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APPLICATION OF PORE-NETWORK MODELS FOR ANALYSIS OF DARCY-SCALE TWO-PHASE THEORIES

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Special thanks to:
S. M Hassanizadeh
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M. Celia
D. Wildenschild
L. Pyrak-Nolte

Averaging, Upscaling, and New Theories in Porous Media Flow and Transport, Bergen, October 14-15, 2010

TODAY

PART I: TWO-PHASE FLOW AT PORE SCALE
PART II: NOVERLTY OF PORE-NETWORK MODELS FOR DARCY-SCALE ANALYSIS

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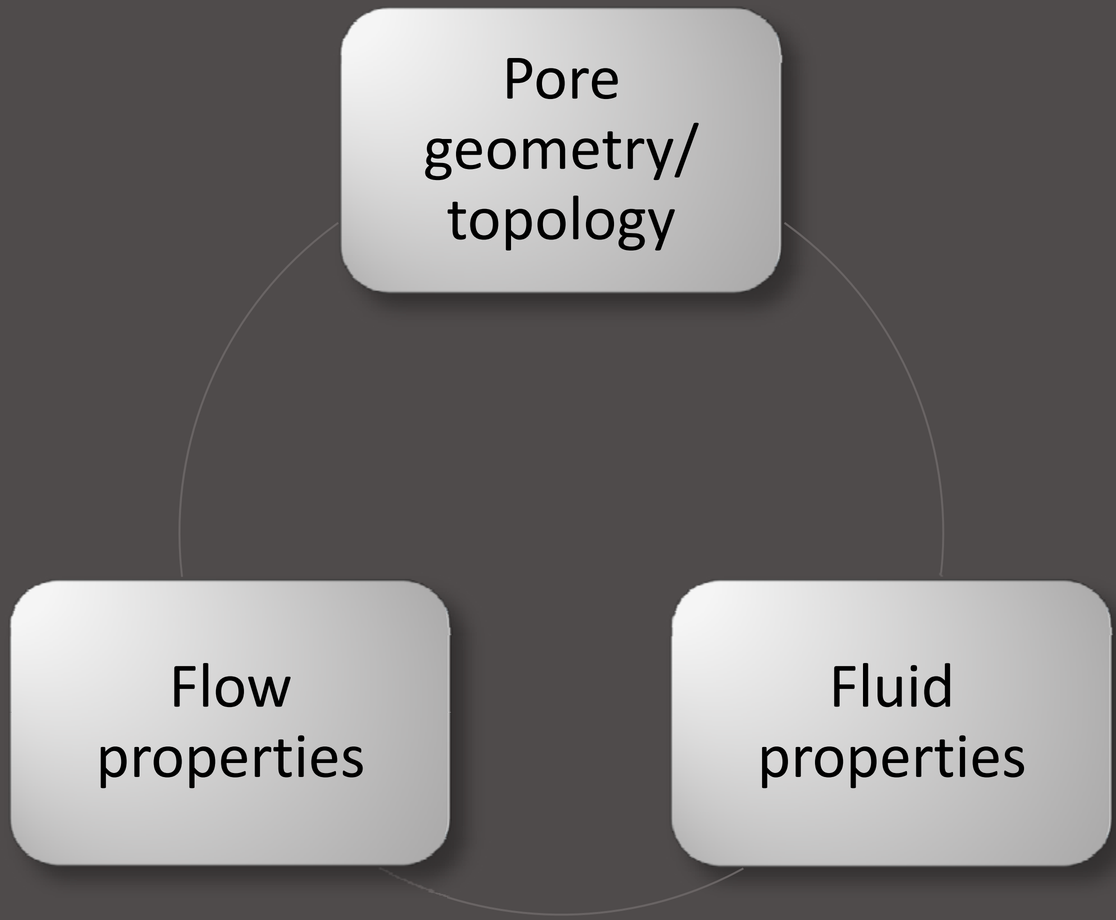
TWO-PHASE FLOW AT PORE SCALE

PARAMETERS AND EFFECTS

NOVELTY OF PORE-NETWORK MODELS

Averaging, Upscaling, and New Theories in Porous Media Flow and Transport, Bergen, October 14-15, 2010

Effective parameters in immiscible two-phase flow



Effective parameters in immiscible two-phase flow

Parameters

Pore geometry and topology

(e.g. aspect ratio, coordination no.)

Dynamic parameters:

Flow conditions

(capillary number, Bond number, …)

Fluid/solid properties

(viscosities, contact angle, interfacial tension)

Darcy-scale observations

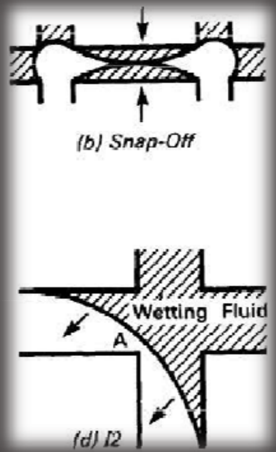
Hysteresis in P^c-S^w curve

Hysteresis in a^{nw}-S^w curve

Residual (nonwetting phase) saturation

Dynamic effects in pressure field

Aspect ratio

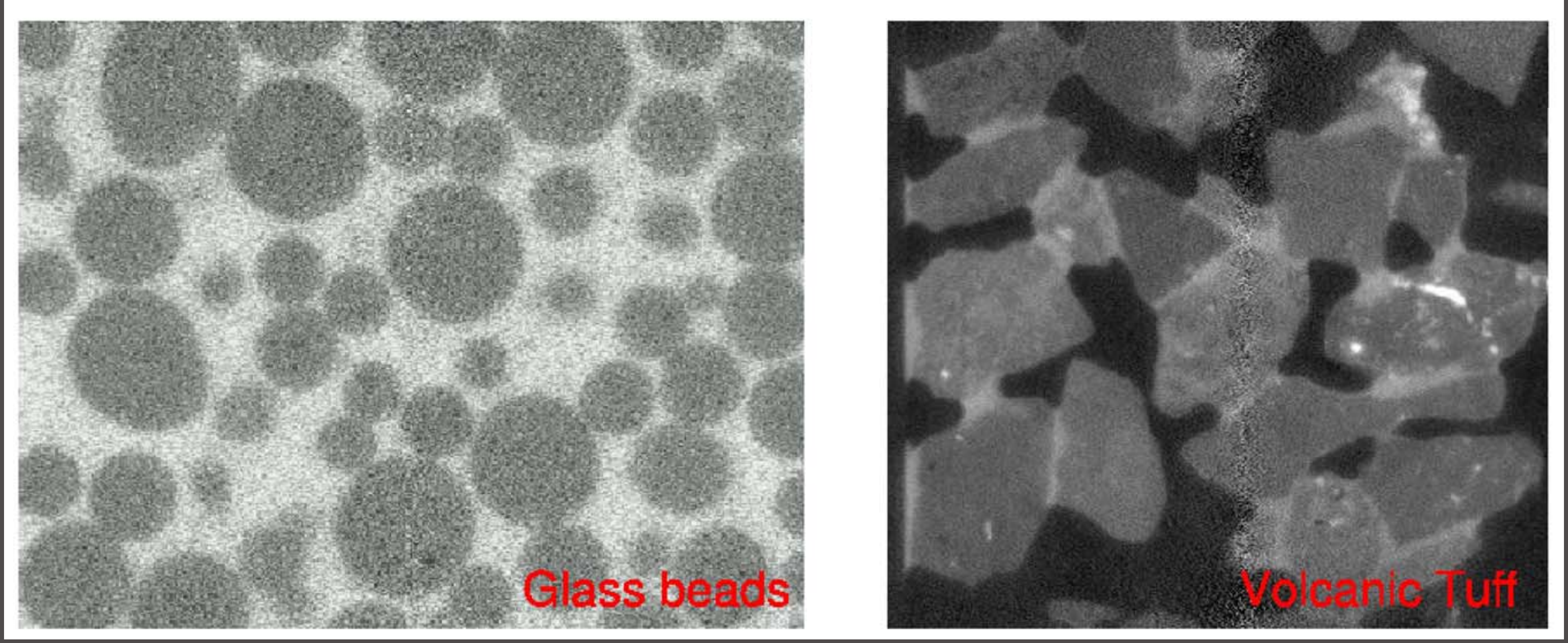


$$\kappa = R_i / r_{ij}$$

Radius of pore body size to pore throat size

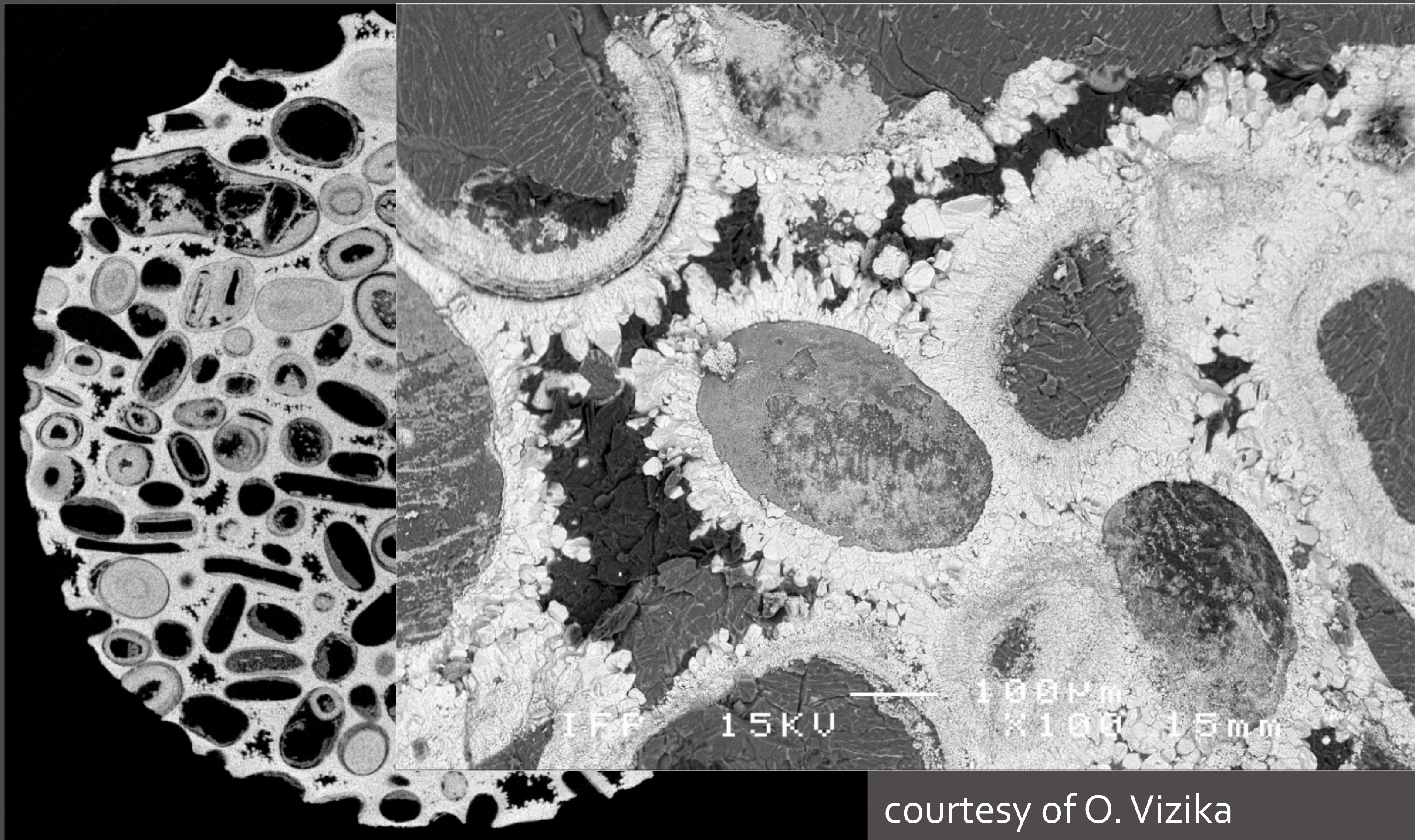
- significant effect during imbibition. i.e. larger aspect ratio, more snap-off! More snap-off, more nonwetting phase trapping (Lenormand and Zarcone, JFM, 1983, 1984; Wardlaw and Yu, 1988; Ioannidis et al. 1991)

