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Quantification of the effects of bed lamination and wellbore deviation on the interpretation of formation-tester measurements

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A B S T R A C T

Formation-tester measurements (FTM) acquired in thinly bedded formations and in highly deviated wells often show a large pressure drop during the drawdown period of a pressure-transient test. The measured large pressure drop can be an indication of a low permeability layer at the probe location. We invoke the effects of bed boundaries to explain additional pressure drop in the FTMs. An accurate analysis of the FTMs requires simulating mud-filtrate invasion prior to the pressure-transient test. Specifically, the interplay between gravity, capillary, and viscous forces leads to a highly non-symmetric fluid distribution around the wellbore perimeter in deviated wells. In this condition, it becomes crucial to have depth control and perform fluid sampling at a suitable probe location with respect to the perimeter of the wellbore. A three-dimensional (3D) compositional fluid-flow simulator is employed to simulate mud-filtrate invasion and subsequently FTMs in deviated wells. The simulator is specifically designed for problems where the greatest variations occur in the vicinity of the wellbore. We test the accuracy of the algorithm with a series of drawdown-buildup tests in highly deviated wells; a comparison of results obtained with the available analytical solutions and the numerical simulator shows a very good agreement. Subsequently, using the developed simulator, we study invasion, pressure transient tests after invasion, and fluid sampling after invasion. Results show that invasion in a high-permeability formation causes non-symmetric distribution of fluid around the wellbore of a deviated well. Simulation results confirm that a probe-type FT records significant pressure drops when it is placed at the vertical vicinity of the well; this effect leads to a lower measured permeability compared to the actual permeability. It was also found that pressure drop during drawdown is affected by invasion; pressure drop in invaded formations is greater than in un-invaded formations. We also quantify cleanup time for sampling with a probe-type FT deployed in deviated wells. Results show that the cleanup is achieved faster when the probe is located at the high side of the well.

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1. Introduction

Over the course of last four decades, formation testers (FT) have been used to measure formation properties including pressure, permeability (k_h, k_v), and fluid properties such as color, viscosity, density, composition, pH, fractional flow, and gas–oil ratio (GOR). Different analytical and numerical methods have been used to analyze pressure transient tests acquired with a FT and to estimate formation properties. Most of the available analytical methods are limited to pressure response due to a packer-type FT. Abbaszadeh and Hegeman (1990) derived analytical expressions for the pressure variations during drawdown-buildup tests in vertical, horizontal, and slanted wells. They derived analytical solutions for different boundary conditions including no-flow and constant pressure at the top and bottom of the formation. Abbaszadeh and Hegeman's (1990) method is based on single-phase fluid flow in a reservoir with an infinite lateral boundary. Similar to Abbaszadeh and Hegeman (1990), Cinco-Ley et al. (1975) introduced an analytical solution to describe pressure-transient well tests assuming a line source. Analytical solutions proposed by Kuchuk and Wilkinson (1991) and Ozkan and Raghavan (2000) were obtained in the Laplace domain. Recently, Onur et al. (2004) suggested approximate analytical solutions for pressure tests conducted with a dual packer-probe wireline formation tester (WFT) in a deviated well. Similar to other analytical solutions, Onur et al.'s solution is valid only for spherical single-phase fluid-flow regimes. Several researchers have attempted to apply numerical methods to overcome limitations of analytical expressions for pressure

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Nomenclature

Abbreviation

3D	three-dimensional
FT	formation tester
FTM	formation-tester measurement
IMPEC	implicit pressure and explicit concentration
PVT	pressure–volume–temperature
UTFEC	The University of Texas at Austin's formation evaluation compositional fluid-flow simulator
WBM	water-base mud
WBMF	water-base mud filtrate
WFT	wireline formation tester

