Models of multiphase flow in porous media, including fluid-fluid interfaces

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Original Darcy's law was proposed for 1D steady-state flow of almost pure incompressible water in saturated homogeneous isotropic rigid sandy soil under isothermal conditions

$$q = -K \frac{\partial h}{\partial x}$$

$$h = p/\rho g + z$$

"Extended" Darcy's law is assumed to apply to 3D unsteady flow of two or more compressible fluids, with any amount of dissolved matter, in heterogeneous anisotropic deformable porous media under non-isothermal conditions

$$q_i^\alpha = -K_{ij}^\alpha \frac{\partial h^\alpha}{\partial x_j}$$

$$h^\alpha = p^\alpha / \rho^\alpha g + z$$

"Extended" Darcy's Law

$$q = -K \frac{\partial h}{\partial x} \quad \Rightarrow \quad q_i^\alpha = - K_{ij}^\alpha \frac{\partial h^\alpha}{\partial x_j}$$

We have added bells and whistles to a simple formula to make it (look more complicated and thus) applicable to a much more complicated system!

One must follow a reverse process:
- develop a general theory for a complex system
- reduce it to a simpler form for a less complex system

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Standard two-phase flow equations

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

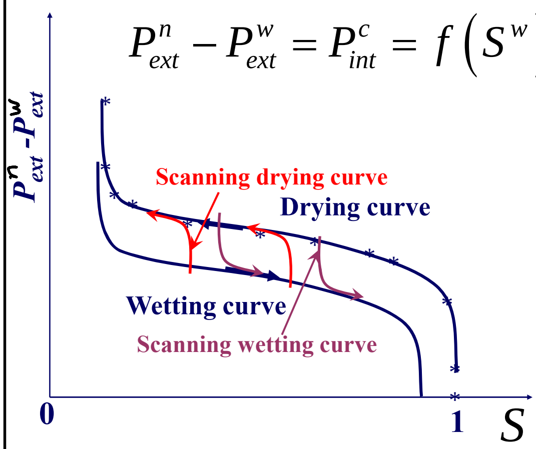
$$\mathbf{q}^\alpha = -\frac{k^{r\alpha}}{\mu^\alpha} \mathbf{K} \bullet \left(\nabla P^\alpha - \rho^\alpha \mathbf{g} \right)$$

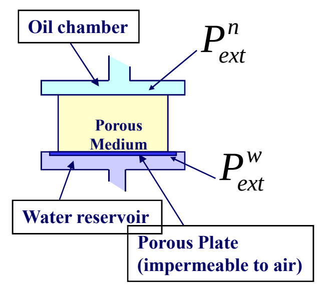
$$P^n - P^w = f\left(S^w\right) = P^c$$

$$k^{r\alpha} = k^{r\alpha}\left(S^w\right)$$

Measurement of Capillary Pressure-Saturation Curve in a pressure plate

$$P^n_{ext} - P^w_{ext} = P^c_{int} = f\left(S^w\right)$$

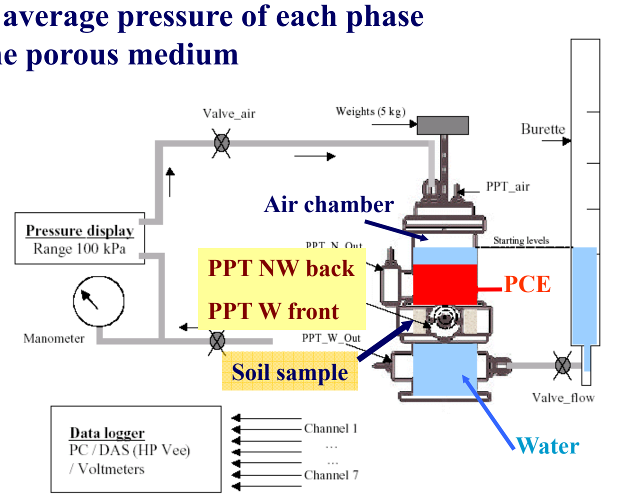




Often it takes more than one week to get a set of wetting and drying curves

Two-phase flow dynamic experiments (PCE and Water)

Selective pressure transducers used to measure average pressure of each phase within the porous medium



Hassanizadeh, Oung, and Manthey, 2004

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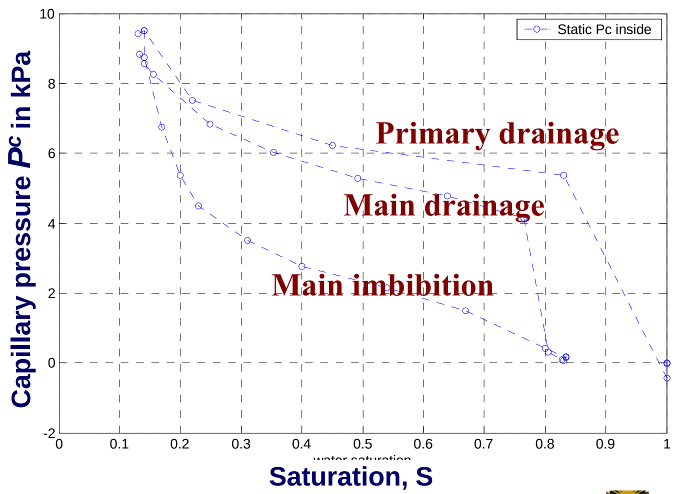
Two-phase flow dynamic experiments (PCE and Water)

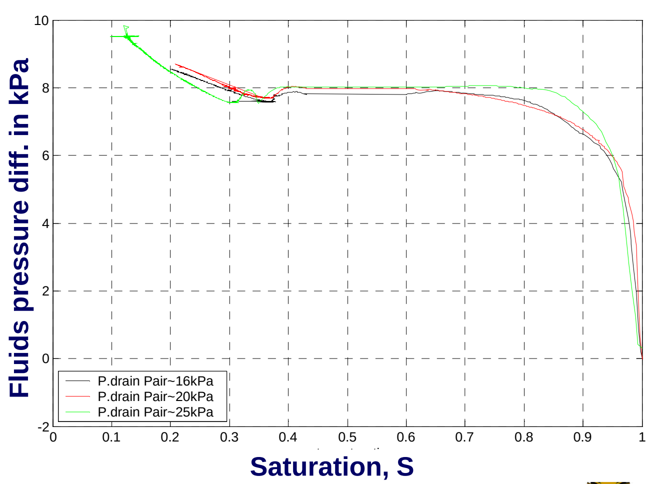
P^c-S Curves



Hassanizadeh, Oung, and Manthey, 2004

Two-phase flow dynamic experiments (PCE and Water)

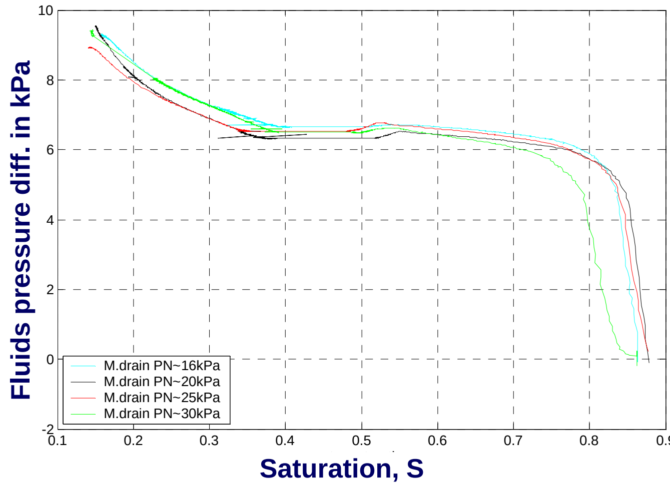
Dynamic Primary Drainage Curves



Hassanizadeh, Oung, and Manthey, 2004

Two-phase flow dynamic experiments (PCE and Water)

Dynamic Main Drainage Curves



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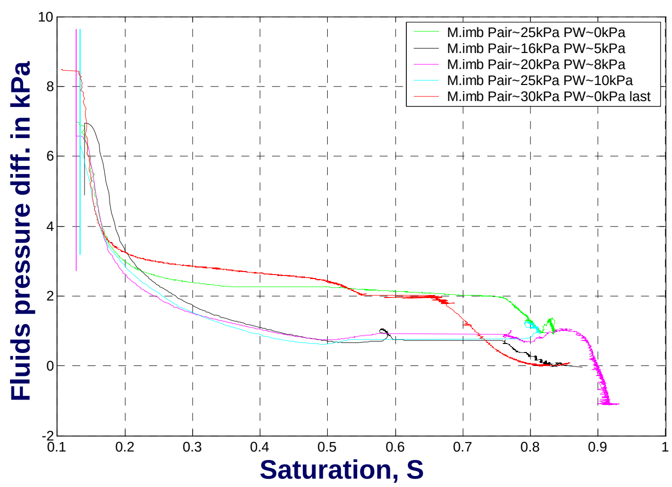
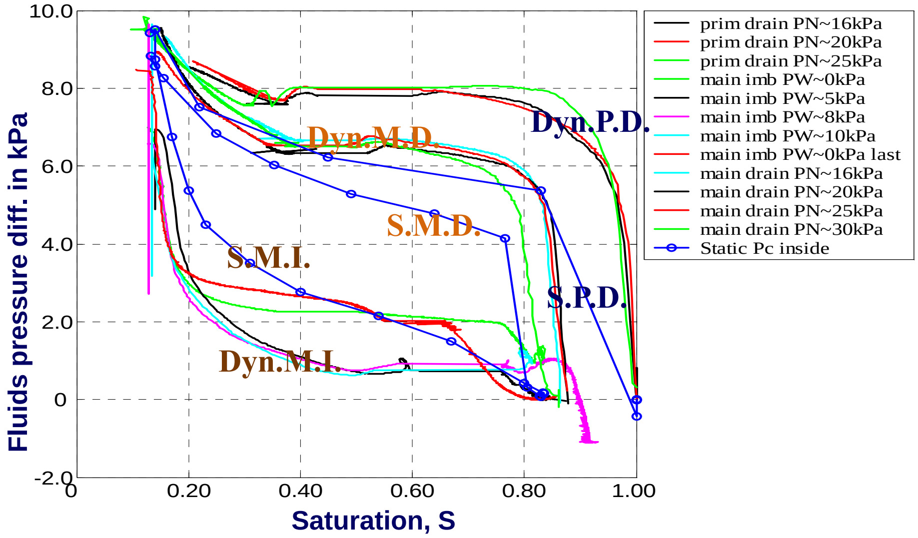
Hassanizadeh, Oung, and Manthey, 2004

Two-phase flow dynamic experiments (PCE and Water)

Dynamic Main Imbibition Curves



Two-phase flow dynamic experiments (PCE and Water)



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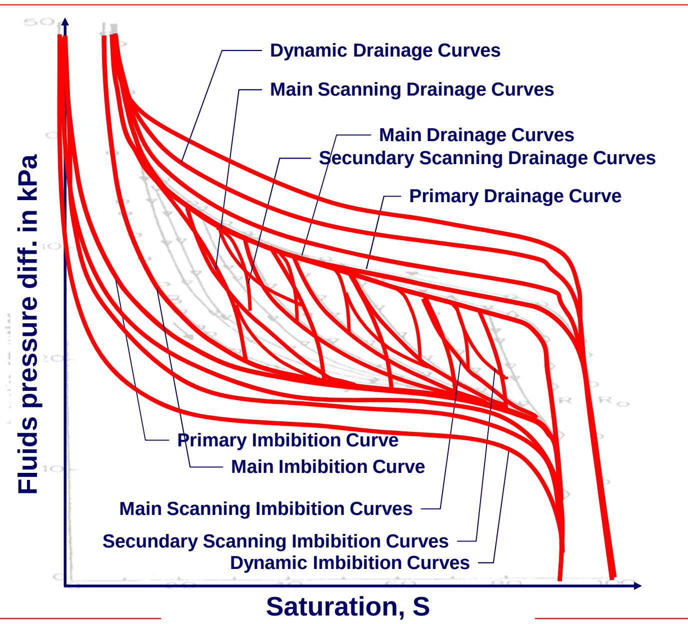
Hassanizadeh, Oung, and Manthey, 2004

There is no unique p^c-S curve.



