Liquid imbibition in porous media investigated by pore network modeling and pore scale experiments

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Introduction. Processes involving capillary induced liquid flow are encountered frequently in nature and various engineering applications. For example, capillary flow is one of the indispensable mechanisms in plants to bring water from the roots to the tips. The mathematical descriptions and physical explanations of such processes are usually complicated because of the intricate pore-scale structure of the porous media and its interactions with liquid. Oftentimes, simplifications are crucial in order to circumvent these complexities. In this sense, pore network modeling is one of the most popular and powerful computational methods that are used to study flow and transport processes within both scientific and engineering societies. The essence of this method is to model the void space of a porous medium by a representative network of pores, and in turn to simulate the liquid transport in single pores by simplified pore-scale physics.

Problem Definition

Traditionally, the flow problem in porous media is investigated by phenomenological approaches (macro-scale), in which the detailed pore-scale physics are averaged into effective parameters. However, these approaches are limited in their predictions of pore-scale influences on liquid flow. Therefore, the pore network modeling is essential for microscopic studies of capillary induced liquid flow.

Objectives

This project aims to develop a pore network model that shall contribute to a better understanding of how the structure of porous media as well as the liquid properties influence the liquid flow, in particular, in the sense of liquid phase distributions and flow rate. Moreover, experimental results are required to assess the model.

Cooperation

- Prof. Dr. F. Scheffler (ICH, FVST, OvGU): digital microscope
- M. Sc. Z. Kutelova (IVT, FVST, OvGU): contact angle measurement
- Dr. J. Müller (P&G): Pampers® Baby Wipes

Pore Network Model Description

- Pore network
  - Regular lattice with different network structures (Fig. 1)
  - Throats: cylindrical ducts with uniform length and distributed radius assigned according to a given pore size distribution
  - Nodes: junctions of multiple throats without volume

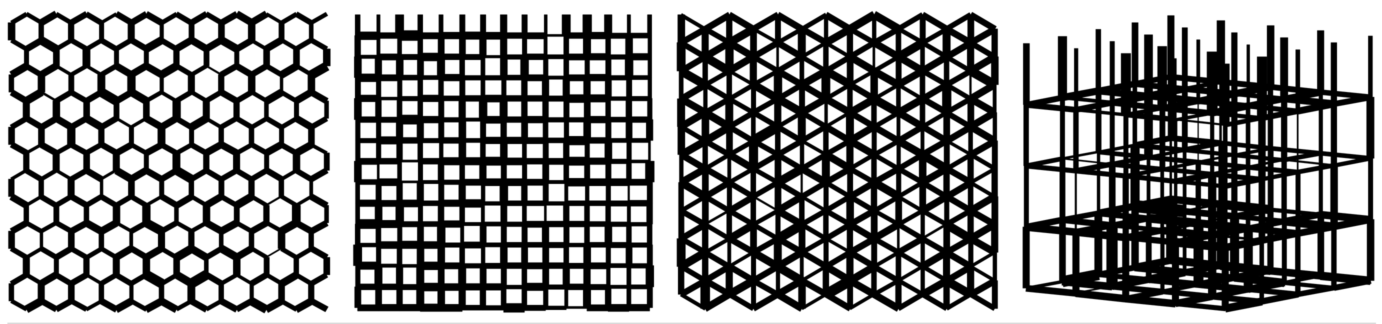

Figure 1. Pore networks with different lattice structures in 2D and 3D.

