Two-phase flow in industrial porous media
Experiments, theory, and modelling

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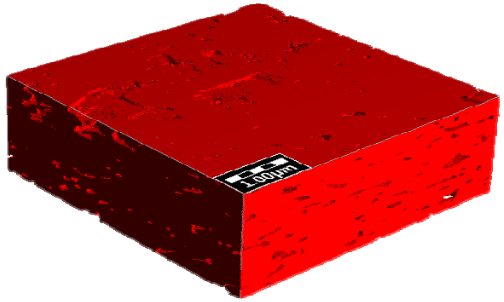
Michael Celia; Princeton University, USA

Outline of presentation

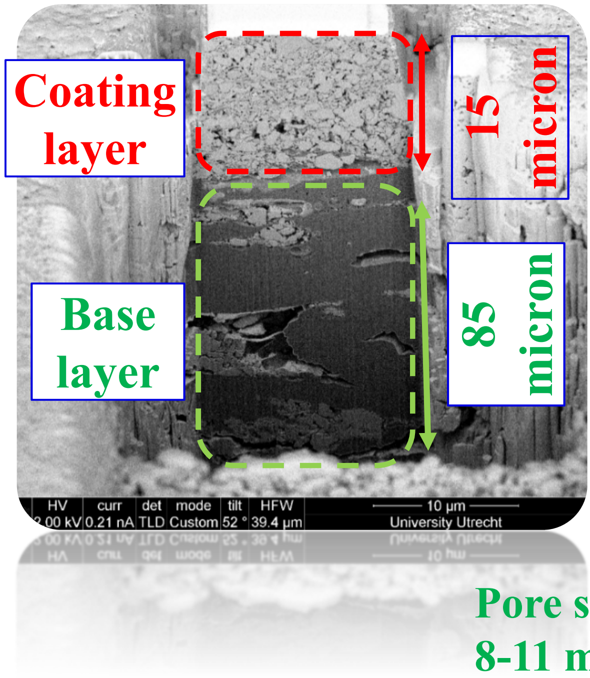
- Examples of industrial porous media
- What is so special about them?
- Criticisms of current modeling approaches
- A new modelling approach

Penetration of Ink into Coated Paper during inkjet printing

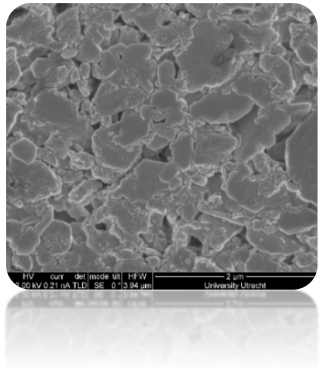
Both paper and ink are complex materials



Pore size:
100-600 nano-m.

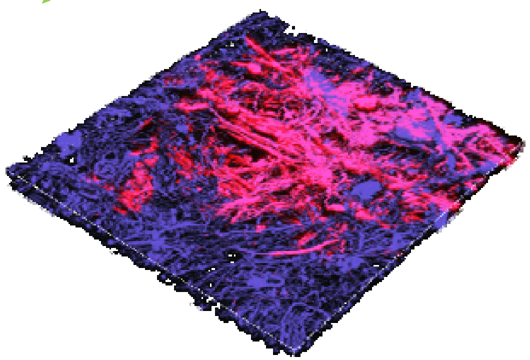


FIB-SEM



Confocal

Pore size:
8-11 micron



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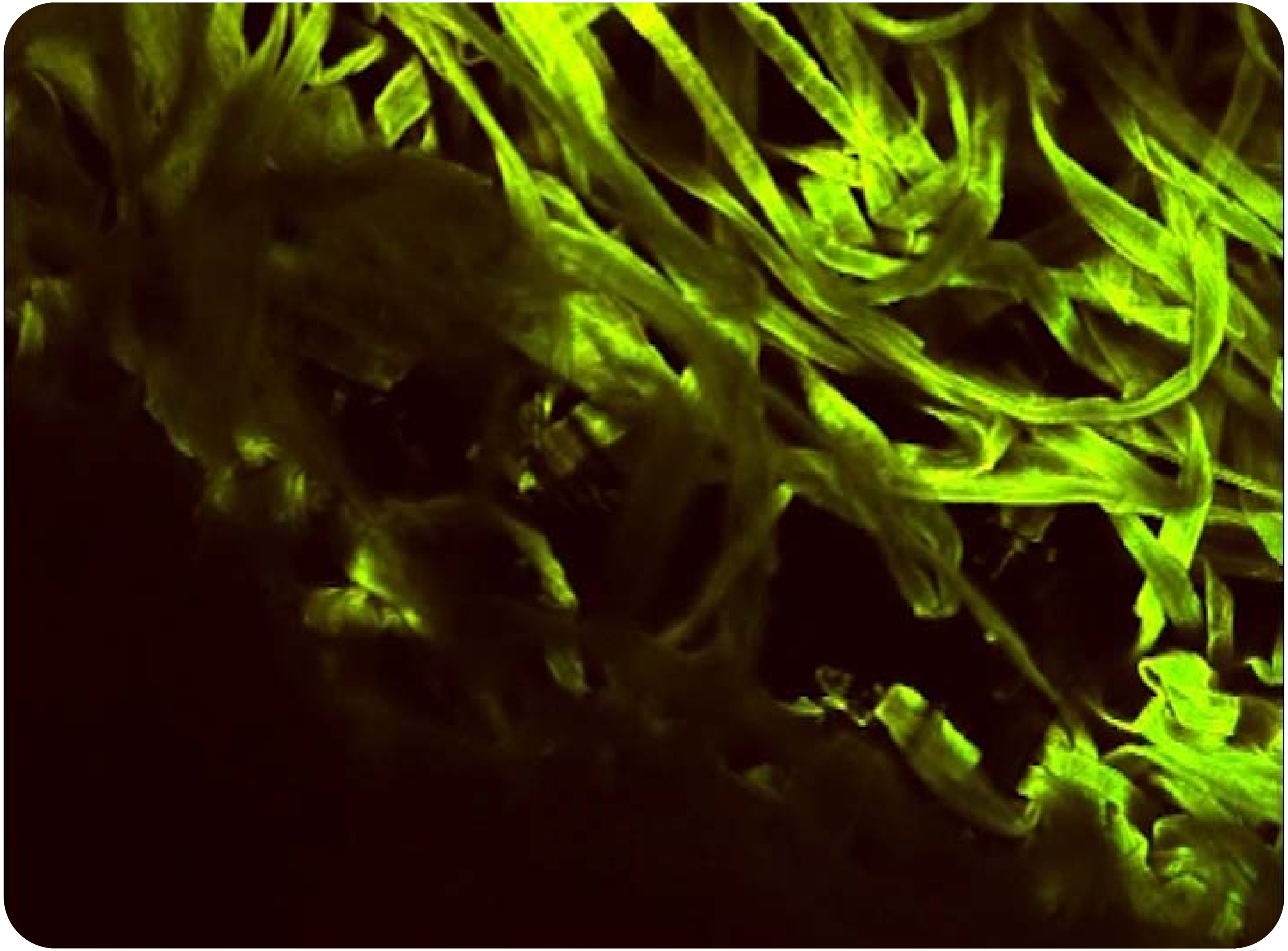
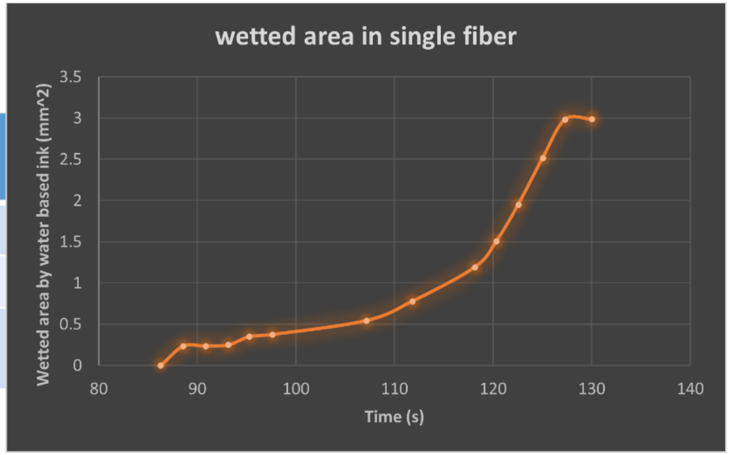
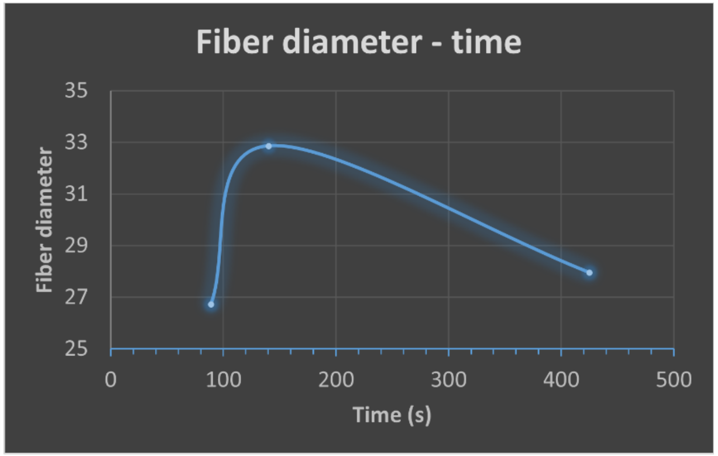
Water movement inside and between fibers