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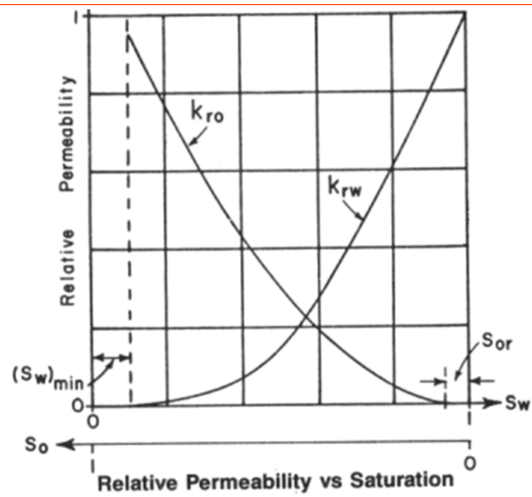
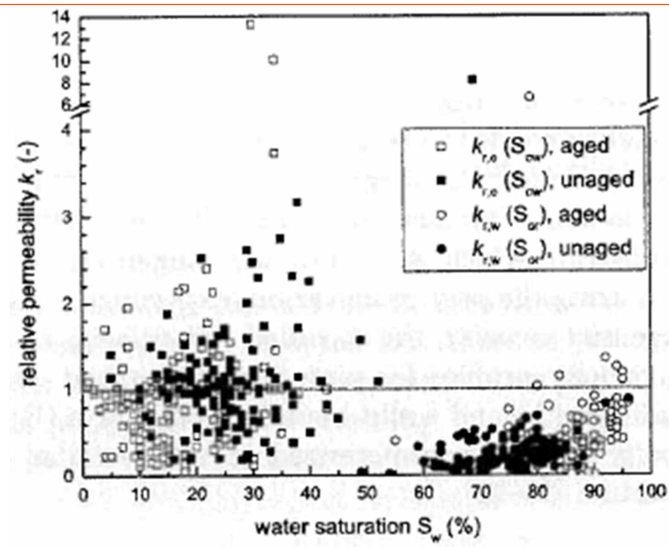
Relative permeability-saturation curve



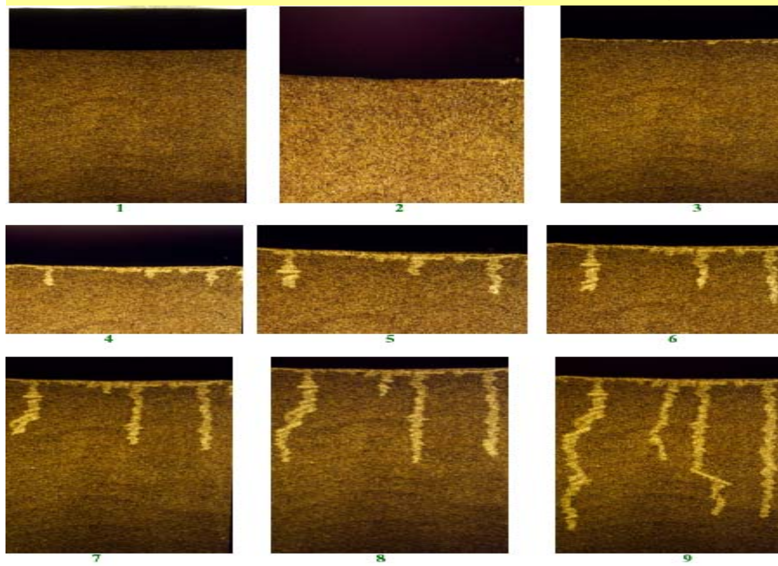
$$k_r^i = k_r^i(S^w, \text{medium properties}, Ca, \text{oil/water flow rate ratio}, \text{viscosities ratio}, \theta_A^0, \theta_R^0, Co, Bo, \text{pressure gradient}, \text{flow history})$$

Relative permeability is supposed to be less than 1.



Water and oil relative permeabilities in 43 sandstone reservoirs plotted as a function of water saturation; *Berg et al. TiPM, 2008*

Standard theory does not model the development of vertical infiltration fingers in dry soil



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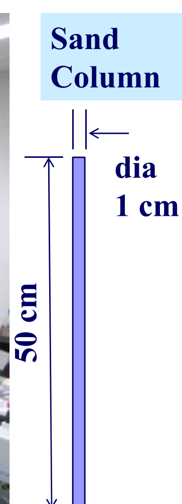
Experiments by Rezanejad et al., 2002

Non-monotonic distribution of saturation during infiltration into dry soil; experiments in our gamma system



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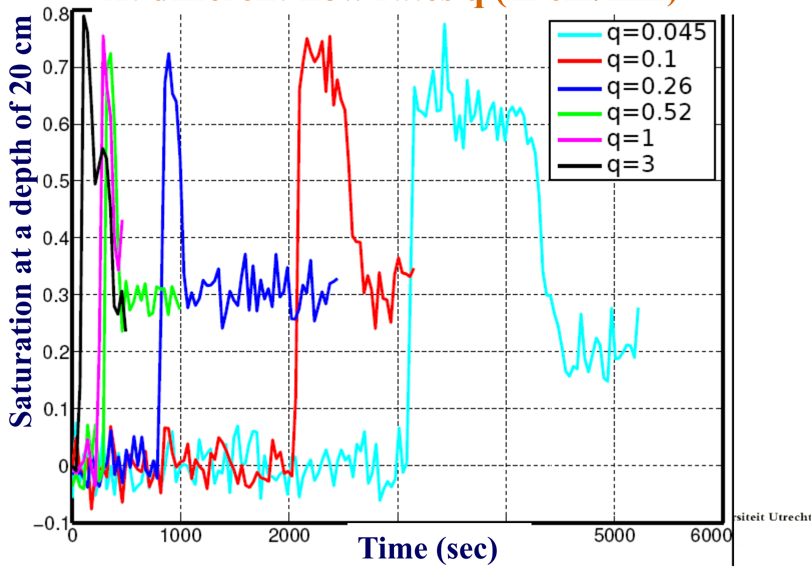
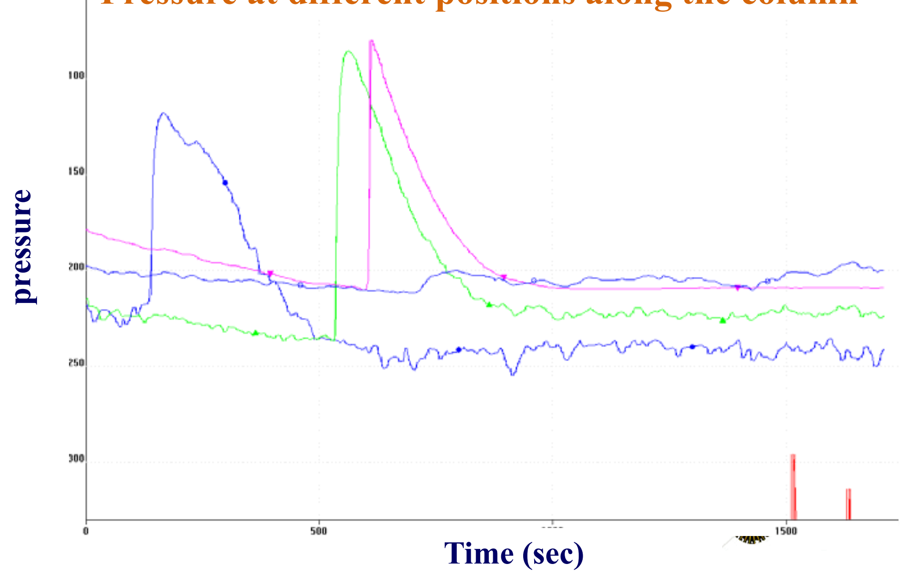
Non-monotonic distribution of saturation during infiltration into dry soil; experiments in our gamma system

At different flow rates q (in cm/min)



Non-monotonic distribution of pressure during infiltration into dry soil; experiments in our gamma system

Pressure at different positions along the column



Outline

Thermodynamic basis for macroscacle theories of two-phase flow in porous media

Experimental and computational determinations of capillary pressure under equilibrium conditions

Experimental and computational determinations of capillary pressure under non-equilibrium conditions

Non-equilibrium capillarity theory for fluid pressures

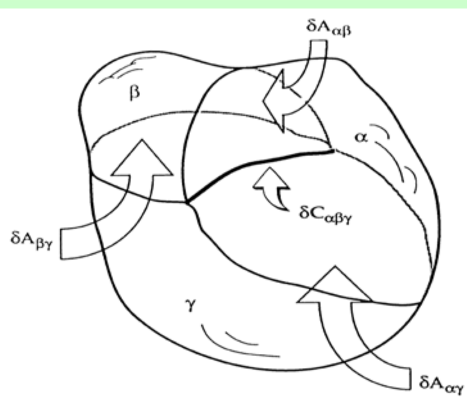
Truly extended Darcy's law

Averaging-Thermodynamic Approach

First, a microscale picture of the porous medium is given:

Porous solid and the two phases form a juxtaposed superposition of three phases filling the space and separated by three interfaces: solid-water, water-oil, solid-oil, and a water-oil-solid common line.

There is mass, momentum, energy associated with each domain.



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Averaging-Thermodynamic Approach

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Porous solid and the two phases form a juxtaposed superposition of three phases filling the space and separated by three interfaces: solid-water, water-oil, solid-oil, and a water-oil-solid common line.

Microscale conservation equations for mass, momentum, and energy are written for points within phases or points on interfaces and the common line.

These equations are averaged to obtain macroscale conservation equations.

No microscopic constitutive equations are assumed.

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Porous solid and the two phases form a juxtaposed superposition of three phases filling the space and separated by three interfaces: solid-water, water-oil, solid-oil, and a water-oil-solid common line.

Microscale conservation equations for mass, momentum, and energy are written for points within phases or points on interfaces and the common line.

These equations are averaged to obtain macroscale conservation equations.

No microscopic constitutive equations are assumed.

Macroscopic constitutive equations are proposed at the macroscale and restricted by 2^{nd} Law of Thermodynamic.

