Relative Water and Gas Permeability – From Capillary Tube Models to Pore Networks

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Abstract

Permeability is an essential parameter describing flows of methane gas and water through hydrate-bearing sediments. It is also one of the most critical parameters to estimate gas production rate so that to determine whether expensive deepwater drilling from hydrate deposit is economically feasible. However, studies on relative permeability in hydrate-bearing sediments are extremely limited, compared with other fundamental physical properties of hydrate-bearing sediments. This in part is due to experimental difficulties of controlling constantly low temperature, moderate pressure, and hydrate saturation, and continuously monitoring and quantifying the volume of water and gas phases throughout the experiments. Hydrate simulators use mainly van Genuchten and Brooks-Corey models to describe relative permeability; yet, the values of input parameters for these models lack experimental support and physical rationales.

Permeability is a measure of the ability of sediments to allow fluids (gas or liquid) to pass through it. It is a physical property of the porous medium itself, even though different pore fluids pass through the same porous medium with different velocity (i.e., conductivity) affected by fluid viscosity and pressure gradient. For hydrate-bearing sediments, the intrinsic reservoir permeability k_{int} refers to the permeability of host sediments without hydrate. The presence of hydrate in sediments reduces pore spaces and thus decreases the permeability, which is usually called the effective permeability k_{hyd}. A majority of experimental, numerical, and analytical studies if not all so far are inherently looking into how the effective permeability k_{hyd} decreases with increasing hydrate saturations S_h, i.e., the permeability reduction curve. The permeability reduction curve has been experimentally measured using various natural soils and designed porous microfluidic chips, numerically simulated using pore network modeling and Lattice Boltzmann method, and analytically formulated based on capillary tube flow, fractal, and percolation theories.

The flow in sediments becomes much more complicated during hydrate dissociation, as gas and water coexist in hydrate-bearing sediments and thus a multi-phase flow system where water-gas capillarity affects flow patterns should be described using relative permeability. The relative permeability of water k_{r_w} is the permeability of water at different water saturations (i.e., unsaturated condition) normalized by the permeability measured when the sediments is fully saturated by water; and so for relative gas permeability k_{r_g}. Both relative water and gas permeability are normalized values ranging from zero to one. Three basic parameters are needed to describe relative permeability: a shape factor m in van Genuchten model and λ in Brooks-Corey model, residual water saturation S_{rw}, and residual gas saturation S_{rg}. Two- and three-dimensional pore network model simulations have been performed to probe how these parameters vary at different hydrate saturations, which have not yet been validated by experimental nor theoretical work.

Challenges in understanding relative permeability in hydrate-bearing sediments include (1) experimental determination of relative water/gas permeability in hydrate-bearing sediments with constant but different saturations of hydrate, (2) experimental and numerical determination of relative permeability during hydrate dissociation, i.e., hydrate saturation is not constant and thus the effective permeability as the denominator is changing, (3) theoretical studies of how lithological properties (e.g., grain size, fines content, packing, stress etc.) and dissociation process affect the three basic parameter in relative permeability, and (4) techniques of upscaling pore- and core-scale results to reservoir scale applications.