Capillary end effects and their impact on pore-scale steady-state relative permeability data

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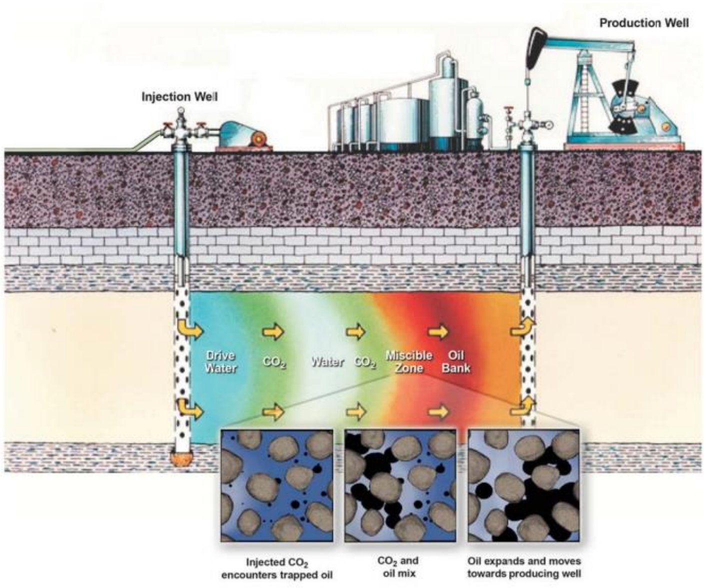
General context

- Prediction of **subsurface multi-phase flow**
  - Estimation of **relative permeabilities**



From https://www.energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery

Multi-phase Darcy's law:

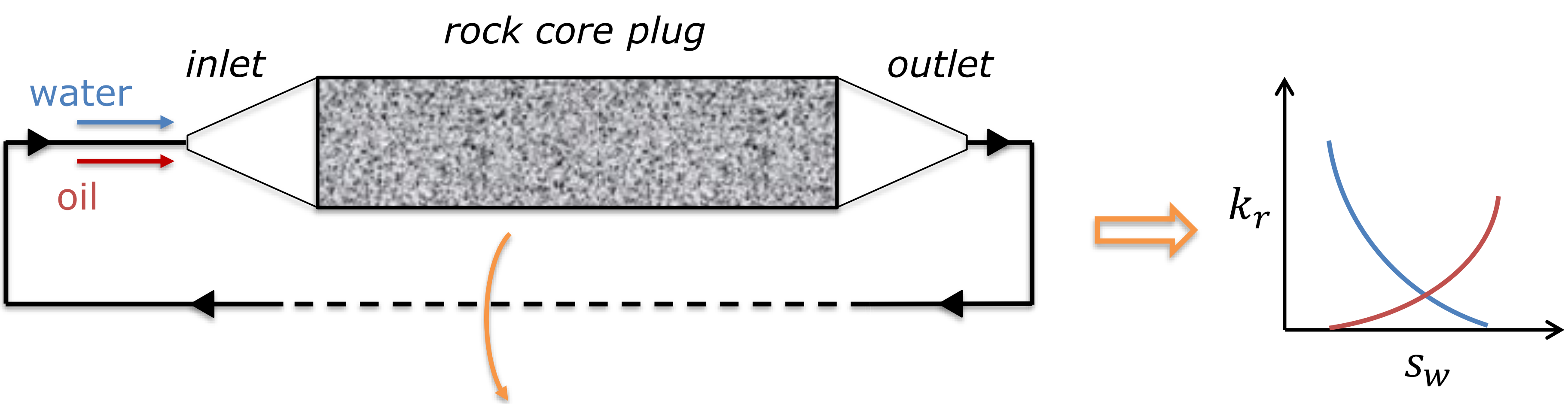
$$v_D^\alpha = \frac{\kappa_{rel}^\alpha \kappa_{abs}}{\mu^\alpha} \nabla P^\alpha$$

$$\kappa_{rel}^\alpha = f(S^\alpha, Ca, \theta, \dots)$$

What are capillary end effects?

Let’s start with an example…

- Closed-loop experimental apparatus for water/oil **flooding experiments** aimed at determining **relative permeability curves**

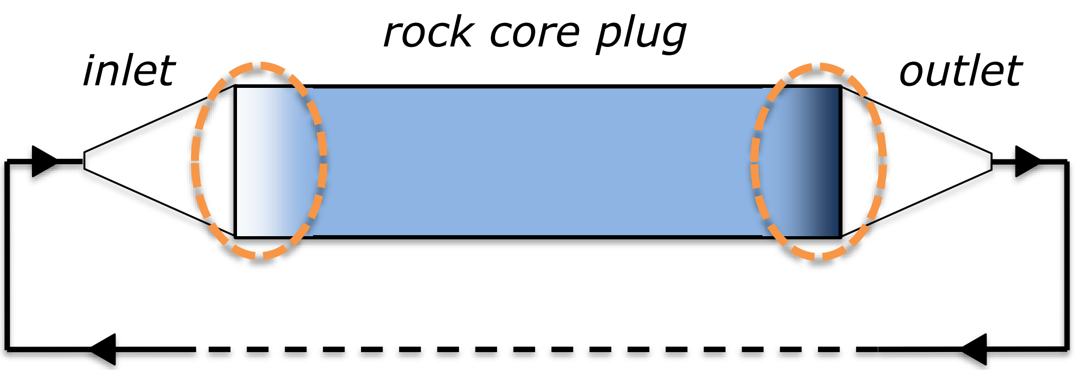


What are capillary end effects?