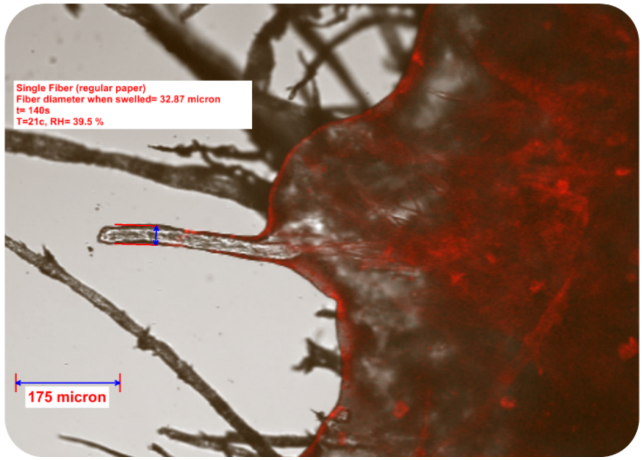


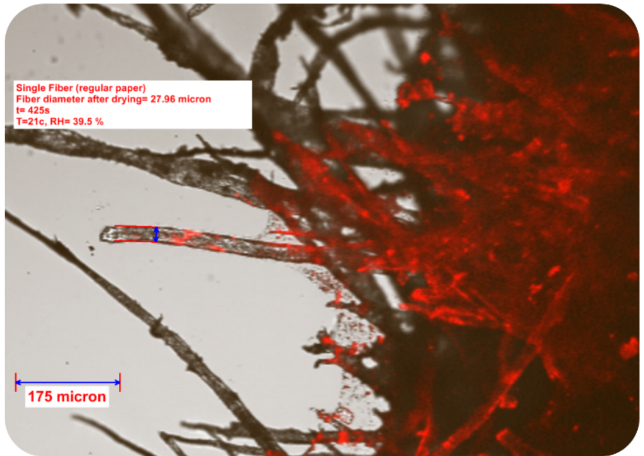
Water movement in paper
Swelling Effect:

Time (s)	Diameter (micron)	Condition
89	26.74	Before swelling
140	32.87	swelled
425	27.96	Drying after swelling

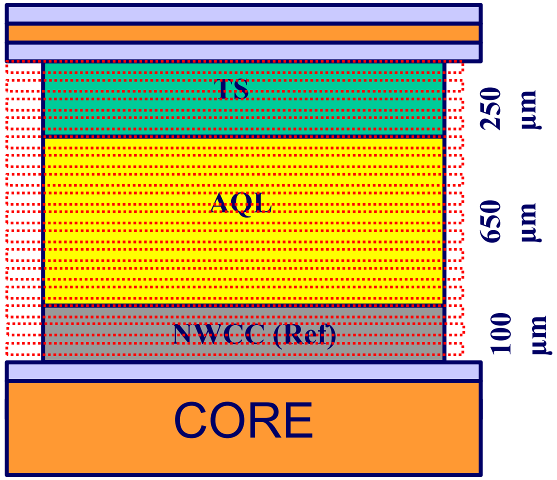






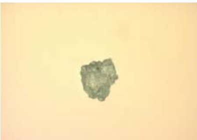


Water movement in layers of diaper



What is SAP (Super Absorbent Polymer)?

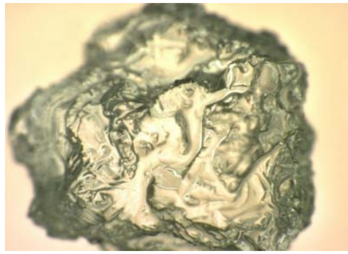
- White powder made of water soluble hydrophilic polymer
- One gram of SAP can absorb up to 1000 grams of distilled water but only 30 grams of urine!



stiff/glassy
45 to 850μm

fluid penetrates into polymer network →

gel-like state



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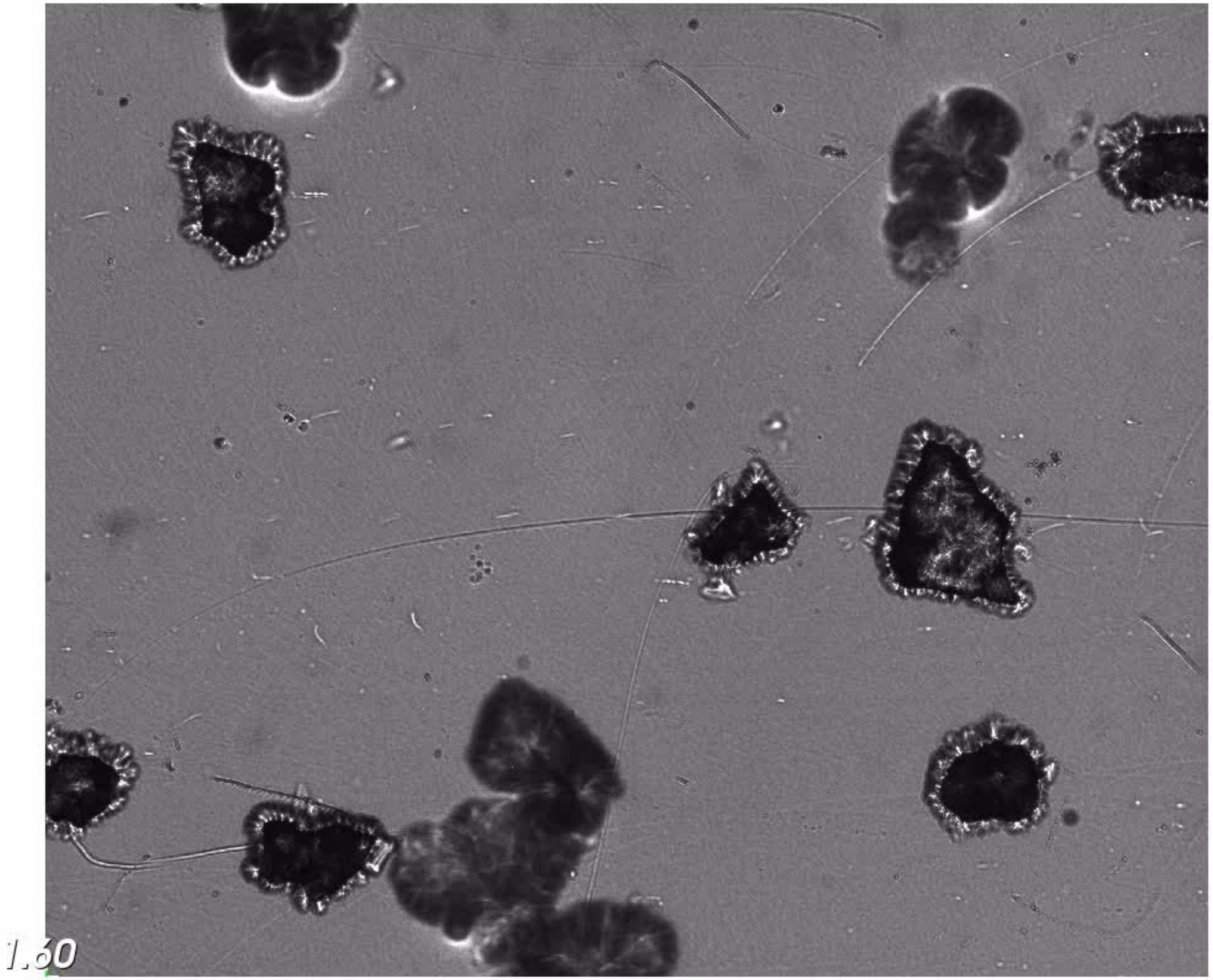
Swelling of SAP particles



