Journal of Petroleum Science and Engineering 157 (2017) 999–1006

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Gas-well water breakthrough time prediction model for high-sulfur gas reservoirs considering sulfur deposition

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ARTICLE INFO

Keywords:
Gas-well water breakthrough time (GWWBT)
High-sulfur gas reservoirs (HSGRs)
Sulfur deposition
Non-Darcy seepage

ABSTRACT

The sulfur-solubility decreases as a result of the decrease in gas reservoir pressure, leading to the solid-phase sulfur deposition. As a consequence, both the reservoir porosity and permeability decrease, subsequently influencing gas well water breakthrough time (GWWBT) in high sulfur gas reservoirs (HSGRs) with edge/bottom water. To acquire the value of GWWBT, a GWWBT prediction model for HSGRs should be established while taking into account sulfur deposition. Accordingly, based on gas Non-Darcy seepage law and sulfur deposition theory in porous media, a novel GWWBT in high sulfur gas reservoir with bottom water was developed in this study. The effect of dynamic factors (e.g., sulfur deposition, gas Non-Darcy flow, irreducible water saturation, and residual gas saturation) on GWWBT was involved in this model. The GWWBT was calculated via the proposed method and three classical models in five field basic parameters, and was compared with five filed values, respectively. This result indicates that the calculation of proposed method is in closer agreement with the field production data, and illustrates that the new proposed model is more reliable. In addition, the influence of dynamic factors was further discussed in detail by this proposed model.

1. Introduction

Active edge/bottom water gas reservoir accounts for approximately 40–50% of water drive gas reservoirs. Most existing gas reservoirs of China have varying degrees of water drive; most of China's high-sulfur gas reservoirs (HSGRs) are close to water bodies of bottom water (Wang et al., 2011). The water body flows to the gas reservoir during HSGR development, forming two-phase gas-water seepage with decreasing pressure. This results in a decrease in the gas-well recovery rate (Wang et al., 2011; Zeng et al., 2013; Li, 2014; Liu et al., 2015; Yu et al., 2016) which can be mitigated using an effective bottom water coning profile and by controlling the breakthrough time accordingly.

Previous scholars have proposed many prediction models for gas-well water breakthrough time (GWWBT) after investigating bottom water coning problems in conventional bottom water reservoirs. Sobocinski and Cornelius (1965), for example, studied the relation between bottom water coning and time based on the physical model of sandstone, but which was built form the static water-oil contact to breakthrough conditions. Kuo and Desbrisay (1983) modeled the dynamic relationship between bottom water coning and time numerically, which is without considering residual oil saturation, irreducible water saturation. Shi et al. (1992) used the system identification method and a one-dimensional differential equation for filtering flow to establish a GWWBT prediction method, the application of this model is limited known mechanism model and huge amounts of oilfield statistical data. Li (2001) and Tang (2003) obtained water breakthrough prediction time equations for bottom water reservoirs in which plane radial flow and spherical flow are taken into account, while residual oil saturation, irreducible water saturation, and oil/water viscosity are neglected. Zhang et al. (2004) proposed a water breakthrough model for condensate reservoirs with bottom water based on a relatively simple water coning model in which gas condensing effects were taken into account, but this model is only applicable for condensate reservoirs. Zhao and Zhu (2012) derived a water breakthrough time prediction equation for low-permeability bottom water reservoirs with barriers by applying the material balance principle and non-Darcy flow theory, which takes the hemispherical radial flow below the water coning barrier and plane radial flow above the barrier into consideration. However, this equation considering start-up pressure gradient is only applicable for low-permeability gas reservoirs. Xiong et al. (2014) proposed a formula for water coning

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http://dx.doi.org/10.1016/j.petrol.2017.08.020
Received 28 February 2017; Received in revised form 20 July 2017; Accepted 4 August 2017
Available online 10 August 2017

breakthrough time in bottom water oil reservoirs in which oil-water mobility ratio, original irreducible water saturation, and residual oil saturation are taken into account, this formula is only applicable for oil reservoirs. Li et al. (2015) improved upon this model by adding oil-water contact and water coning profile factors but disregarding the impact of non-Darcy effects. Huang et al. (2016) deduced bottom-water gas reservoir water coning time based on the theory of percolation flow in porous media; their model also includes gas non-Darcy effects, skin factor, degree of opening, and daily gas production, without irreducible water saturation and residual gas saturation. Sulfur deposition is missing from these models, however, rendering them inapplicable to HSGRs.

In bottom-water HSGRs, sulfur solubility decreases as gas reservoir pressure decreases, which leads to solid-phase sulfur deposition (Roberts, 1997; Zeng et al., 2005; Yang et al., 2004; Du et al., 2006; Guo et al., 2009). This further causes a decrease in reservoir porosity and permeability which affects GWWBT. Extant prediction models cannot yield accurate results without considering sulfur deposition. In this paper, a novel GWWBT model was established with consideration of sulfur deposition for HSGRs.

2. Gas-well water breakthrough time

The physical bottom water coning model is shown in Fig. 1.
Assumptions:

(1) Capillary forces, gravity, reservoir anisotropy, stress sensitivity, slippage, and skin factor effects during the displacement process are ignored;
(2) Imperforated formation is assumed for the bottom of the distal radial flow and bottom hemispherical centripetal flow, while perforated formation is assumed for the plane radial flow.