Example: inlet/outlet connections of a closed-loop experimental apparatus

Evidence:

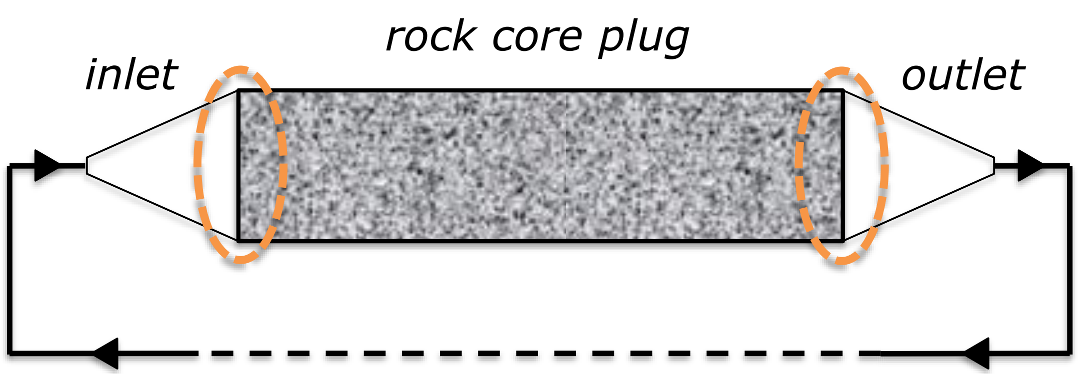
- accumulation of **non-wetting** phase at **inlet**
- accumulation of **wetting** phase at **outlet**



What are capillary end effects?

Example: inlet/outlet connections of a closed-loop experimental apparatus

Origin:
- discontinuity in a porous medium **solid matrix**…
- … that creates a discontinuity in **capillary pressure**

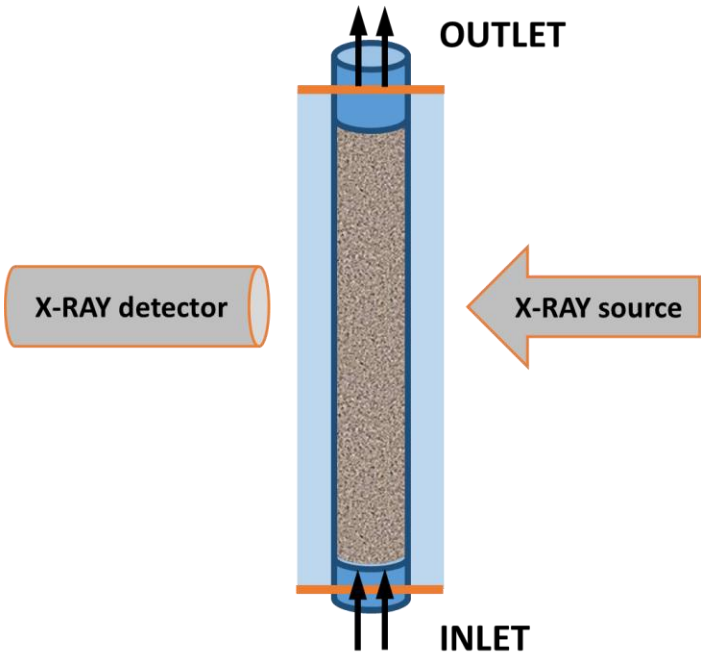


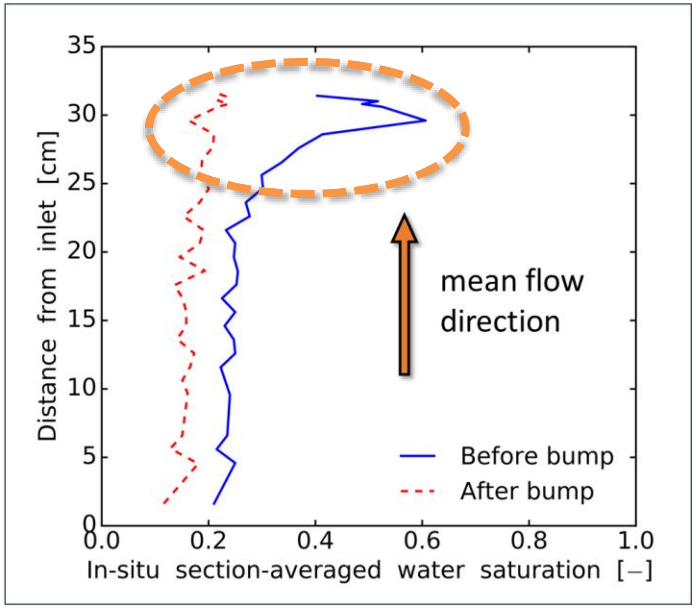
$$\boxed{P_c = f(\bar{r}_{pores}\,, \ldots)}$$

