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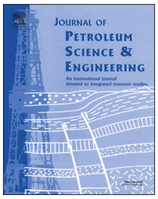

Technobites

The critical parameters of a horizontal well influenced by a semi-permeable barrier considering thickness in a bottom water reservoir

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ABSTRACT

It is well known that barriers have significant impact on the production performance of horizontal wells developed in a bottom water drive reservoir. In most cases, reservoir barriers are semi-permeable. Based on our previous research results on impermeable, semi-permeable barriers that ignore thickness, in this paper, a model is derived for a horizontal well of a bottom water drive reservoir with a semi-permeable barrier considering thickness. It also presents analytical equations to calculate critical parameters such as production rate, pressure and potential difference. The effects of barrier parameters on our model results were further investigated. The results showed that the larger the barrier size, thickness or the higher the barrier location, the higher are the critical parameters of a horizontal well. In a case, where the barrier permeability equals the formation permeability, the barrier width or thickness equals zero, the critical production rates converge to the same values of the case that has no barrier. When the barrier permeability equals zero, the problem is regarded as a case of impermeable barrier. This model can be applied to predict horizontal wells' critical production parameters in bottom water reservoirs with different size, thickness, and permeability of semi-permeable barriers.

1. Introduction

Since Muskat and Wyckoff (1935) introduced the water coning phenomenon and theory to petroleum engineering, horizontal well's critical rate calculations (Chierici et al., 1964; Chaperon, 1986; Giger, 1989; Guo and Lee, 1992; Fan and Lin, 1994; Aulie et al., 1995; Permadi et al., 1995; Luo et al., 2008; Permadi and Jayadi, 2010), water breakthrough time predictions (Ozkan and Raghavan, 1990; Papatzacos et al., 1991; Cheng et al., 1994; Bahadori, 2010) and water cut reductions (Smith and Pirson, 1963; Folefac and Archer, 1990; Wojtanowicz et al., 1994; Siddiqi and Wojtanowicz, 2002; Ould-amer et al., 2004; Jin et al. 2010; Bekbauov et al., 2013) have been investigated. The methods reported in the literature for controlling water cut in oil production include perforating far away from the original water–oil contact (WOC), producing oil below the critical rate, producing oil and water separately with downhole water sink (DWS) or downhole water loop (DWL) technology, and injecting polymers to form a barrier.

Normally, the calculated horizontal well critical rate is much smaller than the actual oil production rate in bottom water reservoirs; however, some wells experience a very long period of water-free production (Permadi et al., 1995; Yue et al., 2009, 2012; Yue, 2010). This difference results from two main reasons – firstly, appropriate initial conditions (Yue et al., 2009, 2012) should be applied to the calculation of critical rate (Yue et al., 2009; Yue, 2010), and secondly, geological conditions are far more complicated than assumptions of homogeneous models. In addition, reservoir barriers have great impact on the calculated results of critical rate. It has been reported that reservoir barriers can significantly increase critical rate and delay water breakthrough time (Karp et al., 1962; Strickland, 1974; Li and Song, 1993; Siddiqi and Wojtanowicz, 2002; Hou, 2007; Zhang et al., 2008; Jin et al., 2010; Qin et al., 2011). It is necessary to consider the barrier effects during the laboratory research and the production process. Optimizing the barrier size, thickness and position is very important in order to get an appropriate production rate. The quantitative impacts of these parameters on bottom water coning in vertical wells have been investigated by various research groups (Smith and Pirson, 1963; Strickland, 1974; Siddiqi and Wojtanowicz, 2002). However, there are few quantitative investigations on barriers

