Petrophysical Studies of Unconventional Gas Reservoirs Using High-Resolution Rock Imaging

Research Objectives
The principal objective of this project is better understanding of the physical mechanisms that limit gas recovery from tight rock formations. We employ high-resolution 3D imaging of low-permeability reservoir rocks combined with two-phase, pore-scale fluid flow modeling. This project is carrying out microtomography 3D digital imaging of low-permeability sandstones and shales. Imaging results are being used to develop pore scale 2-phase flow simulation codes to model gas flow in tight rocks. Pore-scale modeling is verified using available petrophysical data. The results of pore-scale studies are applied to investigate the performance of a gas well in a tight reservoir.

Approach
We acquire high-resolution digital images of tight gas reservoir sample rock using x-ray microtomography (micro CT) at the Advanced Light Source facility (ALS) and using the Focused Ion Beam/Scanning Electron Microscope instrument (FIB/SEM) at the Molecular Foundry (MF), located at Lawrence Berkeley National Laboratory (LBNL). This includes selection and preparation of the samples, imaging, and primary image processing into binary digital data. Computations on segmented micro CT data using LBNL’s Maximal-Inscribed Spheres (MIS) and other methods simulate capillary equilibrium fluid distribution and two-phase flow properties of the rock. Pore-scale gas slippage computations simulate the Klinkenberg effect. Development of tight-rock depositional model is used to evaluate the role of microporosity features that cannot be captured by micro CT imaging due to the limitations of resolution. Pore-scale model of the impact of retrograde condensation on the flow properties of the rock employs the MIS study mentioned above. Upscaling of the pore-scale results is applied to model flow into a fractured gas well in a tight reservoir.

Accomplishments
High-resolution 3D images of tight sand and shale samples were acquired at the ALS and MF. Analysis of the elemental distribution in a shale sample is possible using the FIB/SEM/Energy Dispersive x-ray Spectroscopy (EDS) technique at the National Center for Electron Microscopy (NCEM), LBNL. New analytical and numerical methods and codes were developed for image processing, for analysis of the pore space geometry, for numerical evaluation of the capillary-equilibrium fluid distribution, and for estimation of the capillary pressure and relative permeability functions. The models were verified against available laboratory data. A new pore-scale model of wet gas flow with account for retrograde condensation has been developed. Predictive capabilities of our new bimodal production decline model for a fractured shale-gas well have been validated against field data.

Significant Findings
The micron-scale resolution x-ray CT imaging at the ALS provides data suitable for 3D reconstruction of the pore space geometry for the tight sands and shows microfractures in shale samples. Microporosity characterization requires a higher resolution. SEM images show the geometry of clay crystal clusters attached to individual grains. The FIB/SEM imaging technique is capable to resolve the 3D nanometer-scale features of shale samples. For tight sands, pore-scale simulations suggest that the estimated minimal wetting fluid threshold saturation, at which the gas phase is disconnected, is much lower than that for conventional sandstones. At intermediate saturations, the gas and brine (or other wetting fluid) can block each other, where the blockage of gas is of capillary nature, and the brine blockage is dynamic (“permeability jail”). The model of fractured gas well, validated against field data, predicts bimodal production decline curve. During the early stage, the production rate declines with reciprocal square root of time, whereas later the rate declines exponentially. This character of production decline is determined by the extremely low permeability of shale and by the boundedness of the stimulated reservoir volume (SRV). Our optimal-control model of wet gas flow with retrograde condensation and dynamic liquid skin suggests that regulation of the well recovery rate can substantially increase the total gas production.

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