



# Scale dependent dynamic capillary pressure effect for two-phase flow in porous media



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## ABSTRACT

Causes and effects of non-uniqueness in capillary pressure and saturation ( $P^c$ – $S$ ) relationship in porous media are of considerable concern to researchers of two-phase flow. In particular, a significant amount of discussion has been generated regarding a parameter termed as dynamic coefficient ( $\tau$ ) which has been proposed for inclusion in the functional dependence of  $P^c$ – $S$  relationship to quantify dynamic  $P^c$  and its relation with time derivative of saturation. While the dependence of the coefficient on fluid and porous media properties is less controversial, its relation to domain scale appears to be dependent on artefacts of experiments, mathematical models and the intra-domain averaging techniques. In an attempt to establish the reality of the scale dependency of the  $\tau$ – $S$  relationships, we carry out a series of well-defined laboratory experiments to determine  $\tau$ – $S$  relationships using three different sizes of cylindrical porous domains of silica sand. In this paper, we present our findings on the scale dependence of  $\tau$  and its relation to high viscosity ratio ( $\mu_r$ ) silicone oil–water system, where  $\mu_r$  is defined as the viscosity of non-wetting phase over that of the wetting phase. An order of magnitude increase in the value of  $\tau$  was observed across various  $\mu_r$  and domain scales. Also, an order of magnitude increase in  $\tau$  is observed when  $\tau$  at the top and the bottom sections in a domain are compared. Viscosity ratio and domain scales are found to have similar effects on the trend in  $\tau$ – $S$  relationship. We carry out a dimensional analysis of  $\tau$  which shows how different variables, e.g., dimensionless  $\tau$  and dimensionless domain volume (scale), may be correlated and provides a means to determine the influences of relevant variables on  $\tau$ . A scaling relationship for  $\tau$  was derived from the dimensionless analysis which was then validated against independent literature data. This showed that the  $\tau$ – $S$  relationships obtained from the literature and the scaling relationship match reasonably well.

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## 1. Introduction

A capillary pressure ( $P^c$ ) and saturation ( $S$ ) relationship is vital in the characterisation of immiscible two-phase flow phenomena in porous media (e.g., [2,12–14]). This relationship is non-linear in nature and it depends on several factors, e.g., flow dynamics (steady or dynamic), fluid and porous material properties, contact angles, medium heterogeneities (e.g., permeability heterogeneity, non-uniformity in particle size), scales of observation, etc. [2,5,15,24,32,36]). In general, the forces which influence dynamic immiscible flow in porous media act in a manner so as to drive the fluids to a state of static equilibrium, i.e., when the rate of change of saturation ( $\partial S/\partial t$ ) is zero. During this process, the fluid/fluid interfaces in the porous medium move to re-establish a new state of equilibrium [3,11,21,34]. In practice, a state of

stability in the system is utilised to obtain the equilibrium  $P^c$ – $S$  relationship for the system. In pore-scale modelling, the pressure in one of the phases is allowed to increase and a succession of equilibrium fluid configurations is computed in the pore network to obtain the  $P^c$ – $S$  relationship [3]. These are then applied to non-equilibrium conditions with fluids sometimes flowing at high flow rates. The implicit assumption in such an approach is that the disturbances to interfacial properties are rapidly dissipated [27].

At the equilibrium or quasi-static condition described above, the approach for the characterisation of the  $P^c$ – $S$  relationship is typically coupled with an extended version (i.e., an equation of two-phase flow in porous medium) of Darcy's law for single phase flow in porous medium [2,13]. In this case, the capillary pressure is defined as a function of saturation as expressed in Eq. (1).

$$P_{nw} - P_w = P^{c,eq}(S) = f(S) \quad (1)$$

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where,

$P_{nw}$  = average pressure for non-wetting phase ( $\text{ML}^{-1} \text{T}^{-2}$ )

$P_w$  = average pressure for wetting phase ( $\text{ML}^{-1} \text{T}^{-2}$ )

$P^{c,eq}$  = equilibrium (steady state) capillary pressure ( $\text{ML}^{-1} \text{T}^{-2}$ )

$S$  = wetting phase saturation (–)

In the last decade, it has been argued by a number of authors that the application of Eq. (1) to non-equilibrium condition will be inappropriate as the equation lacks the requisite parameters to address the dynamic characteristics of the flow prior to the attainment of flow equilibrium when the rate of change of saturation ( $\partial S/\partial t$ ) may be high. The need for a modification of the traditional relation (i.e., Eq. (1)) was the conclusion of some authors (e.g., [25,26,31]) with a view to accommodating a more complete description of the system under non-equilibrium conditions. Ever since its proposition, a phenomenal factor in the description of dynamic two-phase flow, namely a dynamic coefficient ( $\tau$ ), has been the subjects of several publications [5,6,8,15,16,23,27,35]. The modification is mathematically expressed as in Eq. (2):

$$(P^{c,dyn} - P^{c,eq})|_S = -\tau \partial S/\partial t|_S \quad (2)$$

where,

$P^{c,dyn}$  = dynamic capillary pressure [ $\text{ML}^{-1} \text{T}^{-2}$ ]

$\partial S/\partial t$  = time derivative of saturation [ $\text{T}^{-1}$ ]

While the interpretation of  $\tau$  in terms of its physical meaning seems to be well understood, some of the factors influencing its values are not uniquely characterised, i.e., the significance of the dependence of  $\tau$  on these factors seems to vary from one case to another. According to previous authors (e.g., [15,27]) the dynamic effect is related to the dependence of capillary pressure–saturation relationship on the time derivative of saturation resulting from finite time needed by the fluid to neutralise the effect of the internal and external forces in order to establish flow equilibrium. Other reports have indicated that the length of time needed to attain flow equilibrium and, hence, the dynamic effect, is larger in less permeable medium than in more permeable sample. The same is true for porous medium with higher degrees of micro-heterogeneity. Thus, larger values of  $\tau$  have been reported in the literature for fine grained or low permeability medium [10,15,23,42] and domains with micro-heterogeneities [17,33,35]. Among the other factors that affect the magnitude of  $\tau$ , strong impacts of fluid properties are well acknowledged [15,22,28,29].