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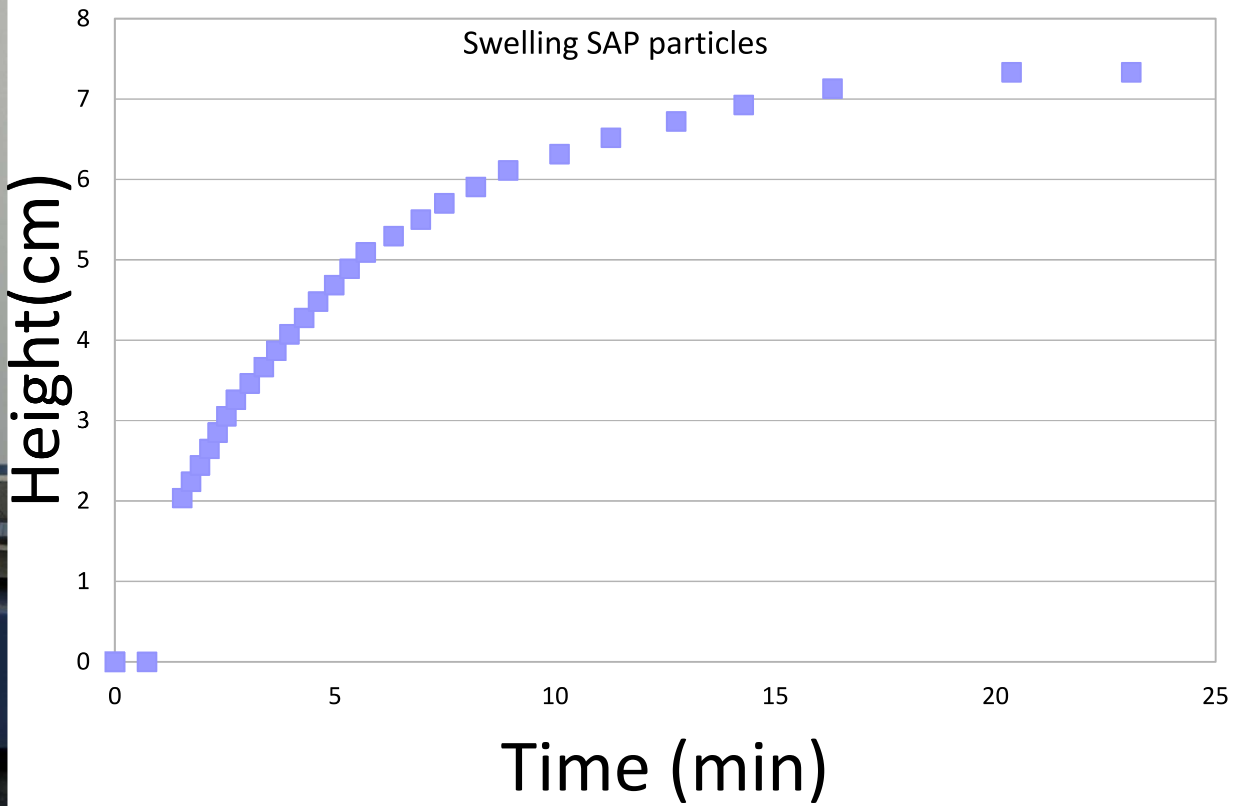
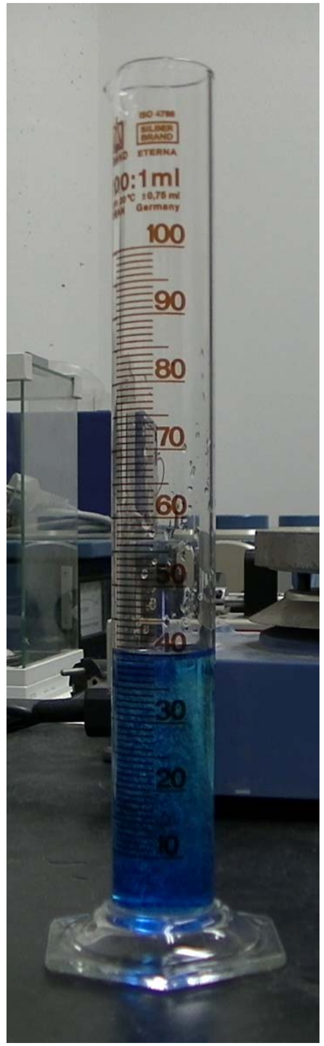
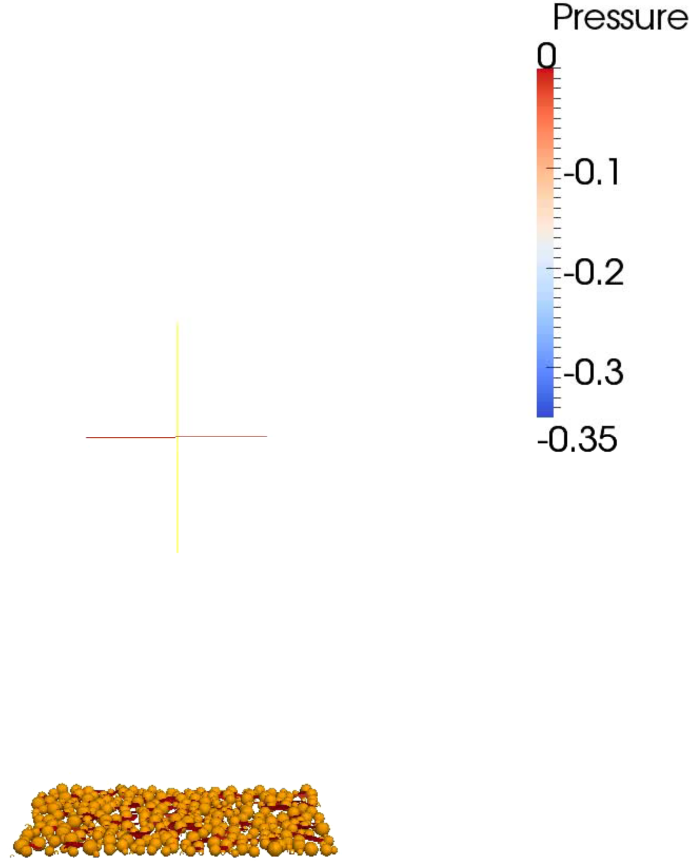
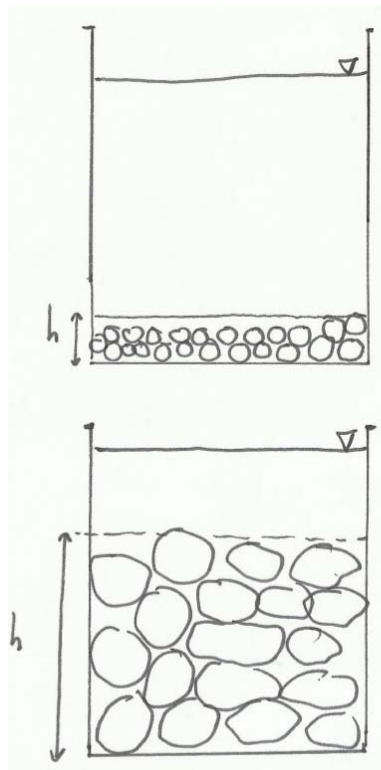
Experiment; Swelling of a bed of SAP particles





Example: Modelling the swelling of a bed of SAP particles using Discrete Element Method (DEM)

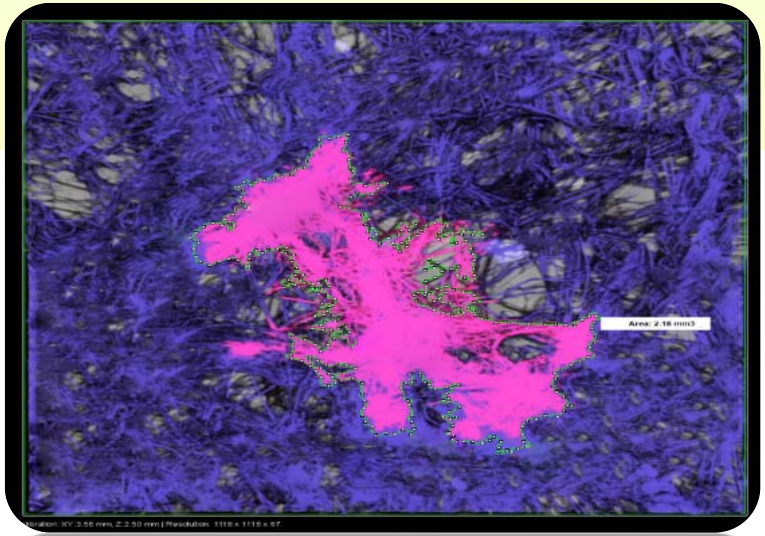




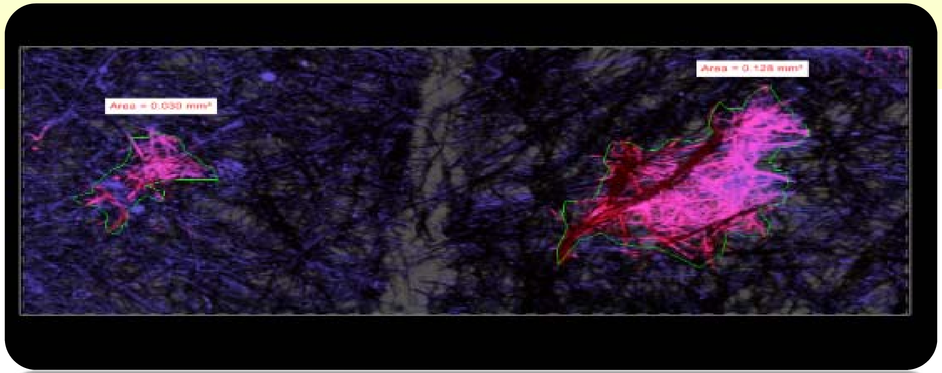
Special features of industrial porous media

- Often there is a stack of thin porous layers
- The space between layers may significantly influence flow of distribution of liquids
- Finite deformation (e.g. swelling) is a major process

Effect of space between two layers on spreading and imbibition:

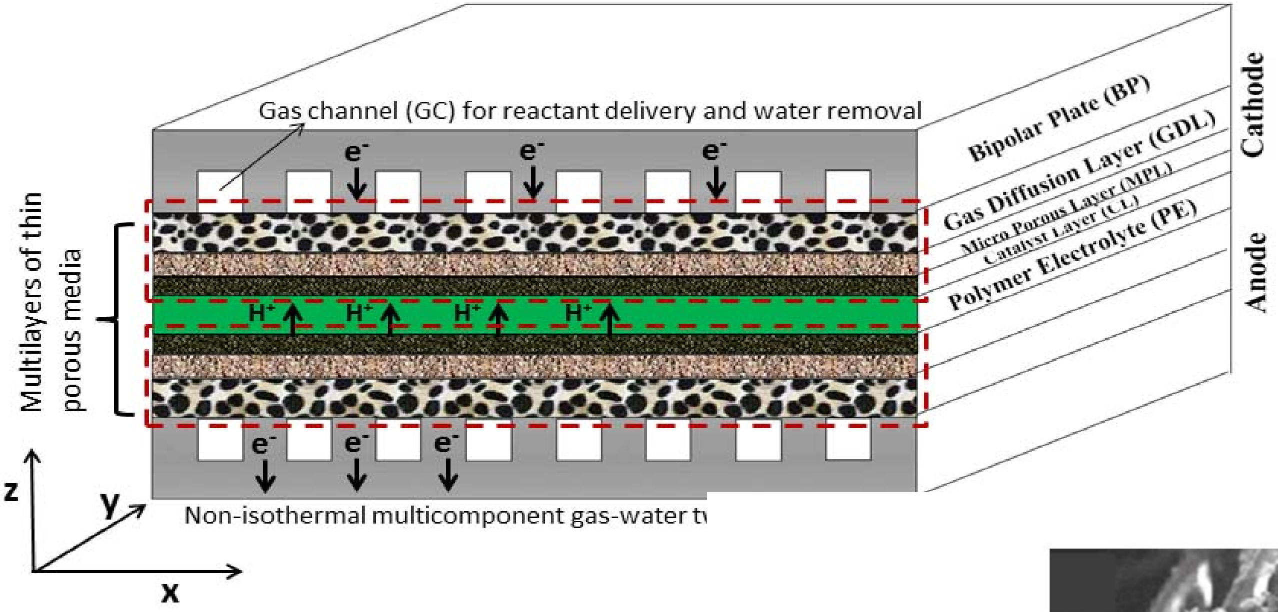


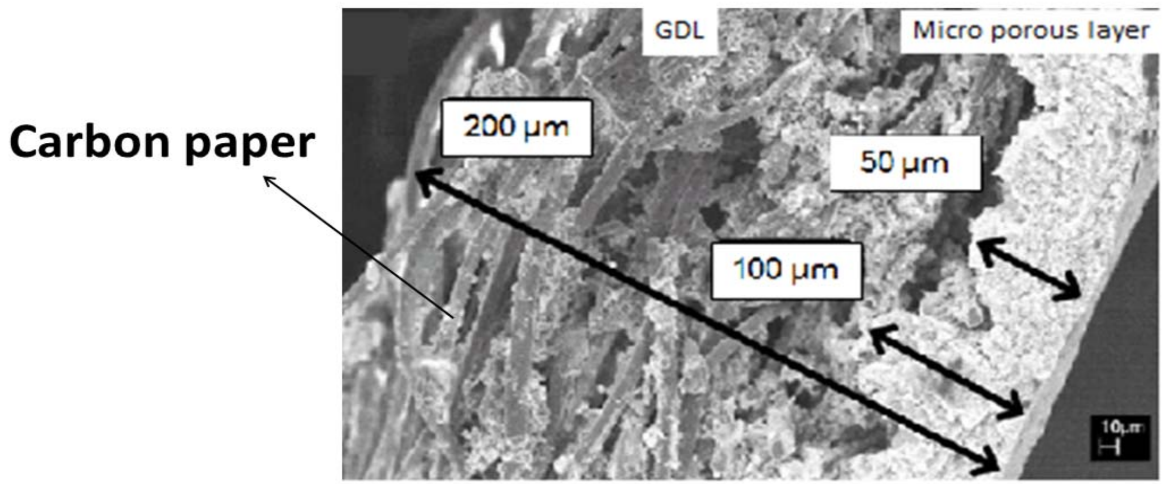
Penetration of a given amount of liquid into one piece of paper with a thickness of 240μm



Penetration of the same amount of liquid into two pieces of the same paper, with a thickness of 120μm, put on each other each

Other examples of industrial porous media: PEM Fuel Cells





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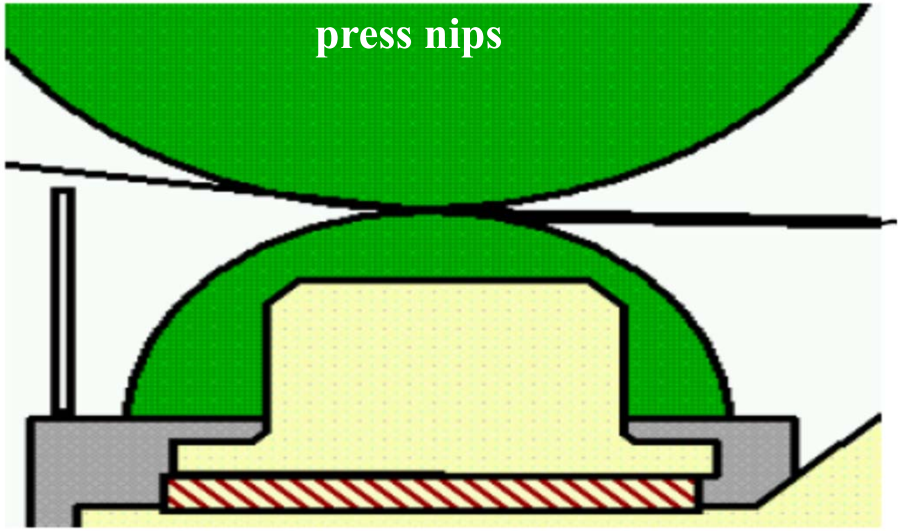
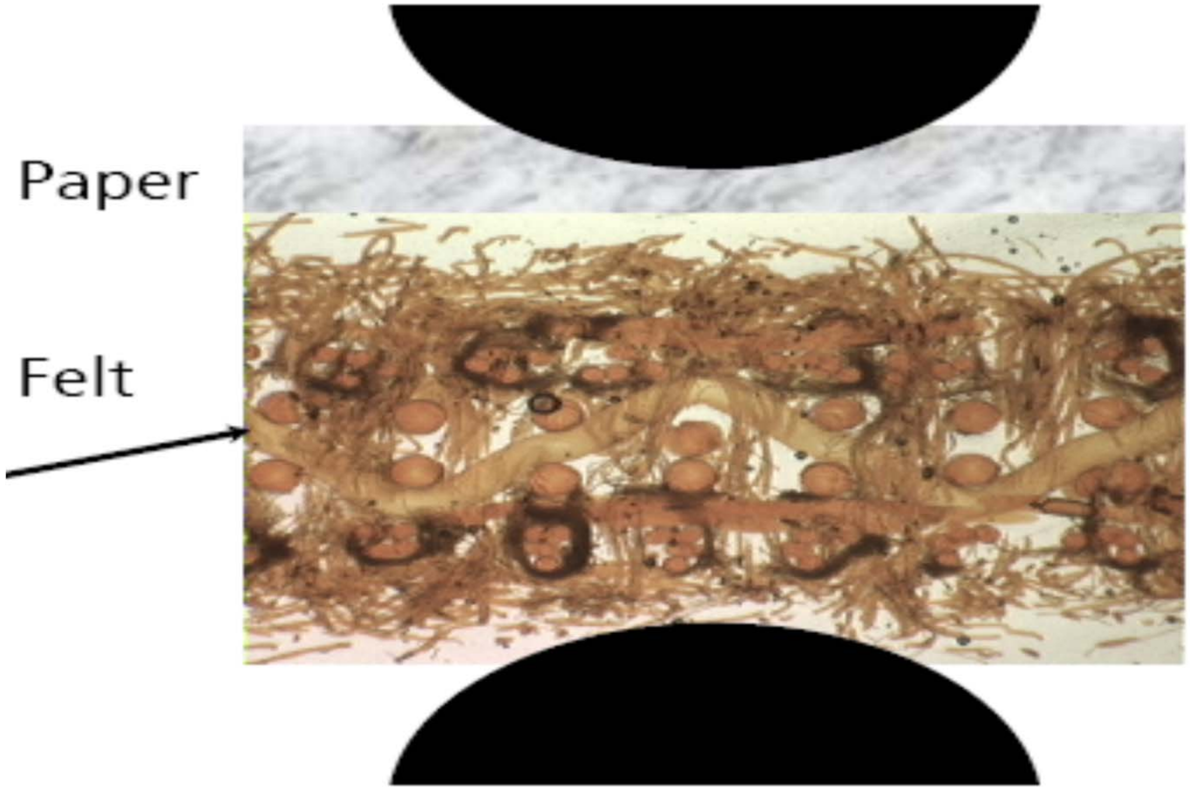
Other examples of industrial porous media: Dewatering of paper pulp



The paper pulp layer is transported through the press aperture on a felt. The paper-felt sandwich is thus compressed, so that the water is pressed out of the paper, is absorbed by the felt, and then flows laterally away from the nips.

Pictures courtesy of Oleg Iliev of ITWM, Kaiserslautern

Dewatering of paper pulp



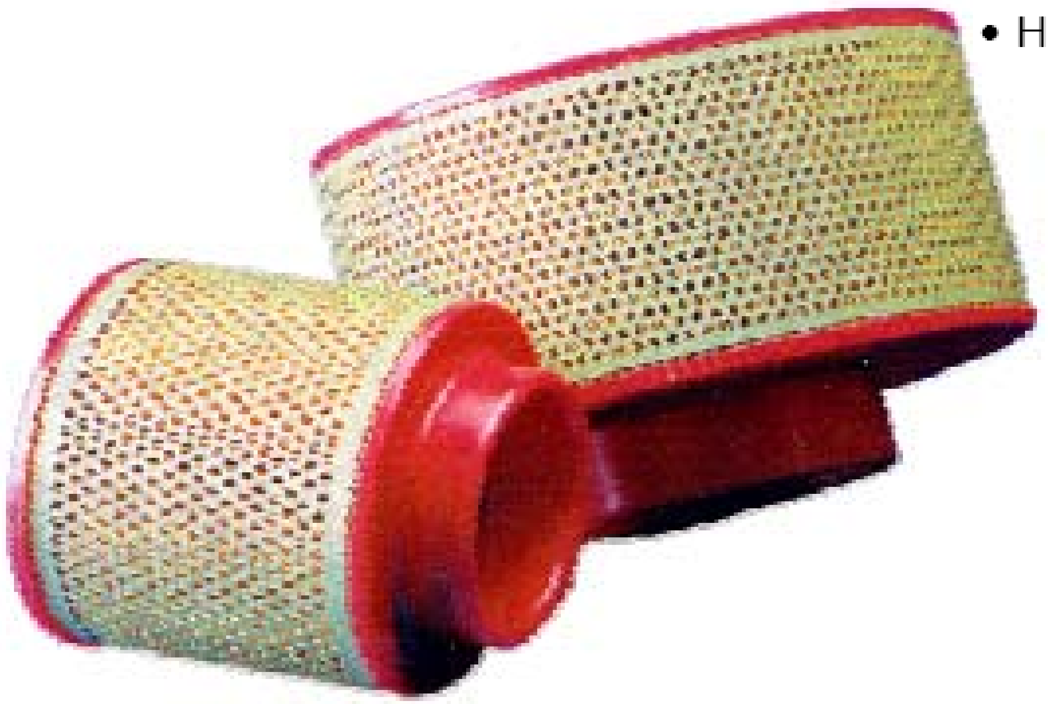
The felt must have enough retaining and conducting capacity for the water pressed from the paper layer.

Pictures courtesy of Oleg Iliev of ITWM, Kaiserslautern

Other examples of industrial porous media: Air and oil flow in oil filters

Oil filters contain various layers of **glass fiber papers** and **non-woven materials**.

- coalescence in paper
- oil deposition by gravity in fleece
- How to choose the filter material?