- Liquid flow algorithm
  - Driving force: capillarity and gravity
  - Pore-level discrete events: create moving menisci in throats according to associated liquid pressures
  - Liquid transport in single throats: Poiseuille's law $\dot{M} = \frac{\pi r^4 \Delta P}{8 \nu L}$
  - Mass conservation at nodes $\sum \dot{M} = 0$

r	throat radius [m]
ΔP	pressure difference [Pa]
L	liquid filled length [m]
ν	kinematic viscosity [$m^2 s^{-1}$]

- Input parameters
  - Liquid phase: surface tension, contact angle, viscosity, density
  - Solid phase: pore size distribution (PSD), geometric dimension, porosity

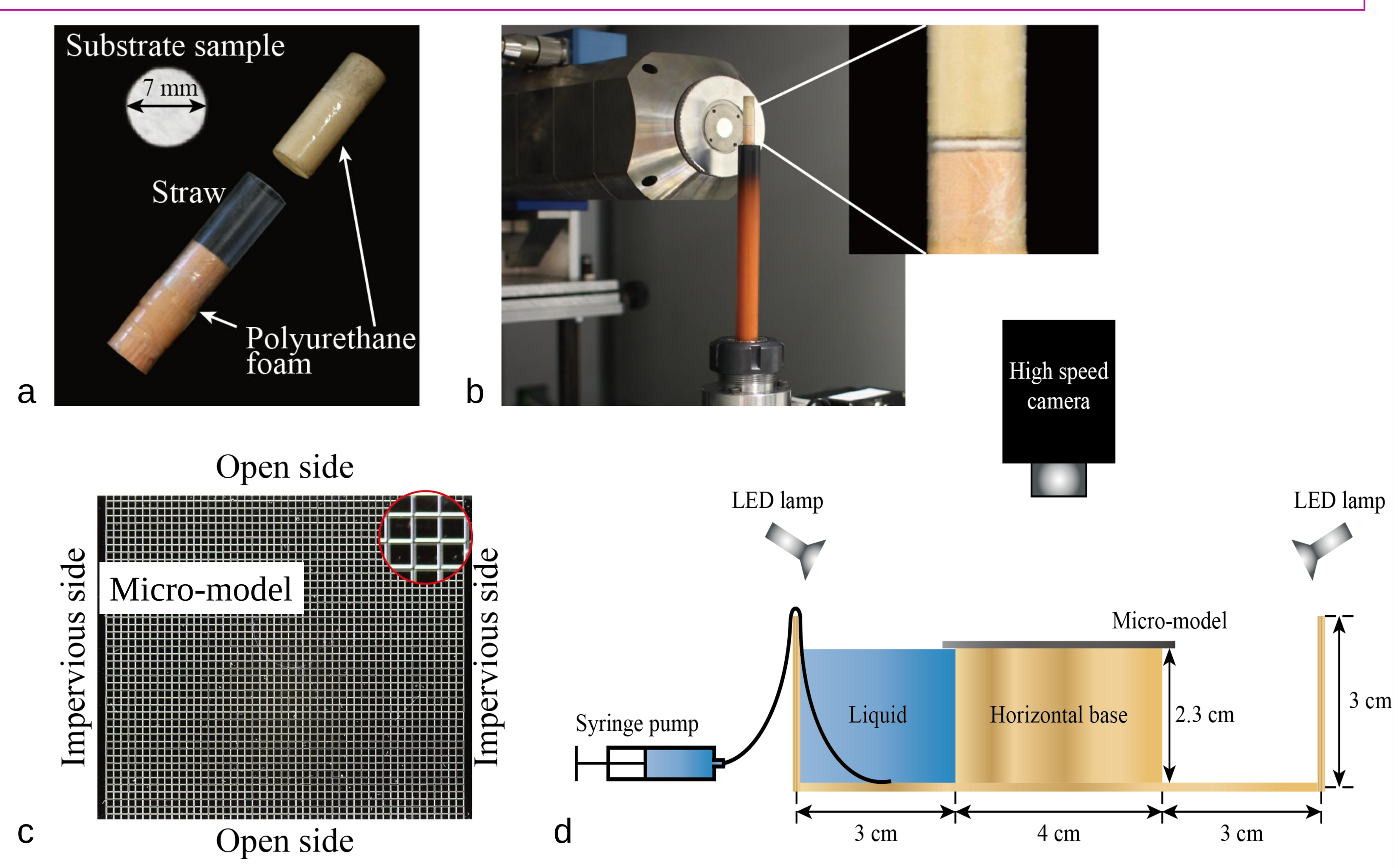

Figure 2. a) Preparation of sample for X-ray scan, b) sample in the X-ray micro tomograph, c) etched glass micro-model, and d) schematic illustration of experimental setup developed for imbibition experiment.

