



Pore-level visualization of foam in micro models for enhanced oil recovery

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Assistant Professor

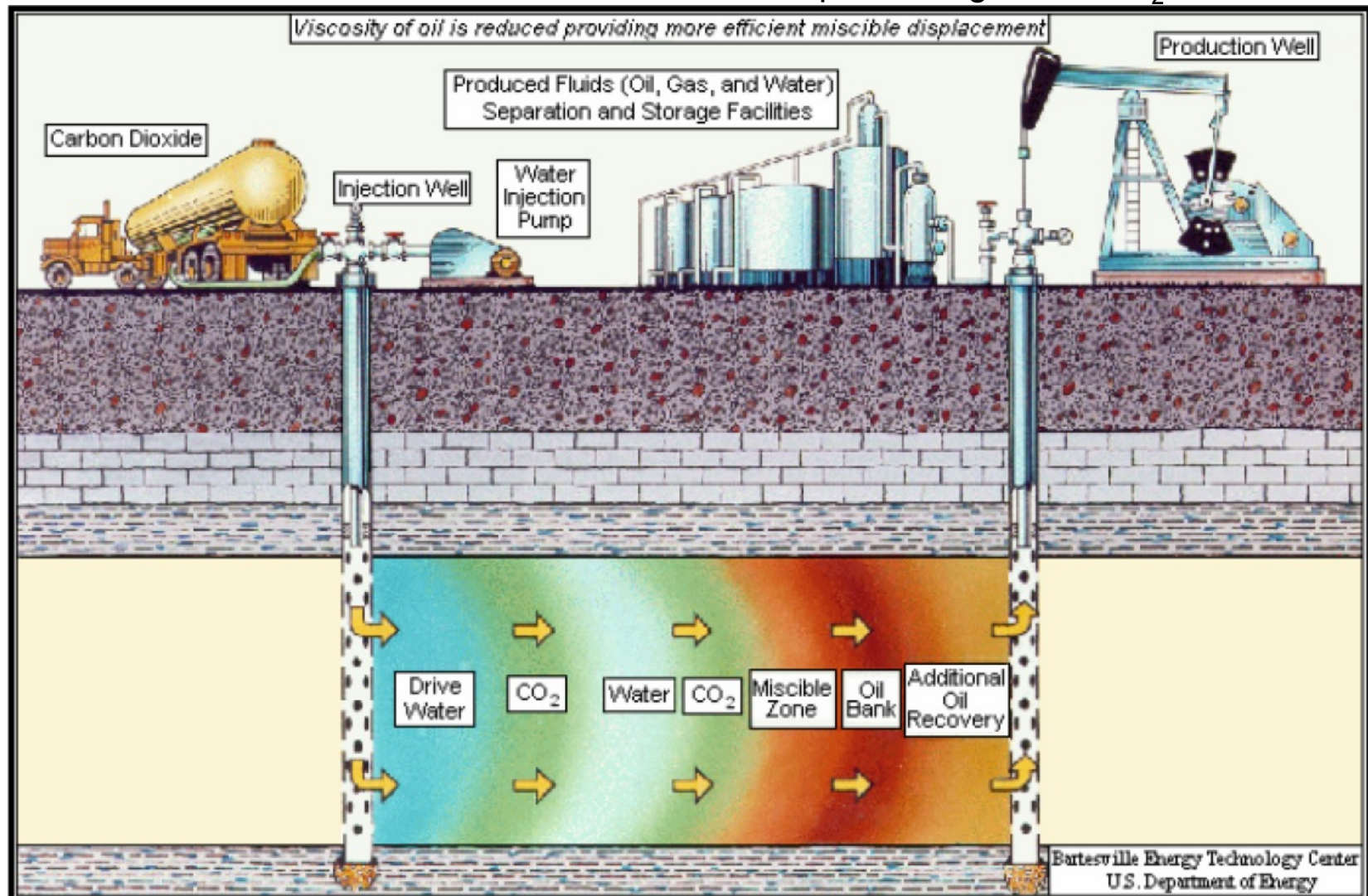
Department of Chemical & Biomolecular Engineering