Roman letters

c_t	total formation compressibility, 1/psi
D	depth measured with respect to a reference level, ft
dr_{mc}	differential mudcake thickness
dt	differential time, day
e_w	exponent of water relative permeability
e_{nw}	exponent of oil relative permeability
e_p	exponent of capillary pressure
f_{ij}	fugacity of component i in fluid phase j, psi
$\underline{h}$	formation thickness, ft
$\overline{\overline{K}}_{ij}$	dispersion tensor, ft^2/day
k_h	horizontal permeability, md
k_{ro}	oil-phase relative permeability, md
k_{rw}	water-phase relative permeability, md
k_s	spherical permeability, md
k_v	vertical permeability, md
$\overline{\overline{K}}$	formation permeability tensor, md
l_w	effective half length of the packer for an anisotropic formation, ft
$\underline{l_w}$	half length of a packer, ft
$\vec{n}$	unit normal vector to a boundary
n_c	number of hydrocarbon components
N_i	number of moles of component i, lbm
n_p	number of fluid phases
Δp_o	pressure drop at the observation probe, psi
Δp_p	pressure drop at the probe, psi
P	pressure, psi
P_j	pressure of fluid phase j, psi
P_{ce}	capillary entry pressure, psi
P_{crj}	capillary pressure between fluid phase j and pressure of the reference fluid phase, psi
q	sampling flow rate, cc/s
q_i	molar flow rate of component i, lbm/day
r_{sw}	effective spherical wellbore radius, ft
r_w	wellbore radius, ft
r'_w	effective wellbore radius for an anisotropic formation, ft
R_{aniso}	permeability anisotropy ratio, fraction
s	skin factor, dimensionless
S_{or}	residual oil saturation, fraction
S_{wirr}	residual water saturation, fraction
S_{wn}	normalized water saturation, fraction
t	time, h
V_b	bulk volume, ft^3
V_p	pore volume, ft^3
V_p^0	pore volume at reference pressure, ft^3
V_t	total fluid volume, ft^3
$\overline{V}_{ti}$	partial derivative of total fluid volume with respect to moles of component i, ft^3/lbm
x_{ij}	mole fraction of component i in fluid phase j, fraction
z_o	distance of an observation probe from the center of a packer, ft
z_w	packer center distance from the lower bed boundary, ft

Greek symbols

γ_j	specific density of fluid phase j, dimensionless
μ	fluid viscosity, cp
ϕ	porosity, fraction
θ_j	azimuthal location on perimeter of the wellbore, deg
θ_w	wellbore deviation angle, deg
ξ_j	molar density of fluid phase j, lbm/ft^3

variations recorded at the sandface during a well test. Angeles et al. (2011) conducted one of the first studies that used modeling of FTs in highly deviated wells to account for the effect of mud-filtrate invasion. Angeles et al.'s model was constructed with non-orthogonal corner-point grids in Cartesian coordinates. However, because their numerical algorithm did not include off-diagonal terms in the permeability tensor, it is not recommended for applications in high-angle wells. Accurate invasion simulation requires a dynamic mudcake growth model coupled to a reservoir fluid-flow simulator which has incorporated full-tensor permeability in fluid-flow equations. This necessity becomes important in deviated wells where gravity segregation of fluids and anisotropy can cause a significant eccentricity in the spatial distribution of mud filtrate in the vicinity of the wellbore. It is observed that WFT measurements obtained in thinly bedded formations vary when the tool is located at different locations with respect to bed boundaries. Several researchers (Wu et al., 2002; Alpak et al., 2004; Suryanarayana et al., 2007; Hadibeik et al., 2012) studied pressure-transient well-test measurements when the probe was placed in the center of the formation. Previous researchers (Xu et al., 1992; Proett et al., 2001; Alpak et al., 2008) have noted that when a probe positions between a boundary separating low- and high-permeability layers, it became significantly more difficult for the probe to obtain a clean in situ sample. Moreover, the existence of a two-phase region in the vicinity of the wellbore makes the permeability measurement more complicated (Angeles, 2008; Hadibeik et al., 2014; Malik et al., 2009; Moinfar et al., 2010; Hadibeik et al., 2013; Nishaboori et al., 2011). This paper discusses numerical simulation of mud-filtrate invasion and formation-tester measurements in highly deviated wells. Numerical simulations are performed using a three-dimensional (3D) multi-phase fluid-flow simulator (UTFEC). We study the effects of bed boundaries and wellbore deviation on FTMs. First, a series of pressure tests are performed in a water-saturated formation. As benchmark verifications, we performed several case studies when single-phase spherical flow takes place and analytical solutions exit. In doing so, synthetic pressure responses for different well deviation angles are calculated with UTFEC and are compared to those obtained with an analytical expression. Then, we investigate probe-type FTMs acquired in thinly bedded formations including mud-filtrate invasion, pressure response during drawdown-buildup tests, and fluid sampling.

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