Examples of porous media: glass-beads vs Tuff



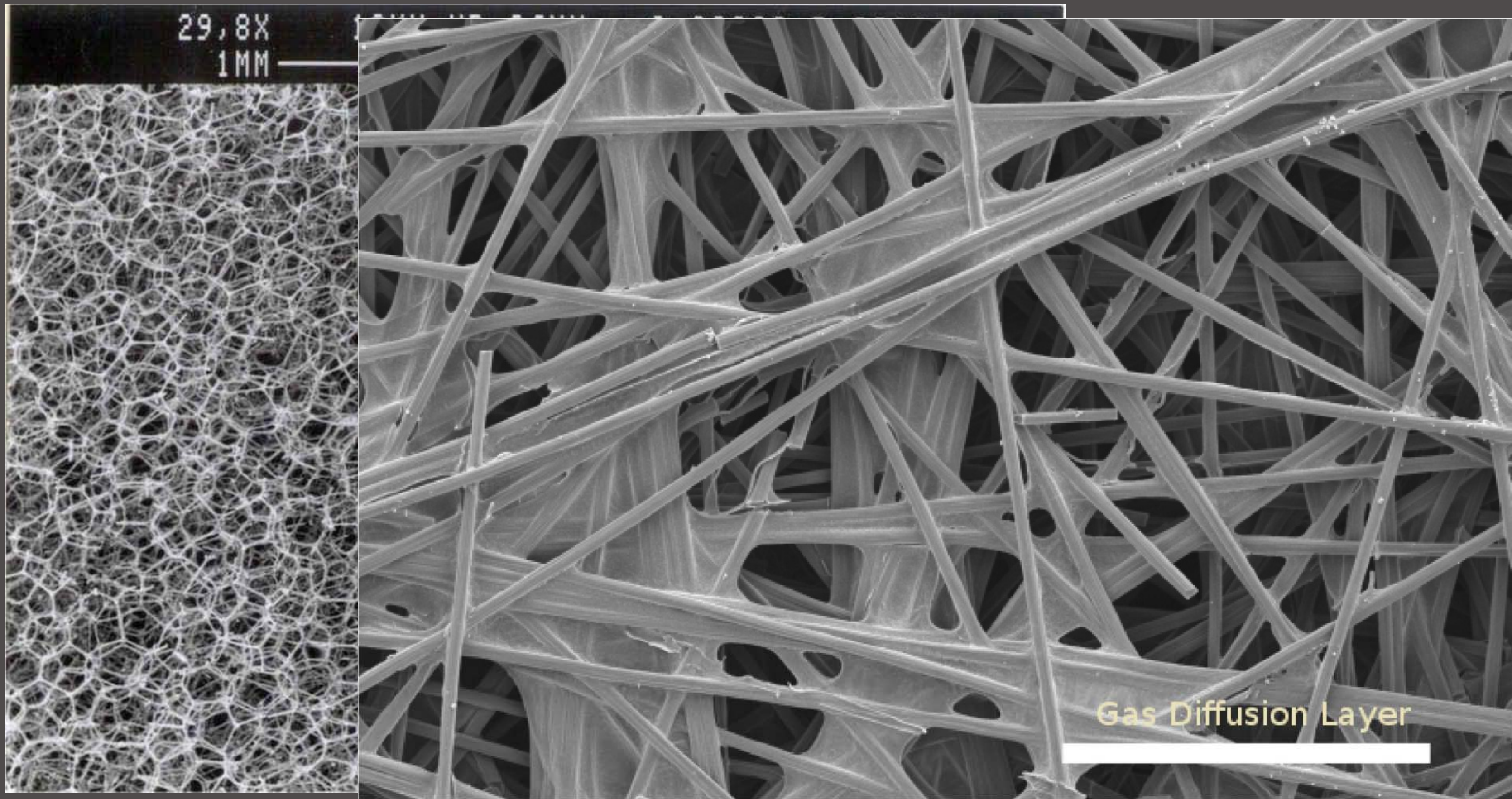
courtesy of D. Wildenschild

Examples of porous media: carbonate



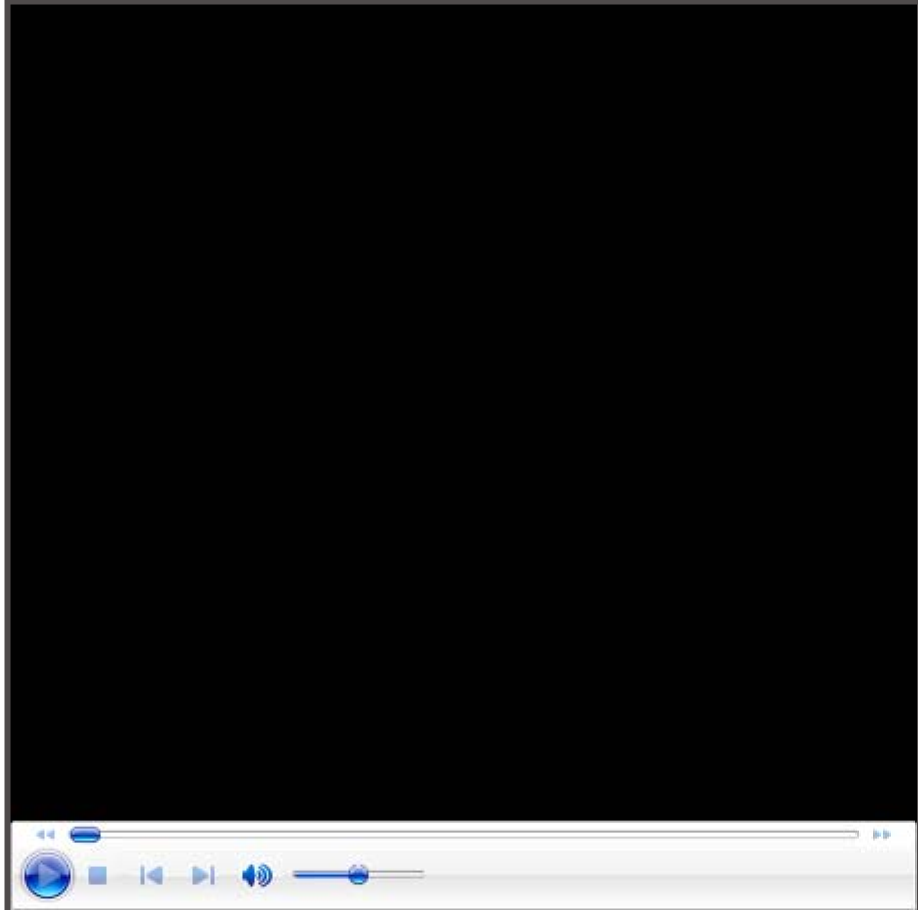
courtesy of O. Vizika

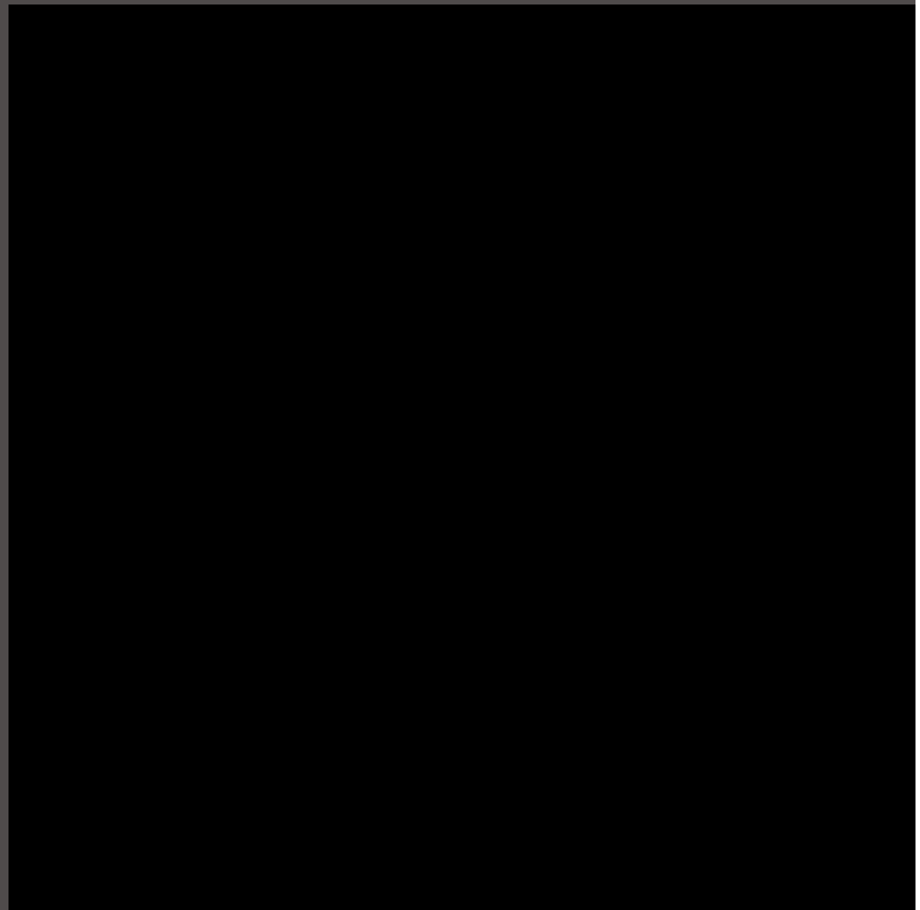
Examples of porous media: fibers



www.bazylak.mie.utoronto.ca/research/

Cooperative filling vs. snap-off

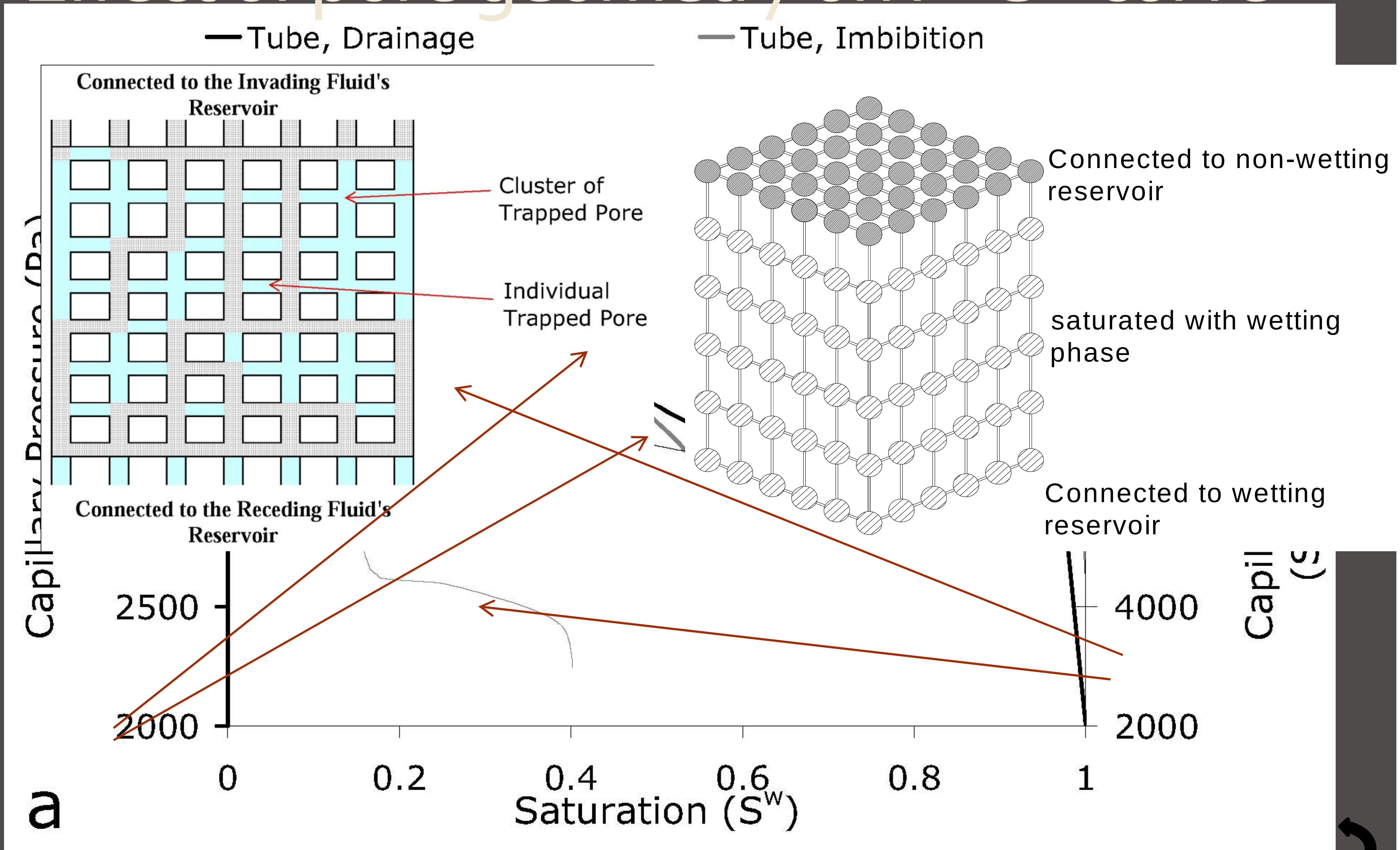




Simulations using LG by Fabiano G. Wolf) http://www.lmpt.ufsc.br/ fgwolf/.