Unsaturated Flow in industrial porous media

Flow in ceramics and ceramic foams

Flow in food drying industry

Flow in biological tissues

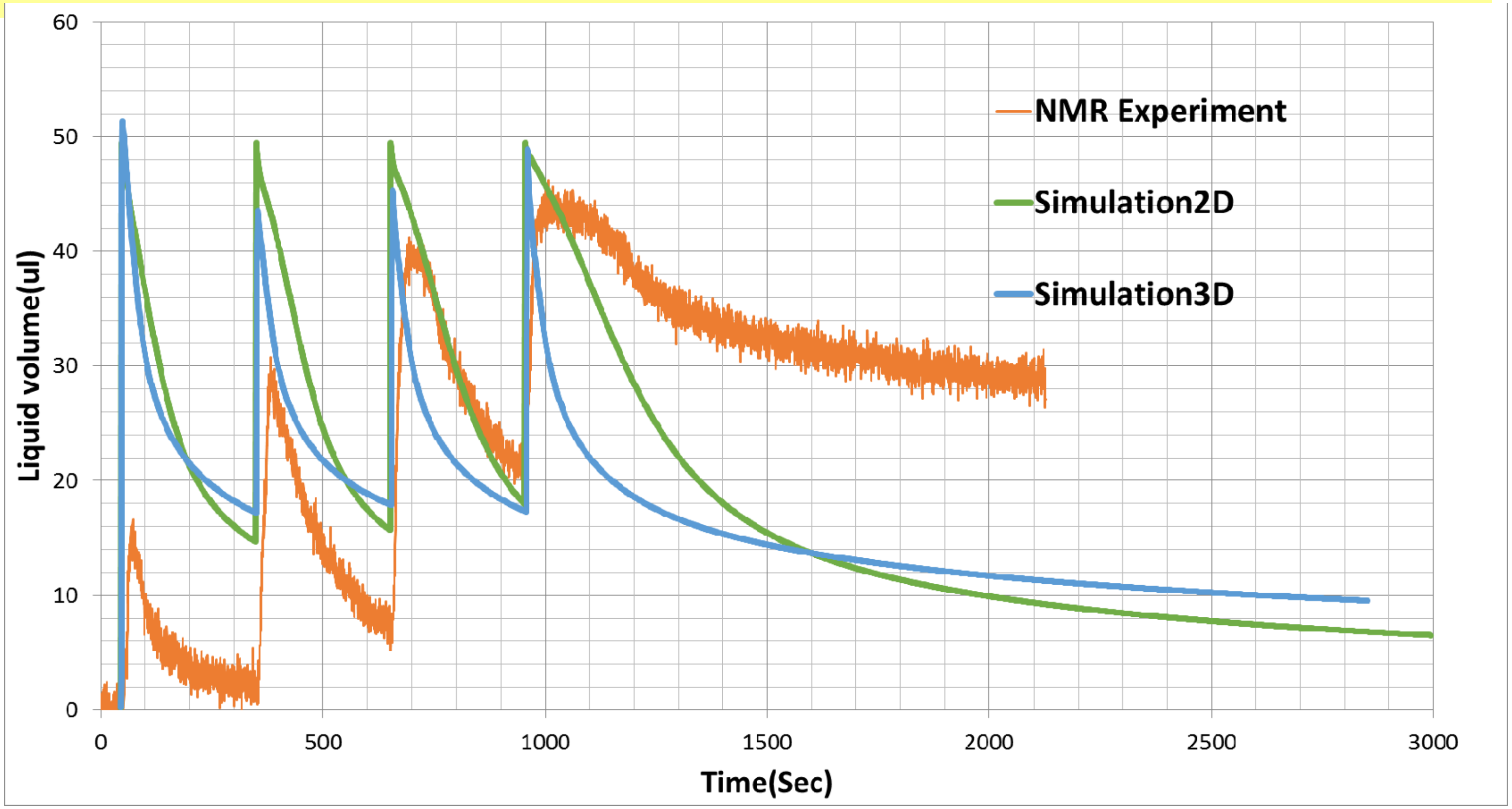
Flow in concrete and other construction materials

Flow in wood

Special features of industrial porous media

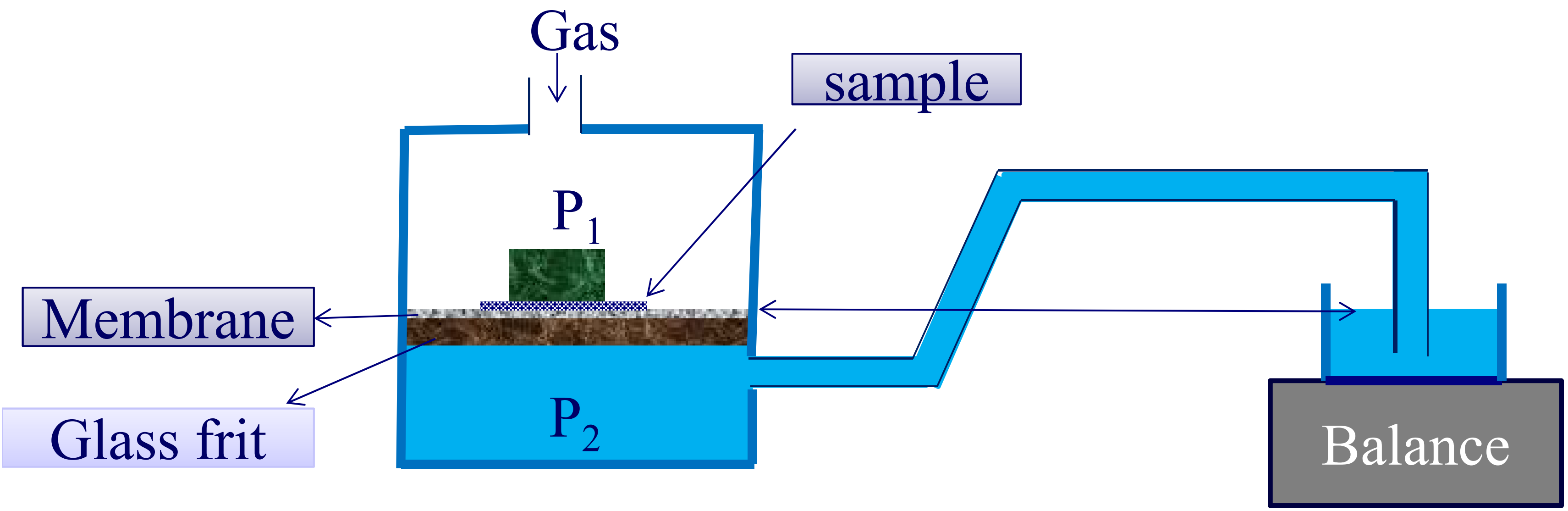
- Often there is a stack of thin porous layers
- The space between layers may significantly influence flow of distribution of liquids
- Finite deformation (e.g. swelling) is a major process
- Infiltration and distribution of liquids happen fast

Spreading of four gushes of liquid



Change of liquid volume with time at a location 4 cm away form the injection point

Measurement of Pc-S curves for layers of a diaper

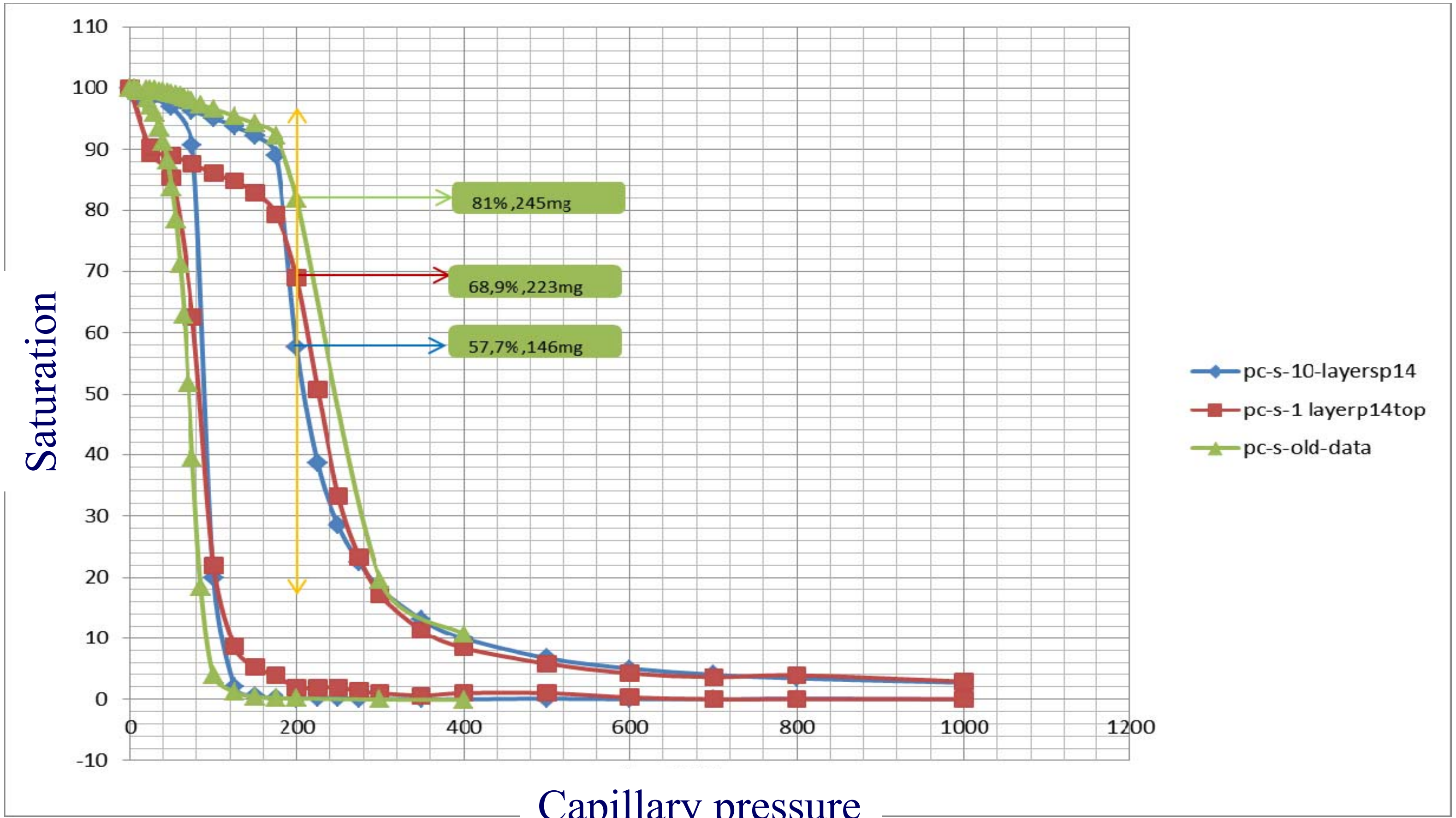


- Membrane is fully saturated during measurement
- During drainage, sample is initially fully wet and gas pressure is zero; gas pressure is increased in steps.
- During imbibition, sample is initially dry and gas pressure is very high; gas pressure is decreased in steps.