The existence of a shaft axis z with homogeneous distribution in the original gas water interface (r axis) was also assumed (Fig. 1). According to the water quality point seepage law, there is a mass point A at the initial gas-water interface with a radial flow for t to point A (z, r) and fluid velocity at point A (V) in the porous media seepage. Using the reservoir of porous medium porosity (ϕ) and irreducible water saturation (S_{wi}), residual gas saturation (S_{gr}), sulfur saturation (S_s), and the actual seepage velocity of water points V_1, the upward seepage velocity of water points is V_{1v} can be calculated as follows:

$$V_1 = \frac{V}{\phi(1 - S_{wi} - S_{gr} - S_s)} \tag{1}$$

$$V_{1v} = V_1 \sin\varphi \tag{2}$$

$$\sin\varphi = \frac{H - z}{\sqrt{r^2 + (H - z)^2}} \tag{3}$$

$$V = \frac{Q_{sc}}{2\pi\left[r^2 + (H - z)^2\right]} \tag{4}$$

Combining Eqs. (1)–(4) yields:

$$V_{1v} = \frac{Q_{sc}}{2\pi\left[r^2 + (H - z)^2\right]\phi(1 - S_{wi} - S_{gr} - S_s)} \frac{H - z}{\sqrt{r^2 + (H - z)^2}} \tag{5}$$

The upward migration distance of water coning is dz in dt can be obtained by equation (5), it is as follows:

$$\int_0^z dz = \int_0^t \frac{Q_{sc}(H - z)}{2\pi\phi\left[r^2 + (H - z)^2\right]^{3/2}(1 - S_{wi} - S_{gr} - S_s)} dt \tag{6}$$

Equation (6) can be rewritten in integrated form as:

$$\frac{1}{3}(H^2 + r^2)^{\frac{3}{2}} - \frac{1}{3}\left[(H - z)^2 + r^2\right]^{\frac{3}{2}} + r^2 \left\{ \begin{array}{l} (H^2 + r^2)^{\frac{1}{2}} \\ +r \ln \dfrac{(H^2 + r^2)^{\frac{1}{2}} - r}{H^2} \\ -\left[(H - z)^2 + r^2\right]^{\frac{1}{2}} \\ -r \ln \dfrac{\left[(H - z)^2 + r^2\right]^{\frac{1}{2}} - r}{(H - z)^2} \end{array} \right\} = \frac{Q_{sc}}{2\pi\phi(1 - S_{wi} - S_{gr} - S_s)} t \tag{7}$$

When the water cone breaks through to the gas well, assuming $r = 0$, $z = H$, $t = t_p$ (bottom water coning breakthrough critical height) in Eq. (7), then the novel GWWBT for HSGRs is:

$$t_p = \frac{2\pi\phi(1 - S_{wi} - S_{gr} - S_s)}{3Q_{sc}} H^3 \tag{8}$$

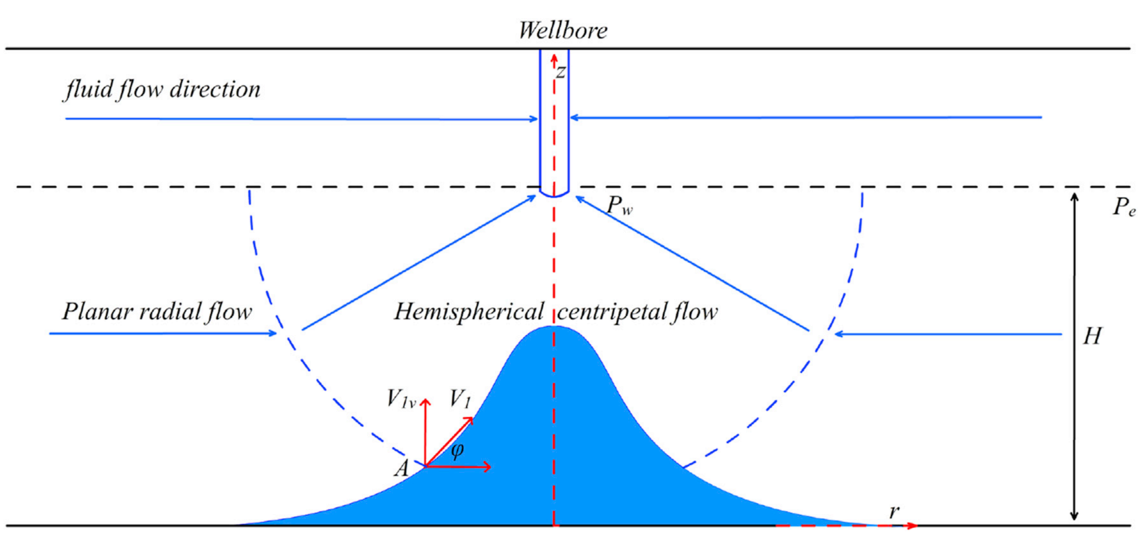

Fig. 1. Schematic diagram of water coning in bottom-water reservoir.