Rice University, Houston, TX



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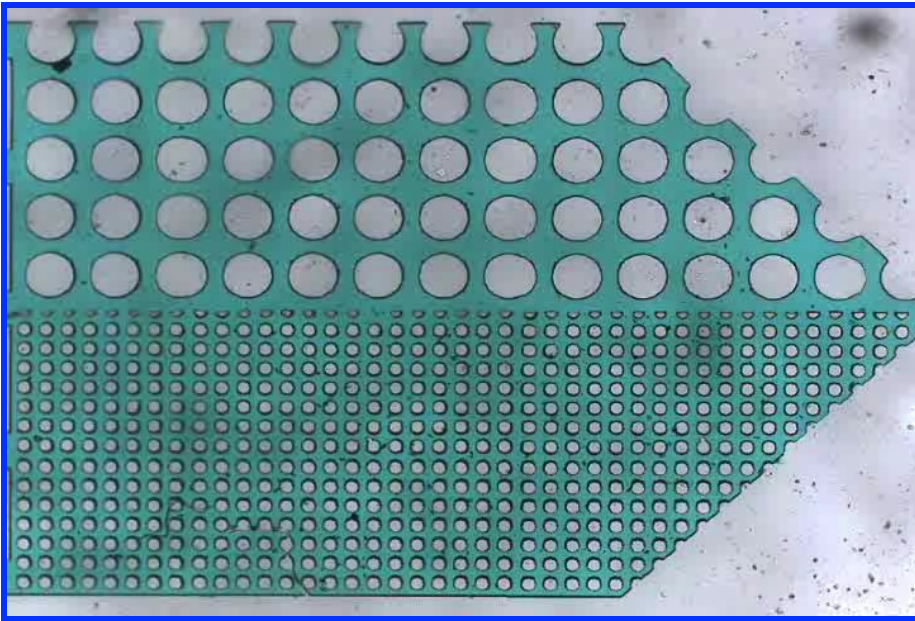
Simplified diagram of CO₂-EOR^[1]



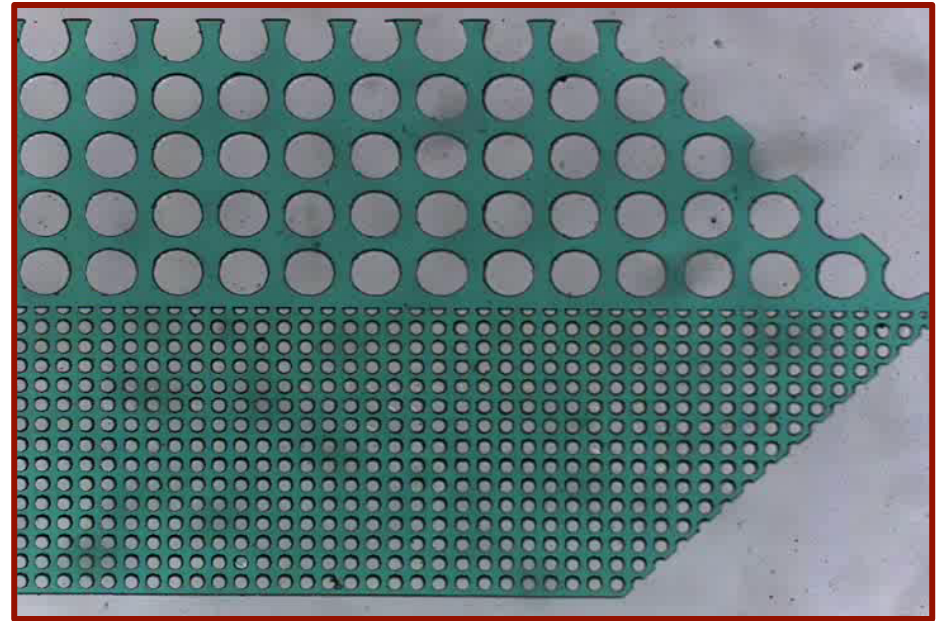
[1] Enhanced Oil Recovery. Web. 22 Apr 2011. <http://www.novomer.com/?action=CO2_PPC_enhancedoil>.

[2] Wilkes, James O. *Fluid Mechanics for Chemical Engineers*. Second Edition with Microfluidics with Microfluidics and CFD. Upper Saddle River, NJ: Prentice Hall, 2006. 387-394. Print.