Experimental evidence

Results from Moghadasi et al. [1] (water-oil flow in water-wet Sandpack)

- Outlet end effect visible after primary drainage at low $\dot{Q}$ ("before bump")



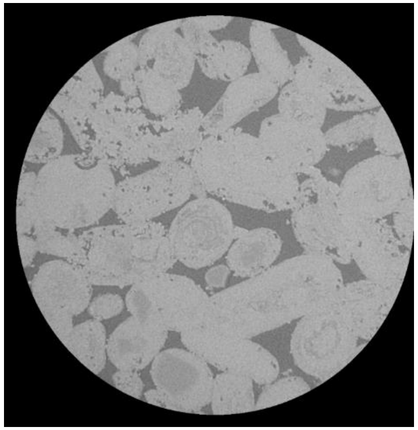


[1] L. Moghadasi, A. Guadagnini, F. Inzoli, M. Bartosek, D. Renna. J. Pet. Sci. Eng., 145, pp. 453–463, 2016.

What about direct pore-scale simulation?

What about direct pore-scale simulation?

- Increasing **availability** of X-ray micro-tomography (**micro-CT**) for the reconstruction of pore spaces
- Increasing **application** of direct pore-scale simulation to predict permeability and relative (2-phase) permeabilities

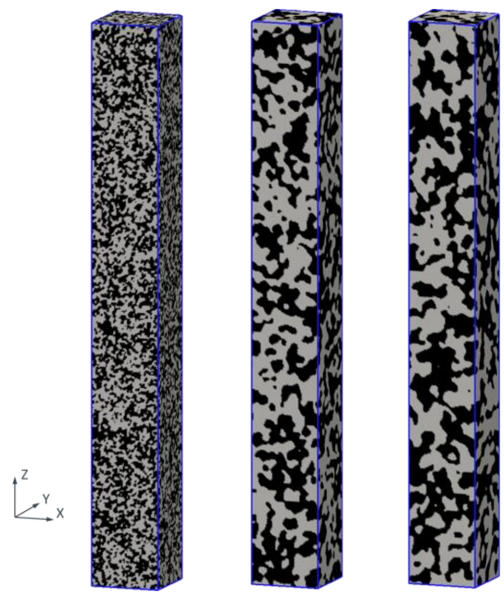


~1 mm

What about direct pore-scale simulation?

- An alternative to micro-CT scans is to use **synthetically** (algorithmically) generated porous media

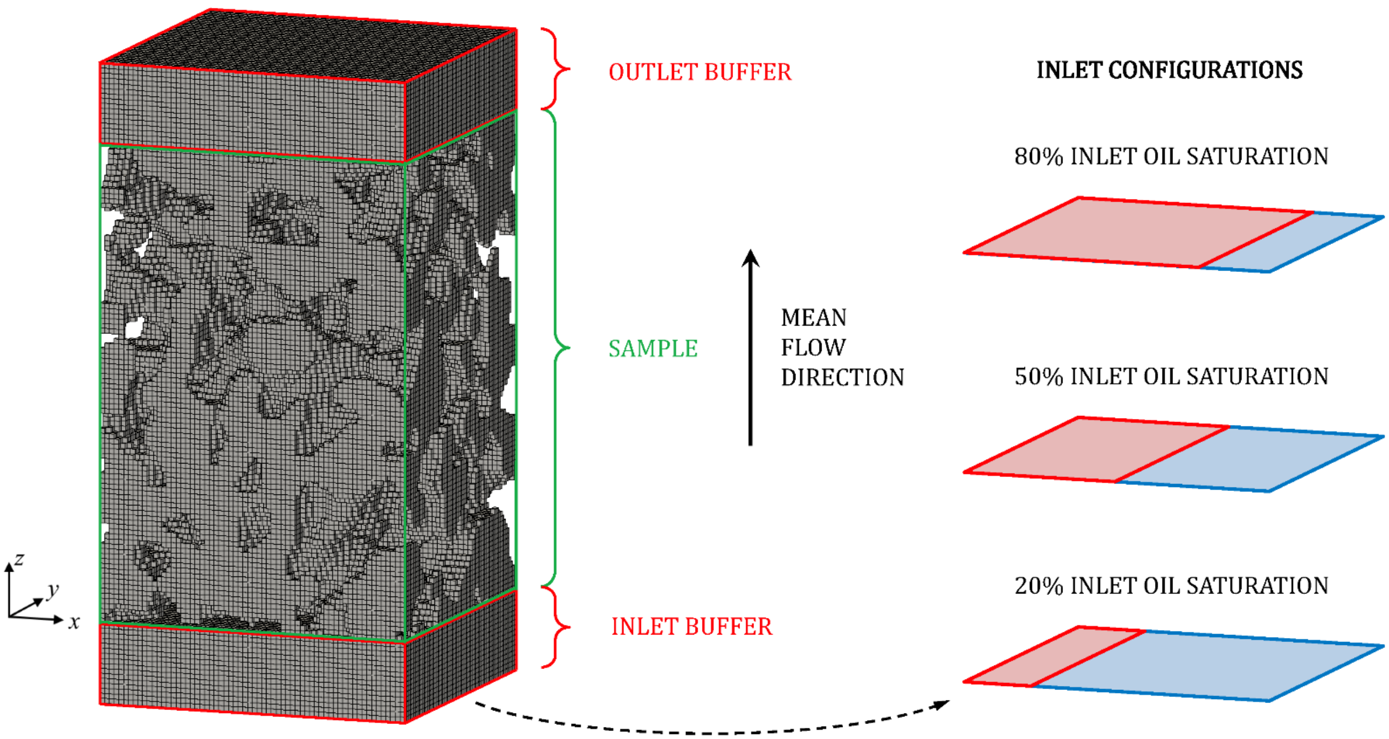
- Here a **stochastic generator** is used to generate the investigated pore spaces [2]



