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Sampling with new focused, oval, and conventional probe-type formation-tester in the presence of water- and oil-base mud-filtrate invasion for vertical and high-angle wells

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ABSTRACT

Speculation about the potential of developing new fluid and pressure sampling methods with probe-type formation testers has existed since the introduction of formation pressure testing while drilling technology was introduced to the industry nearly a decade ago. To replace the existing wireline technology, a new pumping system is required to remove invasion fluids and then to fill single-phase sample chambers. To make this commercially possible, several technology enhancements are necessary in advance. Although wireline pumpout tools may require hours to retrieve representative fluid samples, it is not a practical alternative to spend hours obtaining samples in the drilling environment. Most simulations of wireline formation-tester measurements assumed that invasion ended at the time when fluid pumpout began. Additionally, previous studies assumed a time-constant rate of invasion that was the time average of invasion rate. Both of these assumptions are optimistic for a drilling tool.

The objective of this study is to quantify the viability of sampling in the drilling environment by way of numerical simulations. The study considers the dynamic nature of invasion while drilling when using both new and conventional probe configurations to retrieve fluid samples. With the realistic mudcake model, there are higher rates of invasion soon after drilling. Therefore, to simulate the invasion during drilling, a mudcake model is used that continues to grow in thickness and sealing effectiveness during invasion and throughout the sampling process. Simulation results focus on scenarios in which water-base mud (WBM) and oil-base mud (OBM) invade an oil-bearing zone. Furthermore, it studied the accuracy of functions used to estimate contamination in an OBM environment. The base model consists of a typical probe-type tool in a vertical well wherein fluid samples are retrieved using a time-constant flow rate. Invasion time is varied from 1 to 48 h to compare drilling and wireline sampling tools. Simulations of fluid cleanup times for a variety of rock types and wellbore deviation angles indicate that the oval focused probe retrieves the cleanest fluid sample in the least amount of time.

This study also quantifies mudcake sealing effectiveness, as well as the effect of borehole deviation. Oval (elongated) and focusing guard-style probes are compared to standard probe configurations in various petrophysical rock types.

1. Introduction

Difficulties arise to predict the behavior of probe-type formation testers in porous rock formations during sampling fluids and measuring pressures early in the life of a well. However, this sampling provides valuable information about the capability of the formation to produce oil and/or gas. Therefore, there is a significant demand for formation testers to secure representative downhole-fluid samples, even in complex situations when filtrate is miscible with in-situ reservoir fluid. Moreover, a new generation of formation testers that can reduce both sampling and rig time is highly appreciated.

Although wireline testers are mature technology, new while-drilling formation-testers are emerging, but are currently only designed to measure reservoir pressure (Proett et al., 2003). Even though sampling-while-drilling could be implemented in practice, it is not clear to what extent and how comparable fluid samples would be relative to those acquired with wireline formation-testers. Similarly, it is not clear what type of formation-tester

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Nomenclature

λ	growth factor [dimensionless]
$C(t)$	time varying contamination function [dimensionless]
ΔP	pressure drop across the mudcake [psi]
$x_{mc}(t)$	mudcake thickness [in.]
k_{mc}	mudcake permeability [mD]
$q(t)$	mud invasion flow rate [cm^3/s/cm^2]
ρ_m	mud density [lb/ft^3]
ρ_o	in-situ oil density [lb/ft^3]
μ_m	mud viscosity [cp]
μ_o	formation oil viscosity [cp]
ϕ	porosity [dimensionless]
k	formation permeability [mD]
k_{ro}	oil relative permeability [dimensionless]
k_{rw}	water relative permeability [dimensionless]
GOR	gas–oil ratio [ft^3/STB]
GOR_o	uncontaminated formation GOR [ft^3/STB]
$GOR(t)$	measured GOR [ft^3/STB]
OFP	oval focused probe
FP	focused sampling probe
OP	oval probe
SP	single probe
S_{wirr}	irreducible water saturation
OBM	oil-base mud
WBM	water-base mud
EOS	equation-of-state
FTWD	formation-tester while-drilling
LWD	logging-while-drilling
LBC	Lohrenz–Bray–Clark's correlation

probe should be used to ensure minimally contaminated measurements for a specific tool/formation configuration. Lately, the industry has introduced optical fluid identification modules for real-time monitoring (Mullins and Schroer, 2000), focused sampling probes (Sherwood, 2005) and, quite recently, the oval pad tester (El Zefzaf et al., 2006). Nonetheless, one of the most important issues with wireline formation sampling remains acquiring clean reservoir fluid samples with a minimum of mud-filtrate contamination as early as possible in the life of the well.

