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Petrophysical interpretation of laboratory pressure-step-decay measurements on ultra-tight rock samples. Part 1 – In the presence of only gas slippage

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ABSTRACT

Conventional laboratory characterization of ultra-tight reservoir rock samples involves separate laboratory measurements on different core plugs or on crushed rock samples. Heterogeneity and anisotropy of ultra-tight reservoir samples adversely influence the laboratory correlation among various measured and estimated petrophysical properties. We apply an inversion algorithm to simultaneously estimate the intrinsic permeability (k_i), effective porosity at ambient condition (ϕ_0), pore-volume compressibility (C_p), and Klinkenberg-slip factor (b) of an ultra-tight pyrophyllite sample from a single laboratory-based pressure-step-decay measurement.

The inversion algorithm is valid for nitrogen injection pressure in the range of 50–500 psi. The algorithm assumes ideal-gas behavior of the injected nitrogen, 1D isothermal laminar gas flow, homogeneity of the core, pressure-independent gas viscosity, inverse-pressure dependence of the apparent permeability, pressure-independent Klinkenberg-slip factor, non-negligible pore-volume compressibility, pressure-dependent effective porosity, negligible inertial effects, square of pressure gradient is significantly smaller than pressure times second derivative of pressure along the entire length of the core plug, and time-invariant confining pressure.

Parameter-estimation results based on the proposed inversion scheme are shown to be independent of the values of the initial guess for k_i in the range of 1 nd to 10 μd, ϕ_0 in the range of 0.01–0.20, C_p in the range of 10^{-2} to 10^{-6} psi^{-1}, and b in the range of 0–200 psi. Estimated apparent permeability and effective porosity of the pyrophyllite samples exhibit strong pore-pressure dependence; consequently, both the properties vary substantially along the sample length during the pressure-step-decay measurement. The pyrophyllite samples studied in this work are assumed to be homogeneous. The numerical model of the pressure step decay measurement accounts for the variation in porosity and permeability along the length of core due to the time-dependent pore pressure variation during the experiment. On an average, the effective porosity of the pyrophyllite samples increased by 100% and the apparent permeability decreased by 75% when the pore pressure increased from 50 psi to 500 psi during the measurement. The average values k_i, ϕ_0, C_p, and b of the nine pyrophyllite samples were estimated to be 40 nd, 0.03, 2×10^{-3} psi^{-1}, and 100 psi, respectively.

1. Introduction

Accurate estimation of intrinsic permeability (k_i), effective porosity (ϕ_0), pore-volume compressibility (C_p), and pore-pressure dependency of porosity and permeability is crucial for the economic assessment of shale plays. Conventional methods of estimating the aforementioned petrophysical properties involve different laboratory-based measurement techniques on separate geological core samples under different conditions. Consequently, the laboratory-based estimates of petrophysical properties in shale reservoirs tend to exhibit large variations and cannot be correlated with each other. For instance, permeability of core plugs is measured using unsteady-state methods, such as pulse-decay (Bruce et al., 1953), or steady state method (Boulin et al., 2012; Sinha et al., 2013). However, the permeability of crushed core samples is measured using the Gas Research Institute (GRI) technique (Guidry and Curtis, 1996). Interpretation of unsteady method without reaching to pressure equilibrium through the cores dictates the interdependency of porosity and permeability parameters (Boulin et al., 2012). Such different laboratory-based permeability measurements were reported to vary 2–3 orders of magnitude (Passey et al., 2010; Sondergeld et al., 2010). The

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dependency of permeability and porosity of shale rock samples on the pore pressure and confining pressure further increases the inconsistency in their laboratory estimations. Moreover, the heterogeneity and anisotropy of shale reservoir rocks limit the development of robust correlations among the petrophysical properties. Various petrophysical properties of shale rock samples can be accurately and consistently estimated through simultaneous estimation of the properties from a single laboratory measurement on a single core sample.

In 1968, Brace et al. (1968), estimated the permeability of granite cylindrical samples by interpreting the pressure-decay measurements using a mathematical model that ignored the porosity of samples. Jones (1972) added the Klinkenberg effect to the Brace et al.'s model through an approximate iterative method and a quasi-analytical solution. In their proposed approach, Klinkenberg permeability, Klinkenberg-slip factor, and Forchheimer non-Darcy factor was computed from the unsteady-state laboratory-based pressure measurements. They applied the method to ceramic, sandstone, and carbonate samples. Hsieh et al. (1981) and Neuzil et al. (1981) used a general analytical solution to estimate the hydraulic conductivity and specific storage of shale samples from the pressure-transient measurements. Hsieh et al.'s approach was implemented by Escoffier et al. (2005) to invert modified pressure-transient pulse measurements for purposes of determining the intrinsic permeability and specific storage coefficient of mudstone samples. Finsterle and Persoff estimated the porosity, permeability, and Klinkenberg-slip factor of core plugs from the Geysers geothermal field (Finsterle and Persoff, 1997) using a similar method. Recently, Civan et al. (2012) presented a modified Darcy model to analyze the pressure-pulse-transmission laboratory data to determine the shale permeability, tortuosity, and Langmuir volume and pressure. Determination of permeability and Klinkenberg coefficient from the unsteady-state pressure-pulse-decay measurements was presented by Jannot and Lasseux (2012).