[2] J.D. Hyman and C.L. Winter. J. Comput. Phys., 277, 16–31, 2014.

What about direct pore-scale simulation?

- One typical **simulation set-up** (Guédon et al. [3])



[3] G.R. Guédon, J.D. Hyman, F. Inzoli, M. Riva, A. Guadagnini. Phys. Fluids, 29, 123104, 2017.

What about direct pore-scale simulation?

- Are capillary end effects also present in **numerical simulation**?
  - If yes, then what is their **impact** on the solution?

In the following, results are referred to this simulation set-up:

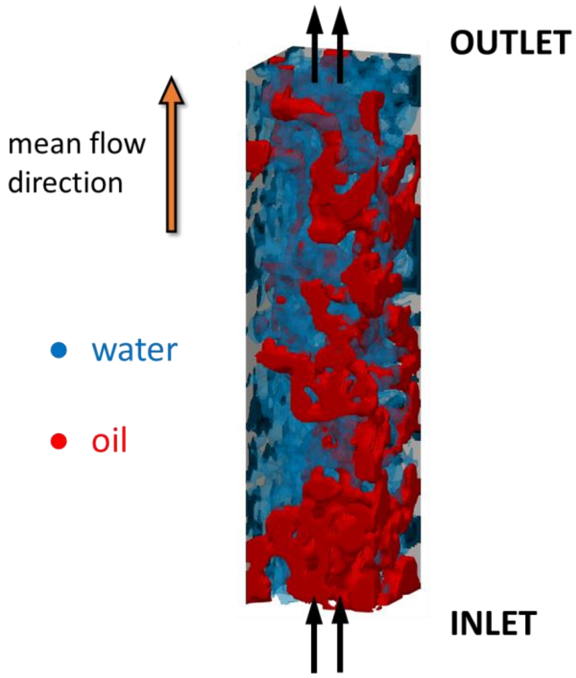
- water/oil simultaneous injection
- 50% inlet oil saturation
- viscosity ratio $\mu_o/\mu_w = 2$
- Capillary number Ca = 10^{-3}
- 48% rock porosity (synthetic)

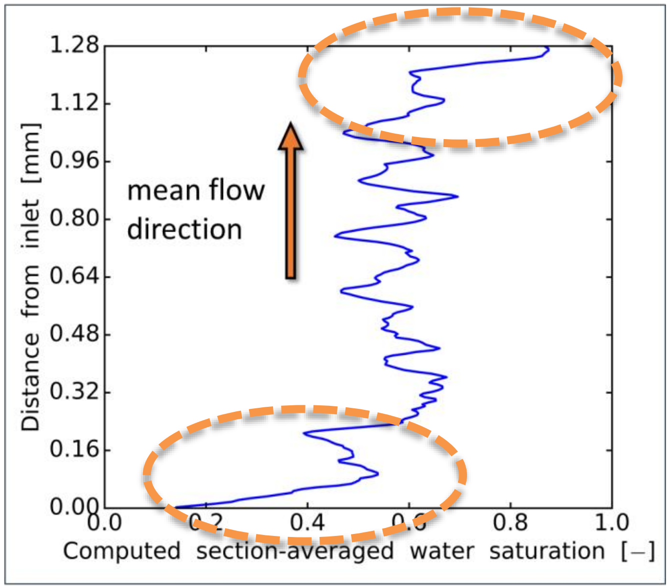
The OpenFOAM® open-source code is used to perform the simulations

What about direct pore-scale simulation?