Foam for EOR



Gas mobility visualized in a
micromodel with contrasting
permeability

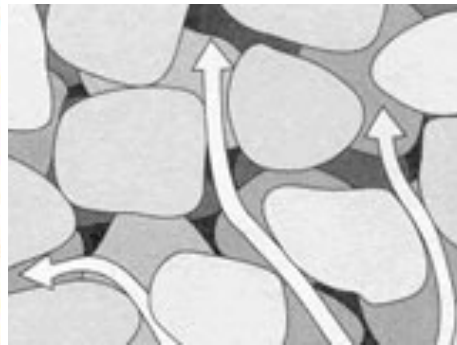


Foam mobility visualized in a
micromodel with contrasting
permeability



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Structure



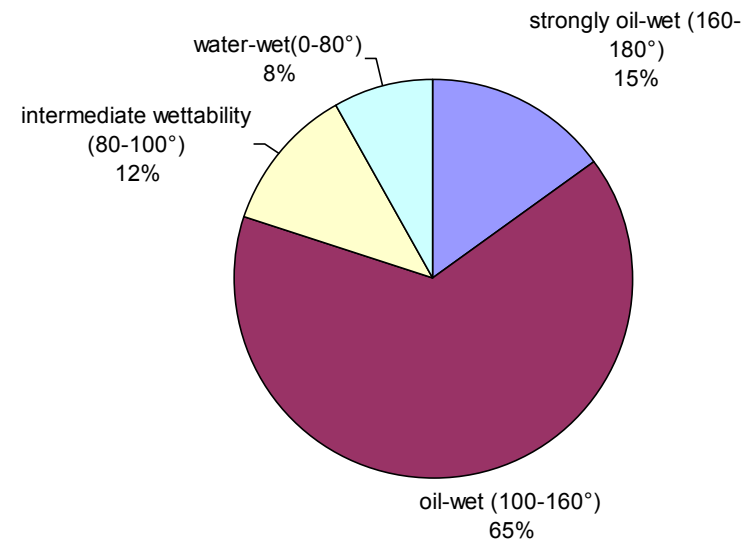
Pores¹ and vugs² in reservoir rock

1. Image Source: U.S. Department of Energy

2. Image Source: www.slb.com/Schlumberger

Micromodels

Wettability



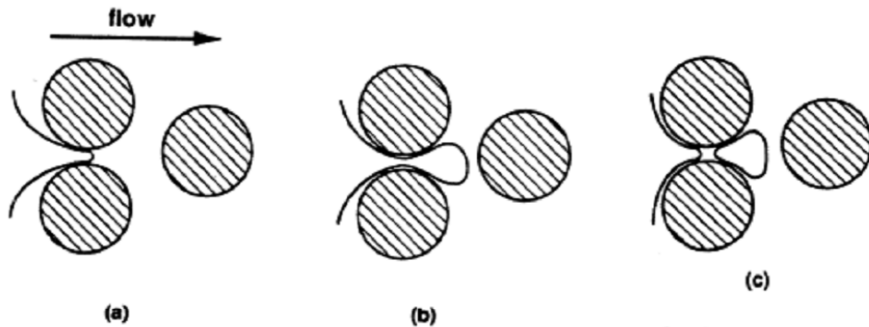
Wettability of carbonate reservoir rocks
(water contact angle, 161 samples¹)

3. Chilingar, G. V.; Yen, T. F., Energy Sources 1983, 7, (1), 67-75.

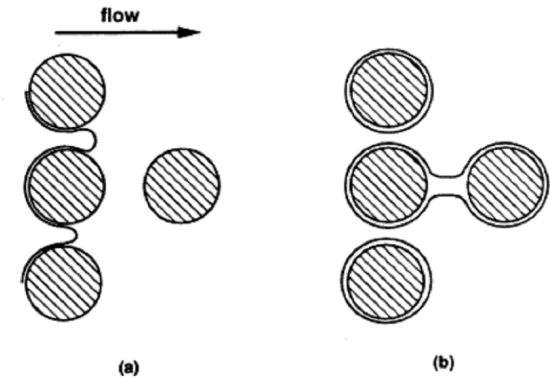


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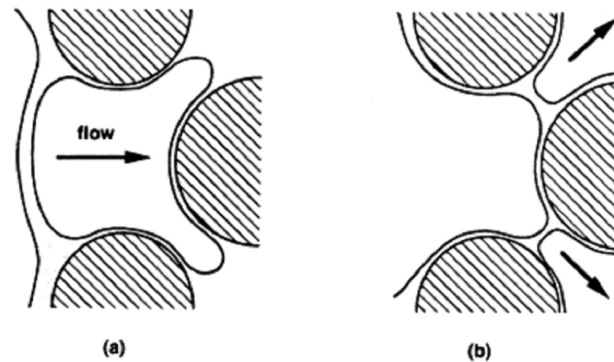
Generation of Foam in Porous Media