Provided by Prof. Pyrak-Nolte

Effect of pore geometry on P^c-S^w curve



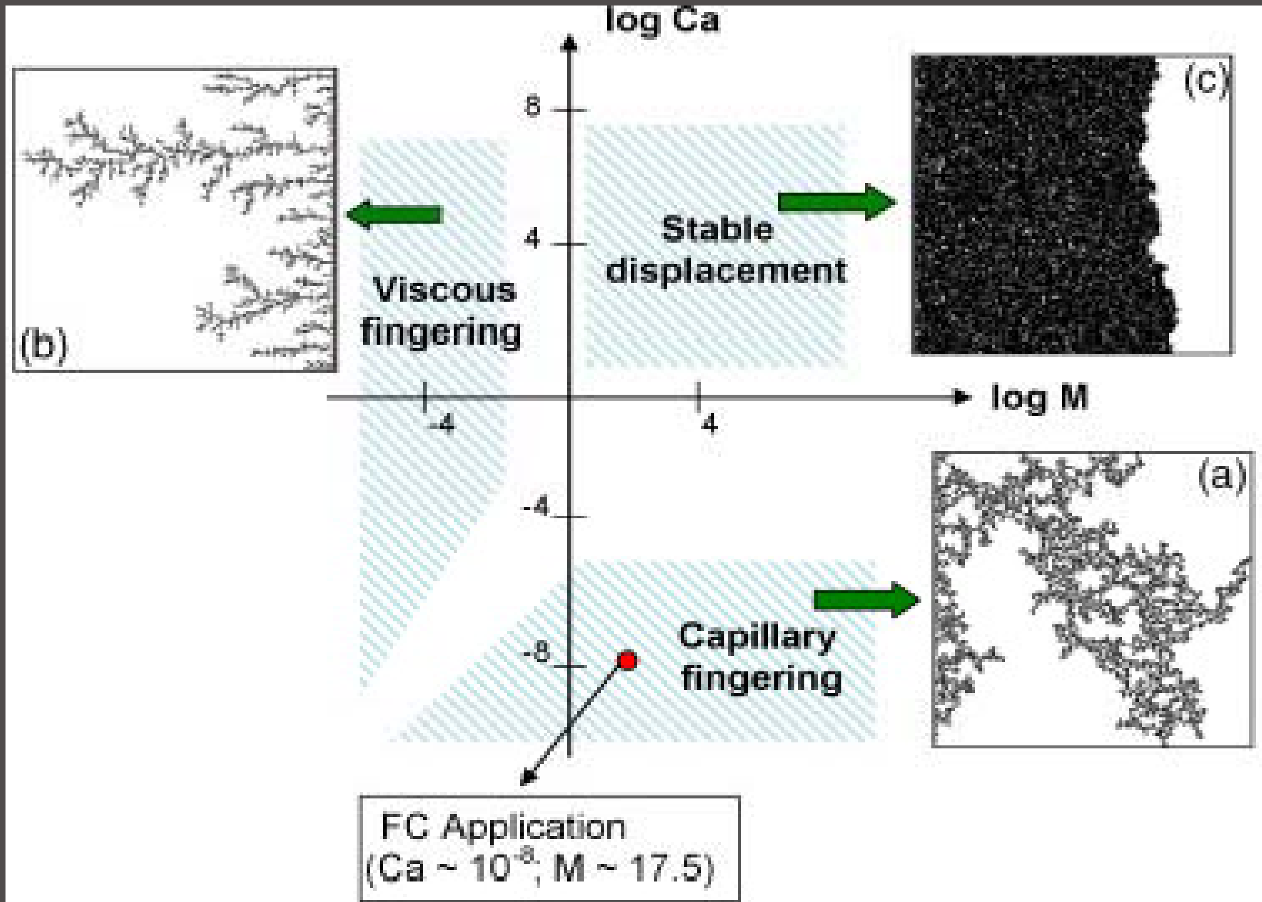
Joekar-Niasar et al ,TiPM, 2008

Effective parameters in two-phase flow

- Dynamic paramters:
  Viscosityratio $M = \frac{\mu^{inv}}{\mu^{rec}}$
  Capillary number, viscous forces to capillary ones $Ca = \frac{\mu^{inv} q^{inv}}{\sigma^{nw}}$

Interaction among parameters ..

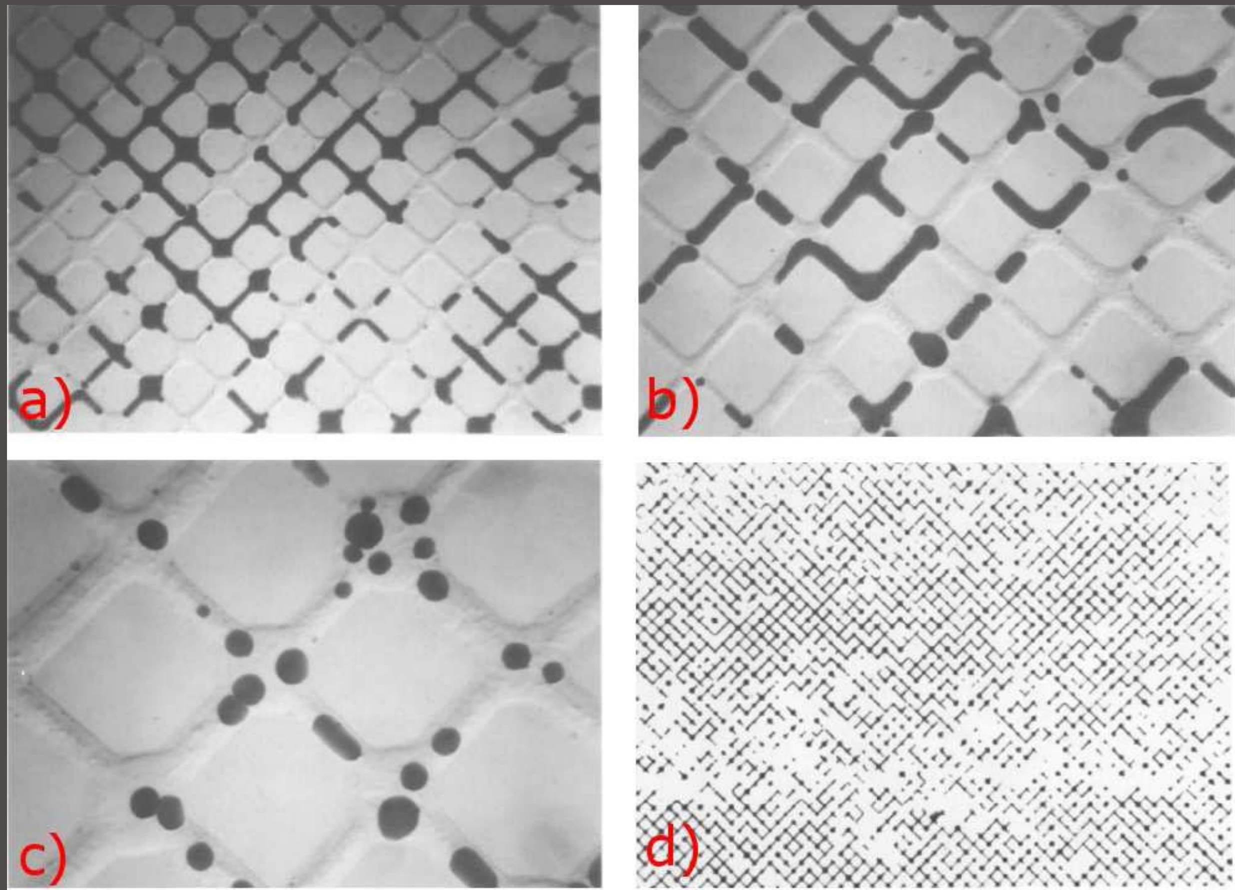
from pore to core



Lenormand et al., JFM (1988)