Answer: yes

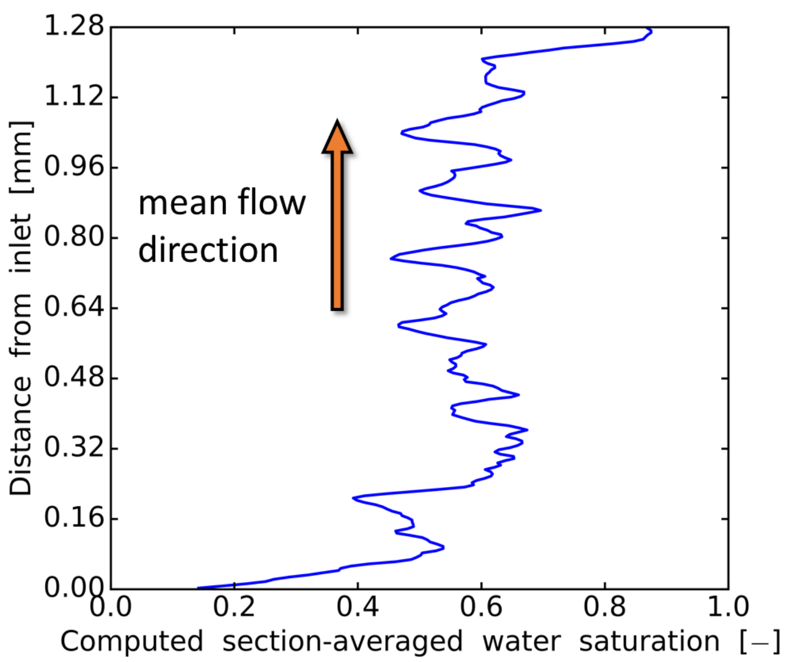
➢ There is a strong impact of boundary effects on saturation distribution…

