



Relative permeability for multiphase flow for oven-dry to full saturation conditions



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ABSTRACT

Numerical simulation of supercritical CO₂ (CO₂) injection into deep geologic reservoirs often requires the modeling of multifluid flow and transport. The classical capillary and relative permeability models assume that the residual water is immobile and irreducible. This assumption is not in agreement with the flow process for CO₂ injection into a saline aquifer. In this paper, the relative permeability (k_r)–saturation (S) relationships for both the aqueous and non-aqueous phases are derived for oven-dry (i.e., zero liquid saturation) to full saturation conditions by extending the classical k_r – S relationships. The extended relative permeability models reduce to the corresponding classical forms when the aqueous saturation is higher than the critical value, but deviates from the latter when the aqueous saturation is lower than the critical value. The implementation of the extended models in the STOMP multifluid flow and transport model is demonstrated by the simulation of dry CO₂ injection from a vertical well into a homogeneous reservoir. The extended models overcome the limitations of the classical models and can simulate the dry-out processes associated with the residual water. The extended models are expected to simulate CO₂ injection and the subsequent processes (e.g., the dry-out of brine and salt precipitation) more accurately than the classical models.

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1. Introduction

Numerical simulation of super-critical CO₂ (CO₂) injection into deep geologic reservoirs often requires the modeling of multifluid flow and transport (e.g., USEPA, 2013). For convenience, the CO₂ in super-critical phase is referred to as the non-aqueous or gas phase hereafter. The calculation of relative permeability of the aqueous (wetting, brine) or the non-aqueous (non-wetting, CO₂) phase using classical models, such as those in Burdine (1953) and Mualem (1976), is based on the definition of the effective saturation, \bar{S}_l , defined as

$$\bar{S}_l = \frac{S_l - S_{lr}}{1 - S_{lr}} \quad (1)$$

where S_l and S_{lr} are the saturation and residual saturation of the aqueous phase, respectively. Most, if not all, relative permeability models assume that the aqueous flow is negligibly small

when a porous medium is at or less than S_{lr} . In other words, the residual water is considered immobile and irreducible. Practically, the reasons for finite value of S_{lr} are that the dominant historical wetting fluid content measurements were in the wet range and the typical fluid capillary data demonstrated an asymptotic behavior.

The hydraulic properties at very low water content, conceptualized as networks of surface capillary channels interspersed with thin films, have been measured and modeled (e.g., Pachepsky et al., 1984; Tokunaga and Wan, 1997; Tokunaga et al., 2000). Theoretically, the classical relative-permeability models are based only on capillary flow while any other flow types (e.g., film or corner flow) are not considered. Consequently, these models generally produce acceptable results at high and intermediate wetting fluid content and relatively poor results at low wetting fluid content. These models do not apply to conditions of $S_l \leq S_{lr}$, such as during CO₂ injection where the residual water can be evaporated by the injected dry CO₂ or water imbibition into the dry-out zone. During CO₂ injection, the evaporation of water can dry out the residual water even when the water is immobile. However, when CO₂ injection stops, water will imbibe into the dry-out zone and the relative permeability at the very low water saturation must be quantified in order to simulate this imbibition process without imposing arbitrary k_{rl} .

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Webb (2000) extended the classical capillary functions (e.g., Brooks and Corey, 1966; van Genuchten, 1980) to oven-dry condition applying the adsorption-based model of Campbell and Shiozawa (1992). Following Ross et al. (1991) and consistent with Webb (2000), the term oven dry is equivalent to zero liquid saturation conditions. However, the Webb (2000) model did not address the calculation of relative permeability at low water content. For numerical expedience, modelers hence often introduce arbitrary assumptions (e.g., by imposing the relative permeability being zero or other values) that are often not explicitly stated in the model descriptions. Some of these arbitrary methods, making capillary and relative permeability functions inconsistent, is discussed by Oostrom et al. (2016). To solve this problem, Zhang (2011) assumed that the classical capillary function definition applies to the full range of saturation and defined a state-dependent S_{lr} for the condition of $S_l < S_l^m$, where S_l^m is the critical wetting-phase saturation. In this way, the original capillary function definition and corresponding compatible relative permeability can be used without additional change. The Zhang (2011) model produces a small, but non-zero, aqueous saturation at the oven-dry condition. Physically this is possible because not all the water molecules are driven out from a formation or rock sample at the standard oven temperature (i.e., 105 °C). An inconvenience of the Zhang (2011) model is that no explicit algebraic relationship is available to express capillary pressure, P_c , as a function of S_l when $S_l < S_l^m$. Hence, an iterative process would be needed to find P_c values corresponding to $S_l < S_l^m$. The algorithm can be readily implemented but requires slightly more computational effort than the classical models.

Peters (2013) described the full range capillary function as the summation of two curves, one for the capillary water and the other for the adsorbed water. The resulting total $P_c(S_l)$ relationship is equivalent to the Webb (2000) model except that Peters (2013) introduced an empirical weight to separate the two components, while Webb (2000) used a tangent line method. Peters (2013) further calculates the relative permeability using the commonly used models for capillary flow for each of the two capillary function components. As the residual saturation is not a constitutive parameter in the adsorption capillary model, actual water saturation, instead of the required effective saturation, was imposed in Peters (2013) for the calculation of aqueous relative permeability, k_{rl} , due to the adsorbed water.