Experiments and Simulations

- Liquid phase distribution
  - Pampers® Baby Wipes: nonwoven substrate wetted by lotion
  - Experiments: taking 3D images of dry and wet samples using X-ray computed micro tomography (Figs. 2a-b, 3), and extracting the structural properties of dry samples and the lotion saturations in wet samples from the obtained images
  - Simulations: liquid imbibition into a representative pore network
  - Pore network generation for a single wipe (Fig. 4): 3 horizontal sub-layers with distinct structural properties, i.e. PSD and porosity, obtained from X-ray scans
  - Results: lotion saturations of each sub-layer at the equilibrium state (Table 1)

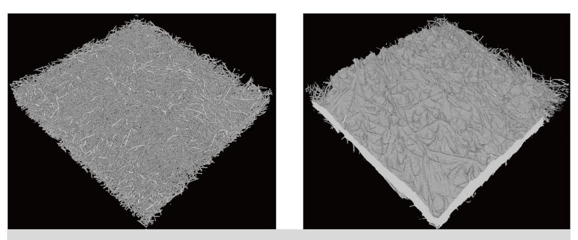

Figure 3. 3D images of dry (left) and wet (right) samples obtained from the X-ray scans.

Table 1. Lotion saturations at the sub-layers of wipes obtained from experiments and simulations.

	Substrate 1		Substrate 2	
	Exp.	Sim.	Exp.	Sim.
Sub-layer 1	0.28	0.32±0.04	0.43	0.52±0.03
Sub-layer 2	0.63	0.54±0.03	0.92	0.84±0.03
Sub-layer 3	0.14	0.20±0.03	0.41	0.45±0.03

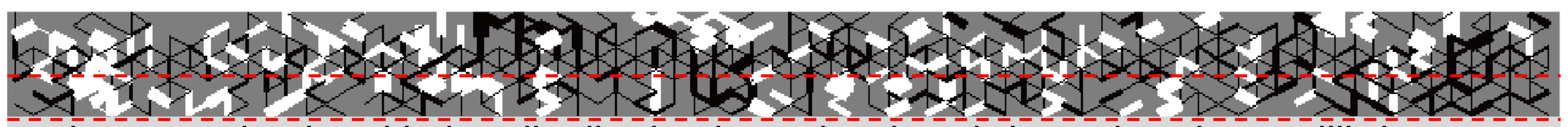

Figure 4. Simulated lotion distribution in a wipe (3 sub-layers) at the equilibrium state. Lotion is depicted in black.

- Imbibition rates
  - Etched glass micro-model (Fig. 2c): flow channels etched in a glass substrate with a designed pattern: square lattice with two opposite open sides, normal distribution of channel width
  - Experiments: recording liquid imbibition in the micro-model from one open side with 40%, 60% and 80% ethanol solutions (Fig. 2d)
  - Simulations of the experiments using the pore network model and comparisons with the experimental results (Fig. 5-6)