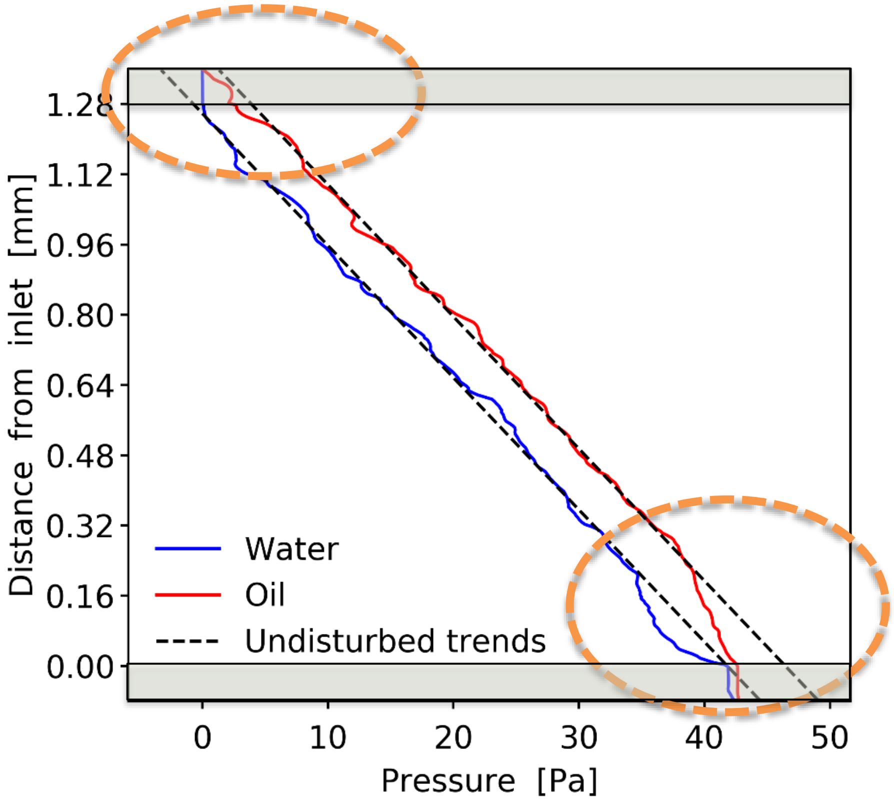




- … and pressure distribution

inlet/outlet buffers

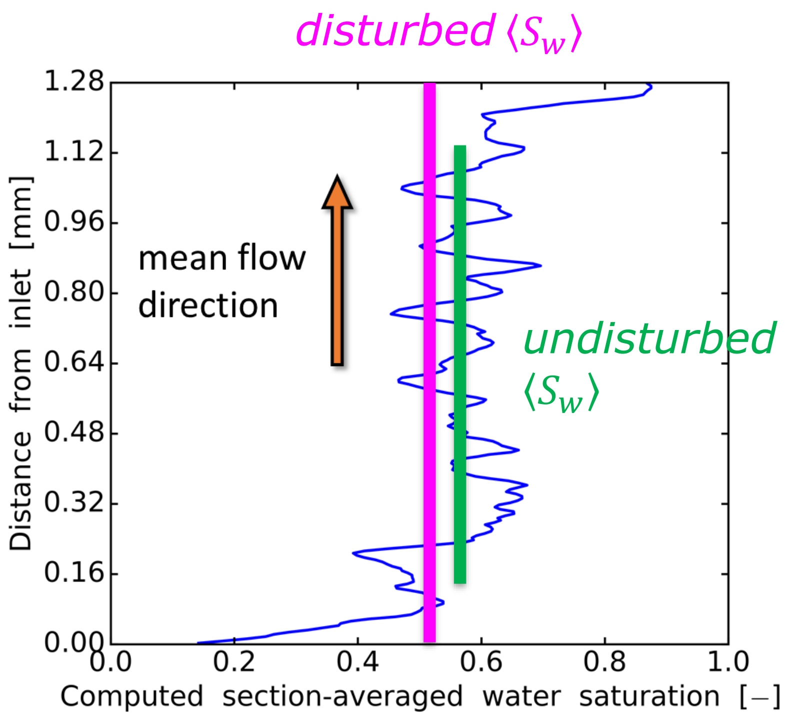


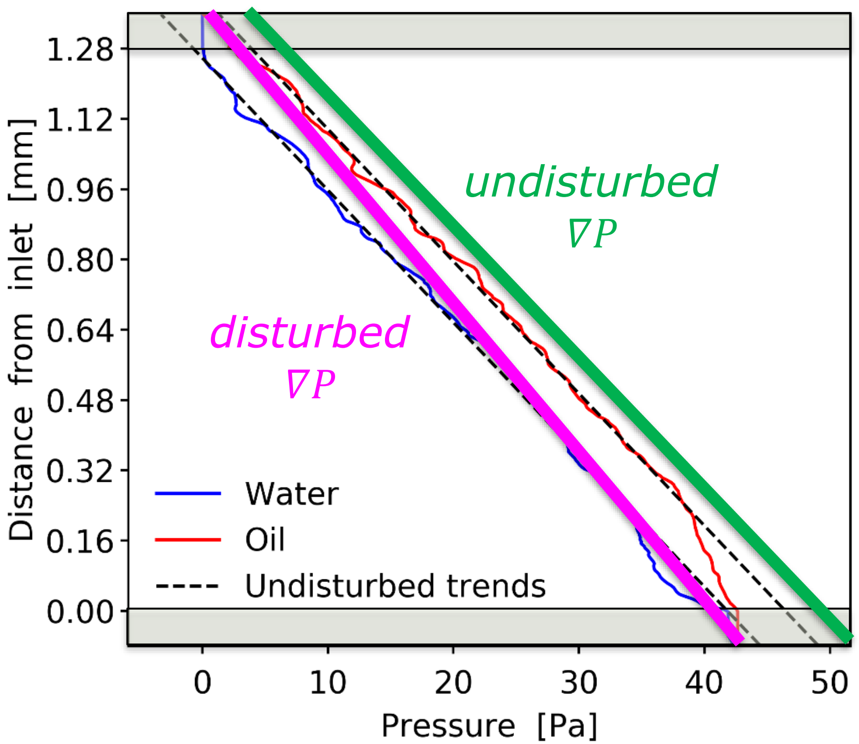


What about direct pore-scale simulation?

