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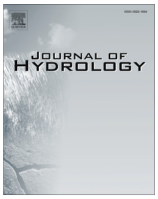

Changes in residual air saturation after thorough drainage processes in an air–water fine sandy medium

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SUMMARY

In a previous study we investigated the unstable and stable residual air saturations in an air–water two-phase system in a sand medium during a series of consecutive drainage–imbibition cycles with gradually increasing initial air saturations. In a reciprocal study reported here we extended the previous investigation by determining residual air saturations in consecutive imbibition processes starting from four gradually decreasing levels of initial air saturation (and thus increasing water saturation). Three parallel column tests with 9–12 consecutive drainage–imbibition cycles were performed, in which the first three imbibition processes started from the highest initial air saturation that could be obtained with our experimental system. The results show that all the residual air saturations resulting from the imbibition processes were almost constant after thorough drainage processes (even those following imbibition processes starting from low initial air saturations), and thus independent of the initial air saturation. The results also indicate that once the residual air in interconnected pores at the end of an imbibition process was present in the form of connected, pore network-scale air globules, the residual air remained in this state in subsequent imbibition processes, even if they started from low initial air saturations. It may be deduced that the presence of thin water films on the walls surrounding large pores and large volumes of air in their central parts during an imbibition process resulted in residual air being in the form of connected, pore-network scale air globules in interconnected pores. In contrast, thick water films and small volumes of air in the central parts of the pores resulted in residual air in the form of single pore-scale air globules in interconnected pores. Thus, stronger dynamic flow conditions (e.g., higher capillary numbers) may be required to remobilize connected, pore network-scale air globules than single pore-scale air globules in a forced imbibition process.

1. Introduction

During drainage and imbibition processes of two-phase porous media there are two kinds of residual saturations: the residual wetting fluid (WF) and nonwetting fluid (NWF) saturations that occur at the end of the drainage and imbibition processes, respectively. The former refers to the WF saturation at an arbitrarily high capillary pressure that may be reached in a drainage process and the latter to the NWF saturation, the volume that cannot be displaced by the WF and is trapped in pore networks of a porous medium at zero capillary pressure/the end of the imbibition process (Corey, 1994; Bear, 1972; Guarnaccia et al., 1997). The two residual saturations are key parameters for characterizing and modeling the migration of immiscible fluids in a porous medium.

In a previous study (Li et al., 2013), we investigated the saturation–capillary pressure (S–p) relationship, including residual air saturations, under gradually increasing initial air saturations in a sandy medium during three series of consecutive drainage–imbibition cycles, in which the starting points of the drainage processes were the end points of the preceding imbibition processes, and vice versa. The results showed that the residual air saturation changed suddenly from an unstable to a stable and constant state when the initial air saturation exceeded a threshold level (0.49 in our

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experimental system). We also found that the Land model (Land, 1968) needs modification to describe phenomena under randomly starting imbibition path and dynamic flow conditions, and the entry pressure of a sandy medium is both medium-specific and independent of the starting points and paths of drainage and imbibition processes. Furthermore it was deduced that the air in the unstable and stable residual air saturation states may be mainly composed of individual air globules trapped in the center of the pores and connected air globules in interconnected pores, respectively.

X-ray computed tomography (XCT) is a powerful tool for detecting micro-scale pore characteristics that has been applied in investigations of pore structure and tortuosity (Provis et al., 2012), two-phase relative permeability (Schembre and Kovscek, 2003), and estimation of the average water film thickness in pore structures, employing the Beer–Lambert law (Jung et al., 2012). Tippkötter et al. (2009) used microfocus CT to visualize both soil matrices and soil water in natural soil aggregates, and were able to resolve films and estimate film thicknesses (at 3 and 10.6 μm, respectively) for two soils. Zhou et al. (2010) investigated pore structure and trapped gas bubbles in Berea sandstones using a micro-focused X-ray CT scanner, and discovered that trapped bubbles have a pore-network scale size and are distributed in several pores at the end of an imbibition process. However, Peng et al. (2012) reported that, due to the resolution limitations, either a non-representative view of the sample or inaccurate results could be produced from XCT image processing. Low-resolution XCT can capture the large-pore porosity, but overestimates the pore size and pore connectivity. High-resolution XCT provides more accurate descriptions of the pore shape, porosity, and pore size. Brusseau et al. (2006) also suggested that the interfacial area associated with films and surface roughness cannot be accurately represented using MCT, possibly due to inadequate resolution. Wildenschild and Sheppard (2013) reported that open questions still remain, especially with respect to the thickness of water films, although water films in pores are clearly detectable. Thus, XCT technologies are available for characterizing pore structures and flow types in pore networks, but high and appropriate resolution XCT is required for accurate measurements of the thickness of water films in pore structures.

