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Streamline-based inversion of formation properties from formation-tester measurements acquired in high-angle and horizontal wells

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ABSTRACT

A new method is developed based on streamlines to determine the reservoir properties from formation-tester measurements. To do so, a previously developed finite-difference reservoir model is coupled with a streamline method to simulate the near-wellbore dynamic measurements in the presence of invasion and arbitrary fluid distributions. The streamline method is specifically developed to overcome technical challenges in modeling deviated wells in heterogeneous reservoirs efficiently.

In this study, synthetic reservoir models are constructed based on measurements acquired in offshore well A with 15° deviation angle. The streamline-based method is then implemented to simulate packer-type formation-tester measurements and to appraise permeability of multi-layer reservoirs. In addition, transient measurements from a focused-sampling probe-type formation tester is modeled with streamline method to estimate relative permeability and anisotropy in offshore well B. Inversion results indicate that the accuracy of estimated formation properties is higher for formations with larger mobility because more streamlines trace flow into probes from large-mobility layers. For offshore well A, in the presence of 5% zero-mean Gaussian additive noise, the uncertainty of permeability varies from 6% to 38% for layers with high and low mobilities, respectively. The uncertainty increases to 8% and 41% for high and low mobility cases, respectively, when 5% skewed-Gaussian noise contaminates the measurements.

The coupled finite-difference and streamline-based inversion method (FDSM) is then compared to a previously validated finite-difference reservoir model (FDM). The coupled FDSM is 8 times faster than FDM on an average when estimating properties of heterogeneous reservoirs using inversion on formation-tester measurements acquired in highly deviated wells. Computational advantage of FDSM is due to application of one-dimensional solutions of fluid saturations and concentrations along streamlines instead of three-dimensional FDM numerical calculations. Despite the efficiency, history matching of measurements indicates up to 6% difference between FDSM and FDM in results.

In high-angle wells, mud-filtrate invasion causes a non-symmetric distribution of invading fluid around the wellbore perimeter. Moreover, presence of large permeability–porosity contrast among layers increases complexity of numerical computations and uncertainty. This study proposes that the streamline-based inversion method is an excellent candidate to overcome these difficulties efficiently.

1. Introduction

Dual-packer and probe-type formation-tester measurements are used to determine reservoir properties such as pore pressure and permeability (Angeles et al., 2010; Hadibeik et al., 2014). Several analytical models have been developed to interpret these measurements using pressure transient analysis from vertical wells and for layer-by-layer analysis of measurements (Agarwal, 1979; Goode and Thambynayagam, 1987). However, Clarkson (2009) showed that these models do not account for complexities of layered-heterogeneous reservoirs, multi-phase and multi-component fluid flow, and fluid compressibility, among other important factors.

Therefore, accurate numerical techniques have been used in industry to address complexities of reservoir models and to predict formation-tester measurements (Zeybek et al., 2004). Most of these simulations were taking into account some but not all complexities,

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Nomenclature

Abbreviation

CPU central processing unit
FDM finite-difference method
FDSM joint streamline and finite-difference method

Symbols

ϕ porosity [dimensionless]
μ viscosity [cp]
α regularization parameter [dimensionless]
σ standard deviation [dimensionless]
$\overline{\overline{W_x}}$ model weighting matrix [mD^{-1}]
$\overline{\overline{W_d}}$ data weighting matrix [dimensionless]
$C(x)$ objective function [dimensionless]
$e(x)$ data mismatch vector [dimensionless]
F_w fractional flow of the water phase [dimensionless]
$J(x)$ Jacobian matrix, [dimensionless]
k_v vertical permeability [mD]
k_h horizontal permeability [mD]
k_r relative permeability [dimensionless]
M mobility [mD/cp]
P pressure [psi]
P_f formation pressure [psi]
S_w water saturation [dimensionless]
S_{wirr} irreducible water saturation [dimensionless]
t time [s]