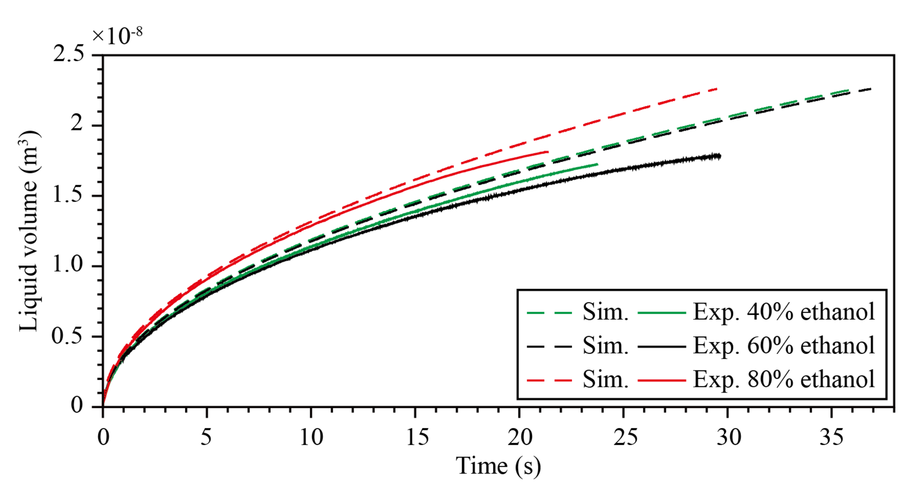

Figure 5. Liquid volume versus time obtained from the experiments and simulations.

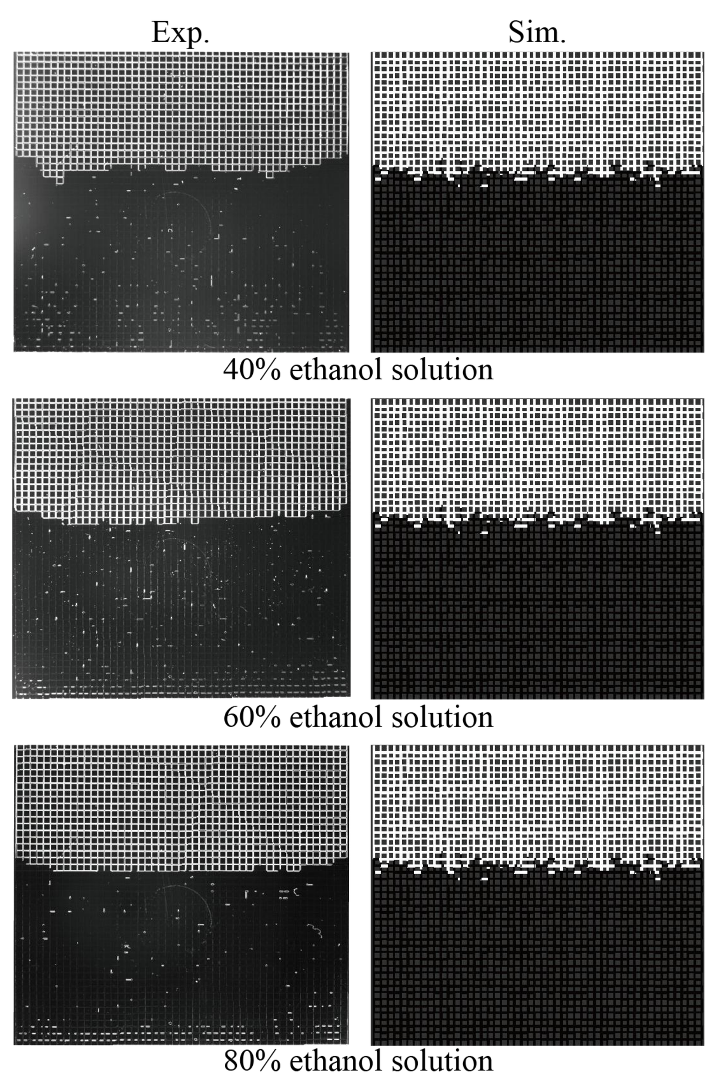

Figure 6. Phase distributions at network saturation 0.6 for different ethanol solutions.

Summary

- Structural properties as well as lotion saturations of wipes are obtained by X-ray computed micro tomography.
- Simulated saturations at each sub-layer of a wipe show relatively good agreements with the experimental data.
- Optical experiments with etched glass micro-model are conducted.
- Imbibition simulations are conducted with different pore structures.
- Pore network simulation predicts fairly the imbibition rates measured by the etched micro-model.

Outlook

Pore network model
- Incorporate node volume into the model
- Couple vapor diffusion to the current pore network model
- Extend the model to 3D

Experiments
- Improve the quality of images obtained from X-ray computed microtomograph
- Measure local distribution of lotion

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