Equations of conservation of mass

For each phase:
$$\frac{\partial\left(nS^{\alpha}\rho^{\alpha}\right)}{\partial t}+\nabla\bullet\left(\rho^{\alpha}\mathbf{q}^{\alpha}\right)=\sum_{\beta\neq\alpha}r^{\alpha,\alpha\beta}$$

Divide by a constant ρ and neglect mass exchange term:

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

For each interface:

$$\frac{\partial\left(a^{\alpha\beta}\Gamma^{\alpha\beta}\right)}{\partial t}+\nabla\bullet\left(a^{\alpha\beta}\Gamma^{\alpha\beta}\mathbf{w}^{\alpha\beta}\right)=r^{\alpha,\alpha\beta}+r^{\beta,\alpha\beta}$$

Divide by a constant $\Gamma^{\alpha\beta}$:

$$\frac{\partial a^{\alpha\beta}}{\partial t}+\nabla\bullet\left(a^{\alpha\beta}\mathbf{w}^{\alpha\beta}\right)=E^{\alpha\beta}$$

Macroscale capillary pressure; theoretical definition

$$P^{c}=-S^{n}\frac{\partial H^{n}}{\partial S^{w}}-S^{w}\frac{\partial H^{w}}{\partial S^{w}}-\frac{\partial H^{nw}}{\partial S^{w}}-\frac{\partial H^{ns}}{\partial S^{w}}-\frac{\partial H^{ws}}{\partial S^{w}}$$

H **is macroscopic Helmholz free energy, which depends on state variables such as S^w, $a^{\alpha\beta}$, ρ^{α}, T, etc.**

$$P^{c}=F(S^{w},a^{wn})\quad\text{or}\quad a^{wn}=F(P^{c},S^{w})$$

$$P^{c}\overset{?}{=}P^{n}-P^{w}$$

$$P^{n}=-\left(\rho^{n}\right)^{2}\frac{\partial H^{n}}{\partial\rho^{n}}\qquad P^{w}=-\left(\rho^{w}\right)^{2}\frac{\partial H^{w}}{\partial\rho^{w}}$$

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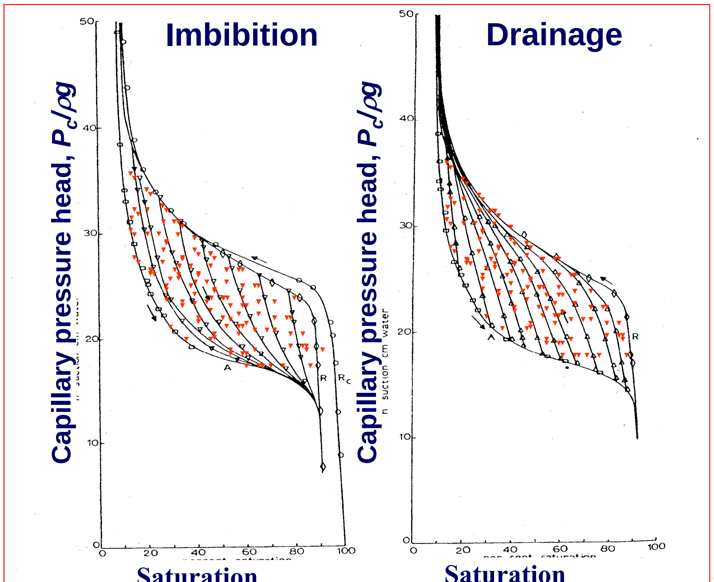
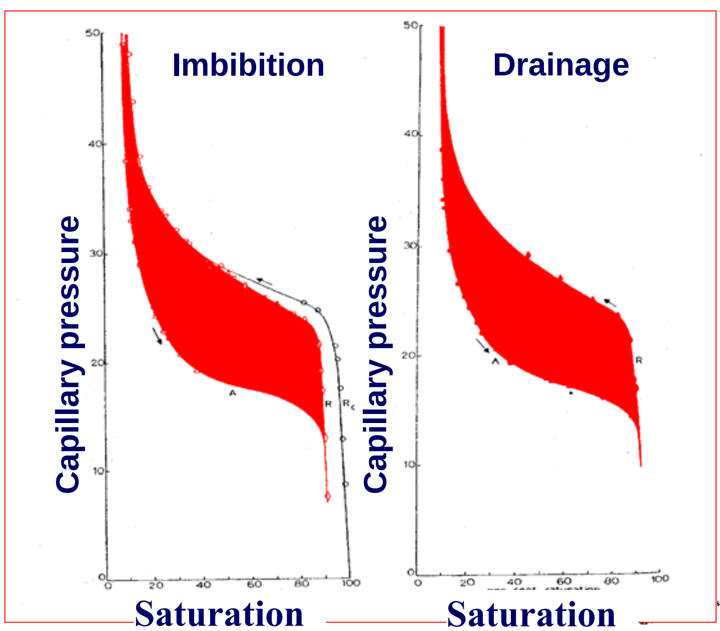
Hassanizadeh and Gray, WRR, 1990

Capillary pressure-saturation data points measured in laboratory



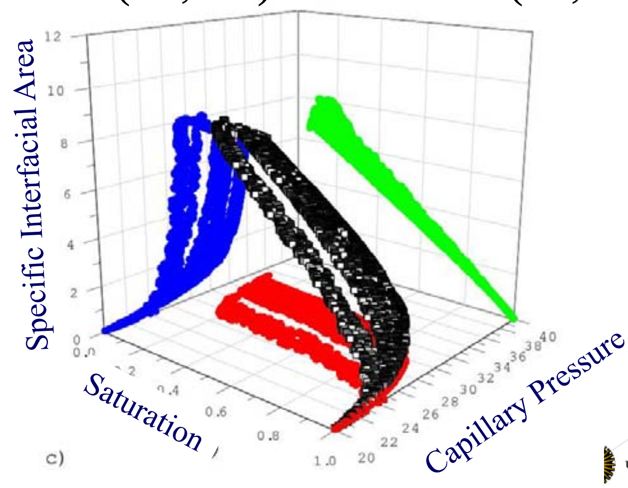
Capillary pressure-saturation curve is hysteretic

Capillary pressure and saturation are two independent quantities



Macroscale capillary pressure; theoretical definition

$$P^c = F(S^w, a^{wn}) \quad \text{or} \quad a^{wn} = F(P^c, S^w)$$



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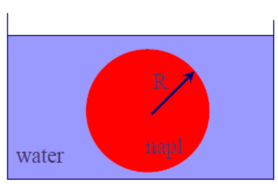
Interfacial area and saturation are two independent properties



$r =$

$$V_1 = \frac{4}{3}\pi R^3$$

$$p_1^c = \frac{2\sigma}{R}$$

$$a_1^{wn} = \frac{3}{R}$$

So, microscale p^c is proportional to a^{wn}.

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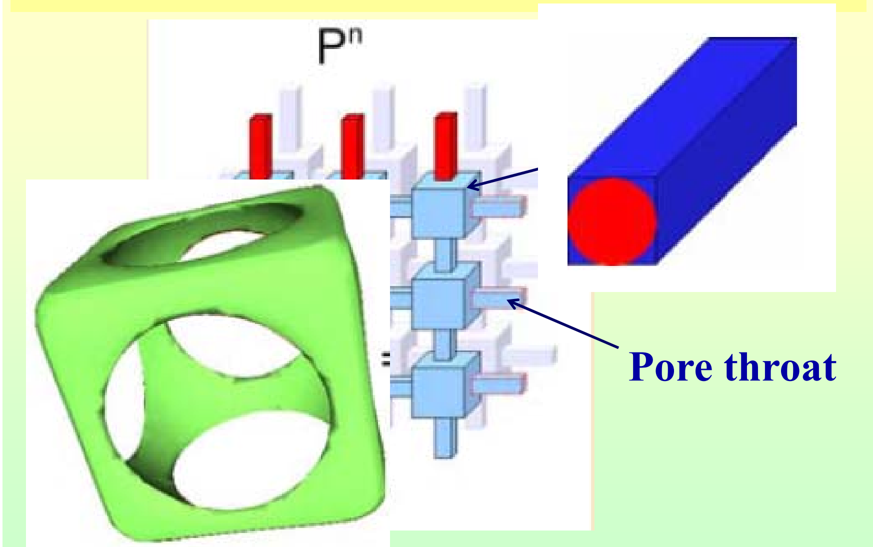
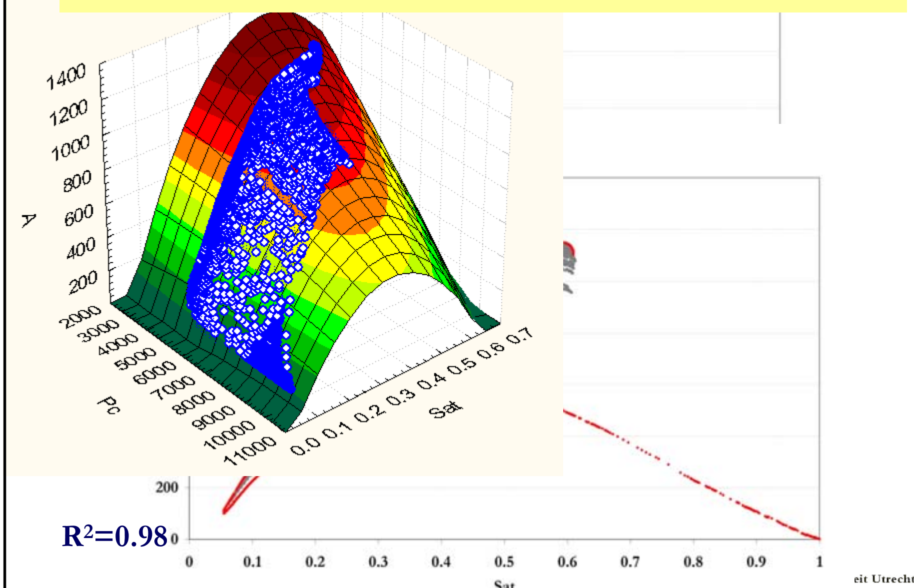
Macroscale capillary pressure

Dynamic Pore-network modeling (Joekar-Niasar et al., 2010, 2011)



Joekar-Niasar et al. 2008

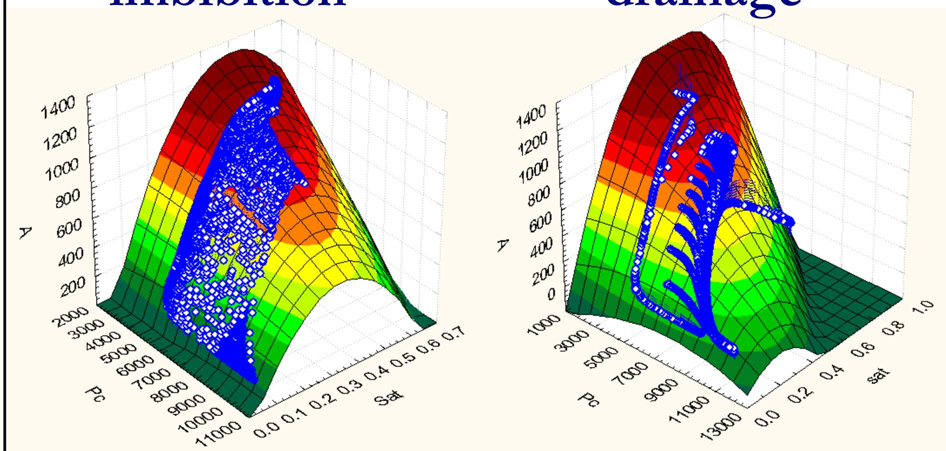
P_c-S_w-a_{wn} relationship; imbibition



Joekar-Niasar et al. 2008

Equilibrium P_c-S_w-a_{wn} surfaces

imbibition **drainage**



$$a_{wn}(S_w, p_c) = \left(a_{00} + a_{10}S_w + a_{01}p_c + a_{20}S_w^2 + a_{11}S_w \cdot p_c + a_{02}p_c^2\right)$$