which made them limited for industry to adopt (Pimonov et al., 2010; Hadibeik et al., 2012). On the other hand, inversion methods based on these numerical simulations are time consuming, especially in highly deviated wells (Malik et al., 2007). This is because previous numerical inversion methods exercised a finite-difference method for simulation of pressure and saturation measurements. To improve computational efficiency of pressure and fractional flow calculations, a previously developed streamline-based model (Hadibeik et al., 2011), which is well-suited for heterogeneous reservoirs penetrated by deviated wells, is applied for inversion. The inversion is used to estimate reservoir properties in synthetic models and field data. Alpak et al. (2011) showed that the joint inversion of pressure and fractional flow measurements is an ill-conditioned problem. As the number of unknown parameters in the inversion increases, the problem becomes more complex and its solution becomes non-unique. Angeles et al. (2007) invoked regularization and weighting factors to balance the effects of pressure and fractional flow measurements in the combined cost function. This study applies streamline-based inversion to estimate petrophysical properties from contamination and transient pressure measurements of formation testers.

2. Description of streamline-based inversion method

Due to the ill-posed nature of nonlinear minimization problems, a regularization approach is required because few measurements exist for performing the minimization. The regularized inversion approach is a strategy to unite measurements that have different resolutions. Consequently, a Gauss–Newton inversion method including Hessian information (Aster et al., 2005) is used to provide a stable solution for estimating reservoir properties. To balance model parameters and measurement mismatch, an adaptive approach is applied during minimization to choose a proper regularization parameter. Thus, a dual-physics method of joint inversion is formulated to estimate the underlying petrophysical model. Inversion of dual-physics measurements is an optimization problem to minimize a quadratic cost function based on physical constraints (Torres-Verdín et al., 2004). A weighted regularized Gauss–Newton method is used for this purpose.

The measurement vector is defined as

$$P = \begin{bmatrix} \Delta P_1 & \Delta P_2 & \cdots & \Delta P_i & \cdots & \Delta P_M \end{bmatrix}, \quad (1)$$

where P is the vector of pressure differences, M is the number of measurement points, ΔP_i for drawdown test is the initial pressure at start of pumpout minus pressure at any time; ΔP_i for the buildup test is the final stabilized pressure minus pressure at any time. Angeles et al. (2007) reported that use of pressure differentials substantially increases minimization stability. Contamination fractional flow vector is given by

$$fw = \begin{bmatrix} fw_1 & fw_2 & \cdots & fw_i & \cdots & fw_M \end{bmatrix}, \quad (2)$$

where fw is the vector of fractional flow measurement points and fw_i is the contamination sampled at ith time. Data mismatch vector, $\overline{e}(\overline{x})$, is a vector whose ith element is the residual error of ith-normalized measurements and is defined as

$$\overline{e}(\overline{x}) = \begin{bmatrix} e_1 & e_2 & \cdots & e_i & \cdots & e_M \end{bmatrix}, \quad (3)$$

where e_i is

$$e_i = \frac{\Delta P_{sim}|_i - \Delta P_{meas}|_i}{\Delta P_{meas}|_i}, \quad (4)$$

for pressure measurements; for contamination measurements, e_i is

$$e_i = \frac{fw_{sim}|_i - fw_{meas}|_i}{fw_{meas}|_i}, \quad (5)$$

where $fw_{sim}|_i$ is simulated fractional flow at ith time, and $fw_{meas}|_i$ is the measured fractional flow at that time. The model parameters in the inversion process are the layer permeabilities in the offshore well A, and anisotropy and relative permeability end-points in the offshore well B.

Both pressure and fractional flow measurements are employed to estimate the abovementioned model parameters based on the inversion method described by Angeles et al. (2010). The difference between this study and the previous studies is the use of streamline method to calculate the contamination fractional flow.

3. Estimation of permeability from formation-tester measurements: example A

The following assumptions are embedded in the inversion process used in the first field example: (1) relative permeability and capillary pressure curves are from the Brooks-Corey model, (2) mud-filtrate invasion radius is a function of formation permeability, (3) gravity effects are neglected in the streamline-based inversion model, (4) porosity is calculated from neutron–density logs, and (5) fluid viscosity is constant, obtained from laboratory measurements.

A dual-packer formation tester performs drawdown-buildup tests at a lower section of the well, where high resistivity values indicate hydrocarbon presence. Fig. 1 describes both tool configuration and the earth model used to construct synthetic models