Measurement of Pc-S curves for layers of a diaper

Pc-S curves for a single layer, and stacks of 3 layers or 10 layers

Each set of curves takes 12 hours to obtain!



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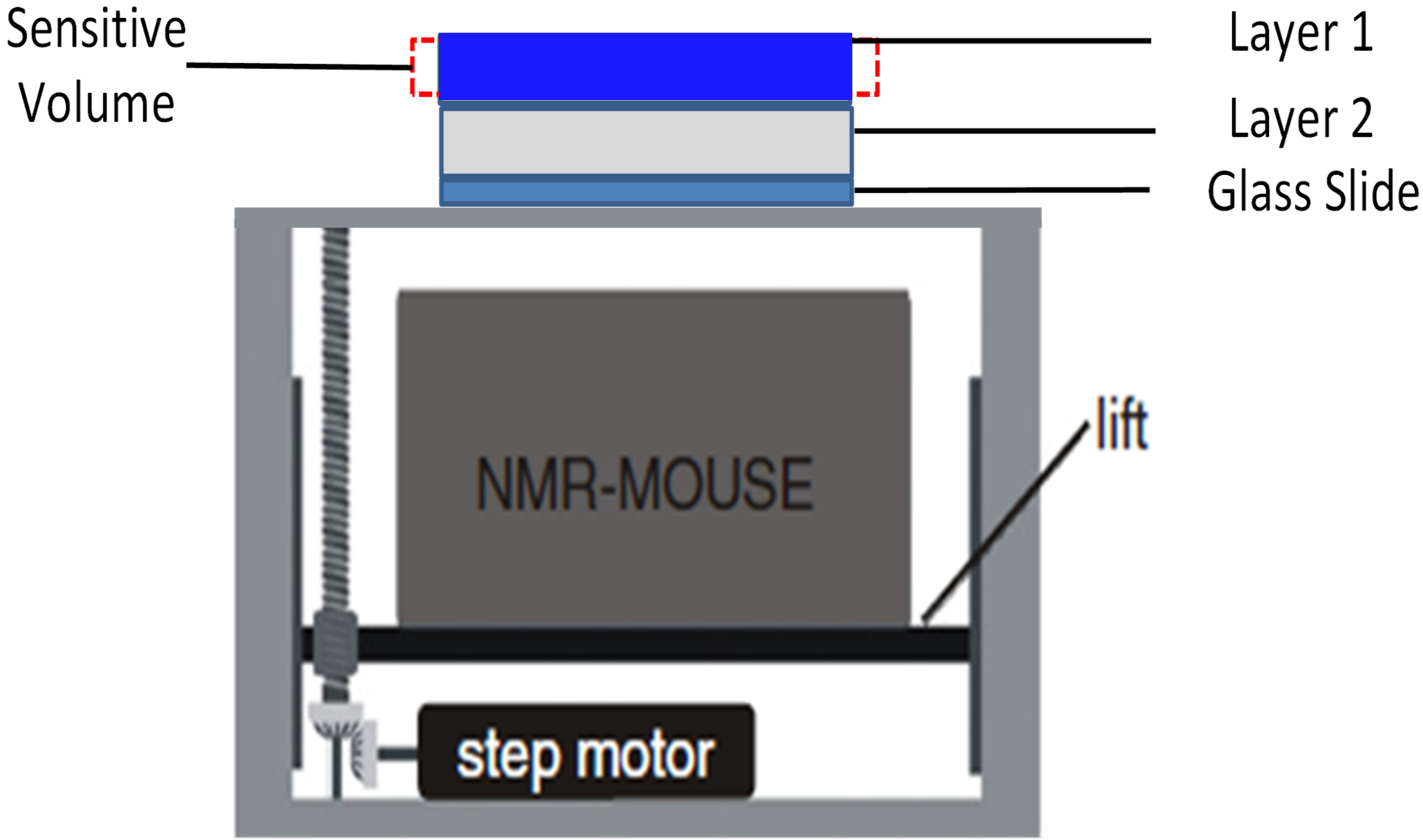
Dynamic redistribution of water from a wet layer to a dry layer



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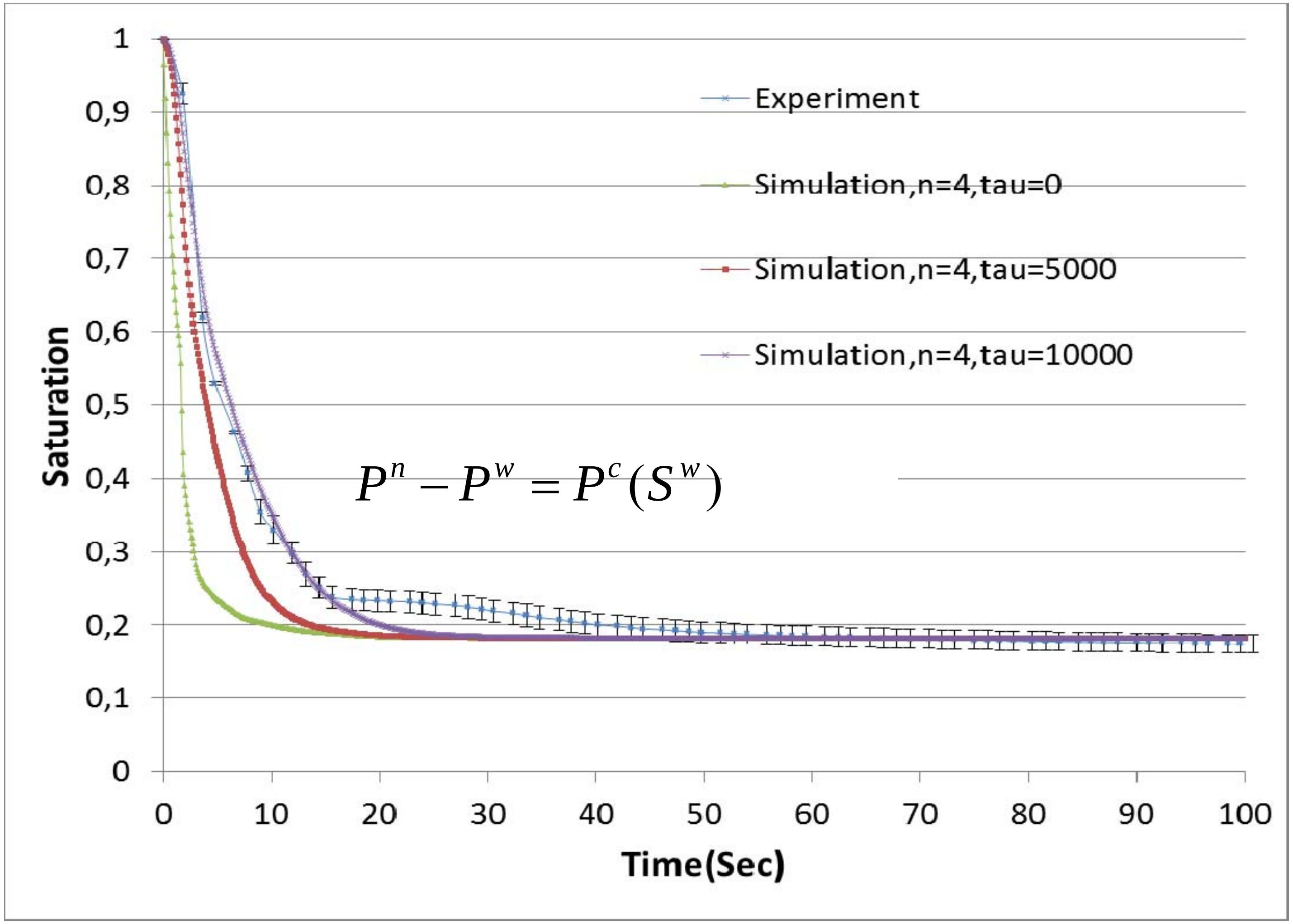


Special features of industrial porous media

- Many industrial porous media are made of a stack of thin layers
- Lateral dimensions are much larger than thickness
- Thickness of layers is not much larger than their pore or grain sizes
- The use of standard continuum equations of multiphase flow is questionable

Objections to the use of 3-D standard equations

- REV cannot be defined for thin porous media

Continuum equations are not applicable!

- We need to discretize the layers in three dimensions.

Huge computational effort is needed for modelling systems such as fuel cells at the stack level!

- We only measure layer-averaged material properties.

We need the distribution of properties across the thickness.

- The space between the layers cannot be modeled properly.