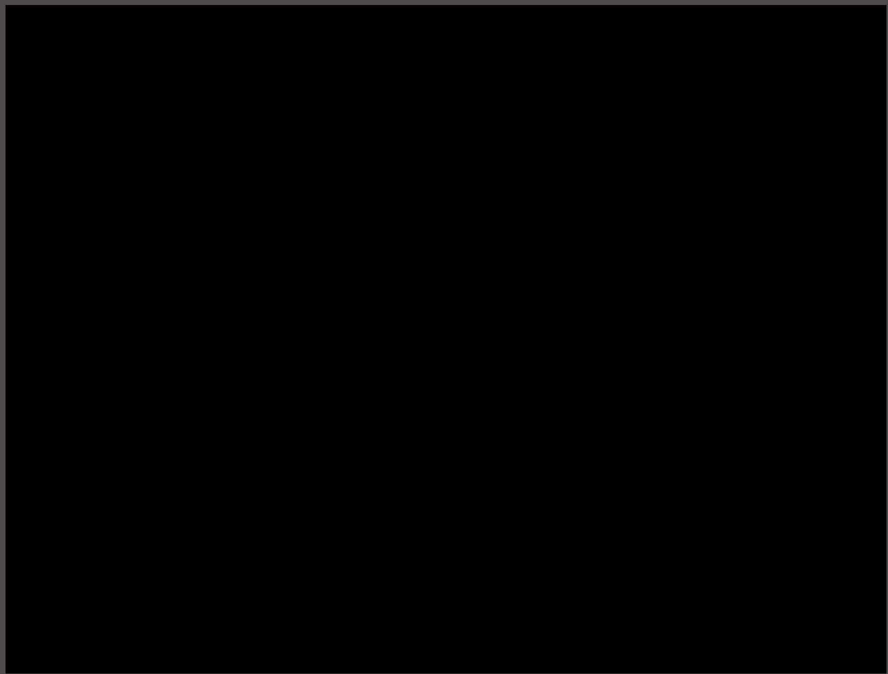
Dynamic conditions (capillary number)

Ganglia flow regimes (a) Large ganglia dynamics (b) Small ganglia dynamics (c) Droplet traffic flow (d) Connected-path flow (*Avraam and Payatakes, 1995*).

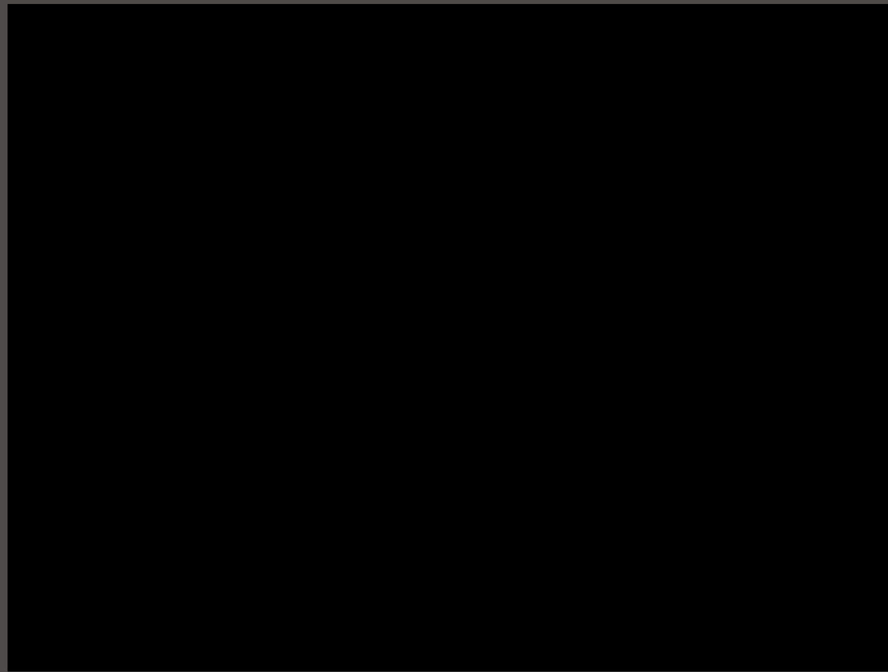


Ref: D. G. Avraam, and A. C. Payatakes, 1995, Flow Regimes and Relative Permeabilities during Steady-State Two-Phase Flow in Porous Media, J.Fluid Mech. 293, 181-206

Dynamic conditions (capillary number)



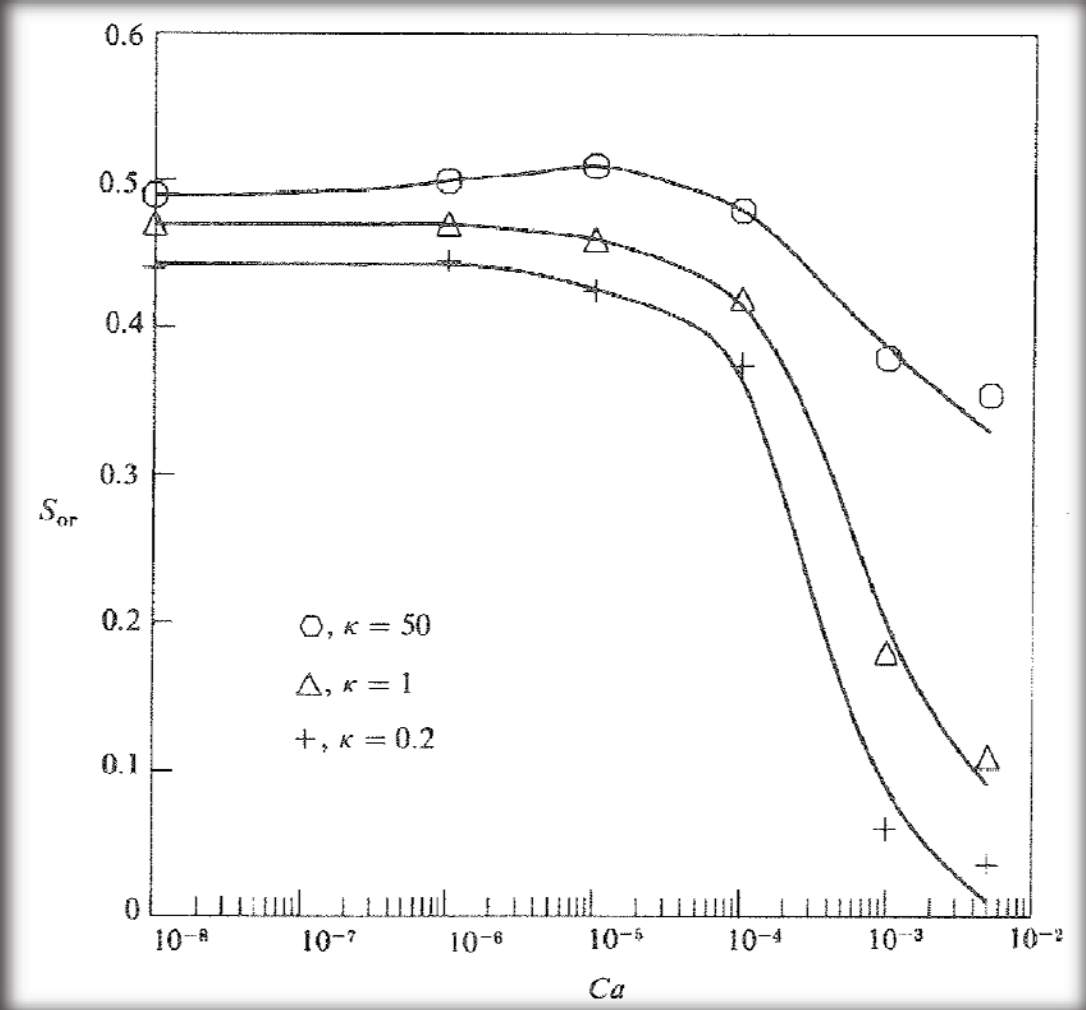
Ca(wetting)=10^{-7}
M(n/w)=3.35



Ca(wetting)=10^{-6}
M(n/w)=3.35

Ref: D. G. Avraam, and A. C. Payatakes, Flow Regimes and Relative Permeabilities during Steady-State Two-Phase Flow in Porous Media, J.Fluid Mech. 293, 181-206

