et al. (2013) Prediction method for water breakthrough time of high yield gas Wells in marginal water reservoirs. Science & technology & engineering, 13 (29): 8745-8747+8754.

[20] Li, Y S, Yang, Z X, Wu, R D, et al. (2017) Prediction model of water breakthrough time for boundary water condensate gas reservoirs considering the influence of retrograde condensate. Special oil & gas reservoirs, 24 (5): 107-110.

[21] Ming, R Q, He, H Q. (2018) A new model for prediction of water breakthrough time in high yield Wells of boundary water condensate gas reservoirs. Special oil & gas reservoirs, 01: 1-6.