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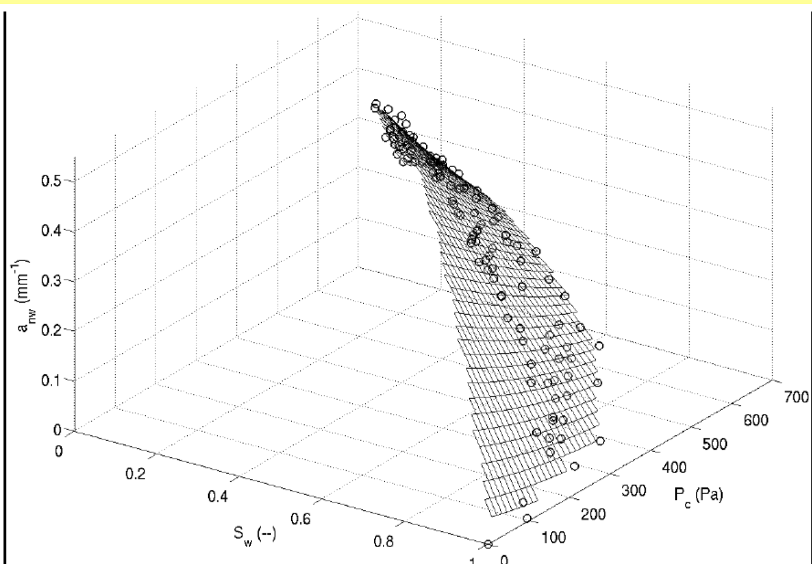
Joekar-Niasar et al. 2008

P_c-S_w-a_{wn} Surface
Results from Lattice-Bolzmann simulations



Porter et al., 2009

Capillary Pressure-Interfacial Area-Saturation data form a (unique) surface

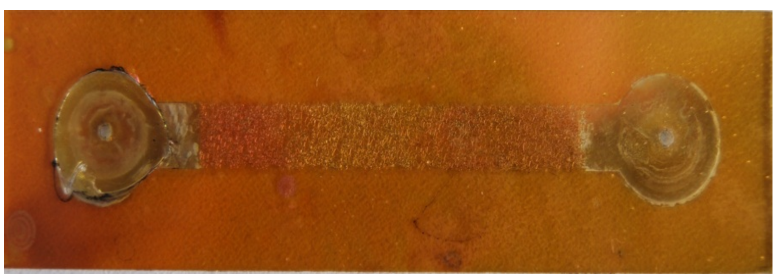
This has been shown by:

- Reeves and Celia (1996); Static pore-network modeling
- Held and Celia (2001); Static pore-network modeling
- Joekar-Niasar et al. (2007) Static pore-network modeling
- Joekar-Niasar and Hassanizadeh (2010, 2011) Dynamic/static pore-network modeling

- Porter et al. (2009); Column experiments and LB modeling
- Chen and Kibbey (2006); Column experiments

- Cheng et al. (2004); Micromodel experiments
- Chen et al. (2007); Micromodel experiments
- Bottero (2009); Micromodel experiments
- Karadimitriou et al. (2012); Micromodel experiments

A new generation of micro-model experiments



A micro-model (made of PDMS) with a length of 35 mm and width of 5 mm;
It has 3000 pore bodies and 9000 pore throats with a mean pore size of 70 μm and constant depth of 70 μm

Karadimitriou et al., 2012

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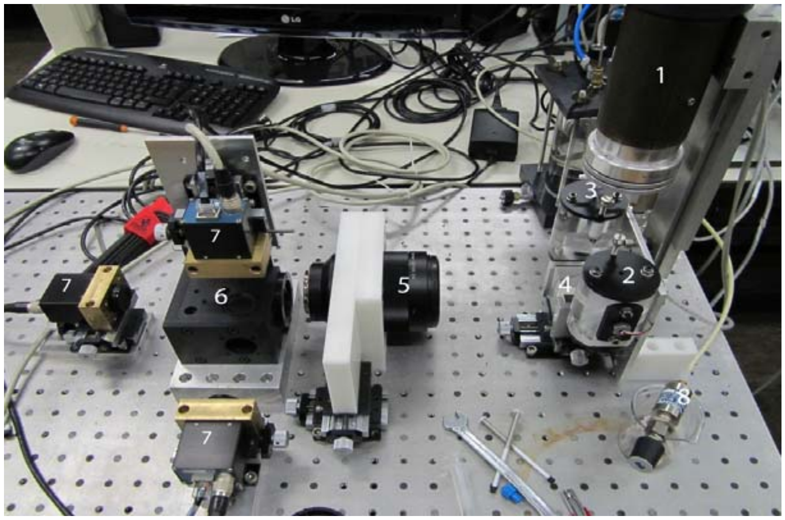
A new generation of micro-model experiments



Micromodel experimental setup

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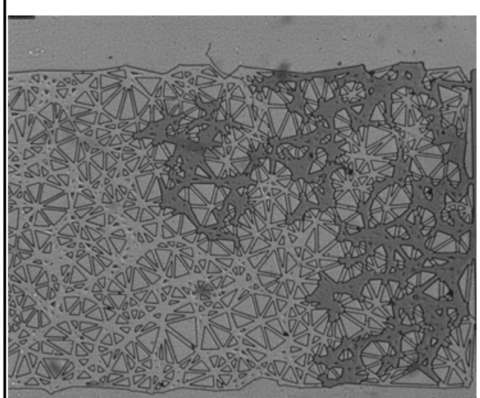
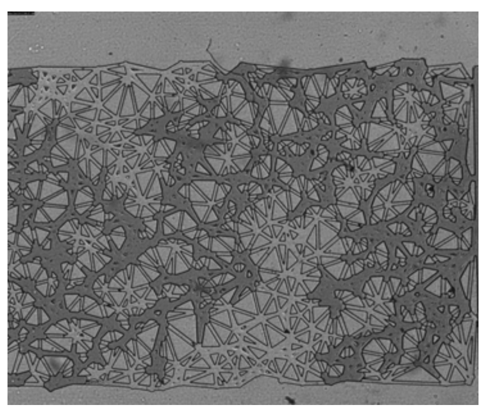
Visualization of interfaces in a micromodel

Drainage **Drainage**





$S^n = 24\%$
$P^c = 4340$ Pa
$A^{wn} = 18.32\ mm^2$

Karadimitriou et al., 2012

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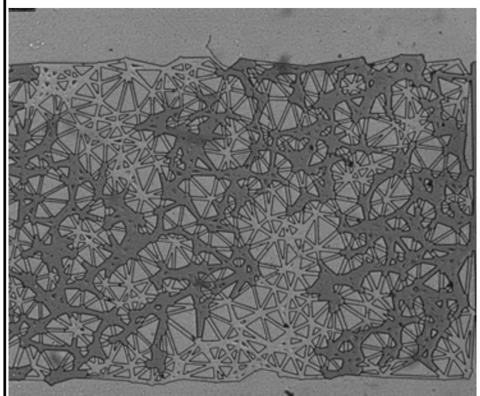
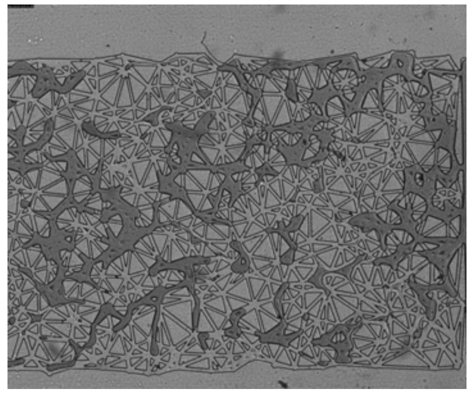
Visualization of interfaces in a micromodel

Drainage **Imbibition**





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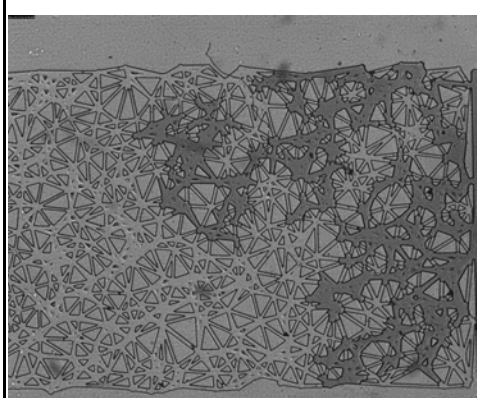
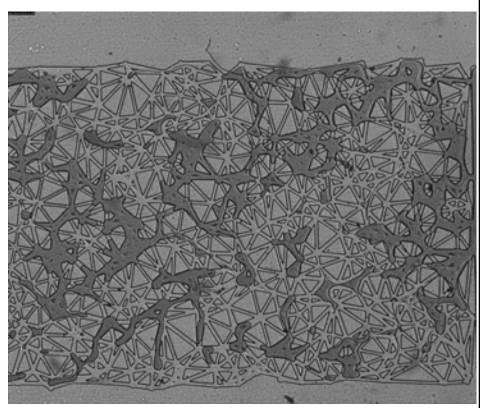
Karadimitriou et al., 2012