Snap-off



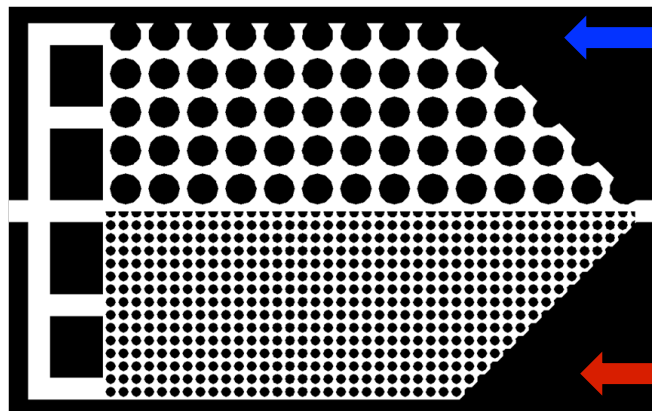
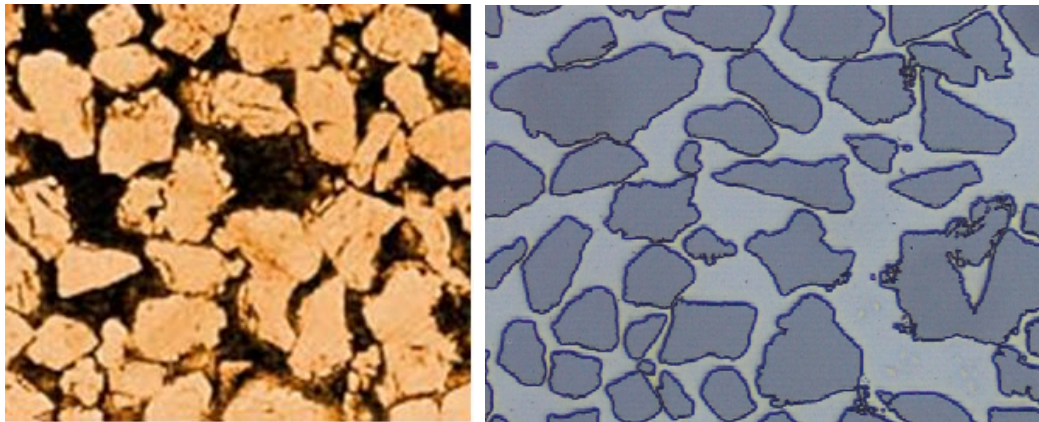
Leave-behind



Lamella Division

(Ransohoff and Radke, 1988)