Simultaneous determination of intrinsic permeability, porosity, and Klinkenberg-slip factor coefficient based on a pressure-step-decay method was first described by Lasseux et al. (2012) and Dadmohammadi et al. (2016). They demonstrated that the petrophysical parameters obtained using the step-decay method exhibits negligible sensitivity to the dead volume, input pressure signal, and upstream gas leakage. Also, they showed that the history matching can be performed solely on the downstream pressure measurements. Lasseux et al. (2012) used a Levenberg-Marquardt algorithm to invert for the intrinsic permeability, porosity, and Klinkenberg-slip factor coefficient, that assumed ideal gas behavior of nitrogen for pressures as high as 800 psi. According to our study of the physical properties of nitrogen as complied in National Institute of Standards and Technology (Thermophysical Properties, 2011), nitrogen exhibits ideal gas behavior for pressures below 450 psi. Further, Lasseux et al. (2012) did not discuss the sensitivity of the inversion results to initial guesses.

By applying this technique, heterogeneity, anisotropy, and the controversy between conventional laboratory measurements of ultra-tight rock petrophysical properties can be eliminated. Heterogeneity and anisotropy are objective characteristics of rocks and cannot be avoided, nor need to be eliminated. One way to quantify heterogeneity is to conduct the relevant tests with as many as possible samples, so that the rock properties are obtained in an averaged-sense and their deviations are statistically significant. Similarly, for the issue of anisotropy, the samples are measured in various orientations. In this paper, we remove the effect of heterogeneity and anisotropy on petrophysical correlations at the core scale to make various physics based petrophysical measurements on core plugs more consistent. For example, in a typical laboratory study, the porosity, permeability, and compressibility measurements are typically done on different samples; consequently, if the formation is heterogeneous or anisotropic, these sample measurements will be uncorrelated and inconsistent. In such cases, it is much better to derive these measurements from a single rock sample. Our objective is to estimate the aforementioned parameters in a short time with acceptable accuracy from a single sample. Therefore, we tested our numerical model and inversion algorithm on pressure-step-decay response of pyrophyllite samples which can be categorized as relatively homogeneous and isotropic material.

In this paper, we develop a numerical model for pressure-step-decay measurement and couple it with a robust error minimization algorithm to process the pressure-step-decay measurements to simultaneously estimate the k_i, ϕ_0, C_p, and b. The accuracy of proposed method was analyzed for synthetic cases and pyrophyllite samples.

The proposed estimation method implements following limiting assumptions –

1. Inversion-derived estimates are assumed to be uncorrelated. Any future study based on the proposed inversion method requires an investigation of the effect of correlation among the four parameters on the inversion results.
2. Intrinsic/absolute permeability and effective porosity are independently altered during the inversion of pressure-step-decay data. This assumption increases the non-uniqueness of the model inversion procedure but avoids the unnecessary empirical simplifications in the estimation process by invoking petrophysical dependencies that may not be present in the geomaterial under investigation. One consequence of this assumption is that the parameter estimates do not strictly honor the empirical trends observed for permeable rock samples. Unlike ultra-tight samples, permeability measurements on permeable samples do not generally need corrections for the effects of gas slippage, transitional flow, and diffusion prior to generating the empirical trends for those petrophysical parameters.
3. We assume that the effective porosity of the rock varies exponentially with the local pore pressure under constant overburden stress. However, the intrinsic permeability and pore compressibility are treated as pressure-invariant properties to simplify the inversion procedure.
4. Ideal gas law and a constant viscosity were assumed for nitrogen that can have about up to 1% error in gas compressibility and up to 5% error in gas viscosity.
5. Pore compressibility estimates for the ultra-tight samples reported in this work are considerably large values that are only valid in the effective pressure range of 500–1000 psi. Several authors have reported that low effective pressure and low porosity result in an exponential increase in the pore compressibility of rock samples.
6. We only studied the sensitivity of the inversion algorithm to uncertainty in initial guess. Future studies on the proposed estimation method requires investigation of the sensitivity of inversion algorithm to uncertainties in model parameters and to the noise in the measured step-decay data.
7. The forward model formulation presented in this paper assumes the square of pore-pressure gradient to be significantly smaller than the pore pressure times the second derivative of pore-pressure with respect to axial distance along the entire length of the sample.

We jointly invert for pore compressibility and effective porosity at zero pore pressure in addition to permeability and slip factor due to the following reasons –

1. Independent measurements of pore compressibility and effective porosity of the samples do not accurately represent the corresponding properties of the core plug during the pressure-step decay measurement.
2. In a pressure step decay measurement, the porosity value of interest is the effective porosity that contributes to fluid flow, and it is not the total porosity of the sample. The total porosity cannot be used when 'History Matching' or inverting the pressure step decay measurements.
3. In absence of experimental facilities to measure effective porosity, we measured total porosity of the samples using helium porosity and report the total porosity measurement against the effective porosity