Dynamic effects on residual saturation



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NOVERLTY OF PORE-NETWORK MODELS FOR DARCY-SCALE ANALYSIS …

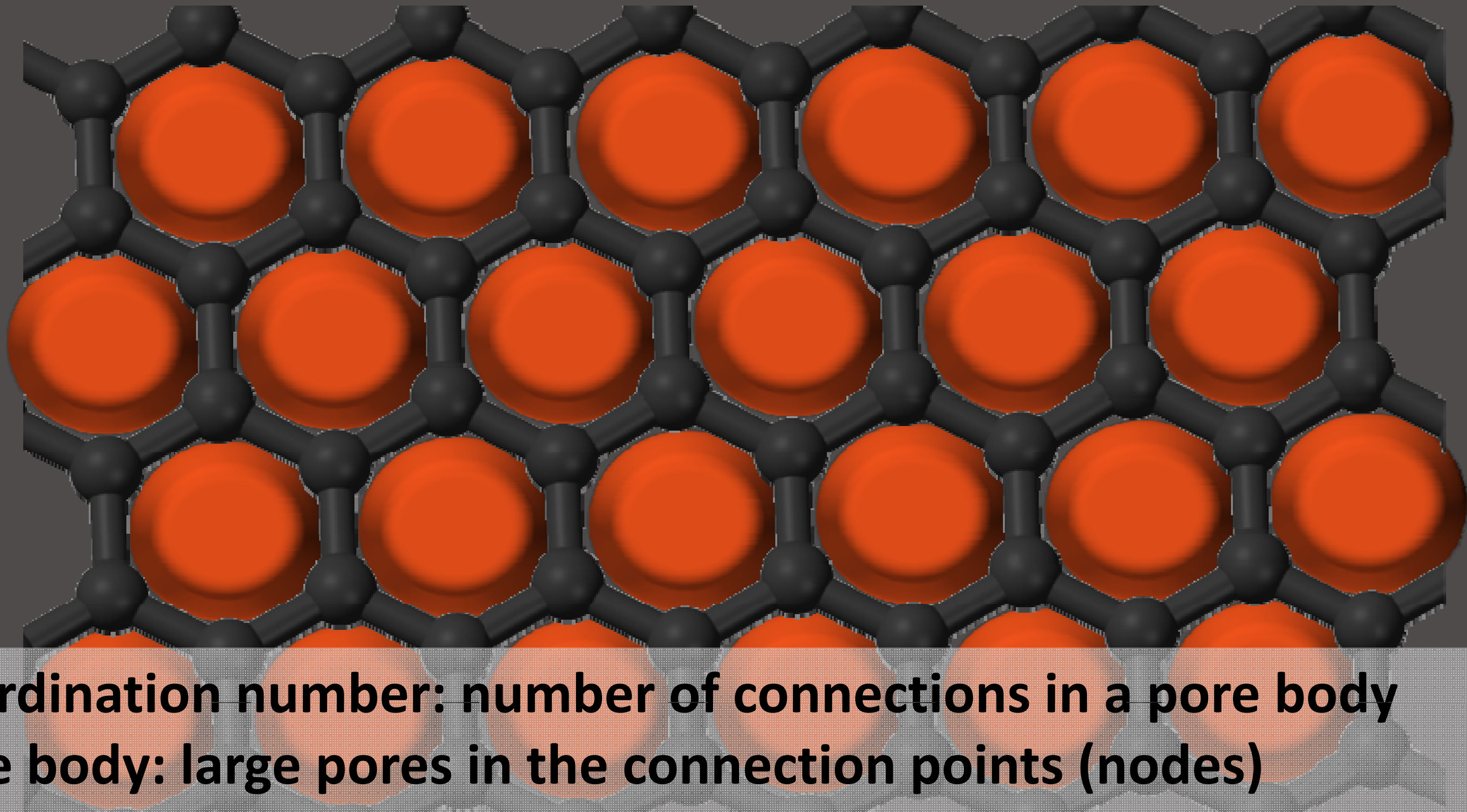
CONVENTIONAL APPLICATIONS

To investigate a hypothesis

✖ Conventional two-phase flow simulators provide biased information.

✓ Pore-scale two-phase flow simulators are required.

Pore-network modelling: definitions



Coordination number: number of connections in a pore body
Pore body: large pores in the connection points (nodes)
Pore throat: long narrow pores connecting the pore bodies

We select pore-network models..

Yes, because	But…
• Physical-based models using pore-scale information. • Application to many static and dynamic processes. • Compared to other pore-scale simulators is not computationally expensive. • Capability to provide up-scaled information.	• Translation of topology and geometry is inevitable, and not always straight forward! • No detail information within a pore (e.g. pressure field in a pore). • Local laws/rules are inevitable, and devil! **be careful**!!!!

Quasi-static vs. dynamic PNMs

Quasi-static

- Computationally very cheap.
- No pressure field is solved.
- Pore-scale geometry and topology are only important.
- Used extensively, for two-phase and three-phase flow; P^c-S^w, k^r-S^w, S^w-a^{nw}, reactive transport, etc.
- …. as a predictive tool

Dynamic

- Computationally expensive.
- Pressure field is solved.
- Network and fluids properties are important.
- Not been used as extensively as quasi-static ones; P^c-S^w, k^r-S^w, S^w-a^{nw}, mobilization of disconnected phase, dynamic pressure field
- Weak tractability due to nonlinearities at pore scale
- A long way to go!

Quasi-static vs. dynamic PNMs

Quasi-static

$$p_i^n - p_i^w = f(\kappa_i) = f(s_i^w)$$

$$s_i^w + s_i^n = 1$$

appended to the local rules:

$$K_{ij}^\alpha = K_{ij}^\alpha(\kappa_{ij}, \mu_{ij}^\alpha)$$

$$p_{e_{ij}}^c = f(r_{ij})$$

$$p_{s_{ij}}^c = f(r_{ij})$$

Dynamic

$$V_i \frac{\Delta s_i^\alpha}{\Delta t} = -\sum_{j=1}^{N_i} Q_{ij}^\alpha, \alpha = w, n$$

$$Q_{ij}^\alpha = K_{ij}^\alpha (p_i^\alpha - p_j^\alpha)$$

$$p_i^n - p_i^w = f(\kappa_i) = f(s_i^w)$$

$$s_i^w + s_i^n = 1$$

appended to the local rules:

$$K_{ij}^\alpha = K_{ij}^\alpha(\kappa_{ij}, \mu_{ij}^\alpha)$$

$$p_{e_{ij}}^c = f(r_{ij})$$

$$p_{s_{ij}}^c = f(r_{ij})$$

Averaging local entities:

- Saturation:

$$S^w = \frac{V^w}{V^w + V^n} = \frac{\sum_1^{N_{pb}} s_i^w V_i}{\sum_1^{N_{pb}} V_i}$$

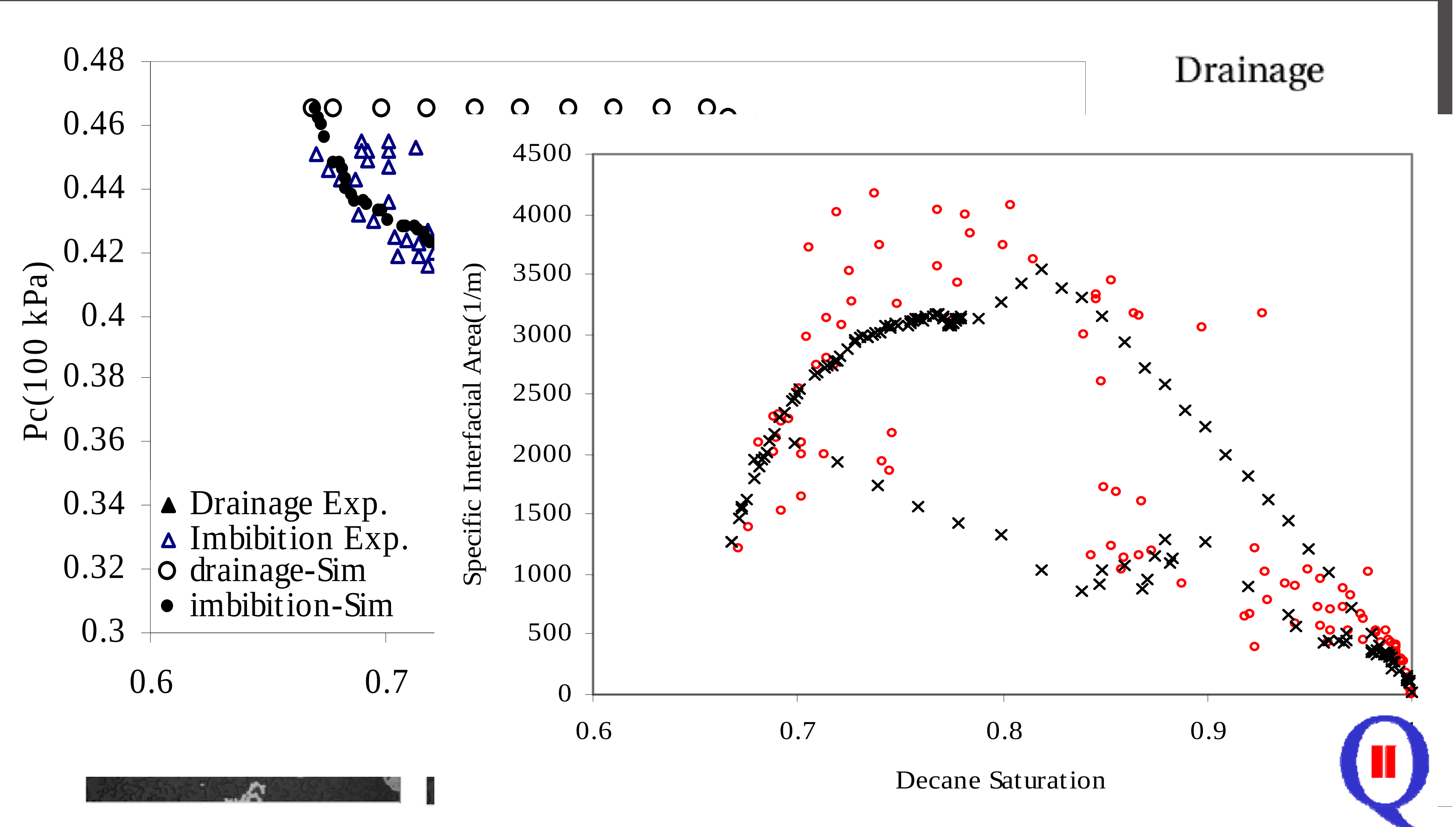
$$S^n = 1 - S^w$$

- Intrinsic phase pressure averaging:

$$P^\alpha = \frac{\sum_1^{N_{pb}} p_i^\alpha s_i^\alpha V_i}{\sum_1^{N_{pb}} s_i^\alpha V_i}, \alpha = n, w$$