Micromodels

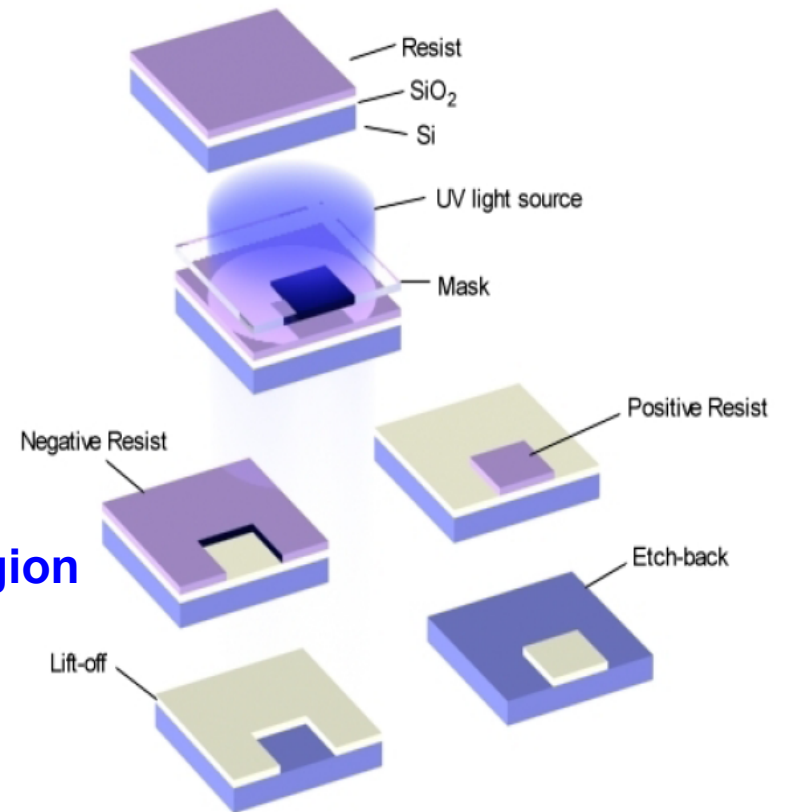


High Permeable Region

- grain radius 150 μm
- pore throat 60 μm
- porosity 0.45

Low Permeable Region

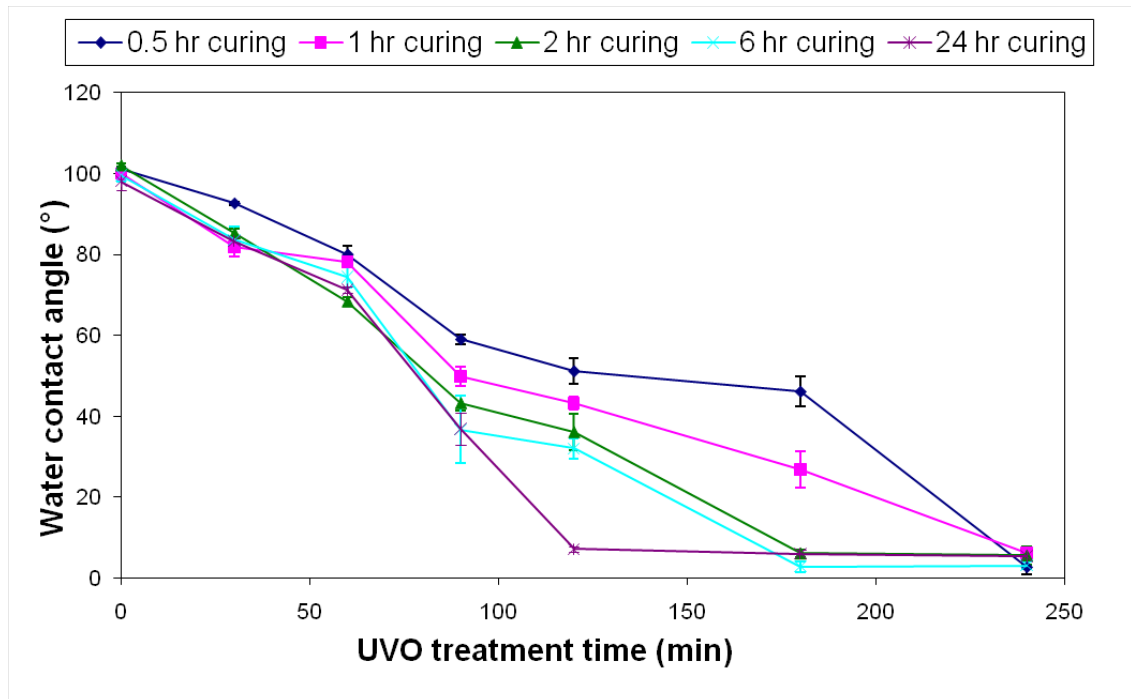
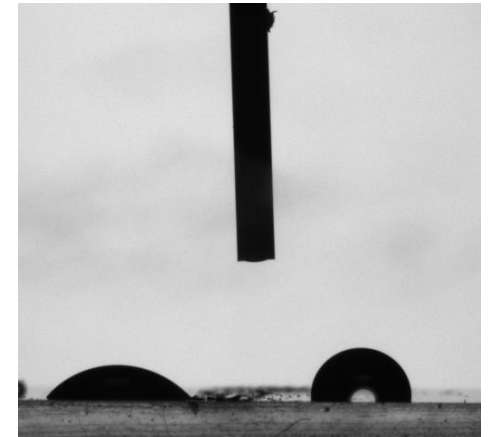
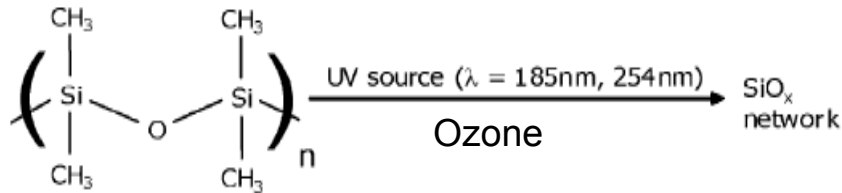
- grain radius 50 μm
- pore throat 20 μm
- porosity 0.45





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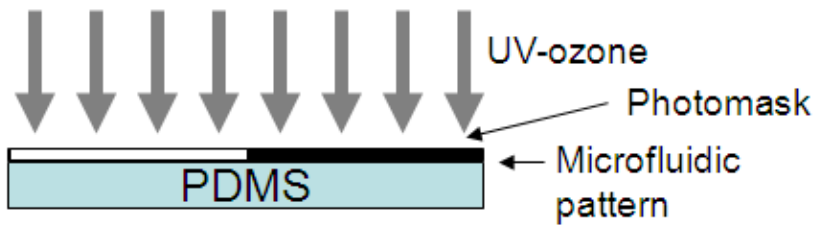
PDMS surface modification by UV-Ozone