In this paper, a formulation of the residual water content is derived for the adsorbed water such that compatible $P_c(S_l)$ and $k_r(S_l)$ relationships can be obtained for the full range of water content using the classical Burdine (1953) or Mualem (1976) models. Furthermore, $k_r(S_l)$ relationships compatible with the extended $P_c(S_l)$ relationship for the non-aqueous phase are derived. The extended models were incorporated in a numerical simulator and demonstrated for injection of CO₂ into three types of sandstone reservoirs.

2. Theory

In this section, after briefly summarizing the classical hydraulic functions and the Webb (2000) extension of the capillary function, the formulation of the relative permeability for the wetting and non-wetting phases compatible with the Webb (2000) model is presented.

2.1. Classical hydraulic functions and the Webb extension

The non-hysteretic Brooks and Corey (1966) and van Genuchten (1980) models (referred to as the BC and VG models, respectively,

hereafter) are two commonly used capillary functions for the aqueous phase:

$$\text{BC model : } \bar{S}_l^I = \begin{cases} (P_c^e / \beta P_c)^\lambda & \text{if } P_c > P_c^e \\ 1 & \text{if } P_c \leq P_c^e \end{cases} \quad (2a)$$

$$\text{VG model : } \bar{S}_l^I(P_c) = [1 + (\alpha \beta P_c)^n]^{1/n-1} \quad (2b)$$

where the superscript I denotes the classical capillary models, β [–] is an interfacial-tension dependent scaling factor, P_c^e [Pa] is the air-entry capillary pressure, and α [Pa⁻¹] is a fitting parameter that is inversely proportional to the air-entry pressure; λ [–] and n [–] are fitting parameters related to particle-size distribution. Assuming that formation pores can be represented as a bundle of cylindrical capillaries, Burdine (1953) and Mualem (1976) developed similar but slightly different expressions for the relative permeability due to capillary flow. Their expressions can be written in a general form as

$$k_{rl}(\bar{S}_l) = \bar{S}_l^L \frac{\Gamma(0, \bar{S}_l)}{\Gamma(0, 1)} \quad (3a)$$

$$k_{rg}(S_l) = (1 - \bar{S}_l)^L \frac{\Gamma(\bar{S}_l, 1)}{\Gamma(0, 1)} \quad (3b)$$

where

$$\Gamma(a, b) = \left[\int_a^b \left(\frac{d\bar{S}_l}{P_c(\bar{S}_l)^\omega} \right) \right]^\gamma \quad (4)$$

L [–] is the connectivity–tortuosity coefficient, and ω [–] and γ [–] are constants; k_{rg} [–] is the relative permeability for the gas (CO₂) phase. Eq. (3a) is equivalent to the Mualem (1976) relationship when $\omega = 1$ and $\gamma = 2$ and the Burdine (1953) relationship when $\omega = 2$ and $\gamma = 1$ for the aqueous phase relative permeability. Substituting the Brooks and Corey (1966) relation (Eq. (2a)) or the van Genuchten (1980) relation (Eq. (2b)) into (3) produces the relative permeability models. The relative permeability model based on the Brooks and Corey (1966) and the Burdine (1953) relationships is referred to as the BC-B model and the model based on the van Genuchten (1980) and Mualem (1976) relationships is referred to as the VG-M model hereafter.

To describe the $P_c(S_l)$ relationships for the full-range of saturation, the aqueous phase is conceptualized as a combination of capillary water and adsorbed water (Webb, 2000; Zhang, 2011). The $P_c(S_l)$ relationships are divided into two segments (Fig. 1), separated by the critical capillary pressure, P_c^m , a point at which the tangent line passes the point corresponding to the oven-dry condition, P_c^d , which is typically assumed to be about 10⁹ Pa (Groenevelt and Grant, 2004; Rossi and Nimmo, 1994). Segment I, valid for $P_c < P_c^m$, can be described by the classical models (e.g., BC and VG functions in Eq. (2)), while an extension, e.g., using the method of Webb (2000), which was based on the log-linear adsorption model proposed in Campbell and Shiozawa (1992), is used for segment II:

$$S_l^{II}(P_c) = \begin{cases} 0 & \text{if } P_c \geq P_c^d \\ S_l^m \ln(P_c^d / P_c) / \ln(P_c^d / P_c^m) & \text{if } P_c^m < P_c < P_c^d \end{cases} \quad (5)$$

The log-linear capillary model has been verified against experiment data in the water-air system by many researchers (e.g., Campbell and Shiozawa, 1992; Fayer and Simmons, 1995; Rossi and Nimmo, 1994; Webb, 2000). The method to determine S_l^m for the van Genuchten (1980) function can be found in Webb (2000) and Zhang (2011), while the method for the Brooks and Corey function is described by Zhang (2011). Briefly, at the critical point, the slope of the $\ln(P_c)$ – S_l curve for segment I is equal to that for segment II. Then P_c^m can be solved equating the two slope expressions using a numerical solver (e.g., the root function in MathCad, Parametric

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