Visualization of interfaces in a micromodel

Drainage **Imbibition**



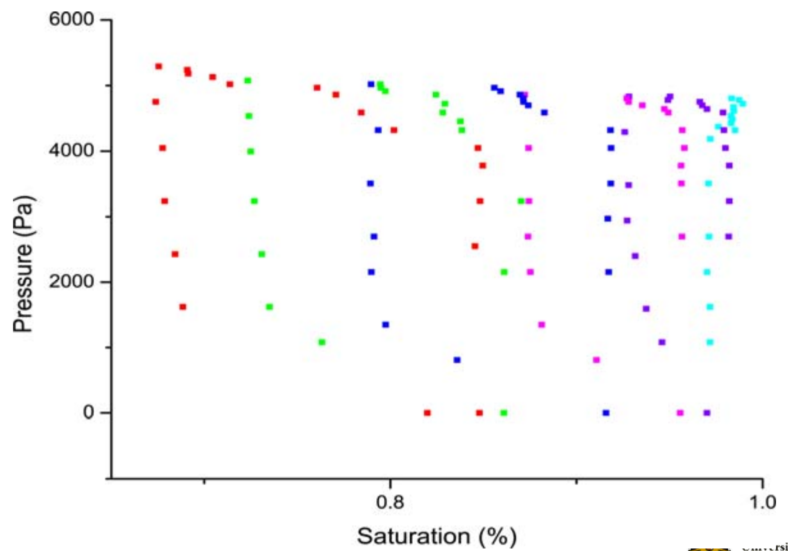


$S^n = 24\%$
$P^c = 4340$ Pa
$A^{wn} = 18.32$ mm^2

Karadimitriou et al., 2012

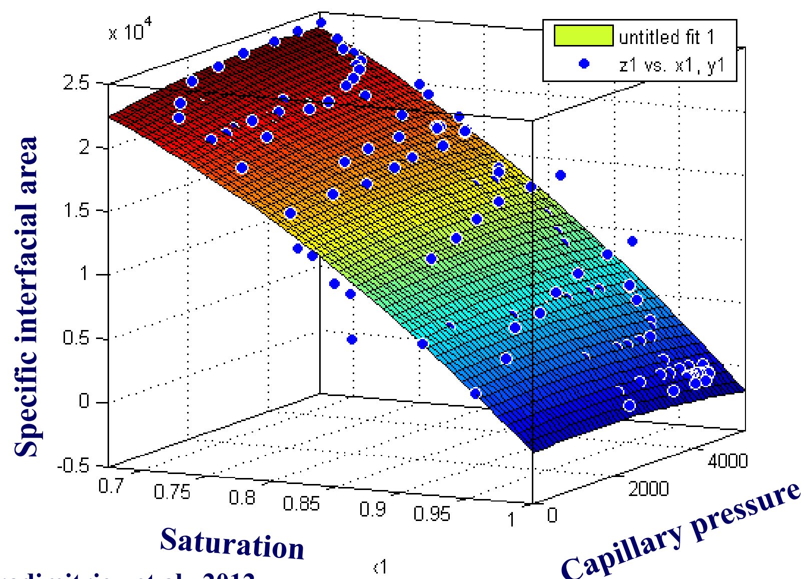
$S^n = 24\%$
$P^c = 2200$ Pa
$A^{wn} = 30.56$ mm^2

Capillary pressure-saturation points



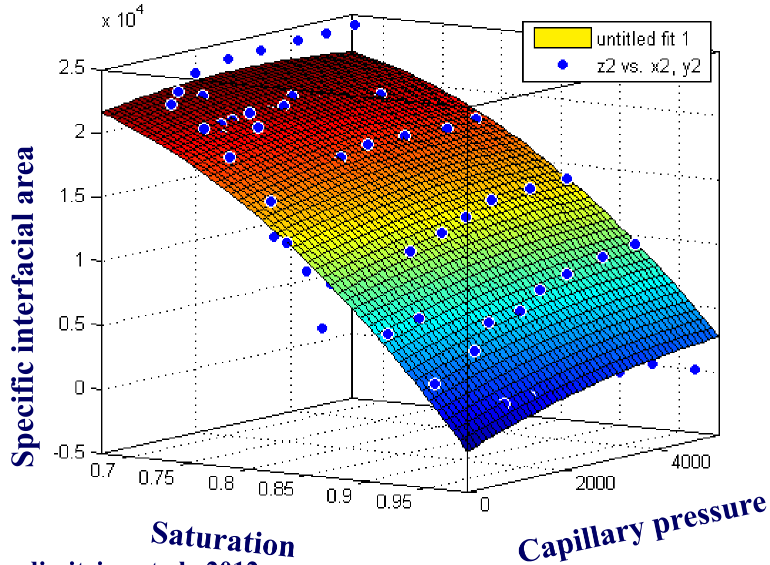
Karadimitriou et al., 2012

Capillary pressure-saturation-interfacial area Surface Fitted to drainage points



Karadimitriou et al., 2012

Capillary pressure-saturation-interfacial area Surface Fitted to imbibition points



Karadimitriou et al., 2012

Capillary pressure-saturation-interfacial area Surface

The average difference between the surface for drainage and the surface with all the data points is 9.7%.

The average difference between the surface for imbibition and the surface with all the data points is -5.77%.

$$a^{wn} = -18070 + 151500 * S - 1.075 * P_c - 137300 * S^2 + 2.577 * S * P_c - 0.0001104 * P_c^2$$

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Karadimitriou et al., 2012

Macroscale capillarity theory

Capillary Pressure-Saturation-Interfacial Area data points fall on a (unique) surface, which is a property of the fluids-solid system.

Fluids Pressure Difference, P^n-P^w is a dynamic property which depends on boundary conditions and fluid dynamic properties (e.g. viscosities).

Non-equilibrium Capillary Equation:

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

The coefficient τ is a material property which may depend on saturation.

It has been determined through column experiments, as well as computational models, by many authors.

Two-phase flow equations with dynamic capillarity effect

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

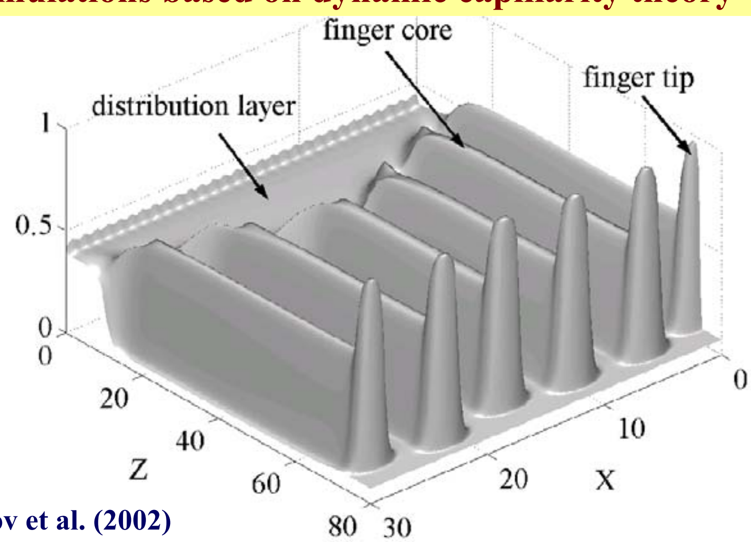
$$\mathbf{q}^{\alpha} = -\frac{1}{\mu^{\alpha}}\mathbf{K}^{\alpha} \bullet \left(\nabla P^{\alpha} - \rho^{\alpha}\mathbf{g}\right)$$

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

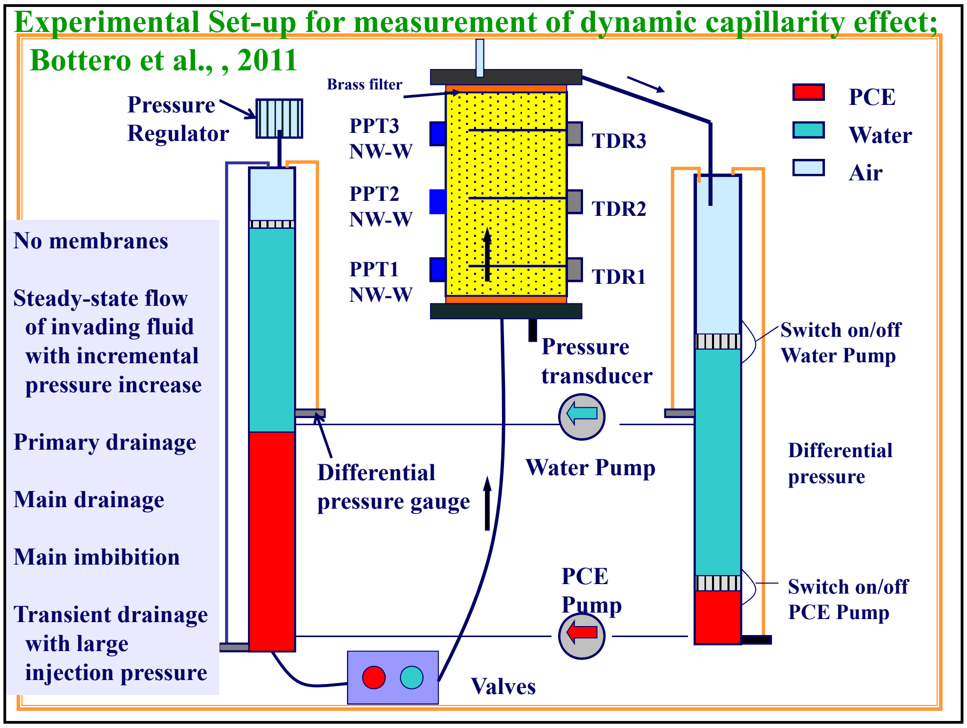
Combine the three equations for unsaturated flow:

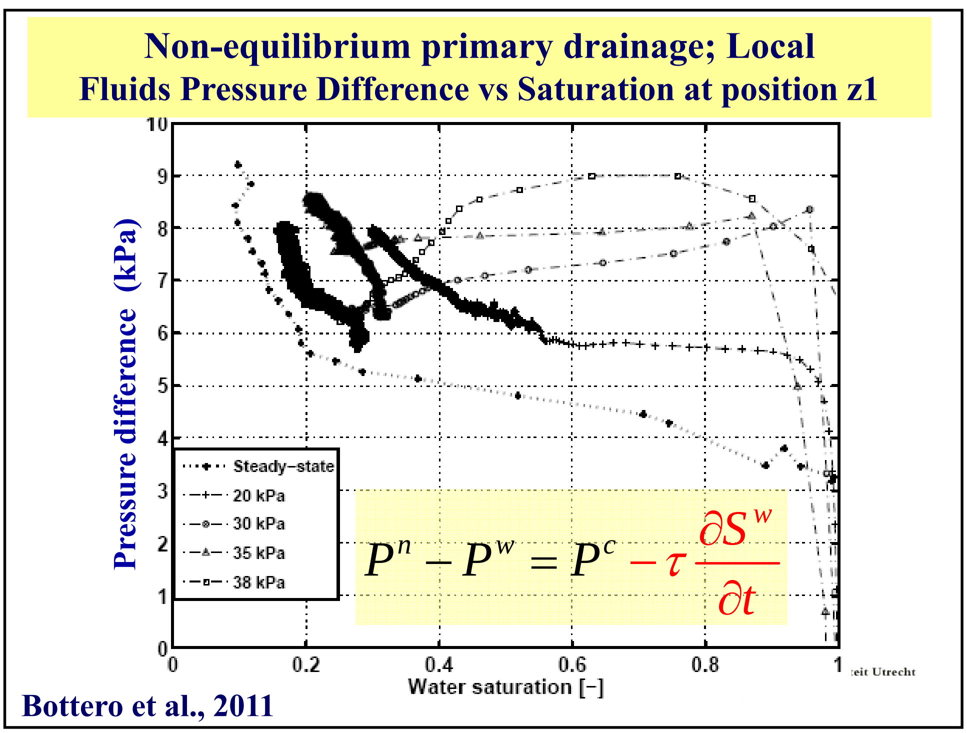
$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \bullet \left(D\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial x} \bullet \left(\tau\frac{\partial^{2} u}{\partial x \partial t}\right)$$

Development of vertical wetting fingers in dry soil; Simulations based on dynamic capillarity theory



Dautov et al. (2002)