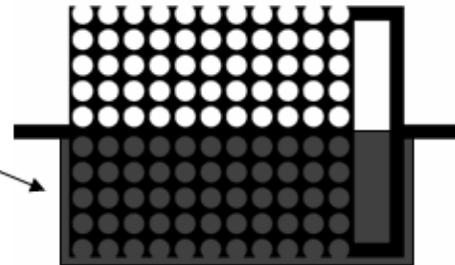
Can modify wettability by controlling ozone exposure and maintain wettability by water immersion

Patterning wettability

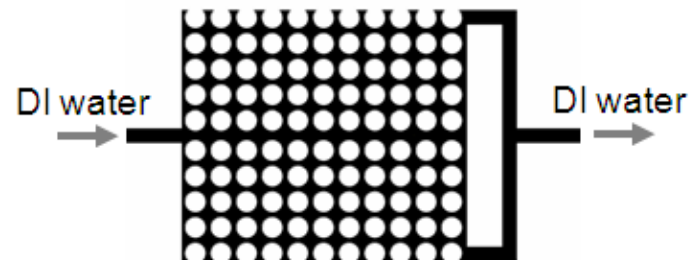
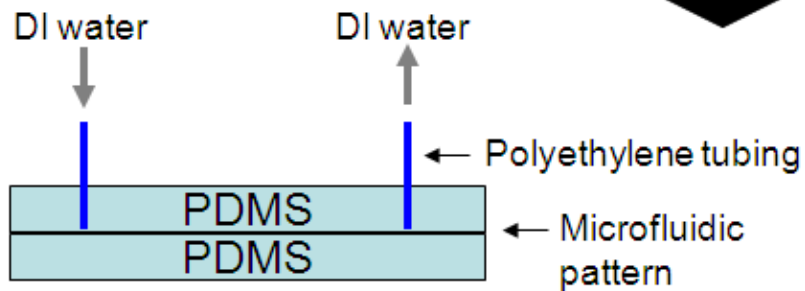
Side view