Approaches Alternative to 3D modelling

1. ***Pore-scale modelling***

   Can be done for a few layers but not for a large number of layers and/or for a large horizontal extent

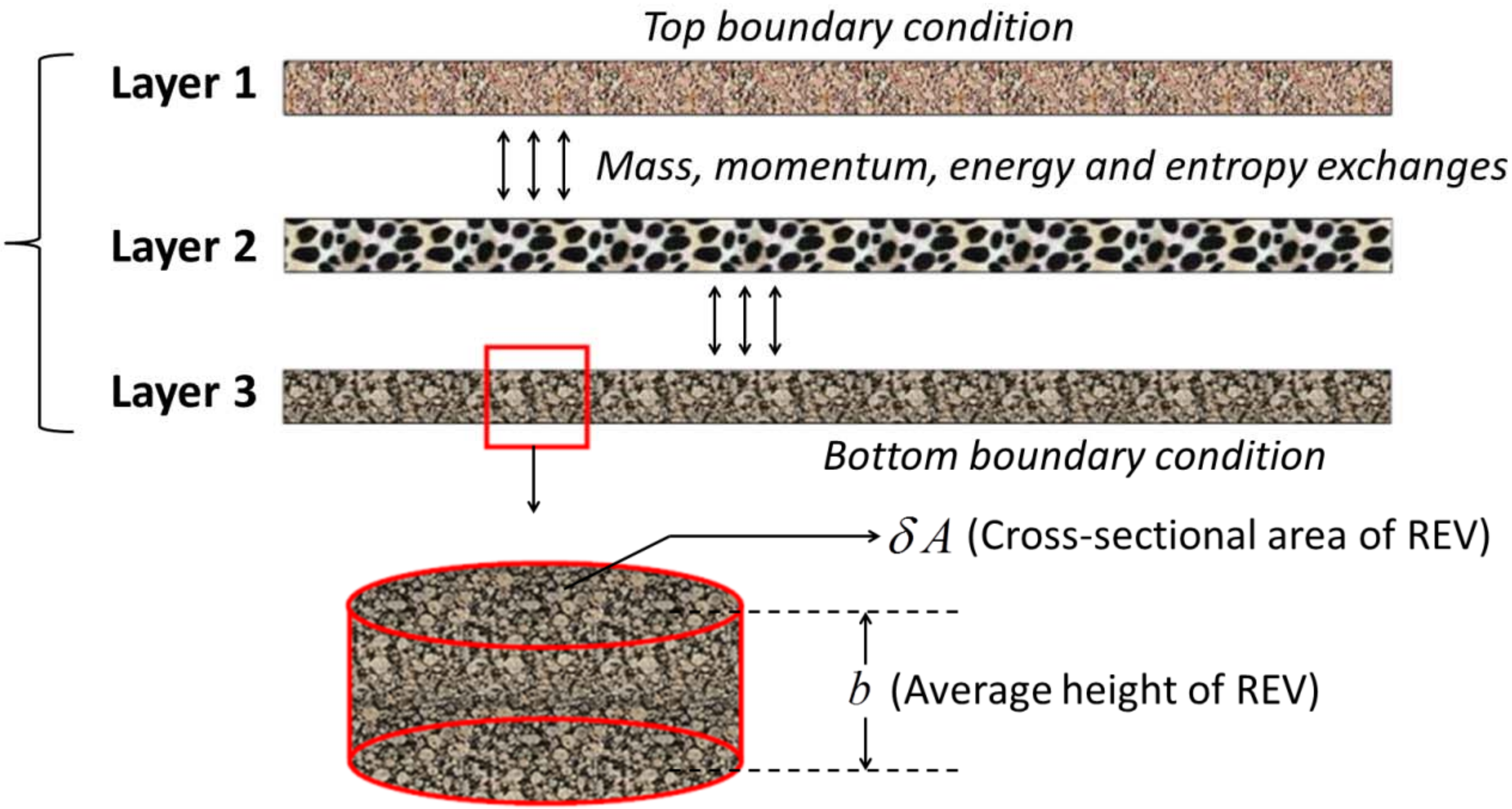
2. ***Our proposed approach***

   Model the layers as interacting two-dimensional continua

   (*Reduced Continua Modelling* (RCM) *approach*)

Developing equations for 2-D continua

Problem domain:



Representative elementary volume (REV)

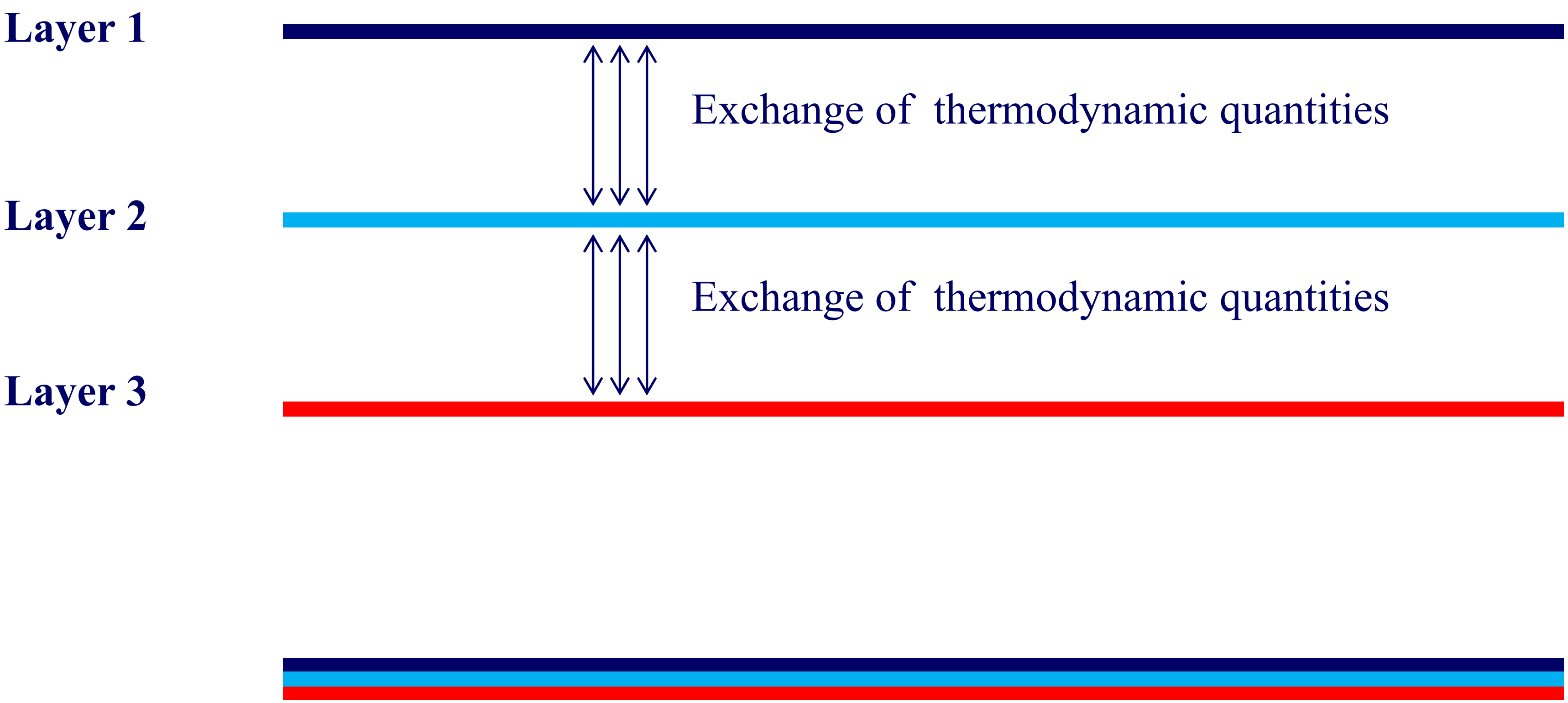
Averaging-Thermodynamic Approach (Hybrid Mixture Theory) for the Development of Basic Equations of Flow and Transport

- **Governing equations at a given scale compose of two ingredients: conservation laws and constitutive equations.**

- **Use the *Averaging Approach* to derive conservation laws at the scale of interest, based on the description at a lower scale.**

- **Use the *Thermodynamic Approach* to derive constitutive laws at the scale of interest (not at a lower scale).**

Reduced Continua Approach



Conclusions

- For study of two-phase flow in industrial porous media, we need to meet major challenges in imaging, visualization, and modelling.

- Finite size of industrial p.m. makes them ideal for full-scale imaging and pore-scale simulations

- Thin porous media should be modelled using Reduced Continua Approach

Post-doctoral position:
development of a novel fiber-scale modelling approach for modelling two-phase flow in fibrous materials.

International Society for Porous Media (interpore.org)

Occurrence of temperature spikes during wetting of paper

Why is spontaneous imbibition occurring?

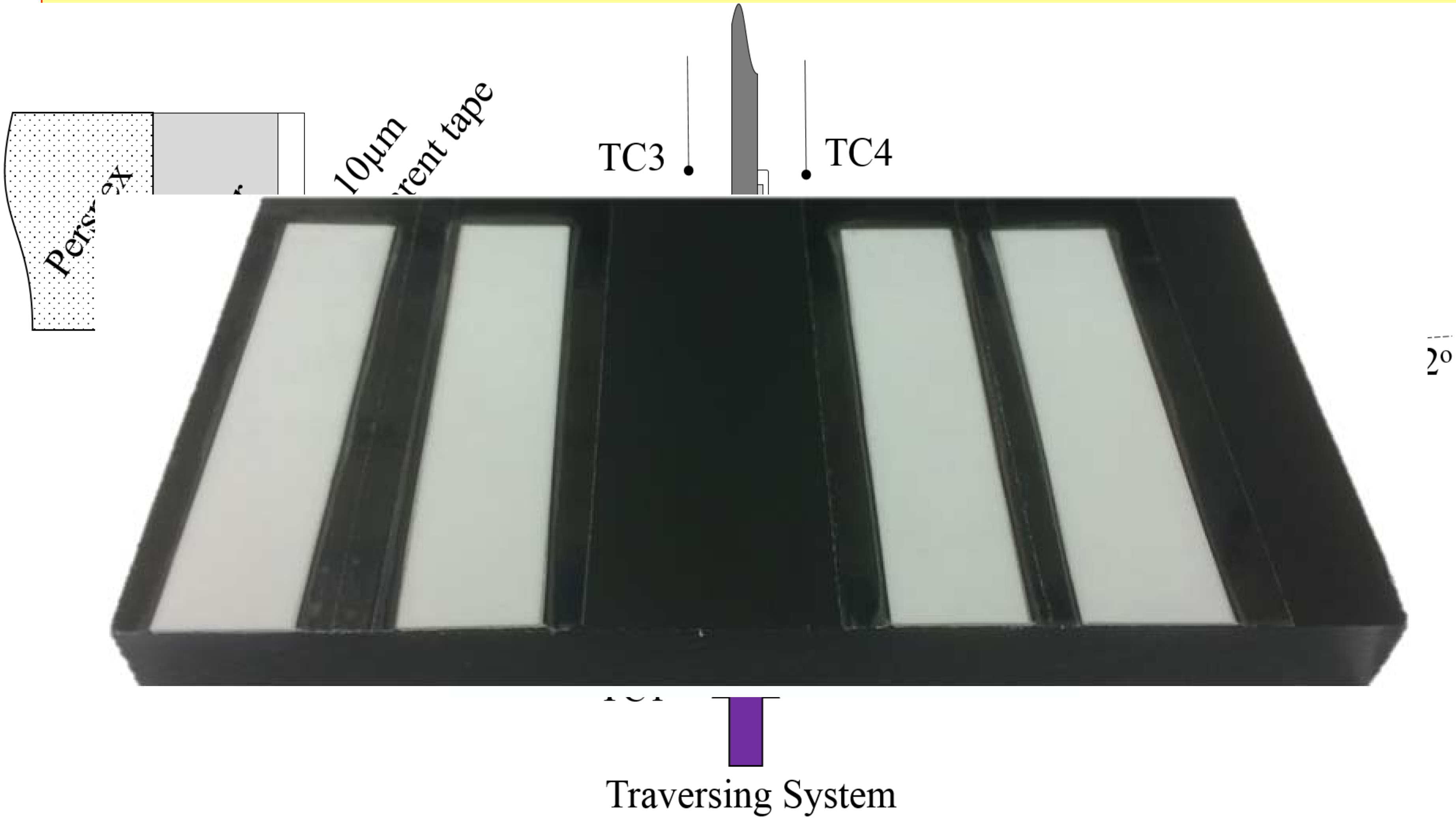
Water invades a hydrophilic material because the whole system goes to a lower energy state.