Experimental Set-up for measurement of dynamic capillarity effect;
Bottero et al., , 2011
Pressure Regulator
Brass filter
PPT3 NW-W
PPT2 NW-W
PPT1 NW-W
TDR3
TDR2
TDR1
PCE
Water
Air
No membranes
Steady-state flow of invading fluid with incremental pressure increase
Primary drainage
Main drainage
Main imbibition
Transient drainage with large injection pressure
Pressure transducer
Switch on/off Water Pump
Differential pressure gauge
Water Pump
Differential pressure
PCE Pump
Switch on/off PCE Pump
Valves


Non-equilibrium primary drainage; Local
Fluids Pressure Difference vs Saturation at position z1
Pressure difference (kPa)
Water saturation [-]
Steady-state
20 kPa
30 kPa
35 kPa
38 kPa
$P^n - P^w = P^c - \tau \frac{\partial S^w}{\partial t}$
Bottero et al., 2011

Value of the damping coefficient τ as a function of saturation; local scale

Sw	$\tau [Pa.s]$
0.85	$1.587 * 10^5$
0.80	$1.451 * 10^5$
0.75	$1.361 * 10^5$
0.70	$1.375 * 10^5$
0.65	$1.404 * 10^5$
0.60	$1.402 * 10^5$
0.55	$1.461 * 10^5$

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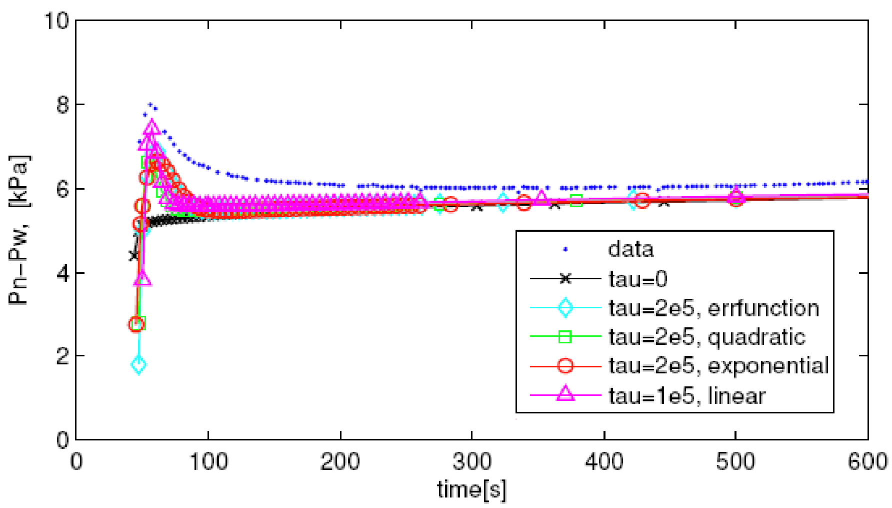
Bottero et al., 2011

Simulation of non-equilibrium primary drainage; Local pressure difference vs time; Injection pressure, 35kPa



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Bottero, 2009

Conclusions on Capillarity Theory:

Capillary Pressure is not just a function of saturation.

Capillary Pressure -Saturation-Interfacial Area form a (unique) surface, which is a property of the fluids-solid system.

Fluids Pressure Difference, P^n-P^w is a dynamic property which depends on boundary conditions and fluid dynamic properties (e.g. viscosities)

Fluids Pressure Difference, P^n-P^w, is equal to capillary pressure but only under equilibrium conditions. Otherwise, it depends on the rate of change of saturation.

Extended theories of two-phase flow

Extended Darcy's law (linearized equation of motion):

$$\mathbf{q}^\alpha = -\rho^\alpha \mathbf{K}^\alpha \bullet \left(\nabla G^\alpha - \mathbf{g} \right)$$

where G^α is the Gibbs free energy of a phase:

$$G^\alpha = G^\alpha \left(\rho^\alpha, a^{wn}, S^\alpha, T \right)$$

Extended Darcy's law :

$$\mathbf{q}^\alpha = -\frac{k^{r\alpha}}{\mu^\alpha} \mathbf{K} \bullet \left(\nabla P^\alpha - \rho^\alpha \mathbf{g} - \psi^{\alpha a} \nabla a^{wn} - \psi^{\alpha S} \nabla S^\alpha \right)$$

where $\psi^{\alpha a}$ and $\psi^{\alpha S}$ are material coefficients.

Extended theories of two-phase flow

Linearized equation of motion for interfaces:

$$\mathbf{w}^{wn} = -K^{wn} a^{wn} \Gamma^{wn} (\nabla G^{wn} - \mathbf{g})$$

where G^{wn} is the Gibbs free energy of wn-interface:

$$G^{wn} = G^{wn}\left(\Gamma^{\alpha}, a^{wn}, S^{\alpha}, T\right)$$

Simplified equation of motion for interfaces (neglecting gravity term):

$$\mathbf{w}^{wn} = -K^{wn}\left[\gamma^{wn}\nabla a^{wn} + \Omega^{wn}\nabla S^{w}\right]$$

where Ω^{wn} is a material coefficient and γ^{wn} is macroscale surface tension.

Summary of extended two-phase flow equations

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

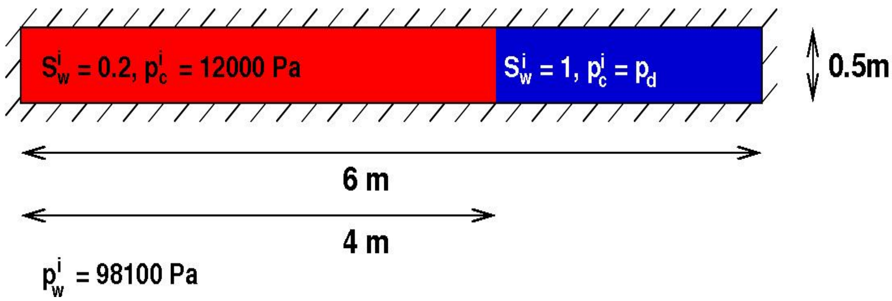
$$\mathbf{q}^{\alpha} = -\frac{1}{\mu^{\alpha}}\mathbf{K}^{\alpha} \bullet \left(\nabla P^{\alpha} - \rho^{\alpha}\mathbf{g} - \psi^{\alpha a}\nabla a^{wn} - \psi^{\alpha S}\nabla S^{\alpha}\right)$$

$$\frac{\partial a^{wn}}{\partial t} + \nabla \bullet \left(a^{wn}\mathbf{w}^{wn}\right) = E^{wn}$$

$$\mathbf{w}^{wn} = -K^{wn}\left[\gamma^{wn}\nabla a^{wn} + \Omega^{wn}\nabla S^{w}\right]$$

$$P^{n} - P^{w} = P^{c} - \tau\frac{\partial S^{w}}{\partial t} \qquad P^{c} = f\left(S^{w}, a^{wn}\right)$$

Simulation of redistribution moisture; a numerical example



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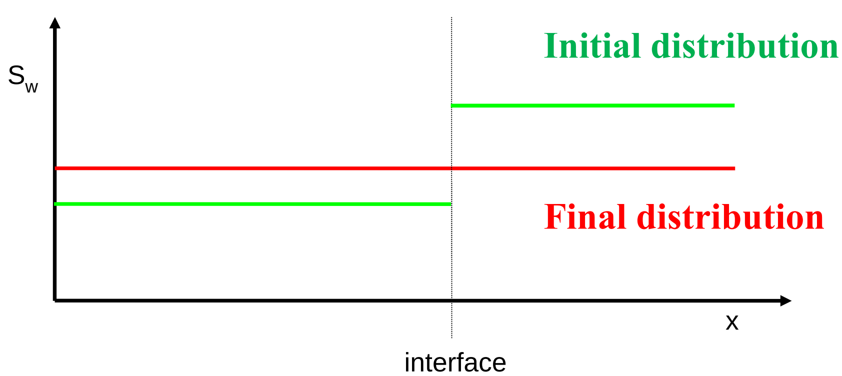
Equilibrium moisture distribution from standard two-phase flow equations with no hysteresis



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Simulating horizontal moisture redistribution with standard two-phase flow equations+hysteresis

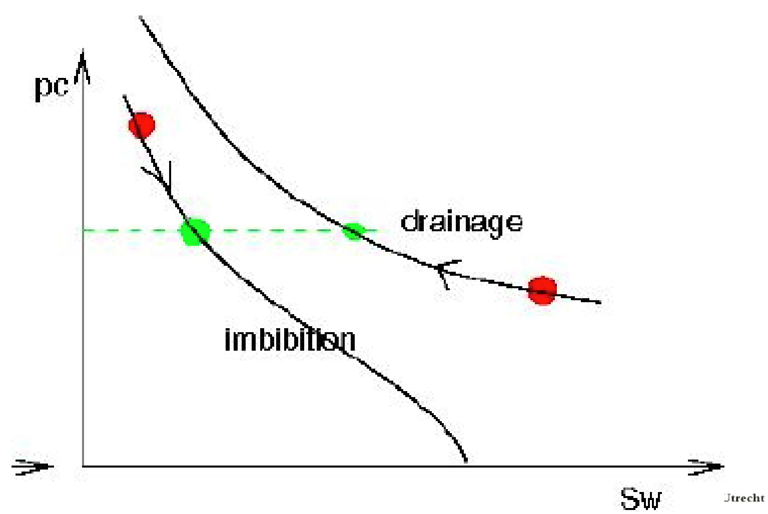
$$n\frac{\partial S^{\alpha}}{\partial t} + \nabla \bullet \mathbf{q}^{\alpha} = 0$$

$$\mathbf{q}^{\alpha} = -\frac{1}{\mu^{\alpha}}\mathbf{K}^{\alpha} \bullet \nabla P^{\alpha}$$

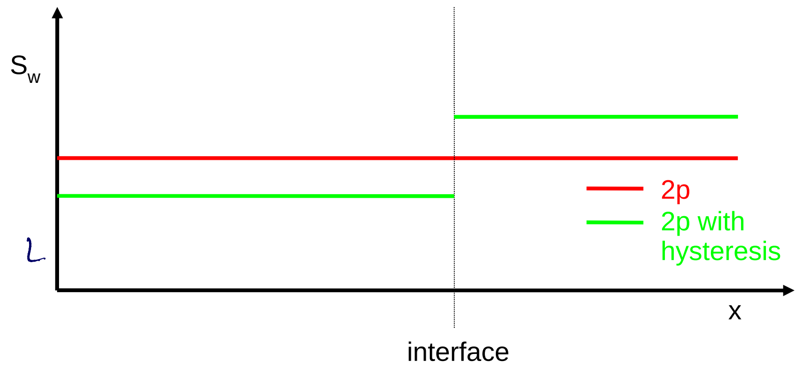
$$P^{n} - P^{w} = f_{d}\left(S^{w}\right) \qquad if \quad \frac{\partial S}{\partial t} < 0$$

$$P^{n} - P^{w} = f_{i}\left(S^{w}\right) \qquad if \quad \frac{\partial S}{\partial t} > 0$$

Solving moisture redistribution problem with standard two-phase flow equations



Equilibrium result from standard two-phase flow equations with hystresis



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Solving a problem with extended two-phase flow equations