Pore-network models can be predictive

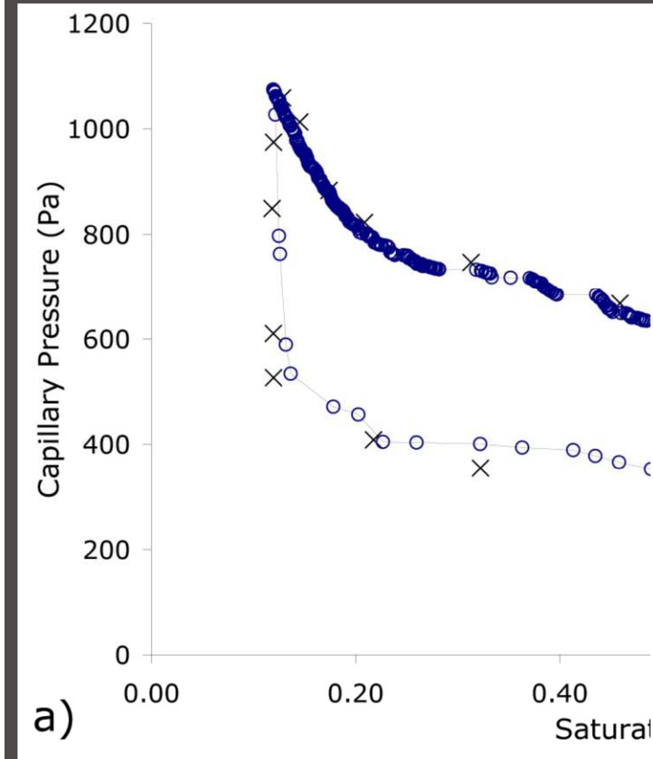
Micromodel: simulations vs. experiments



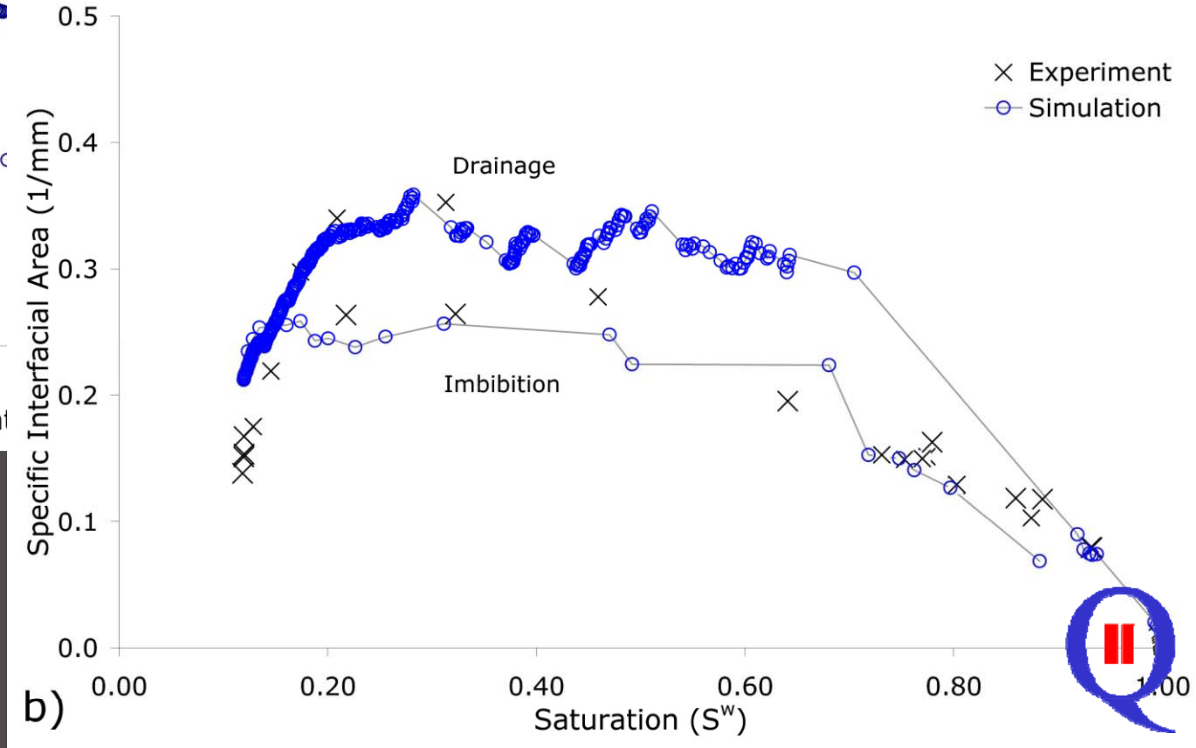
Joekar-Niasar et al, WRR, 2009

Pore-network models can be predictive

Glass beads: simulations vs. experiments



An irregular unstrucutred network with hyperbolic polygonal cross sections.



Joekar-Niasar et al, WRR, 2010

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PARAMETERIZATION AND ANALYSIS

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Extended Darcy's law for two-phase flow

e.g. Hassanizadeh and Gray , WRR, 1993; AWR 1990; Hassanizadeh et al, VZJ, 2002

$$n\frac{\partial S^\alpha}{\partial t} + \nabla \cdot \mathbf{q}^\alpha = \mathbf{0}$$

$$\mathbf{q}^\alpha = -\mathbf{K}^\alpha \cdot \left(\nabla P^\alpha - \rho^\alpha \mathbf{g} - \Psi^{\alpha a} \nabla a^{nw} - \Psi^{\alpha S} \nabla S^\alpha\right)$$

$$\frac{\partial a^{nw}}{\partial t} + \nabla \cdot \left(a^{nw} \mathbf{w}^{nw}\right) = E^{nw}\left(a^{nw}, S^w\right)$$

$$\mathbf{w}^{nw} = -\mathbf{K}^{nw}\left(\nabla a^{nw} \gamma^{nw} - \Psi^{wS} \nabla S^w\right)$$

$$P^n - P^w = P^c - \tau \frac{\partial S^w}{\partial t}$$

$$f\left(P^c, S^w, a^{nw}\right) = 0$$

We use PNMs for investigation of extended theories of two-phase flow!

Today we are looking at these two guys

Joekar-Niasar ,The Immiscibles, 2010

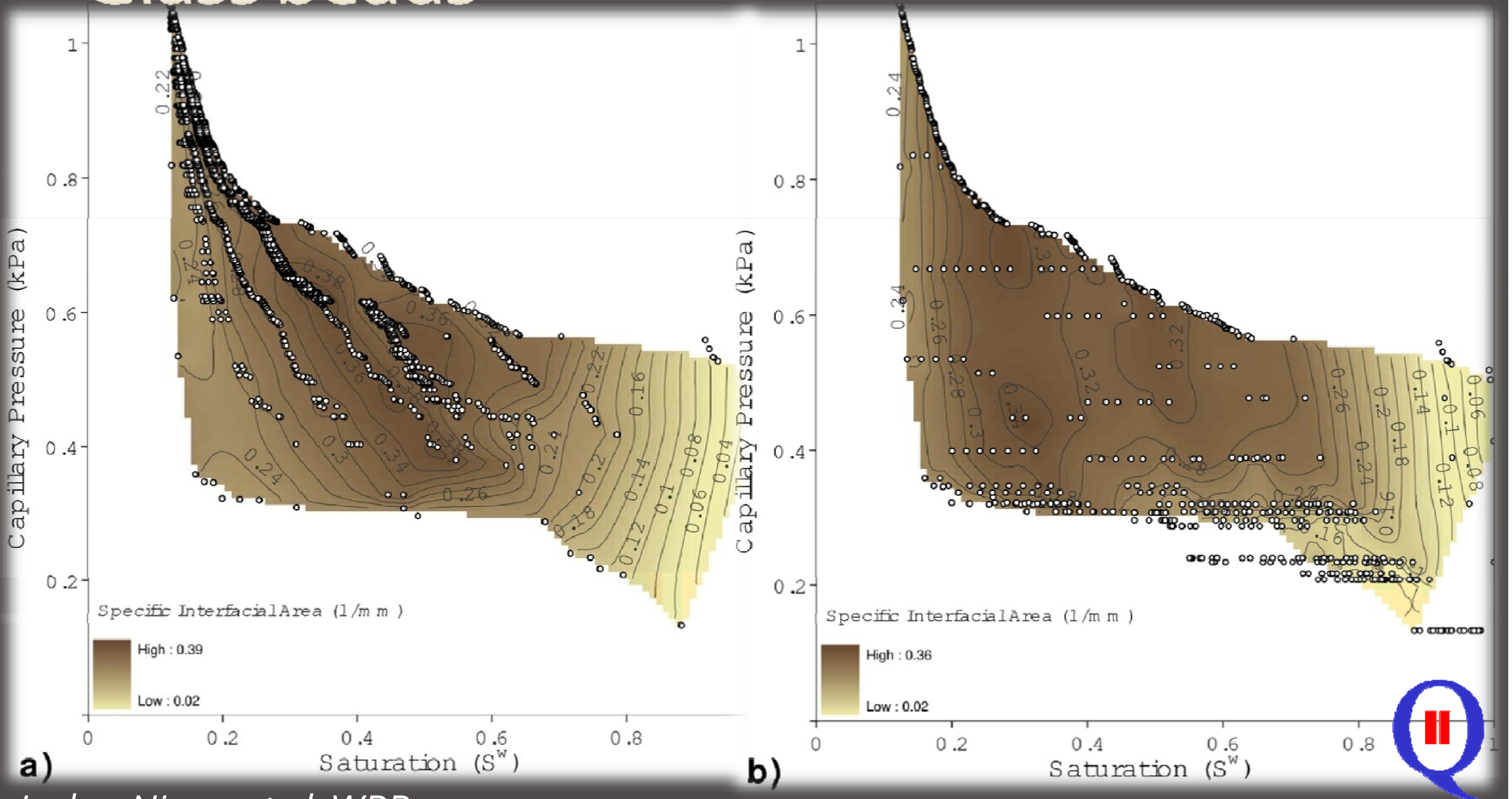
$$(P^c, S^w, a^{nw}) = 0$$

Tested in:

- Glass beads
- Micro-model
- Conceptual

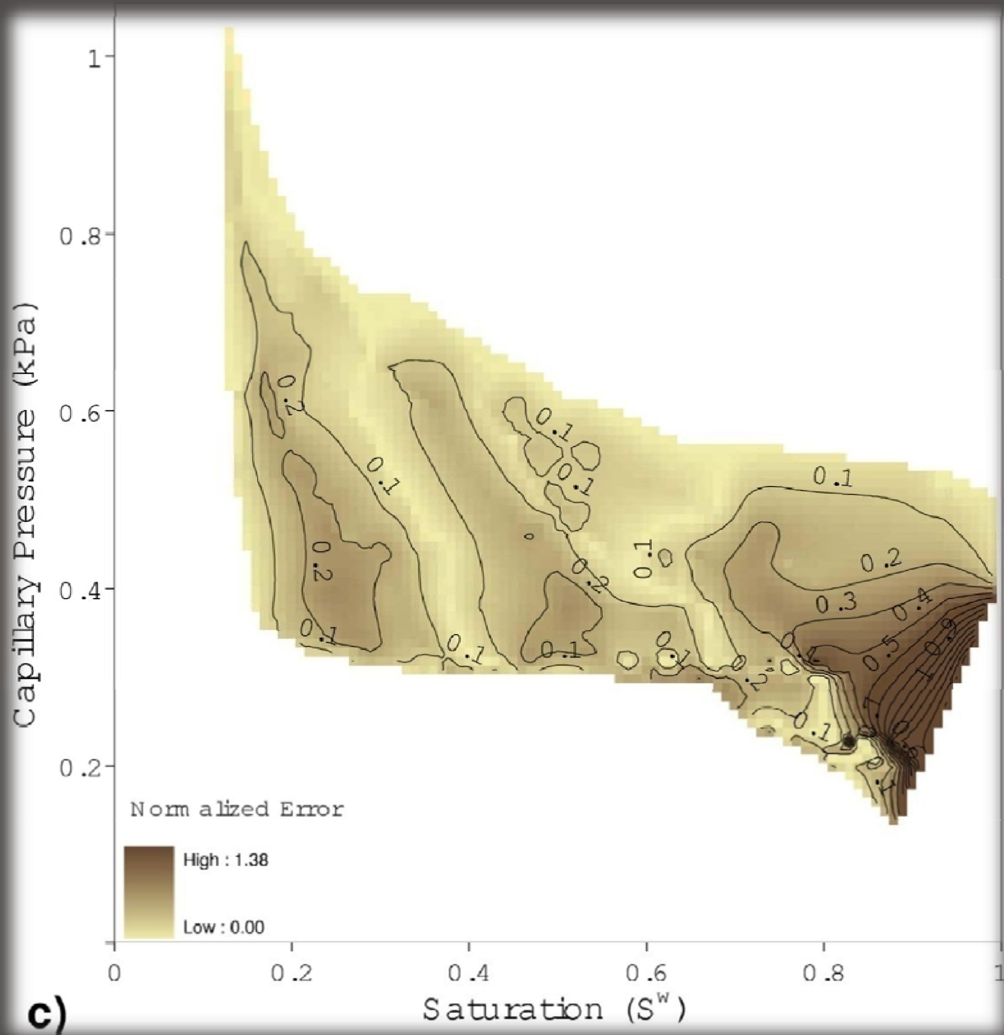
more info: Joekar-Niasar ,*The Immiscibles*, 2010

On uniqueness of P^c-S^w-a^{nw} surface: Glass beads



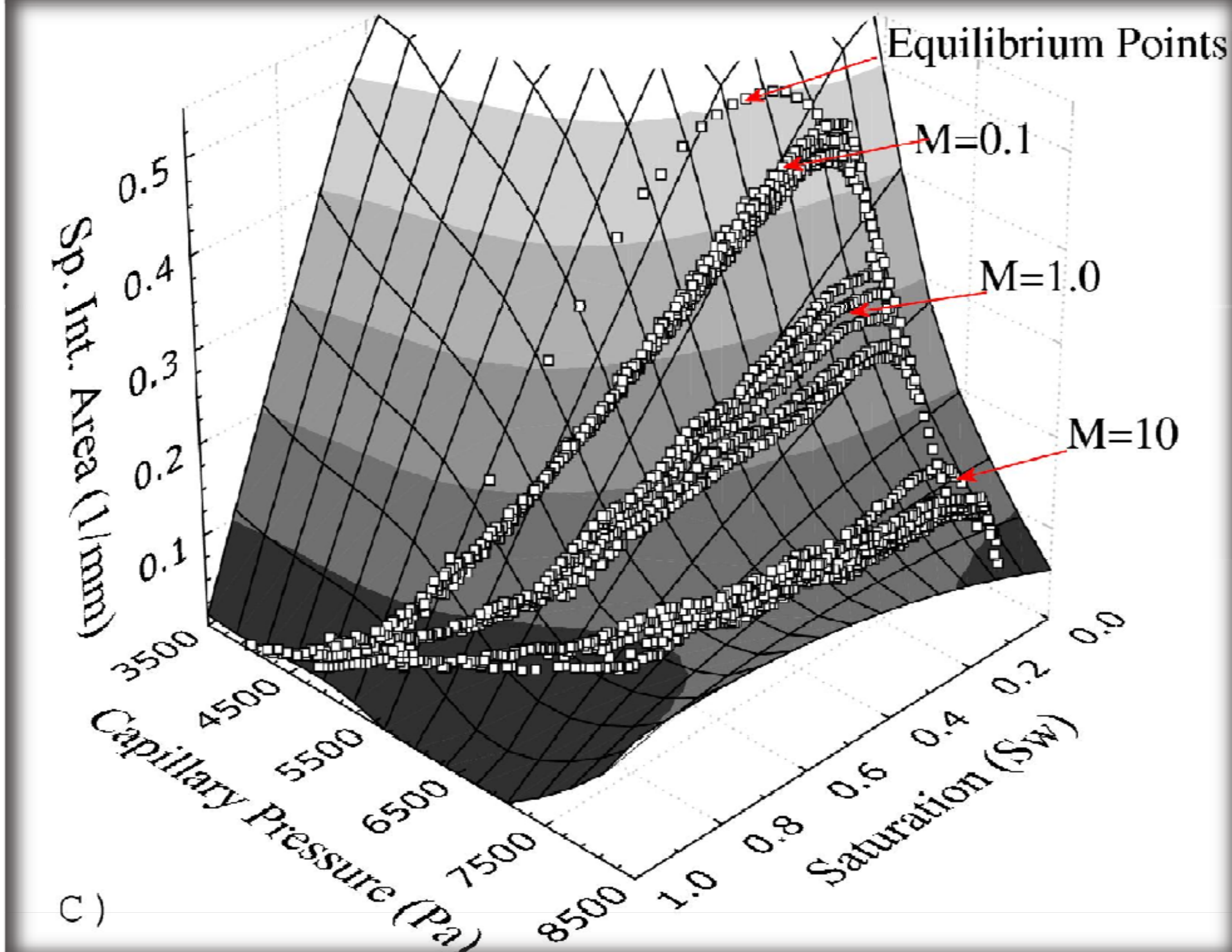
Joekar-Niasar et al, WRR, 2010

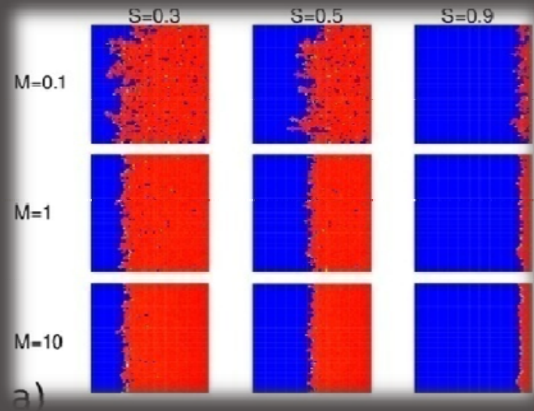
On uniqueness of P^c-S^w-a^{nw} surface: Glass beads