The surface energy of air-solid interface is much larger than that of water-solid surface:

$$\sigma^{as} - \sigma^{ws} = \sigma^{aw} \cos\theta$$

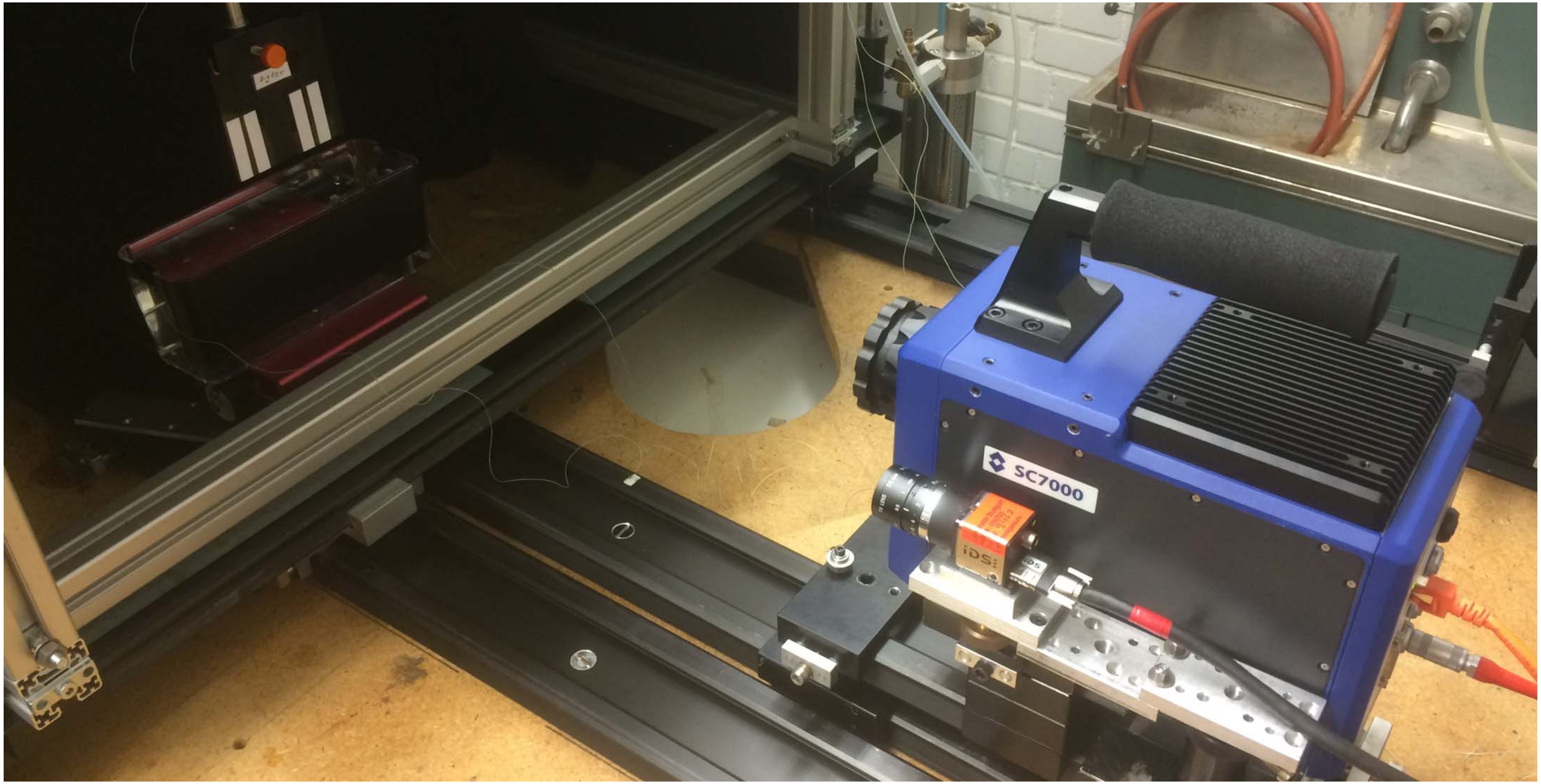
At the wetting front energy is released.

Why is spontaneous imbibition occurring?



Penetration of water into paper;
optical imaging and temperature change

Why is spontaneous imbibition occurring?



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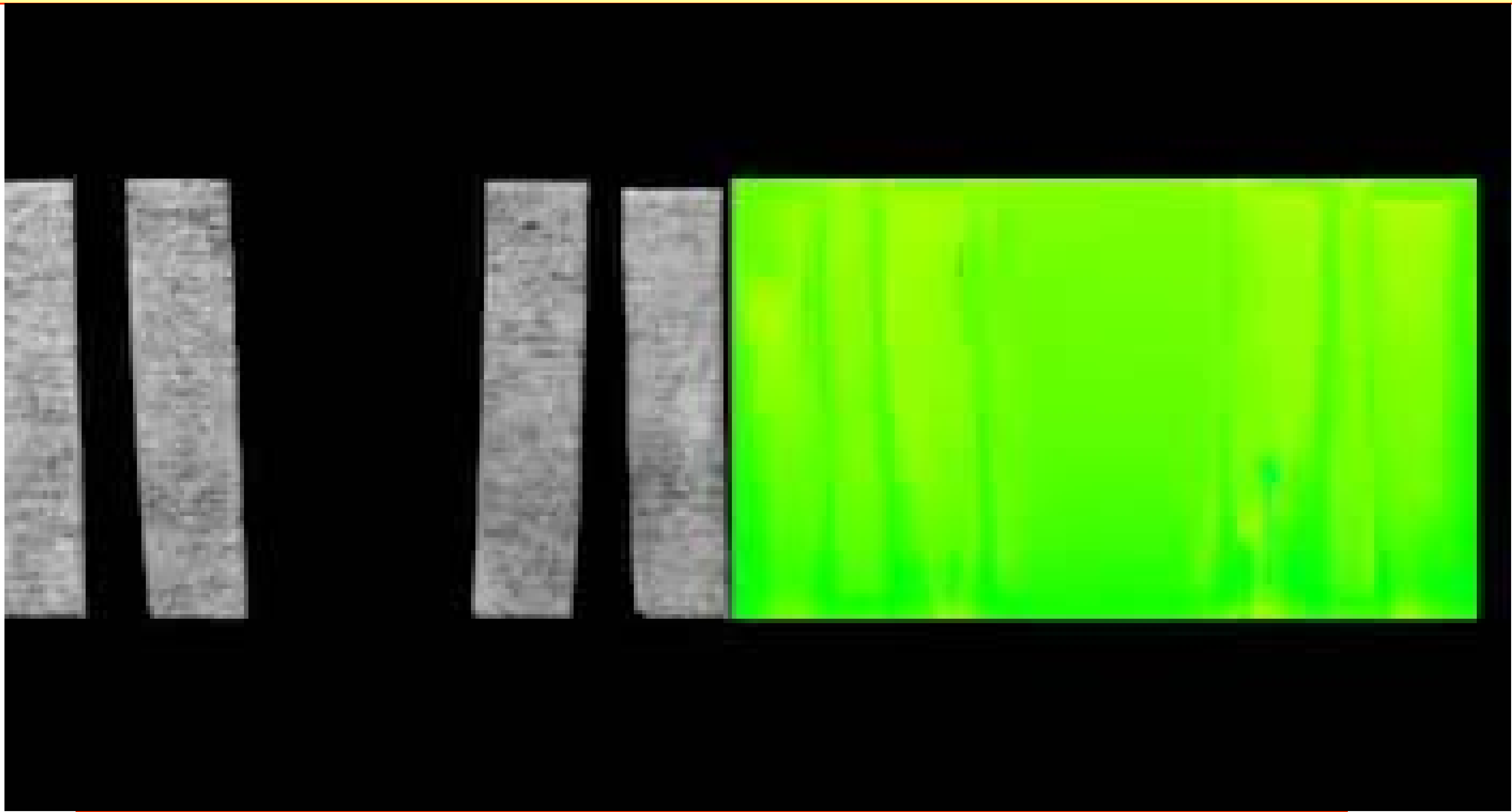

Rise of temperature at the wetting front

Temperature rise is due to the energy released from wetting of solid surface