➢ thus influence $(\boldsymbol{k_r} - \boldsymbol{S_w})$ relationship

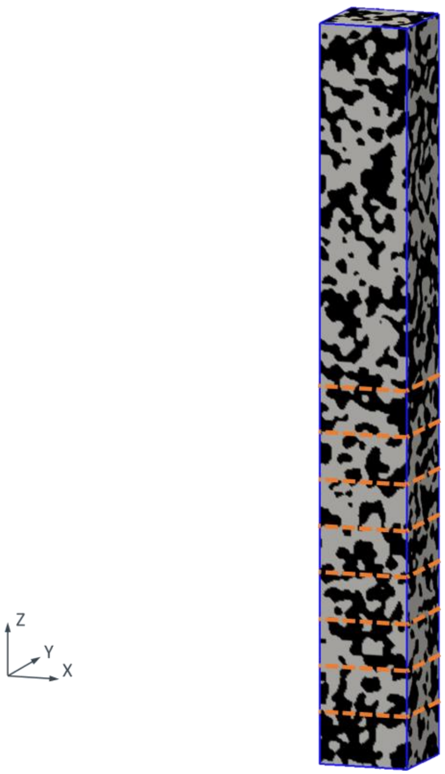
inlet/outlet buffers

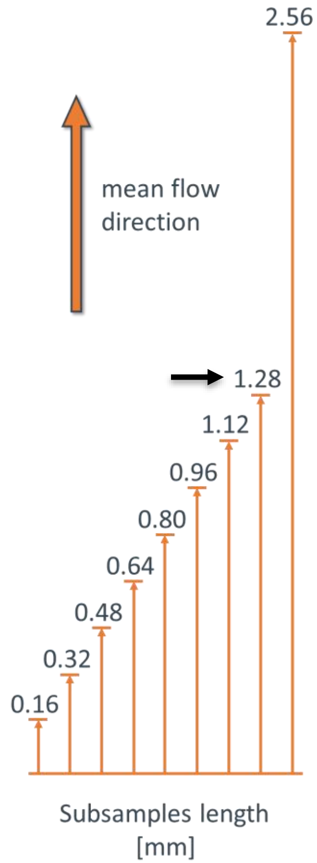


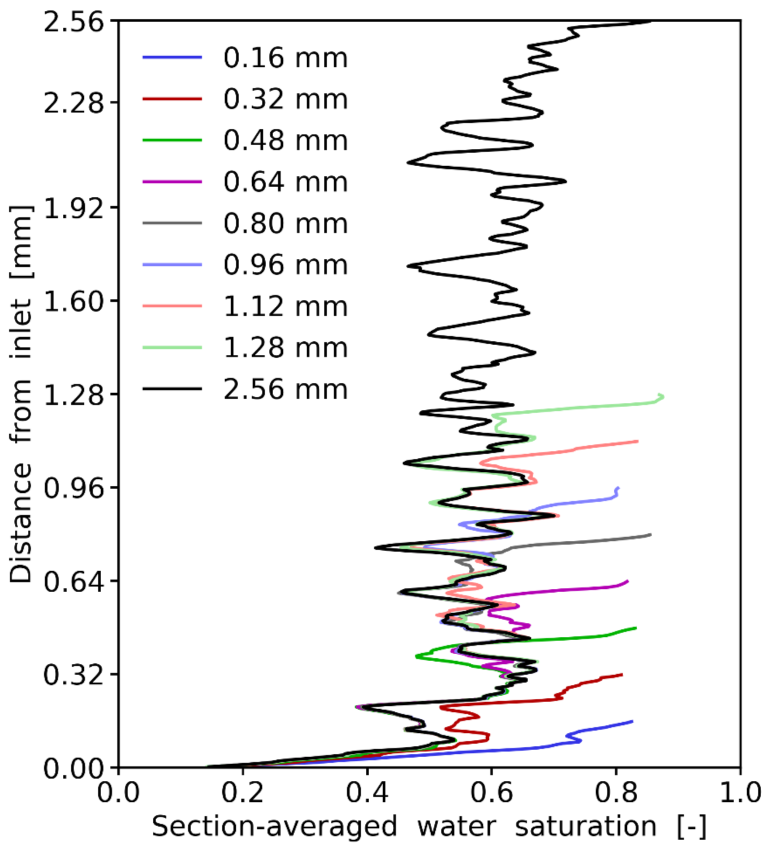


What about direct pore-scale simulation?

➢ What happens when the **length** of the sample increases/decreases?



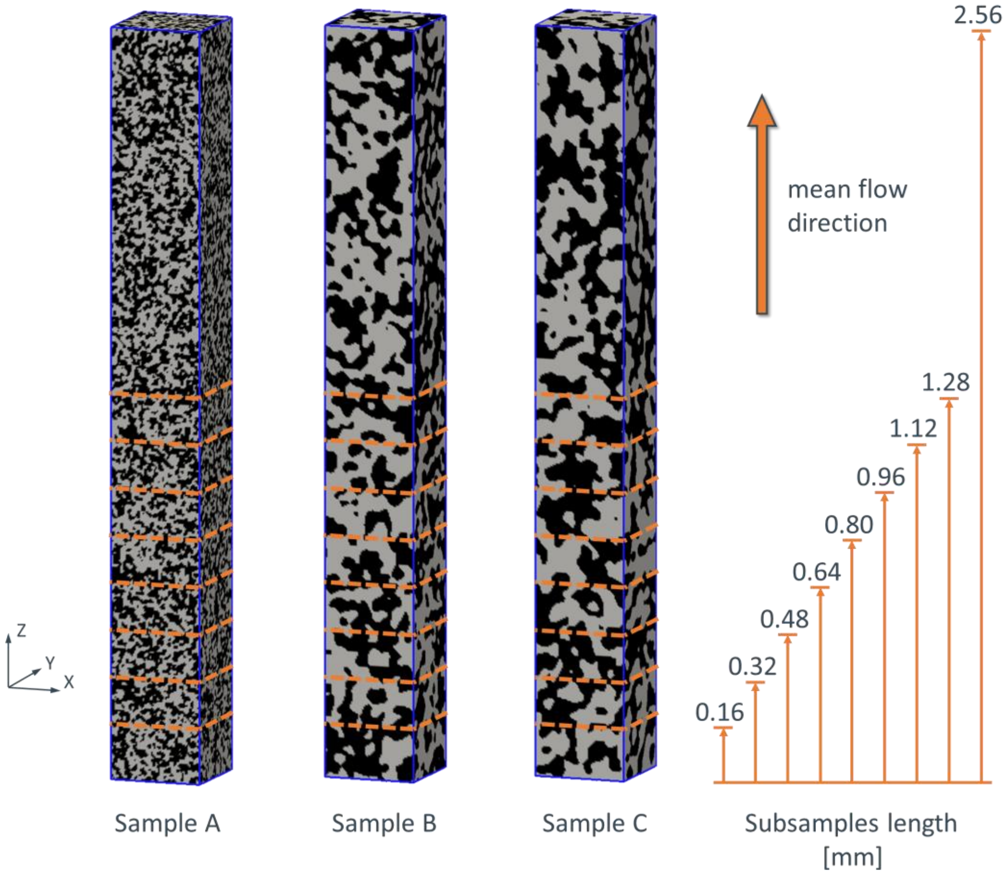




What about direct pore-scale simulation?