Joekar-Niasar et al, WRR, 2010

On uniqueness of P^c-S^w-a^{nw} surface

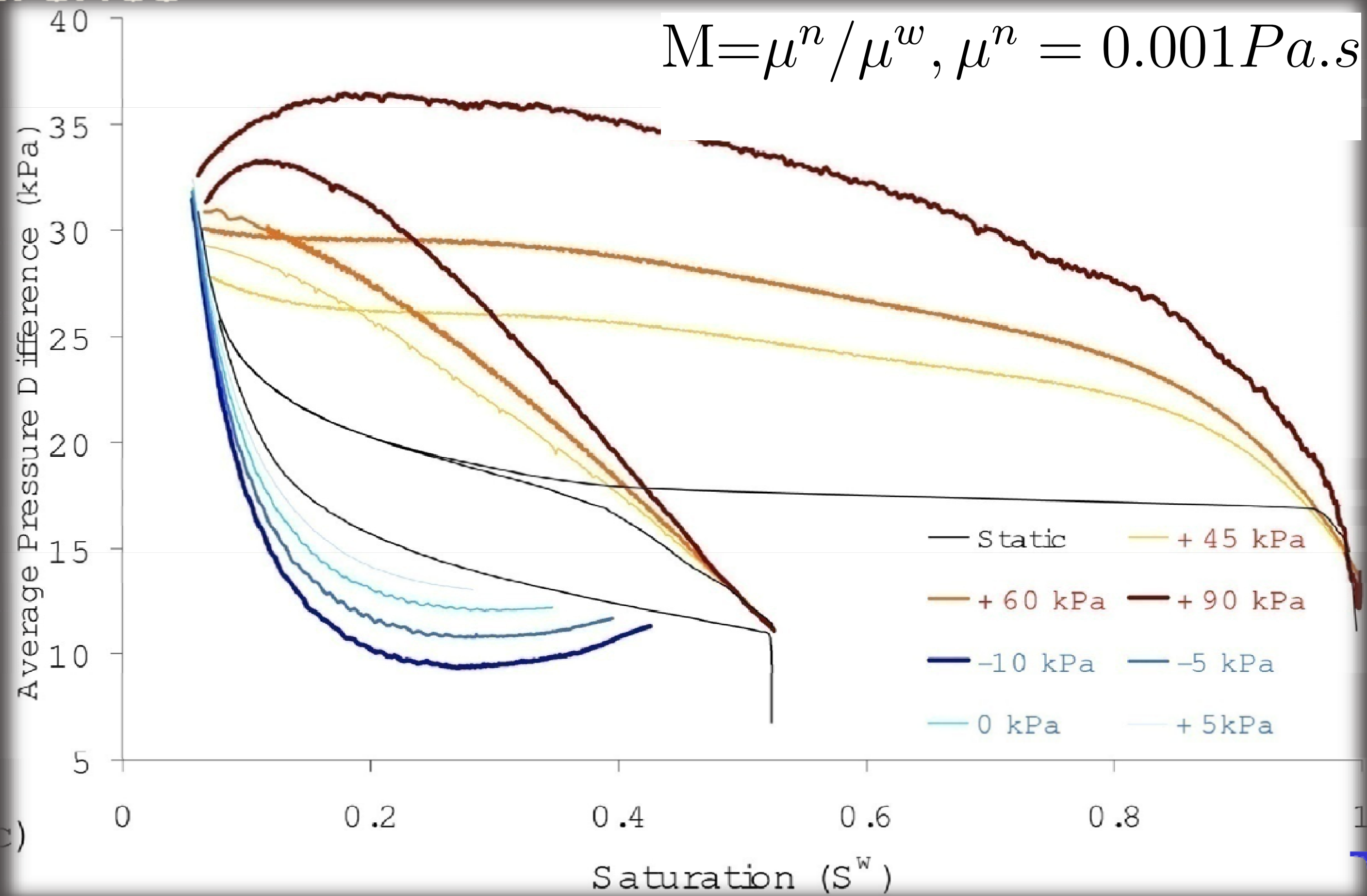




Joekar-Niasar et al
JFM, 2010

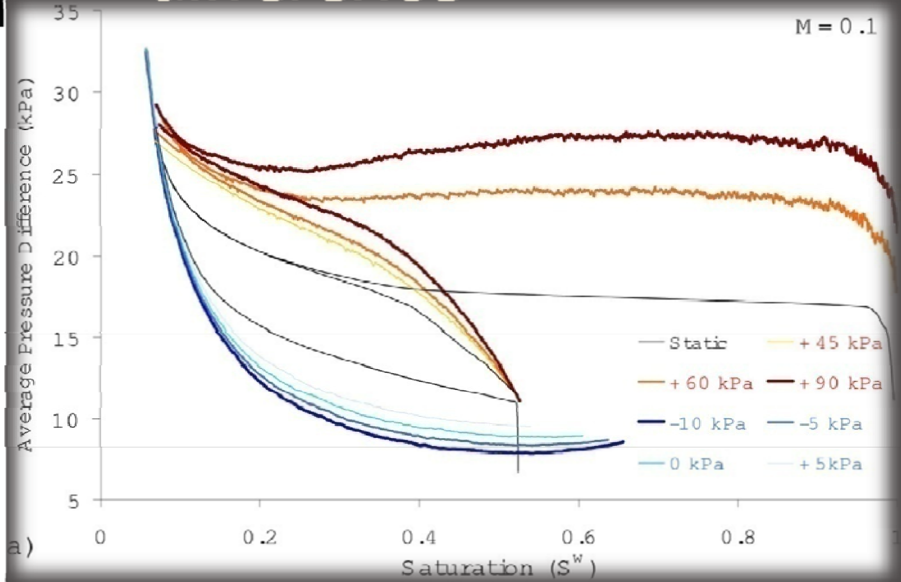
$$P^n - P^w = P^c - \tau \frac{\partial S^w}{\partial t}$$

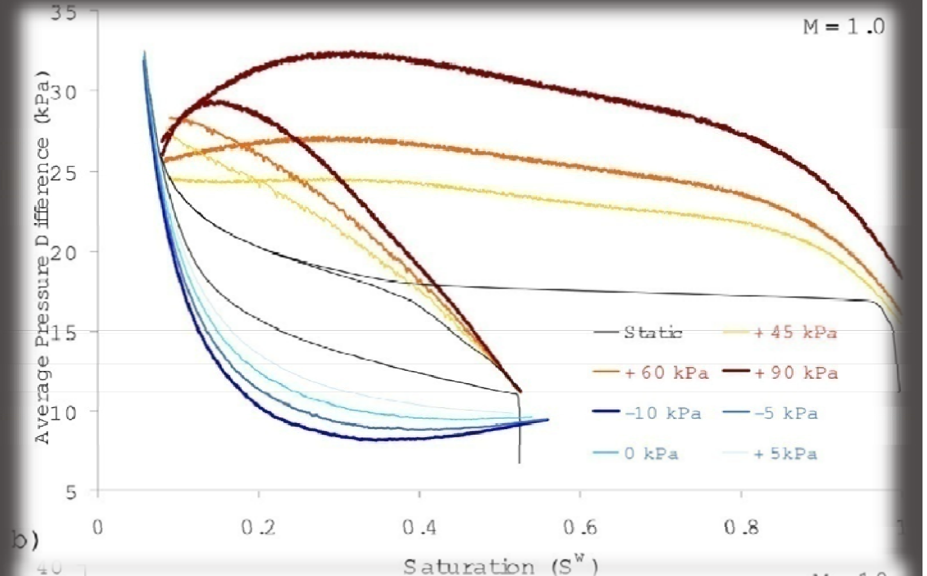
Equilibrium and non-equilibrium phase pressure difference



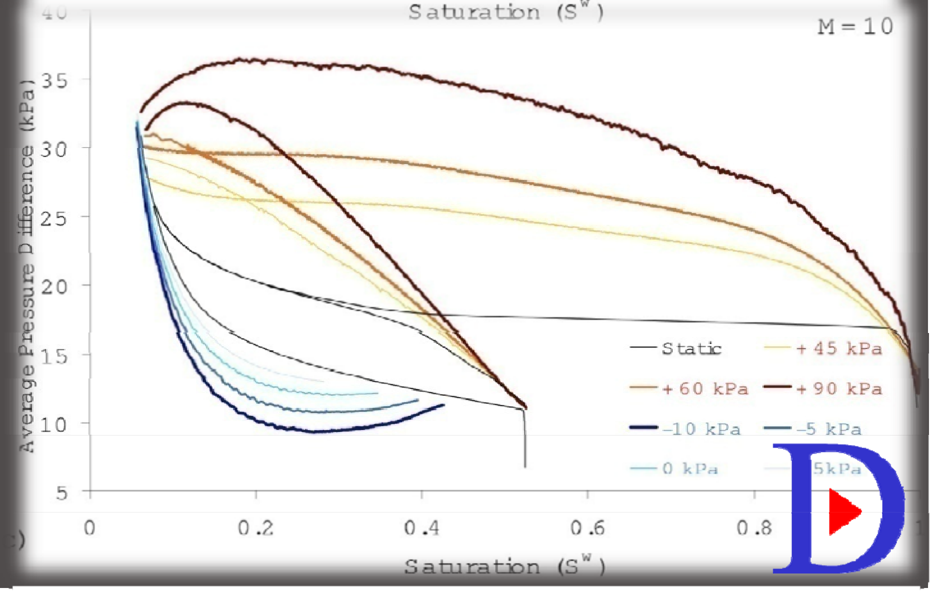
Joekar-Niasar & Hassanizadeh , IJMF, 2010,
*doi:*10.1016/j.ijmultiphaseflow.2010.09.007

Equilibrium and non-equilibrium phase pressure difference



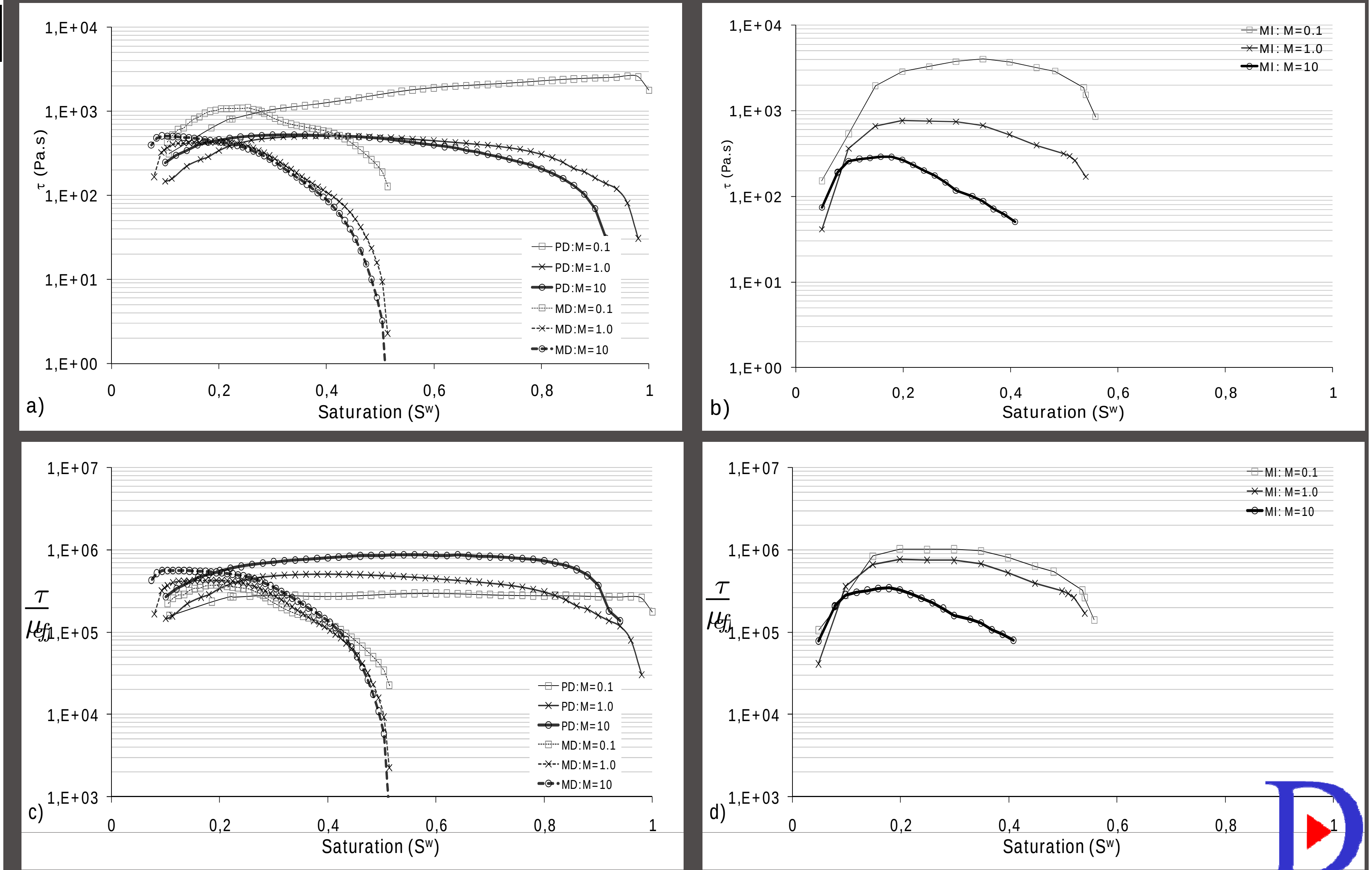


$$\mathrm{M}=\mu^n/\mu^w, \mu^n = 0.001 Pa.s$$



*Joekar-Niasar & Hassanizadeh , IJMF, 2010, doi:*10.1016/j.ijmultiphaseflow.2010.09.007

Non-equilibrium capillarity coefficient



Conclusions

- Equilibrium P^c -S^w-a^{nw} *surfaces* obtained under drainage and imbibition are almost identical.
- It seems that non-equilibrium P^c -S^w-a^{nw} *surfaces* can be identical to equilibrium P^c -S^w-a^{nw} surface.
- Capillary pressure-saturation curve and phase pressures difference-saturation curve are not unique under dynamic conditions.
- Phase pressures differences are highly dependent on boundary pressures and time rate of change of saturation as expected from the theory.
- Dynamic capillarity coefficient is not unique under drainage and imbibition. It is a function of effective viscosity and fluids distribution.

THANKS FOR YOUR ATTENTION

Models are to be used, not believed.

H. Theil