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

$$\mathbf{q}^{\alpha} = -\frac{1}{\mu^{\alpha}}\mathbf{K}^{\alpha} \bullet \left(\nabla p^{\alpha} - \rho^{\alpha}\mathbf{g} \cancel{- \psi^{\alpha a}\nabla a^{wn} - \psi^{\alpha S}\nabla S^{\alpha}}\right)$$

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

$$\mathbf{w}^{wn} = -K^{wn}\left[\gamma^{wn}\nabla a^{wn} + \cancel{\Omega^{wn}\nabla S^{w}}\right]$$

$$p^{n} - p^{w} = P^{c} \cancel{- \tau\frac{\partial S^{w}}{\partial t}} \qquad P^{c} = f\left(S^{w}, a^{wn}\right)$$

Governing eqs for moisture redistribution

There is a self-similar solution for this problem:

$$S = S(\eta) \quad \text{and} \quad p = p(\eta) \text{ with } \eta = \frac{x}{\sqrt{t}}$$

and obtain the problems

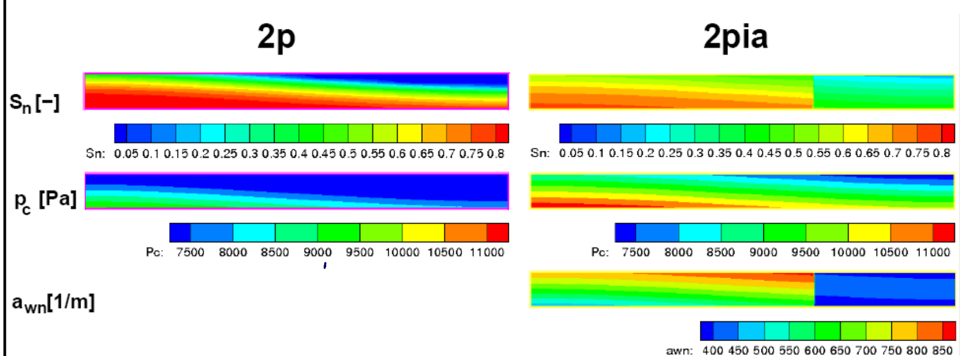
$$(SP_\ell)\begin{cases} -\frac{\eta}{2}S' + (D(S)p^-(S)')' = 0 & \text{for } \eta \in (-\infty, 0), \\ S(-\infty) = S_\ell \end{cases}$$

and

$$(SP_r)\begin{cases} -\frac{\eta}{2}S' + (D(S)\,p^+(S)')' = 0 & \text{for } \eta \in (0, +\infty), \\ S(+\infty) = S_r. \end{cases}$$

With a semi-analytical solution.

Long-term result from extended two-phase flow equations with no hystresis



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CONCLUSIONS

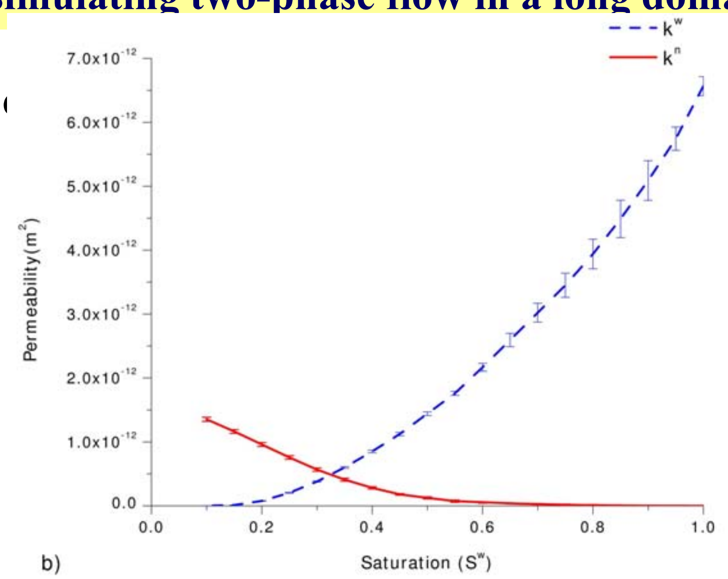
Under nonequilibrium conditions, the difference in fluid pressures is a function of time rate of change of saturation as well as saturation.

Resulting Eq. will lead to nonmonotonic solutions.

Fluid-fluid interfacial areas should be included in multiphase flow theories.

Hysteresis can be modelled by introducing interfacial area into the two-phase flow theory

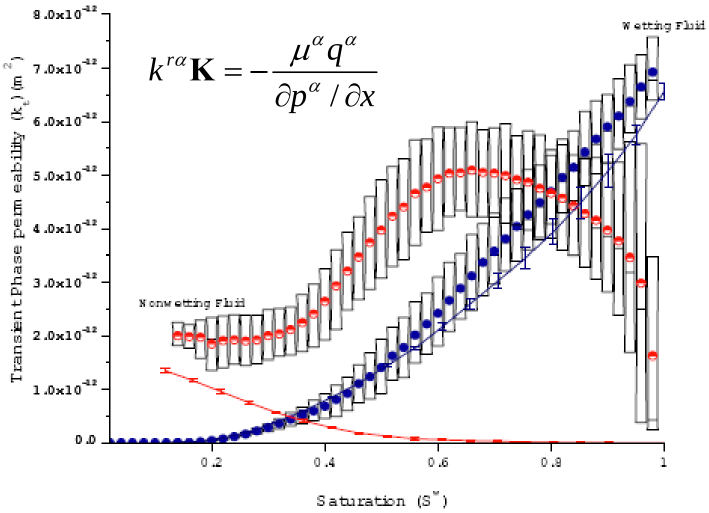
simulating two-phase flow in a long domain



Total permeability $k^{r\alpha}\mathbf{K}$ as a function of saturation for a range of capillary numbers

Transient relative permeability curves

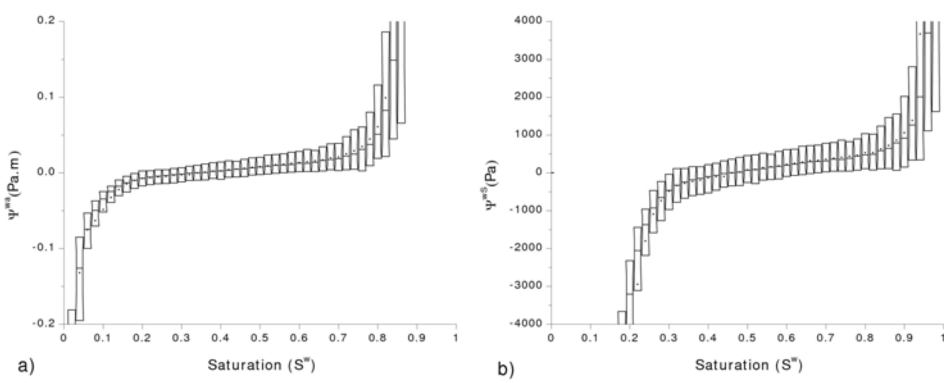
$$k^{r\alpha}\mathbf{K} = -\frac{\mu^{\alpha} q^{\alpha}}{\partial p^{\alpha} / \partial x}$$



Total permeability $k^{r\alpha}\mathbf{K}$ as a function of saturation for a range of capillary numbers

simulating two-phase flow in a long domain

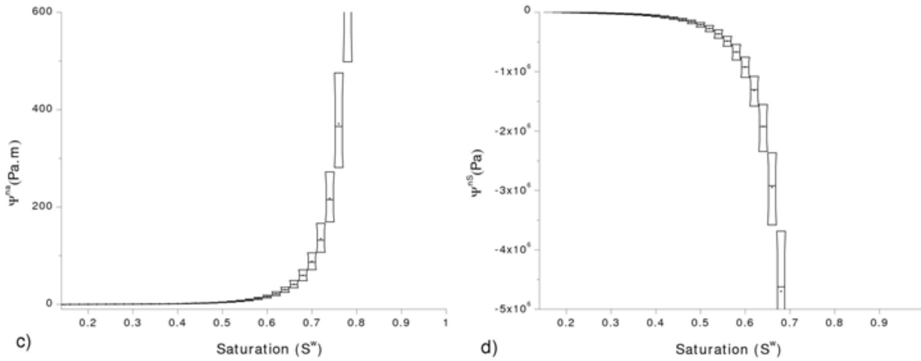
$$\mathbf{q}^{\alpha} = -\frac{k^{r\alpha}}{\mu^{\alpha}}\mathbf{K}\bullet\left(\nabla p^{\alpha} - \rho^{\alpha}\mathbf{g} - \psi^{\alpha a}\nabla a^{wn} - \psi^{\alpha S}\nabla S^{\alpha}\right)$$



Material coefficients ψ^{wa} and ψ^{wS} as functions of S^w for a wide range of capillary numbers

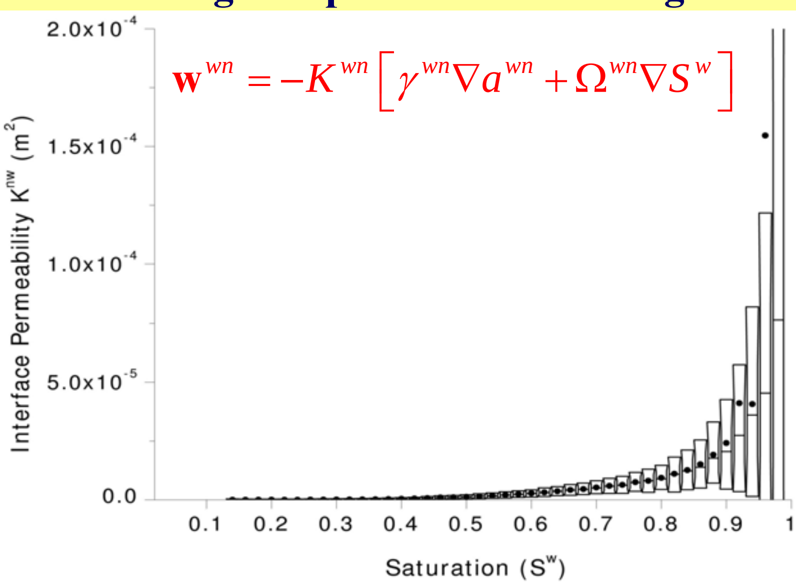
simulating two-phase flow in a long domain

$$\mathbf{q}^{\alpha} = -\frac{k^{r\alpha}}{\mu^{\alpha}} \mathbf{K} \bullet \left(\nabla p^{\alpha} - \rho^{\alpha} \mathbf{g} - \psi^{\alpha a} \nabla a^{wn} - \psi^{\alpha S} \nabla S^{\alpha} \right)$$



Material coefficients ψ^{na} **and** ψ^{nS} **as functions of** S^w **for a wide range of capillary numbers**

simulating two-phase flow in a long domain

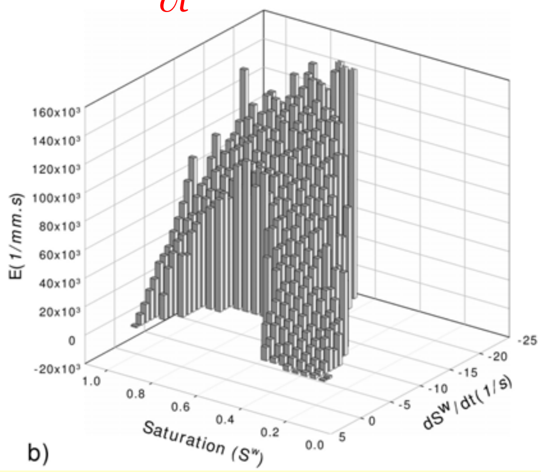


$$\mathbf{w}^{wn} = -K^{wn} \left[\gamma^{wn} \nabla a^{wn} + \Omega^{wn} \nabla S^{w} \right]$$

Interfacial permeability as a function of saturation for a range of capillary numbers

simulating two-phase flow in a long domain

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



Rate of generation/destruction of interfacial area as a function of saturation and rate of change of saturation

CONCLUSIONS

The driving forces in Darcy's law should be gradient of Gibbs free energy and gravity.

