Wettability-controlled phase transition in displacement- and trapping efficiency in 3D porous media: A micro-CT study

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Abstract

Background: Capillary trapping of gas bubbles and oil blobs within water-saturated media plays an important role for underground gas storage and secondary oil recovery. Wettability and roughness of the surface are elementary properties of a porous medium that determine the trapping efficiency. In previous work [1,2], we demonstrated that glass beads and natural sands display a significant difference (15%) of the trapped gas phase. Here, we carry out a systematic study of the capillary trapping efficiency in dependence of the wettability and surface roughness. Methods: We conducted a series of column experiments to study capillary trapping of gaseous CO2 using both glass beads and natural sands as sediments. Based on the high-resolution non-invasive micro-CT visualization method and subsequent image processing, we quantified capillary trapping efficiency, gas-cluster morphology and gas-cluster size distribution. We used the silanization method for varying degrees of wettability resulting in three different contact angles on microscopic soda lime glass slides: (i) Piranha cleaning (= 7°), (ii) untreated glass (= 30°) and (iii) silanized glass (=100°). Results: We observed that by-pass trapping is the dominant trapping mechanism in glass beads (smooth surfaces). The displacement process is piston-like. For natural sands (rough surface), thick film flow occurs, causing an efficient snap-off trapping mechanism. Our results indicate that the capillary trapping efficiency of natural sands is stronger reduced by a transition from water-wet to CO2-wet 3-phase system (increasing contact angle) when compared to glass beads. [1] H. Geistlinger, I. Ataei-Dadavi, S. Mohammadian, and H.-J. Vogel (2015) The Impact of Pore structure and Surface Roughness on Capillary Trapping for 2D- and 3D-porous media: Comparison with Percolation theory. Special issue: Applications of Percolation theory, Water Resour Res, 51, doi:10.1002/2015WR017852. [2] H. Geistlinger, I. Ataei-Dadavi, and H.-J. Vogel (2016) Impact of Surface Roughness on Capillary Trapping Using 2D-Micromodel Visualization Experiments. Transport in Porous Med., DOI 10.1007/s11242-016-0641-y.

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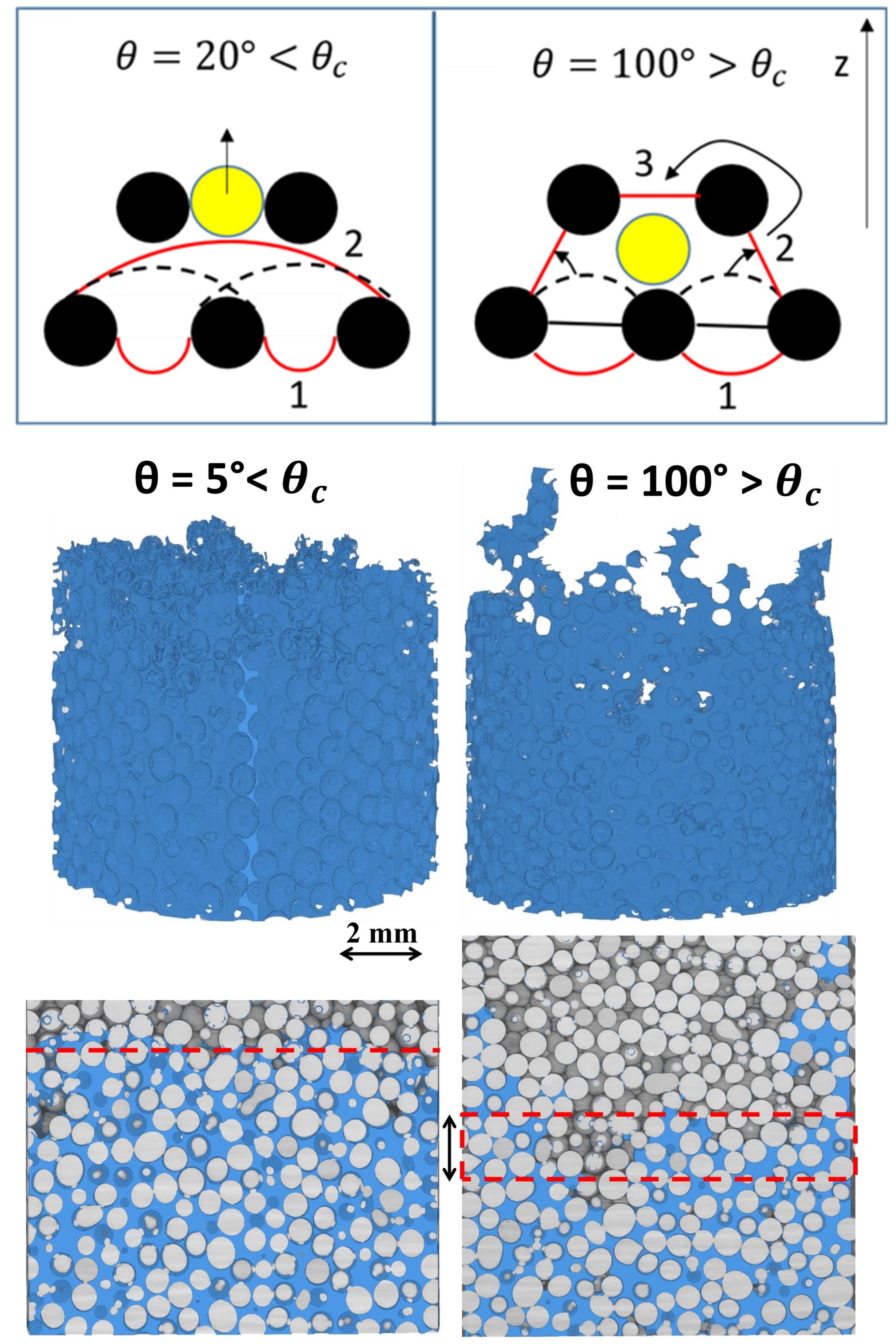
INTRODUCTION:

Fluid invasion, displacement of one fluid by another in porous media is important in large number of industrial and natural processes. Of special interest is the trapping of gas & oil clusters. We study the impact of wettability on fluid pattern formation and capillary trapping in glass beads during fluid invasion at Capillary number of 10^{-7} using micro-CT. The contact angle (CA) on glass beads were varied from **5° to 100°** using Piranha cleaning and silanization. A sharp phase transition at $\theta_c = 86°$ was observed. Below θ_c the morphology of the displacement front was ***flat*** and ***compact*** caused by strong smoothing effect of ***cooperative filling***. Above θ_c the morphology of the displacement front was ***fractal*** and ***ramified*** caused by ***single bursts (Haines Jumps)***. Across this dynamical phase transition the trapping efficiency changes from ***no-trapping*** to ***maximal trapping***.

-- *[**Submitted to Water Resources Research**]* --

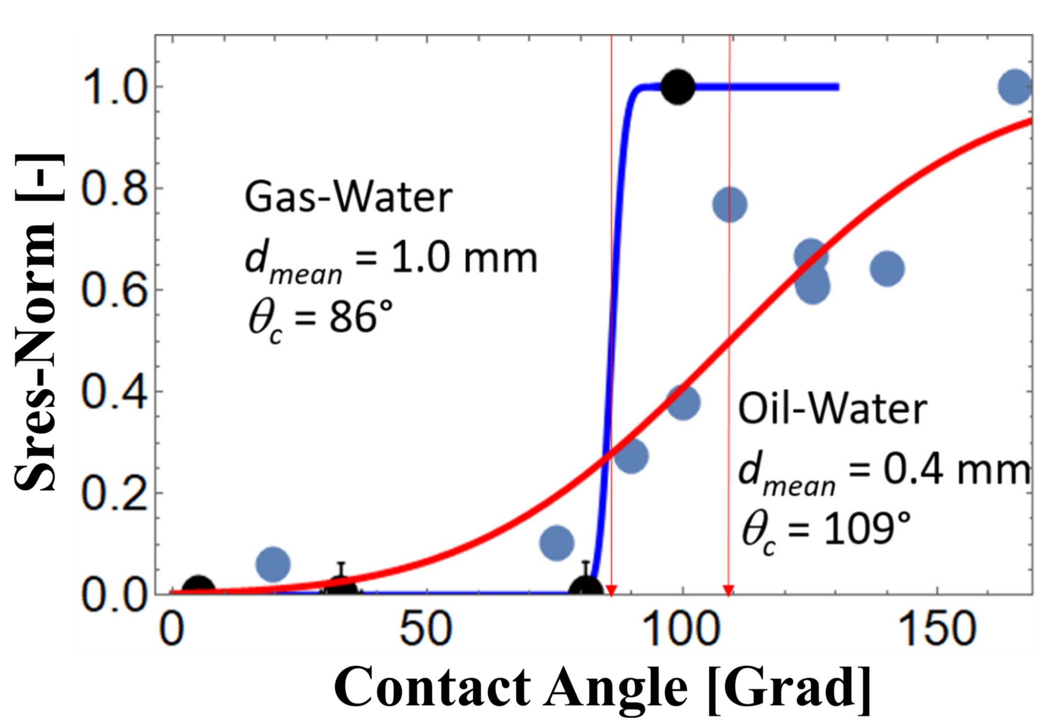
RESULTS & DISCUSSION:

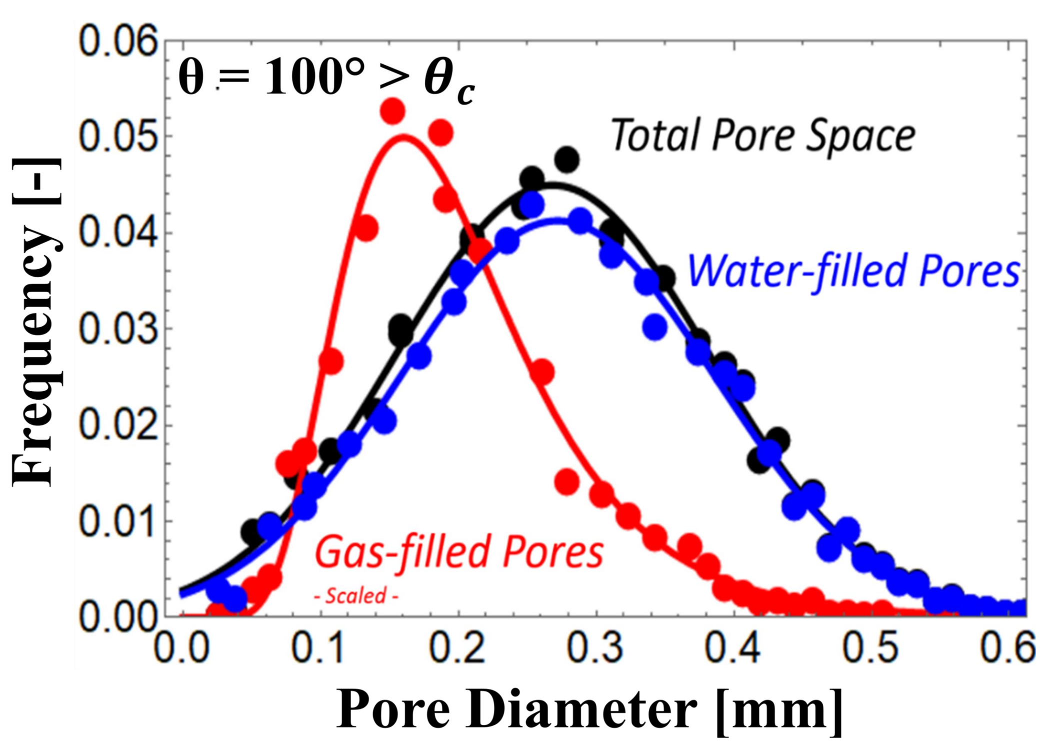
1- Front Morphology:



➤ ***NO SMOOTHING EFFECT RESULTS INTO SIGNIFICANT TRAPPING OF DEFENDING FLUID***

2- Capillary Trapping:

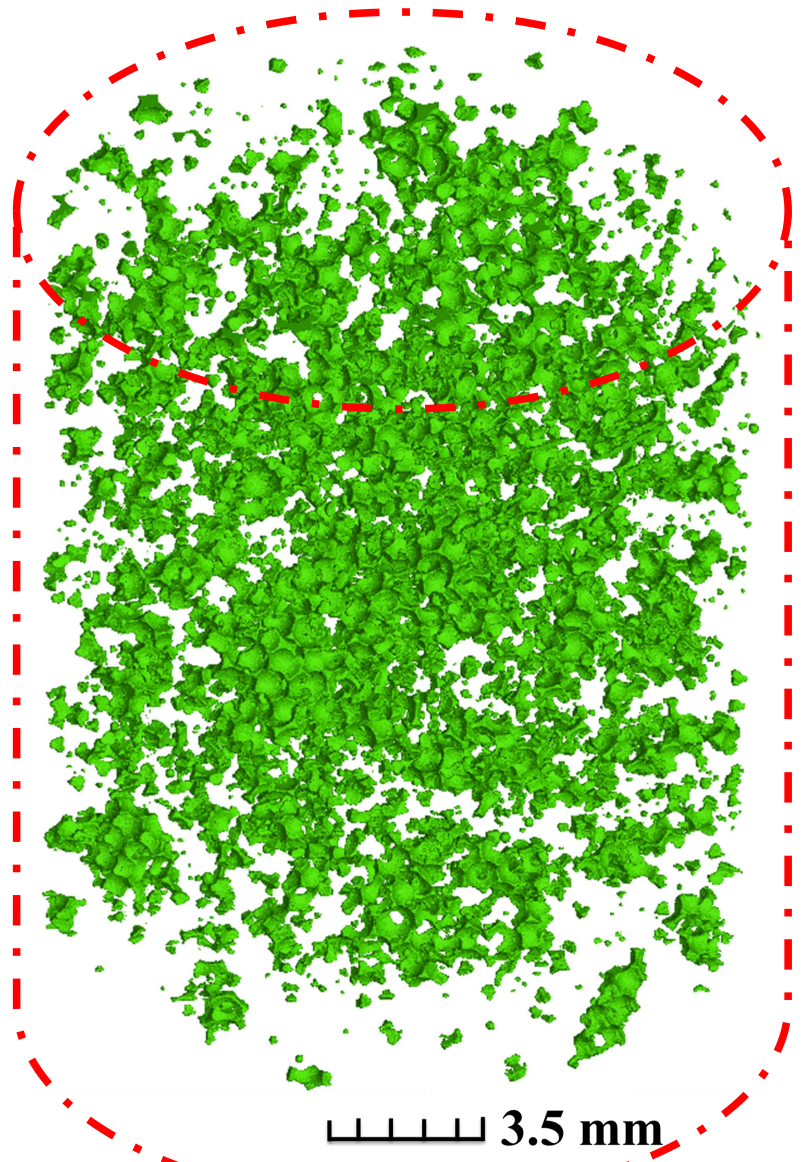


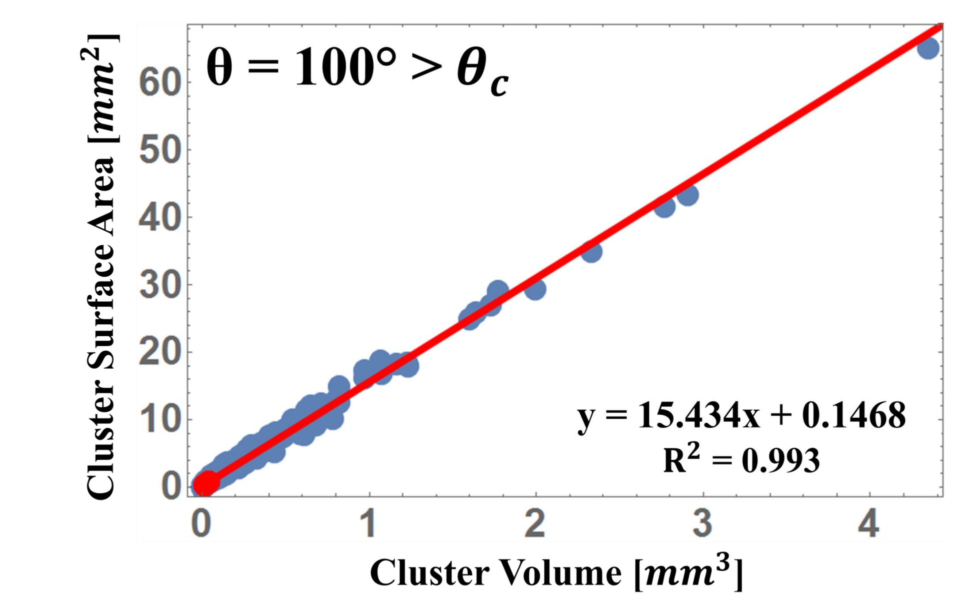


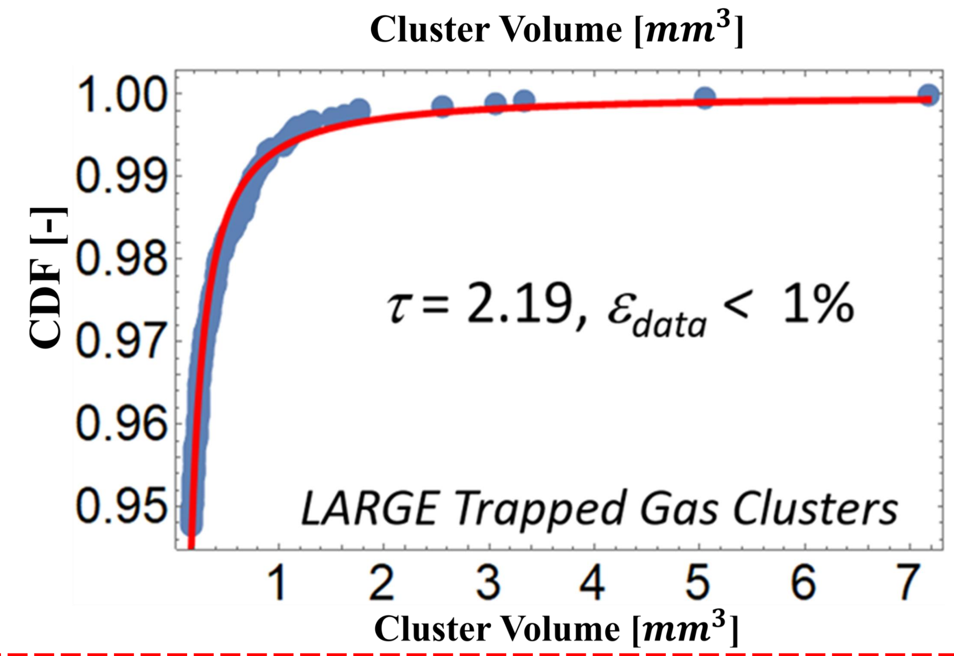
For $\theta > \theta_c$

➤ ***Interfacial area is 1.6 times larger for $\theta > \theta_c$ compared to $\theta < \theta_c$***

