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Effects of fractional wettability on capillary pressure–saturation–relative permeability relations of two-fluid systems

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Abstract

Capillary pressure (P_c)–saturation (S)–relative permeability (k_r) relationships must be quantified to accurately predict non-aqueous phase liquid (NAPL) distribution in the subsurface. Several experimental techniques are presented here for two-fluid P_c–S–k_r relationships for various saturation paths to better define the effect of fractional wettability on these relationships. During the primary drainage path of the P_c–S curves, the air–water system showed no distinct trend as a function of the fraction of sand treated by organosilane (S) to render it non-water wetting. In a NAPL–water system, however, a consistent decrease of capillary pressure with increase of the fraction of non-water wetting sands was observed. The much lower contact angle for air–water (a–w) system may result in the observed insensitivity of the a–w P_c–S curves to fractional wettability, at least for the PD pathway. For the main imbibition path of NAPL–water system, capillary pressure decreased as the fraction of the S component increased, requiring forced imbibition (negative capillary pressures) for a certain range of saturations. Systems with an increasing percentage of the S component also exhibited a higher water k_r and lower NAPL or air k_r at a given saturation for the primary drainage and main imbibition paths in both air–water and NAPL–water systems. The increase of water k_r with increase of the fraction of the S component can be explained by the ability of water to occupy larger and highly conductive pores in such a system. Experimental k_r–S data for the primary drainage path of NAPL–water system presented here were used to test the Bradford et al. [Bradford SA, Abriola LM, Leij FJ. Wettability effects on two- and three-fluid relative permeabilities. J Contam Hydrol 1997;28:171–91] model and the modified Mualem model for estimating the k_r–S curves from measured P_c–S data as a function of fractional wettability. Both models predicted significantly less variation in the k_r–S curves than measured indicating that they did not adequately represent the system under investigation.

Keywords: NAPL; Capillary pressure; Relative permeability; Fractional wettability

1. Introduction

The process by which non-aqueous phase liquids (NAPLs) infiltrate into and redistribute within the subsurface depends on capillary pressure–saturation–relative permeability (P_c–S–k_r) relationships. The P_c–S–k_r relations are affected by interfacial (or surface) tension and wettability. These interfacial properties can vary considerably due to trace and primary constituents in the NAPL and surface properties of the porous media comprising the subsurface. Various experimental attempts have been made to quantify trends between

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interfacial properties and P_c–S–k_r relationships. The results are conflicting, however, reducing any potential to generalize the overall effects.

Several experimental studies have been devoted to quantifying the effect of interfacial tension on the P_c–S–k_r relation. It is clear that decreasing interfacial tension lowers the capillary pressure [20,23,40,41], although relative permeabilities are not affected except for extremely low values of the interfacial tension [2,19,23].

The wettability of a solid refers to the tendency of one fluid to spread on or adhere to the solid surface in the presence of other immiscible fluids [18]. It is important to note that the term wettability is used for the wetting preference of the solid and does not necessarily refer to the fluid that is in contact with the solid at any given time [4]. Generally, the wettability of porous systems can be divided into two basic classes: uniform and non-uniform. A porous system with uniform wettability shows consistent wettability condition (e.g., strongly water-wet, strongly oil-wet, or intermediate-wet) throughout the system considered. Non-uniform or fractional wettability is defined as the condition when different regions of the system have different wetting preferences [4]. Fractional wettability is often encountered in natural porous media as a result of the spatial variation in mineral composition or roughness of the solid surface, or the presence of residual NAPL films, adsorbed surfactant groups, or microorganisms on the solid surface [51].

A few experimental investigations have been conducted to elucidate the effect of fractional wettability on the P_c–S–k_r relation of two-fluid systems [10,51]. Significant differences in the conclusions from these studies, however, prevent us from drawing generalities describing the nature of the influence of fractional wettability. These differences could be due to the experimental fluid pairs, fluid paths, and/or measurement techniques. It is thus very important at this stage to clearly elucidate the effect of fractional wettability on the constitutive relationships. Models that estimate the P_c–S–k_r relations in porous systems with fractional wettability or with mixed wettability (systems where small pores are water-wet and larger pores are intermediate- to oil-wet) have been developed [8,9,11,37,51]. Some have resulted in useful predictions on the effect of wettability variation on the P_c–S–k_r relation. Others, however, need to be tested against appropriate experimental data in order to be used more confidently for numerical simulation or estimation.

2. Background

2.1. Experimental investigations

Table 1 summarizes experimental conditions considered by various authors for their measurements of the P_c–S–k_r relationships in two-fluid systems as affected by fractional wettability. In all experiments reviewed, porous media with fractional wettability have been obtained by mixing different portions of two or three pure components (i.e., quartz sands (Q), organosilane-treated sands (S), or Teflon grains (T)). The Q component is strongly water-wet, while the S and T components are non-water wetting.

2.1.1. Capillary pressure–saturation relations

Little consistency exists among published experimental results describing the effect of fractional wettability on the primary drainage (PD) path of the P_c–S relation for air–water systems (Table 1). Bradford and Leij [10] found that the PD curves for pure Q, QS 3:1, and QS 1:1 media were similar, as were the curves for pure S

Table 1
Experimental conditions performed for the P_c–S–k_r measurements of two-fluid systems by various authors

Authors	P_c–S–k_r	Fractional wettability conditions[a]	Fluid pairs[b]	Fluid paths[c]	Measurement techniques
Bradford and Leij [10]	P_c–S	Pure Q, pure S, QS 3:1, QS 1:1, and QS 1:3	a–w, a–o, and o–w (oil: Soltrol 220)	PD and MI	"Brooks method" [13]
Bauters et al. [6]	P_c–S	Pure Q and four QS mixtures (3.1%, 5.0%, 5.7%, and 9.0% S component)	a–w	PD and MI	Using experimental chamber
Ustohal et al. [51]	P_c–S	Pure Q, pure S, pure T, QS 1:1, QT 1:1, QS 1:2, QT 1:2, and QST 1:1:1	a–w	MI and MD	P_c–S: by adjusting the boundary conditions (upper: no flux for water, lower: changing water pressure)
	k_r–S				k_r–S: steady-state, pressure equilibrium approach [17]
Fatt and Klikoff [25]	P_c–S	Pure Q, pure S, QS 3:1, QS 1:1, and QS 1:3	o–w (oil: kerosene)	PD	Adjusting the boundary conditions (upper: no flux for water, lower: decreasing water pressure)

[a] Q: quartz sand, S: organosilane-treated sand, T: Teflon component.
[b] a–w: air–water, a–o: air–oil, o–w: oil–water systems.
[c] PD: primary drainage, MD: main drainage, MI: main imbibition.