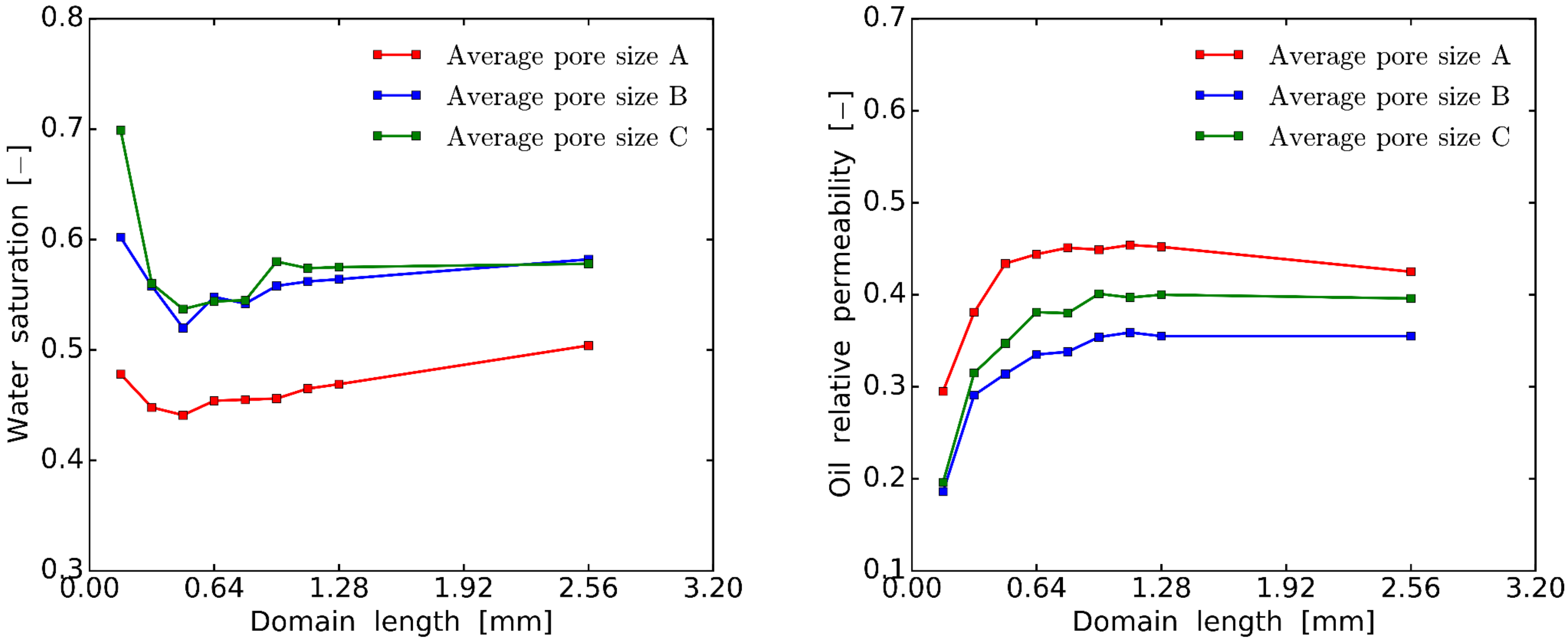
- What happens when the **pore size** changes?
- 3 diverse average pore sizes

Sample	$\bar{r}_{pores}$ [µm]
A	8.5
B	18.4
C	20.2



What about direct pore-scale simulation?

- When the sample is **too small**, the estimates are largely influenced **(error > 20%)**



Conclusions

- Capillary end effects are relevant to **both** experiments and simulations
- They are **negligible** when the length of the sample is *large enough*

$$\mathbf{L}/\bar{r}_{pores} > 60$$

- We expect $L_{min}/\bar{r}_{pores} = f(\phi, Ca, \nabla P/P_c)$
- Here we investigated $L_{min}/\bar{r}_{pores}$ for:
  - Porosity $\phi = 0.48$
  - Capillary number $Ca = 10^{-3}$
  - Ratio $\nabla P/P_c \approx 10^{-4}$ **m**

Our current focus is to characterize capillary end effects against these parameters to improve understanding of these phenomena and to support the preliminary design of experiments and simulations

More about this topic in: G.R. Guédon et al. (2017) *Influence of capillary end effects on steady-state relative permeability estimates from direct pore-scale simulations.* Physics of Fluids, 29, 123104.

Thank you for your attention!