Top view



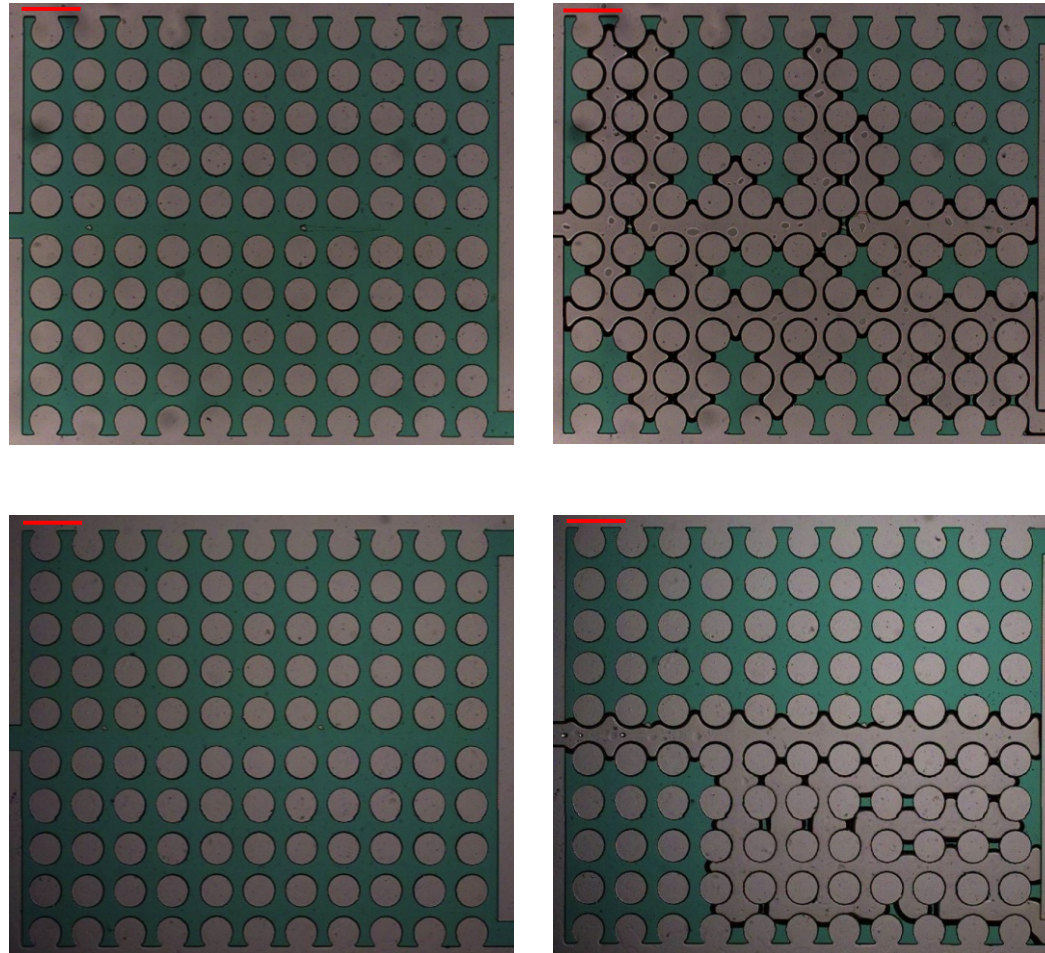
Step 1



Step 2

Wettability patterning

Homogeneous water
contact angle $\sim 100^\circ$

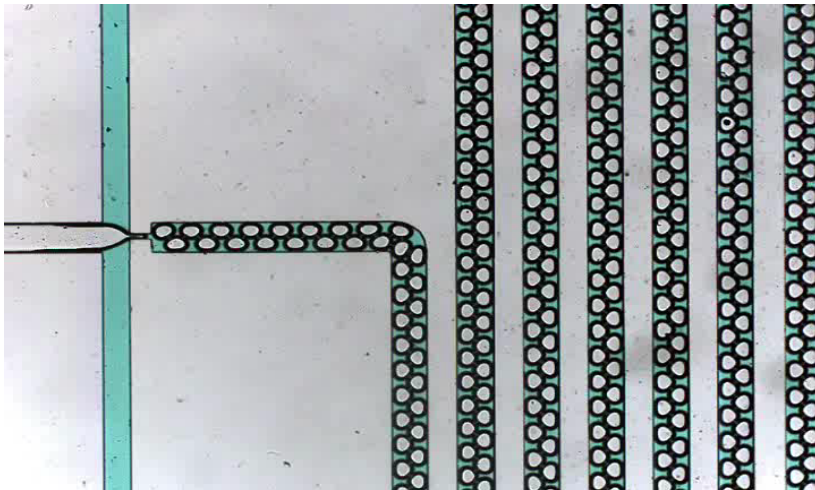
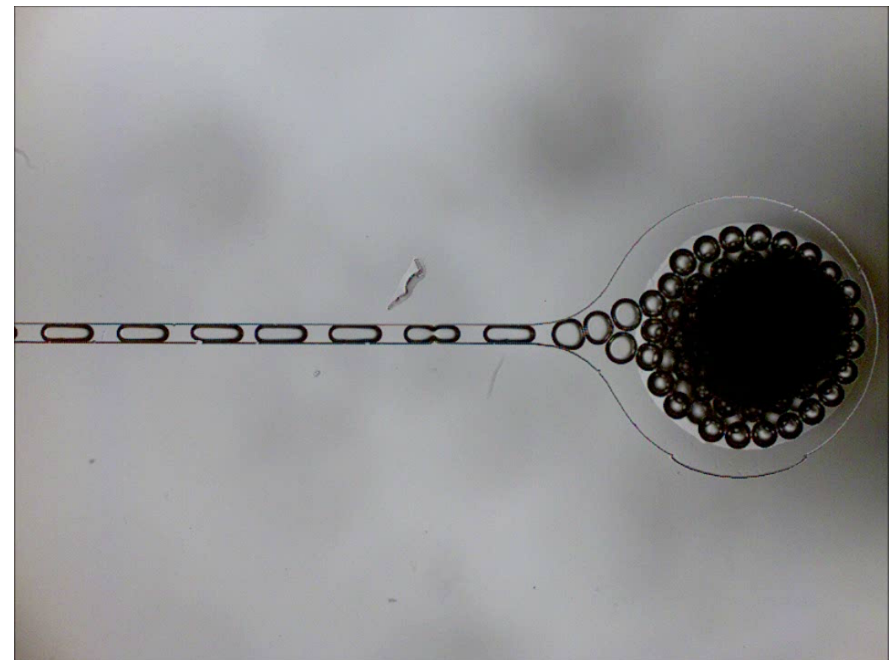
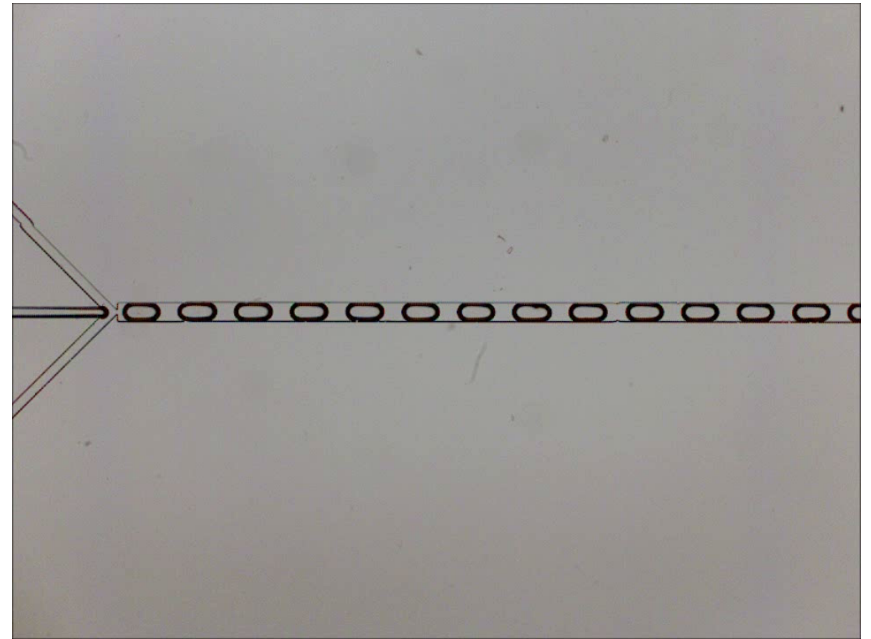
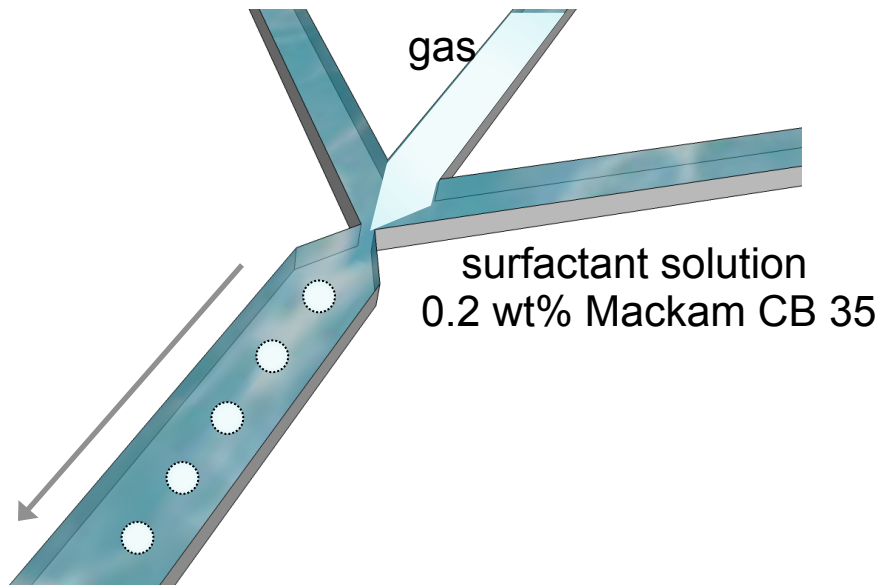