The effect of scale/size of the domain has been linked to the  $\tau$  values as well. It seems that these effects are quantified more commonly in reference to numerical models of pore/core scales and application of different averaging techniques therein. However, these are rarely characterised through experimental studies. Dahle et al. [11] observe a scale dependency in the value of  $\tau$  in their numerical investigation of dynamic effects in  $P^c$ – $S$  relationship using a bundle-of-tubes model. Their model leads to a similar relationship as in Eq. (2) but with the inclusion of an intercept term,  $\beta$ . By determining a dimensionless grouping containing  $\tau$  and  $\beta$ , respectively, they report that the dimensionless grouping shows a dependency on saturation and that  $\tau$  increases as the square of the averaging volume length,  $L$ . This suggests a geometrical increase in  $\tau$  with the length scale of the domain and that its magnitude may become arbitrarily large as we move from core to the field scale. This square of length relationship [11] was however controverted by Bottero et al. [5] in their investigation of non-equilibrium effects at different averaging windows in a porous medium domain of 21 cm height. Bottero et al. [5] determined  $\tau$  experimentally and obtained averages at different windows of observation, namely, 11 and 18 cm sections, within the same porous domain of 21 cm height. An order of magnitude increase in  $\tau$  was found at an averaging window of 11 cm as compared to the local values.

A similar order of increase was obtained in  $\tau$  at an averaging window of 18 cm as compared to the values at 11 cm averaging window. Thus, it can be inferred from the work of Dahle et al. [11] and Bottero et al. [5] that  $\tau$  generally increases with the scale of observation. The proportion of this trend to domain scale is however difficult to affirm from the current studies and there are clear inconsistencies in this regard. Das and Mirzaei [16,17] and Mirzaei and Das [36] found that the functional  $\tau$ – $S$  relation follows non-linear trends at different locations within the same domain using a saturation-weighted technique for averaging domain scale  $\tau$  where local  $\tau$  increases with decrease in  $S$ . However, these authors did not find a clear relationship between the averaged and local values of  $\tau$ . Furthermore, insignificant differences were observed between the local and average (domain scale) values of  $\tau$ , which are in contrast to other findings where  $\tau$  is viewed as a parameter that increases with the scale of domain (e.g., [5,11]). Similarly, in the work of Camps-Roach et al. [8], an up-scaling procedure showed little or no change in  $\tau$  as its values remained almost identical for column scale as it was for the local measurements. Bottero et al. [5], who used averaging techniques such as those discussed by Nordbotten et al. [37–39] for averaging capillary pressure and relative permeability, found that the average values of  $\tau$  showed no dependency on water saturation within a water saturation range of 50% to 85%. This trend is contrary, within the similar saturation range, to what Das and Mirzaei [16,17] have observed on values of  $\tau$  and many other papers such as that by Dahle et al. [11]. Besides the above literature, there are a number of other relevant papers. For example, Bourgeat and Panfilov [7] reported a homogenisation method by which the dynamic capillary pressure effects were studied for oil–water flow in a heterogeneous porous domain. Cuesta et al. [10] reported a travelling wave solution for dynamic two-phase flow in porous media.

It is evident from the literature that a significant amounts of discussion has been made to discuss the dynamic capillary pressure equation (Eq. (2)). From these discussions it can be concluded that the existing publications on the determination of  $\tau$  use both experiments and numerical simulations at pore or/and core scale [5,8,11,16,17]. They use various types of averaging techniques to determine averaged  $\tau$  at domain/larger scale and relate the local and averaged  $\tau$  values. While we acknowledge that the exact values of the coefficient may be different for specific two-phase system, the inconsistencies in the general trend in the results in the literature however raise many questions, e.g., are the observed behaviours of  $\tau$  an artefact of the averaging methods? Similarly, would the extent of the scale dependencies of  $\tau$  be any different if they were measured at different and separate domain scales and not averaging windows within the same domain? Considering the above arguments, one may opine that the scale dependency of a parameter, such as  $\tau$  in this case, should be determined using separate domains for the same conditions, e.g., material properties, boundary conditions, etc. As far as we know, there is no experimental evidence to demonstrate the scale dependency of  $\tau$  in this fashion.

To address these issues we aim to carry out a series of controlled laboratory experiments with separate and different sizes of porous medium with the aim of finding the trend in the magnitude of  $\tau$  depending on the scale. We aim to ensure that our procedure is less-dependent of mathematical averaging method for calculating the coefficient as far as possible. This approach has the advantages of assigning  $\tau$  to independent domain sizes, and reducing any ambiguity, which may arise from intra-domain system averaging. The experiments in this work rely on determining average quantities at the local scale (e.g., measurement sensors for water saturation, pressure). The scales of these measurements points are significantly small as compared to the size of the porous domains at which averaged quantities at the domain scale are calculated. In other words, the processes that govern the  $\tau$  values at

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