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Nomenclatures

$\Delta\Phi_1$	potential difference at the first flow stage, MPa
$\Delta\Phi_2$	potential difference at the second flow stage, MPa
$\Delta\Phi_{m1}$	potential difference without barrier, MPa
$\Delta\Phi_{m2}$	potential difference with impermeable barrier, MPa
$\Delta\Phi_m$	critical potential difference with semi-permeable barrier, MPa
Δp_m	critical pressure difference with semi-permeable barrier, MPa
Q	production rate of the horizontal well, m^3/d
Q_m	critical rate for the formation with semi-permeable barrier, m^3/d
Q_{m1}	critical rate for the formation without barrier, m^3/d
Q_{m2}	critical rate for the formation with impermeable barrier, m^3/d
Q_1	equivalent well flow rate at the first flow stage with impermeable barrier, m^3/d
Q_2	real well total flow rate at the second flow stage with impermeable barrier, m^3/d
γ	parameter for the relationship between Q_1 and Q_2, Dimensionless
L	horizontal well length, m
h	thickness of the reservoir, m
a	distance of the barrier from the top boundary, m
b	width of the barrier, m
c	distance of the barrier from the bottom boundary, m
d	thickness of the barrier, m
K	formation permeability, μm^2
K_1	permeability of semi-permeable barrier, μm^2
R_K	ratio of permeability between formation and semi-permeable barrier, dimensionless
z_w	distance between wellbore and bottom boundary, m
r_w	wellbore radius, m
r'_w	equivalent wellbore radius, m
z'_w	distance between equivalent wellbore and bottom boundary, m
r_e	radius of the drainage boundary, m
B_o	oil formation volume factor, d imensionless
μ_o	oil viscosity, mPa·s
ρ_o	oil density, kg/m^3
ρ_w	water density, kg/m^3
g	gravitational constant, m/s^2
DX	X grid block size, m
DY	Y grid block size, m
DZ	Z grid block size, m

affecting the bottom water cresting in horizontal wells. In particular, no formula is available to calculate the critical parameters for horizontal wells in a bottom water reservoir with a semi-permeable barrier, which is the main target of our study. The impermeable or semi-permeable barrier in reservoir can prevent or slow down water coning or cresting. In this paper we report the results obtained from extending our previous work (Yue et al., 2012) as well as a horizontal well flow model to consider the influences of an impermeable barrier ignoring thickness in the formation. Additionally, the mathematical equations for critical parameters of water cresting were compared with the numerical simulation results. These findings were then used to discuss the critical production problem. The result showed that the increase in barrier permeability leads to a decrease in critical rate, critical potential difference and pressure difference. We have also found that the increase in semi-permeable barrier size, thickness and vertical position of the barrier can result in a higher critical rate and potential difference.

2. Conceptual model for semi-permeable barrier

The semi-permeable barrier has certain fluid flow capacity, and its permeability is lower than its surroundings. The permeability of semi-permeable barrier is K_1. Fig. 1 is the sketch of a horizontal well with a semi-permeable barrier considering thickness in the YZ cross section. The barrier was assumed to be horizontal and right below the horizontal well. The distances from the barrier to formation top and bottom boundaries were a and c, respectively. The barrier width was b and thickness was d. The top boundary was closed, and the bottom boundary was at constant pressure p_e. The reservoir thickness was h, the distance between the wellbore and the WOC was assumed as z_w, while the lengths of the horizontal well and the horizontal well radius were L and r_w, respectively. Points C and C′ were the first locations of water cresting. Points M and M′ were the locations of virtual wells at the barrier end points, which were above points C and C′ (Yue et al., 2012).

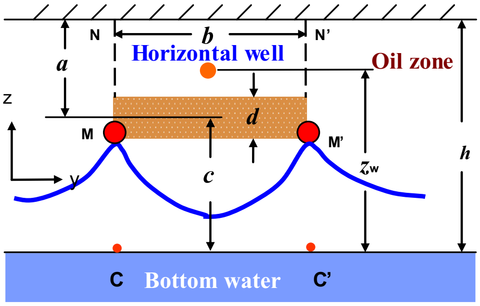

Fig. 1. The sketch of a horizontal well with a semi-permeable barrier in a bottom water reservoir.

3. Development of mathematical model

Reservoir and barrier were assumed isotropic with permeability K and K_1, respectively. As the bottom water cresting was based on Eq. (1) (Giger, 1989; Yue et al., 2009; Yue, 2010), the critical rate could only be obtained if the critical potential difference was known. It is important to note that the conversion factor is 10^{-6} between the gravity and pressure, gravity gradient and potential gradient using our paper's unit system.

$$-\frac{d\Phi_1}{dz}\Big|_{z=0}=(\rho_w-\rho_o)g \tag{1}$$

According to water–electricity similarity principle, which means that Darcy's law is precisely equivalent to the law of electrical conduction, the liquid pressure distribution in steady state porous flow is equivalent to the potential distribution in an electrical conducting medium (Wyckoff et al., 1933; Schaefer, 1947). The entire permeability of reservoir and the pore space can be taken as the superposition of two parts pore spaces. Fig. 2 shows the sketch of the total formation which is divided into two parts. In the first part, the whole formation uses partial pore space to provide permeability of K_1. In the second part, the remaining part of the pore space provides zero permeability in the barrier area; permeability is $K-K_1$ in the other area of the formation except the barrier area. Thus, the first part can be treated as the bottom water reservoir with permeability K_1. The second part can