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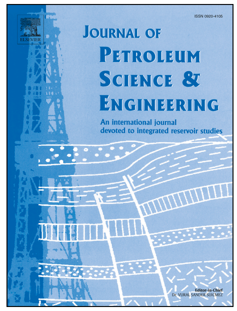

Petrophysical interpretation of laboratory pressure-step-decay measurements on ultra-tight rock samples. Part 2 – In the presence of gas slippage, transitional flow, and diffusion mechanisms

Younas Dadmohammadi, Siddharth Misra, Carl Sondergeld, Chandra Rai

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Petrophysical Interpretation of Laboratory Pressure-Step-Decay Measurements on Ultra-Tight Rock Samples. Part 2 – In the Presence of Gas Slippage, Transitional Flow, and Diffusion Mechanisms

Younas Dadmohammadi, Siddharth Misra, Carl Sondergeld, and Chandra Rai
The University of Oklahoma

Abstract

Ultra-tight formations generally exhibit heterogeneous, anisotropic, and pressure-dependent petrophysical properties. Conventional core analyses tend to generate inconsistent petrophysical estimates when the physical measurements are performed on different core samples extracted from ultra-tight formations. The discrepancies in petrophysical estimates are further escalated due to pressure- and pore-size-dependent fluid flow mechanisms in the nanopores of ultra-tight rocks. In the first part of this two-paper series publication, a method is proposed to simultaneously estimate four petrophysical properties by inverting laboratory-based pressure-step-decay measurement on a single ultra-tight rock sample; thereby, circumventing the petrophysical inconsistencies due heterogeneity and anisotropy. In this second part, an inversion algorithm is developed to simultaneously estimate six petrophysical parameters by processing the laboratory pressure-step-decay measurements. Similar to the first part, the laboratory step-decay measurement involves nitrogen gas injection into an ultra-tight rock sample at multiple stepwise pressure increments and high-resolution pressure-decay measurement at the outlet, which is followed by a deterministic inversion of the measured downstream pressure data based on numerical finite-difference modeling of nitrogen gas flow in the ultra-tight rock sample. Unlike the first part, the forward model of the nitrogen flow through the nanoscale pores of the ultra-tight rock samples accounts for not only the gas slippage but also transitional flow and Knudsen diffusion.

This work improves the petrophysical estimates previously obtained from the inversion of pressure-step-decay measurements modeled based on only a Klinkenberg-type gas slippage as proposed in the first part. A transitional transport model is implemented to account for the separate and simultaneous occurrence of gas slippage and diffusion across an ultra-tight rock sample during a pressure-step-decay measurement performed in the pore pressure range of 5 psi to 500 psi at room temperature. The proposed interpretation method was applied to nine 2-cm-long, 2.5-cm-diameter core plugs extracted from a 1-ft^3 ultra-tight pyrophyllite block. We estimated the intrinsic permeability, effective porosity, pore-volume compressibility, pore throat diameter, and two slippage-diffusion coefficients of each sample. Estimation accuracy relies on the forward model of the fluid flow in ultra-tight rock sample and on the error minimization algorithm implemented in the inversion scheme. For the nine ultra-tight samples, on an average, the estimated intrinsic permeability, effective porosity, pore-volume compressibility, and pore throat diameter are 86 nd, 0.036, 2.6E-3 psi^{-1}, and 195 nm, respectively. Notably, the two slippage-diffusion coefficients indicate that the gas transport mechanism in the nine ultra-tight pyrophyllite samples during the pressure-step-decay measurement is completely dominated by slip flow without any Knudsen diffusion or transitional flow, despite the Knudsen numbers across each sample during the entire duration of the pressure-step-decay measurements were determined to be in the range of 0.01 to 1. This observation contradicts the widely accepted qualitative classification of gas transport mechanism based on the Knudsen numbers and mandates an inversion-based approach to identify the fluid flow mechanism and an appropriate fluid flow model for nanoscale pores.

Keywords: Ultra-Tight Reservoir, Intrinsic Permeability, Effective Porosity, Pore-Volume Compressibility, Inverse Technique, Gas Slippage, Transitional Flow, Diffusion Mechanisms

Introduction

The economic evaluation of shale gas plays requires an accurate estimation of petrophysical properties like intrinsic permeability (k_i), effective porosity (ϕ_0) at an effective pressure of 1000 psi, pore-volume compressibility