The capillary number (*Ca*) — an important hydrodynamic parameter for describing distributions and volumes of trapped nonwetting fluid phases in porous media — represents the strength of viscous forces relative to surface tension acting across an interface between two immiscible liquids. Numerous studies have revealed that dimensionless parameters such as the capillary number and viscosity ratio can influence displacement flow patterns and consequently capillary pressure and relative permeability functions (Aggelopoulos and Tsakiroglou, 2008). Along the center line of a capillary in a pressure-driven flow of a different fluid, Lac and Sherwood (2009) found that if gravity effects are negligible, the motion of a drop is determined by three independent parameters: the size of the undeformed drop relative to the radius of the capillary, the viscosity ratio between the drop phase and the wetting phase, and the capillary number.

Dawson et al. (2013) reported that the bubble movement in a low velocity wetting carrier fluid in a porous medium is governed primarily by viscous forces, surface tension forces, buoyancy forces and pressure drag resulting from the bubble bypassing the wetting fluid flow. The strength of the viscous forces on the capillary scale determines the level of broadening of the bubble upon dynamic encounter of a channel expansion, as well as the bubble's ability to squeeze into a contraction of the tube, with small values of *Ca* facilitating entrapment of bubbles in expanded sections of the tube. If the pore is not too saturated a blob will also move when the capillary pressure difference between its ends is less than the hydrodynamic pressure produced by the viscous fluid flowing in the pore space beside it (Dullien, 1991). In addition, capillary and drag forces promote entrapment of nonwetting fluid blobs in porous media, while buoyant and push forces promote their mobilization (Corapcioglu et al., 2009). Thus, they are mobilized if the sum of push and buoyant forces exceeds the sum of capillary and drag forces.

The flow pushing a finite bubble in motion in a tube of square cross-section is reportedly 30–100 times greater than the flows bypassing the bubble in the corner regions, if effects of gravity are neglected (Wong et al., 1995). However, all of the constant volume-flux flow in a tube has to by-pass a large trapped bubble, thereby generating significant drag forces. When a bubble has a stress-free interface, all the fluid bypassing it contributes to a pressure drag, which builds up a pressure difference between its tail and tip. Moreover, for a large droplet confined in a porous medium the contribution to viscous drag of shear forces at the interface is negligible compared to the pressure drag (Dangla et al., 2011). It should also be noted that body forces such as gravity and inertia are negligible compared with surface forces, due to the small size of capillaries (Wong et al., 1995). Thus, in more detail, the net effect of the pressure drag difference resulting from bypassing of the water phase between the two ends of a blob and the hydrodynamic pressure exerted by the carrier fluid flowing in the pore space alongside it will determine whether it is mobilized or trapped during an imbibition process of an air–water two-phase porous system.

An important trapping mechanism generally in displacements of non-wetting fluids during imbibition processes is snap-off ahead of the displacement front (Chatzis et al., 1983; Chatzis and Morrow, 1984; Kamath et al., 2001; Lenormand and Zarcone, 1984; Mohanty et al., 1980). Smoothly constricted pores with small throats, high pressure gradients in the liquid phase, and lamella or lens movements that establish gradients in the axial profile of interfacial curvatures can all promote snap-off (Kovscek and Radke, 2003). The competition between snap-off events and frontal displacements determines the displacement pattern and value of residual saturation (Hughes and Blunt, 2000). Dynamic effects resulting from flow through wetting films can also affect this competition (Blunt and Scher, 1995; Constantinides and Payatakes, 2000; Mogensen and Stenby, 1998; Hughes and Blunt, 2000, 2001). During strong preferential wetting, in quasi-static displacements or displacements at very low capillary numbers (of the order of 10^{-7}), movement of the wetting film also reportedly plays major roles in both displacement and trapping of the nonwetting phase (Dullien, 1991). All the cited studies offer pore size-scale understanding of the mechanisms involved in entrapment of the nonwetting fluid in an imbibition process.

However, as we discussed in detail in a previous paper (Li et al., 2013), the soil-moisture dynamics of two- or three-phase porous media are highly complex, because they are affected by numerous interacting factors. Thus, despite intensive investigation there are still major uncertainties regarding key parameters involved and their interactive relationships, notably the residual saturations of given fluids in such media in given initial conditions are flow-path and system-history dependent, and they vary with position and time in the medium (Hilfer, 2006). Clearly, these uncertainties need to be resolved to improve our understanding and modeling of flows of fluids and contaminants in porous media.

In the study presented here, as in our previous investigation (Li et al., 2013), we have examined the residual saturations and related phenomena of two phases (air and water) in a column of an undisturbed fine sandy medium. The primary focus has been on the effects of the initial saturation, which is considered as one of the key parameters affecting residual air and water saturations in a porous medium (Land, 1968).