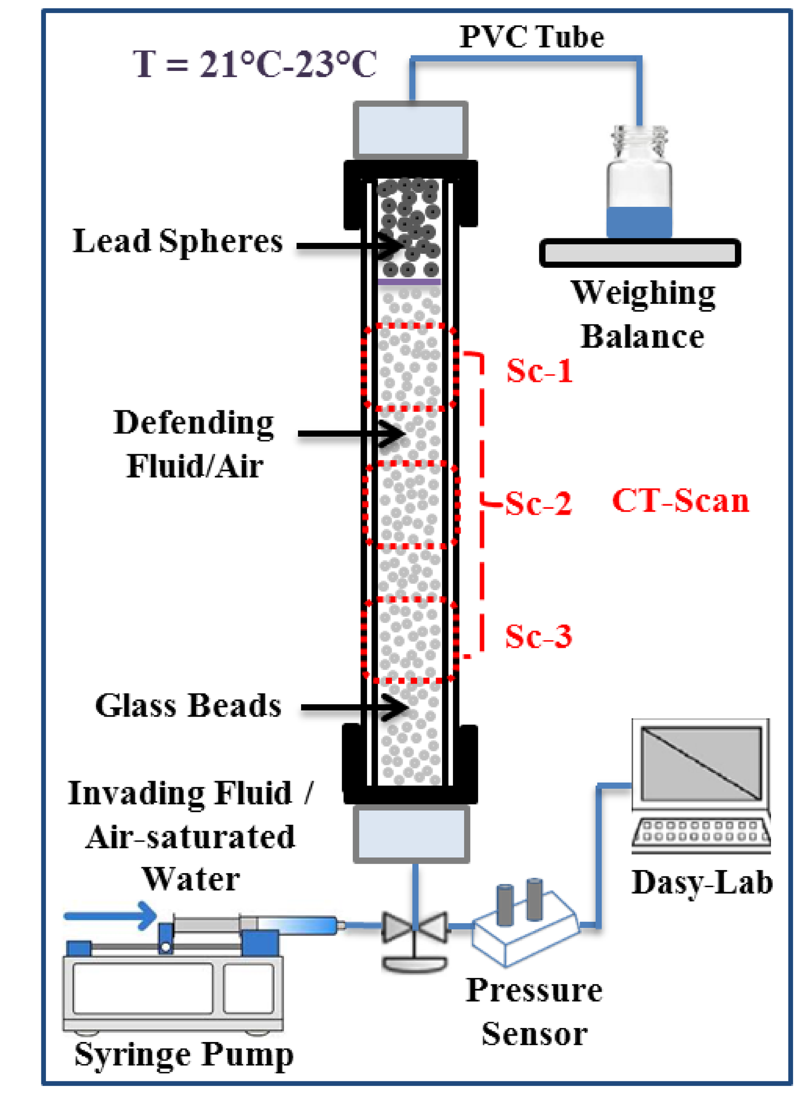
3- Universal Scaling







MATERIAL & METHODS:



- ➤ **Sediments:** Glass beads (rough. < 0.02 µm), ***dmean = 0.98*** and ***PSD = 0.273 mm***
- ➤ **Wettability Alteration:**
  - **θ = *5° ± 2°*;** GBS were Piranha (H_2O_2: H_2SO_4= 1:3) treated & ultrasonically cleaned with de-ionized water
  - **θ = *78° ± 3°*, *ϑ = 99° ± 3°***; Deposition of self-assembled monolayer of dichloro-dimethyl silane on GBS
- ➤ **CA measurement**: *Drop Shape Analyzer 100* (Krüss, Germany) using Analog Glass Plate Method (Herring et al., 2016)
- ➤ **µ-CT:** *Spatial resolution **0.013 mm***, i.e. Fluid meniscus resolved by ***22 voxels along the diameter***

CONCLUSIONS:

- ➤ **Dynamic Phase Transition** (*Wettability governs the percolation transition*)
  - For **θ < θ_c**: Front morphology is ***flat*** and ***compact*** -- ***Cooperative filling*** --
  - For **θ > θ_c**: Front morphology is ***fractal*** and ***ramified*** -- ***Haines Jumps*** –
- ➤ **Cross Over in Trapping Efficiency**
  - The transition (*occurs withing 10°*) in the pattern formation causes a cross-over in trapping efficiency by **100 %**, i.e. ***No trapping** to **maximal trapping*** with gas clusters occupying the *smaller pores*
- ➤ **Universal Scaling of Cluster size distribution: Power-law behavior**
  - For **θ > θ_c**: Invasion Percolation governs the fluid displacement

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- Geistlinger et al., **(2015)**. Capillary trapping mechanisms in strongly water-wet systems: Comparison between exp. & percolation theory. ***Adv. in Water Res.***, 79, 35-50.
- Herring, A et al., **(2016)**. Impact of wettability alteration on 3D nonwetting phase trapping and transport. **Int. J. Greenhouse Gas Contr.**, 46, 175-186.

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