



# The influence of unavoidable saturation averaging on the experimental measurement of dynamic capillary effects: A numerical simulation study



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## ABSTRACT

Many studies over the past four decades have observed that capillary pressure–saturation ( $P_c$ – $S_w$ ) relationships are often different when measured dynamically under rapidly changing pressure inputs. This phenomenon has been referred to as a dynamic capillary effect, and its magnitude is often quantified by the dynamic capillary coefficient,  $\tau$ . Experimentally-reported values of  $\tau$  have varied by orders of magnitude, even for seemingly similar experimental systems. The purpose of the present work is to numerically explore the likely impact of fluid properties on the calculation of  $\tau$  from experimental measurements. Specifically, the emphasis is on understanding how spatial averaging of the saturation profiles resulting from different fluid combinations contributes to the apparent magnitude of  $\tau$  derived from experimental measurements.

Simulations of dynamic drainage in a packed sand column were conducted using the CompSim multiphase flow simulator. Four nonwetting phase fluids with viscosities spanning four orders of magnitude were studied. Comparison between local and spatially-averaged rates of saturation change show significant differences, with the magnitude of the difference increasing with increasing viscosity to interfacial tension ratio and increasing drainage rate. Results show that at averaging scales likely to be experienced during experimental saturation measurements, this effect is likely to produce significant differences in the ultimate magnitude of the calculated  $\tau$  values for different fluid systems and drainage rates. This result means that conventional flow phenomena may produce an inherent systematic bias in experimental measurements of  $\tau$ , amplifying measured values for high viscosity or low interfacial tension systems and for experiments where higher drainage rates are used.

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## 1. Introduction

Multiphase flow in porous media plays a central role in a number of industrial and environmental phenomena. Examples include enhanced oil recovery, remediation of non-aqueous phase liquids (NAPLs) in groundwater, and CO<sub>2</sub> geological sequestration. A quantitative understanding of the fundamental mechanisms underlying multiphase flow is essential to precisely describing and accurately modeling these phenomena.

The capillary pressure–saturation relationship ( $P_c$ – $S_w$  relationship) is a constitutive relationship that influences the movement and distribution of immiscible fluids in porous media. The  $P_c$ – $S_w$  relationships for a variety of soil types have been examined under steady-state conditions for over six decades. Many empirical equations have been developed to describe the equilibrium

relationships between capillary pressure ( $P_c$ , the difference between the non-wetting and wetting phase pressures) and wetting phase saturation ( $S_w$ , the fractional volume of pores filled with wetting phase). For example, the Brooks–Corey [1] and van Genuchten [2] equations are among the most widely used equations. These empirical equations have been found to fit data from equilibrium  $P_c$ – $S_w$  experiments well.

Many studies have observed that  $P_c$ – $S_w$  relationships measured during dynamic drainage or imbibition (i.e., where capillary pressure is changed too rapidly to allow saturation to reach an equilibrium value) can differ from equilibrium  $P_c$ – $S_w$  relationships [3–13]. The observed rate-dependence of capillary pressure in porous media experiencing dynamic saturation change is often referred to as a dynamic capillary effect. Many efforts have been made to quantitatively investigate dynamic effects in  $P_c$ – $S_w$  relationships, and a number of different parameters have been used to describe the observed effects. One of the most common parameters used to describe dynamic capillary effects in recent studies is the

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dynamic capillary coefficient,  $\tau$ . The dynamic capillary coefficient,  $\tau$ , is given by Eq. (1) [14–16]:

$$\tau = -\frac{P_c^d - P_c^s}{(\partial S_w / \partial t)} \quad (1)$$

where  $P_c^d$  is dynamic capillary pressure (i.e., the observed pressure difference between non-wetting and wetting phases when saturation is changing),  $P_c^s$  is static capillary pressure (pressure difference between phases under static conditions (no flow)), and  $\partial S_w / \partial t$  is the rate of saturation change. It should be noted that some authors have suggested that the term “dynamic capillary pressure” is misleading because  $P_c^d$  is an observed pressure difference between phases rather than a true capillary pressure [11]. However, we adopt this widely-used terminology in the interest of concise discussion.

Although a large number of values of  $\tau$  have been reported, remarkable uncertainty in its magnitude exists. In general, reported experimentally-measured  $\tau$  values have spanned more than three orders of magnitude, even for seemingly similar systems (e.g., [7–11,14]). Our previous experimental study in a small-volume unsaturated (air–water) sand system [12] suggested that experimental artifacts (i.e., finite sensor response and flow-induced gas pressure gradients) may account in part for the considerable uncertainty in  $\tau$  values; further study is needed to uncover other contributors.