To measure the effectiveness of fluid sampling in the drilling environment, it is important to consider how invasion occurs while drilling (Skibin and Zazovsky, 2010). It is, therefore, pertinent to consider current techniques used for simulation of mud-filtrate invasion. Previously, simulations of fluid cleanup were initialized with a known volume of mud-filtrate invasion (Malik et al., 2009). Other works simulated mud-filtrate invasion before the onset of fluid pumpout, but then the invasion rate was stopped after pumpout began (Alpak et al., 2008; Angeles et al., 2009). Given that the mudcake is not fully formed at these early stages of drilling, and mud-filtrate invasion continues regardless of the formation testing, both methods are optimistic when analyzing logging-while-drilling (LWD) measurements.

The objective of this paper is to compare while-drilling and wireline testers to quantify their effectiveness under various petrophysical rock types, different fluid conditions, and different borehole deviation angles. These comparisons include the simulation results of different formation-tester probe geometry to assess their cleanup times versus pressure drops imposed on the formation.

Mud-filtrate invasion is simulated using a modification of the method proposed by Wu et al. (2004). A 3D multi-phase, multi-component reservoir simulator is used to incorporate the impacts of mud-filtrate invasion before and during formation testing, that includes gravity and capillary pressure effects. Subsequently, the effects of various contamination functions are investigated to evaluate the assessment of fluid sample quality with time of sampling.

Elaborating on the definition of contamination is critical when filtrate is miscible with reservoir fluid. Previous studies proposed to measure gas–oil ratio (GOR) to distinguish the level of contamination of a fluid sample (Alpak et al., 2008). This study indicates considerable differences in the assessment of cleanup time when other types of physical measurements are used to estimate levels of fluid contamination (e.g., viscosity and density of mud filtrate). These methods are evaluated to assess contamination against simulations in which contamination is known a priori. In addition, numerical simulations consider the effect of borehole deviation on the performance of various probe configurations.

2. Numerical simulation of formation-tester measurements

The studies in this paper use a multi-phase, multi-component reservoir simulator supported by CMG.[4] A black-oil reservoir method exercised to simulate the cases of WBM filtrate invasion. In this model, all fluid-saturation dependent properties such as capillary pressure, relative permeability, and other rock-fluid properties are included in the simulations, and the model accounts for the effect of gravity. For simplicity, it is assumed that the imbibition and drainage capillary pressure and relative permeability curves during the process of mud invasion and the pump-out sampling stage are identical. To model the OBM filtrate invasion and sampling, a compositional equation-of-state (EOS) simulator is used to take into account the effect of phase behavior and concentration changes.

The type of probe used and its overall dimensions determine how the fundamental base grid blocks are defined. Matching the probe to the simulation grid is a critical step in the modeling because modeling errors can occur in this region as a result of high pressure and fluid-concentration gradients. The goal is to size the grid blocks so that the number and size of grid blocks result in convergence of the solution. Ideally, when a grid is refined and the solution converges, small variations in the gridding will not affect the result of numerical simulation. Fig. 1 shows the numerical study for the oval and oval focused probe. Grid refinement continues until it minimizes the effect of numerical error attributable to discretization.

2.1. Validation of the numerical model

For single and focused-sampling probes, the grid mapping used closely matches that used by Angeles et al. (2009). Applying similar grid mapping has the advantage of using an established grid for the numerical discretization and convergence. For the new oval and oval-focused probes, the size of grid blocks must conform to the size of the probe geometry, making it necessary to validate the new gridding strategy. As a result, a base-case model was defined with 317,580 finite-difference grids that constrained the maximum error bounds to less than 0.05% for the simulated fractional flow rate and pressure. Fig. 1 shows results from grid refinement studies for the model of oval and oval-focused probe.

The base-case model is assumed an anisotropic homogenous reservoir. The same capillary pressure and relative permeability curves are used for drainage and imbibition. This simplification is

[4] CMG: Computer Modelling Group Ltd.