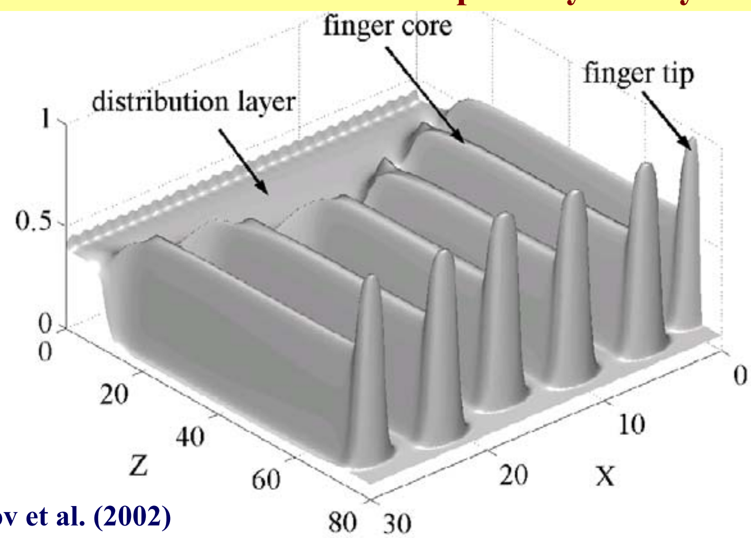
Difference in fluid pressures is equal to capillary pressure but only under equilibrium conditions.

Under nonequilibrium conditions, the difference in fluid pressures is a function of time rate of change of saturation as well as saturation.

Fluid-fluid interfacial areas should be included in multiphase flow theories.

Hysteresis can be modelled by introducing interfacial area into the two-phase flow theory

Development of vertical wetting fingers in dry soil; Simulations based on new capillarity theory



Dautov et al. (2002)

Development of vertical wetting fingers in dry soil; Simulations based on new capillarity theory

Dynamic Capillary Pressure Mechanism for Instability in Gravity-Driven Flows; Review and Extension to Very Dry Conditions; JOHN L. NIEBER, RAFAIL Z. DAUTOV, ANDREY G. EGOROV, and ALEKSEY Y. SHESHUKOV; TiPM

Stability analysis of gravity-driven infiltrating flow; Andrey G. Egorov, Rafail Z. Dautov, John L. Nieber, and Aleksey Y. Sheshukov

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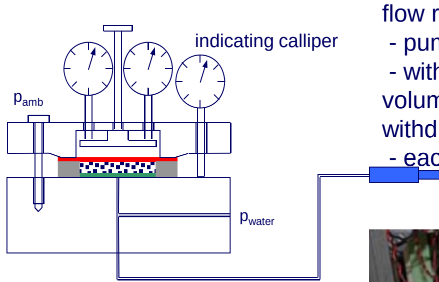
p_c - S_w measurement: the measurement cell



sample diameter: 25 mm
flow rates for every step:
- pumping: 3 µl / min
- withdrawing: 3 µl / min

volume infused / withdrawn
- each step: 3 µl

green: hydrophilic membrane
grey: sealing
dotted: sample (GDL)
red: hydrophobic membrane
blue: syringe pump

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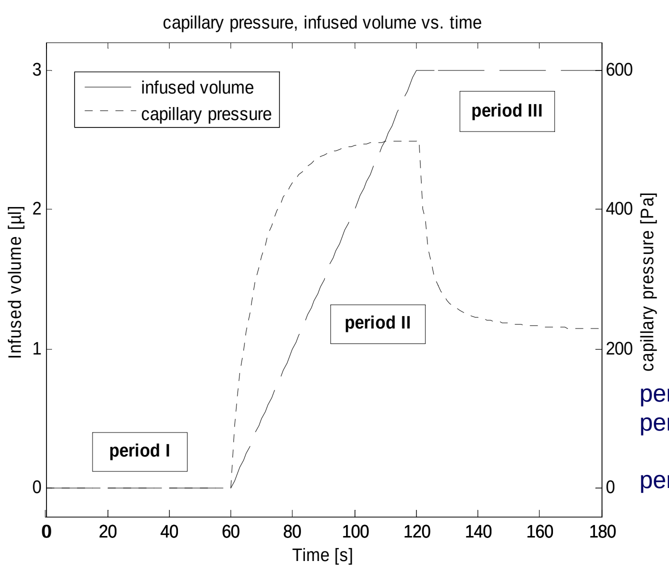
p_c - S_w measurement: operation strategy



period I: initial state
period II: pumping water into the sample
period III: relaxation period

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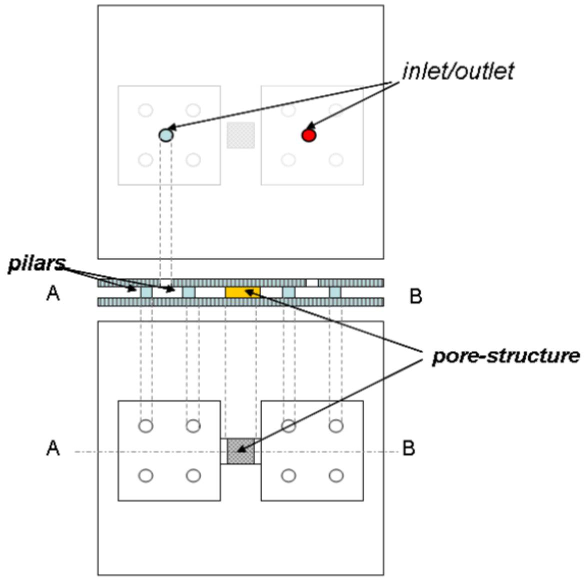

Figure 1.2: Schematic representation of the micro-model

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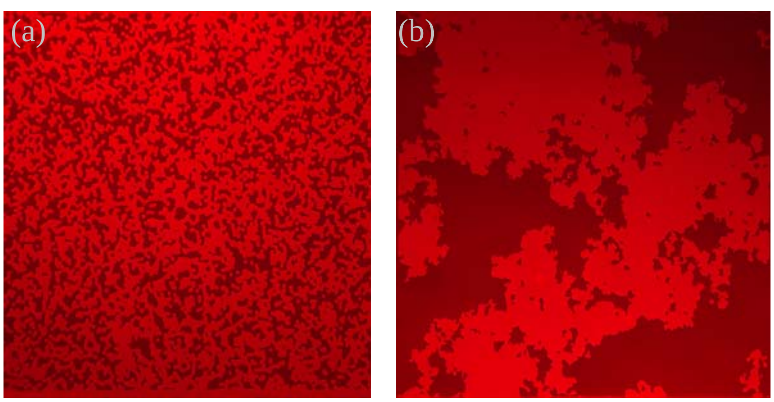
Micromodel experiments



Dark area is solid and light area is pore space

J.-T. Cheng, L. J. Pyrak-Nolte, D. D. Nolte and N. J. Giordano, Geophysical Research Letters, 2004

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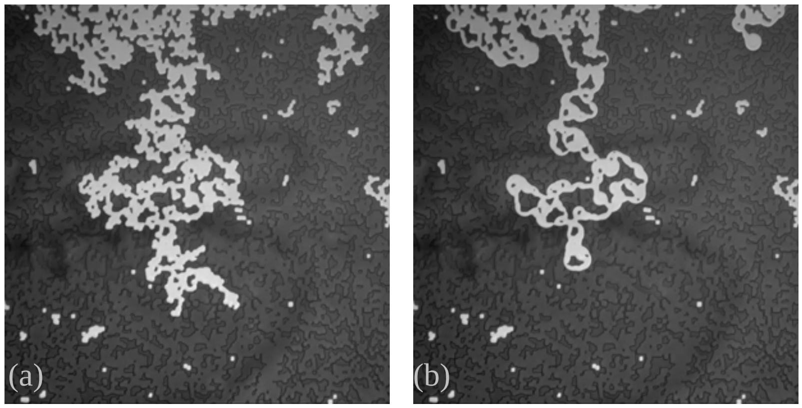
Measuring a^{wn} interfaces in a micromodel

Drainage **Imbibition**



J.-T. Cheng, L. J. Pyrak-Nolte, D. D. Nolte and N. J. Giordano, Geophysical Research Letters, 2004

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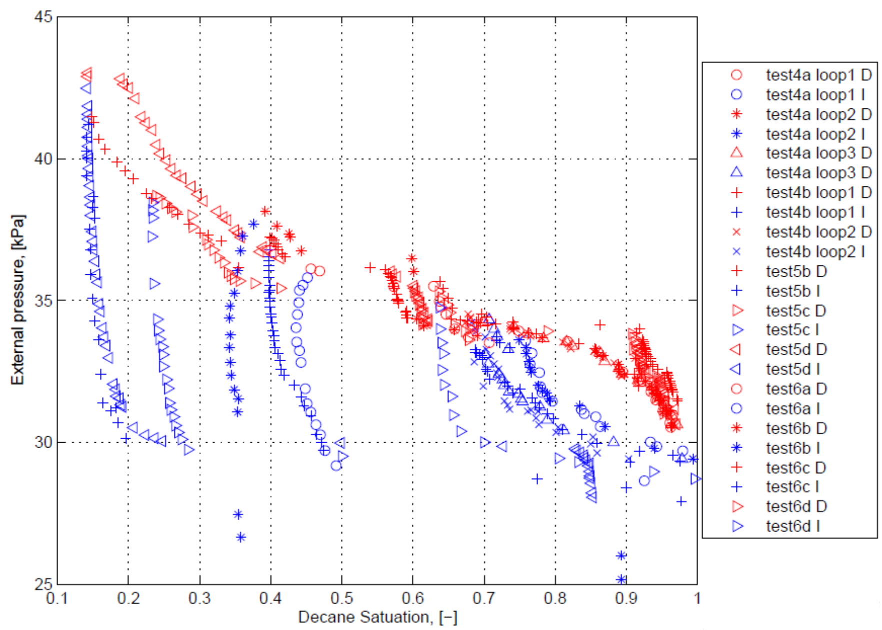
Equilibrium drainage and imbibition experiments*



*Experiments performed by S. Bottero at Purdue Univ.