Variability in  $\tau$  has been observed not only in its magnitude, but also in its dependence on system properties (e.g., porous medium grain size, fluid properties). Even reported results examining the effect of volume averaging on  $\tau$  have been contradictory. For example, Camps-Roach et al. [8] reported little dependence of  $\tau$  values on averaging volume for an air–water system. In contrast, Bottero et al. [11] reported an order of magnitude difference in values of  $\tau$  for different averaging volumes in a tetrachloroethylene (PCE)–water system with a similar sand. In our previous work [12], we used calculations to show that the difference between the scaling behavior of those two specific systems was primarily the result of the different fluids used (air–water vs. PCE–water), and their effect on the saturation profile. Using Eq. (1) to calculate  $\tau$  requires measurement of the rate of change in  $S_w$  (i.e.,  $\partial S_w / \partial t$ ). If  $\partial S_w / \partial t$  obtained in a small domain (e.g., for a point) differs significantly from that obtained in a large domain, the difference in  $\tau$  calculated can be remarkable.

The objective of this study is to explore scale dependence of dynamic capillary effects during drainage in air–water and organic–water multiphase flow systems. In particular, the emphasis is on understanding how the fluid properties in the system influence the saturation profile, and the resulting impact on the magnitude of measured  $\tau$ . While a number of experimental and modeling studies have examined the effect of volume averaging on observed dynamic capillary effects ([8,10,11,17–22]), few have directly explored the impact of fluid properties on the spatial distribution of fluids, and the resulting implications for experimental measurement of  $\tau$ . In this study, a series of primary drainage curves are simulated for air–water or organic liquid–water flow in a fine sand to investigate the difference in saturation-related properties (i.e., the  $S_w$  and  $\partial S_w / \partial t$  profiles) between different fluid systems. The purpose of the work is to investigate how a small difference between  $P_c^d$  and  $P_c^s$  – either resulting from an experimental or sensor artifact (e.g., [12]) or from a true dynamic capillary effect – would be amplified in the calculation of  $\tau$  by fluid- and scale-specific impacts on  $\partial S_w / \partial t$  (the denominator of Eq. (1)). Because experimental sensors and other methods used to measure saturation have a finite spatial range (i.e., they detect an averaged saturation over some volume), a quantitative understanding of this relationship is of critical importance to understanding the effect of fluid properties on measured  $\tau$  values.

It is important to emphasize that while this work examines the effect of saturation averaging on determination of  $\tau$ , it does not explore the results of averaging in capillary pressure. While the effects of pressure averaging are of interest in numerical models where the impact of different grid resolutions must be understood, it is critical to recognize that, from an *experimental measurement* standpoint, an average pressure in a porous medium has no physical meaning. A transducer-based pressure sensor used to determine a phase pressure needed to calculate capillary pressure measures a single pressure value representing the force of fluid acting on a small internal semiconductor diaphragm within the pressure transducer. While that pressure may or may not be equivalent to the pore pressure in a given phase at a given time or location with a porous medium, depending on issues of fluid continuity and porous membrane conductivity (e.g., [12]), it is not possible to design a pressure sensor based on a single pressure transducer that measures an ‘averaged’ pressure over any scale within a porous medium. (In contrast, all measurements of saturation are spatial averages with varying domain sizes, depending on the method used (e.g., time-domain reflectometer (TDR) or other sensor, gamma ray attenuation, outflow volume tracking) and the details of the specific application.) Because nearly all reported studies of dynamic capillary effects have used direct pressure measurements from transducer-based pressure sensors to indicate phase pressures (e.g., [3,4,6,8–12]), the approach used here is appropriate for interpreting the effects of fluid properties on the experimental measurement of dynamic capillary effects.

## 2. Numerical simulations

### 2.1. Description of the simulator

The CompSim simulator was used in this work. CompSim is a three-dimensional, three-phase, multi-component finite difference model developed for subsurface multiphase flow and transport problems [23,24]. CompSim has been used to simulate fate and transport in a wide range of environmental applications in single and multiphase systems (e.g., [24–26]). The model incorporates a number of equations describing the  $P_c$ – $S_w$  relationship including Brooks–Corey and van Genuchten, with extensions to include three-phase systems. The robust Newton–Raphson method is applied to linearize the highly nonlinear terms in the discretized multiphase flow and transport equations. A variety of implicit and explicit numerical discretization methods are coupled in the model, of which employed here is the fully implicit upstream weighted method. Spatial discretization of the parameters is achieved by one-point upstream weighting.

It is noted that this work uses conventional multiphase flow calculations to explore how unavoidable saturation averaging during experimental measurements could emulate dynamic effects, impacting the magnitude of measured  $\tau$  values. As such, no dynamic capillary effects are explicitly included in the simulations, and no assumptions are made about the underlying causes of observed dynamic capillary effects.

### 2.2. Simulation parameters

One-dimensional vertical simulations were conducted in a simulated sand column 15.24 cm (6 in) high, for the reason that a majority of reported dynamic  $P_c$ – $S_w$  measurements have been conducted in columns between 10 and 20 cm in length. The simulated column was subdivided to 1187 grid blocks, with each block 0.127 mm high except the grid at the two ends, which were 0.9525 mm. CompSim uses a block-centered finite difference scheme for all nodes, with the exception of the nodes on domain

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