Left: initially saturated with dye solution; Right: after 2 min air injection at a volumetric flow rate of 1.0 ml/hr. The red scale bar at the upper left corner represents 500 μm .



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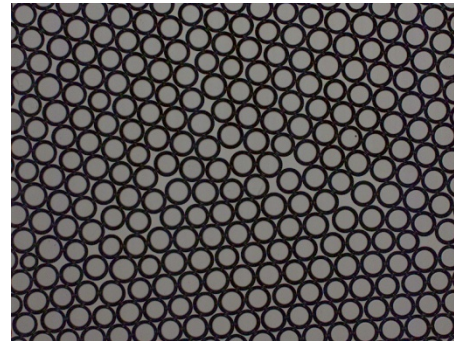
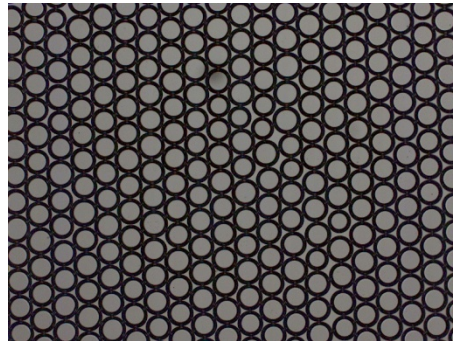
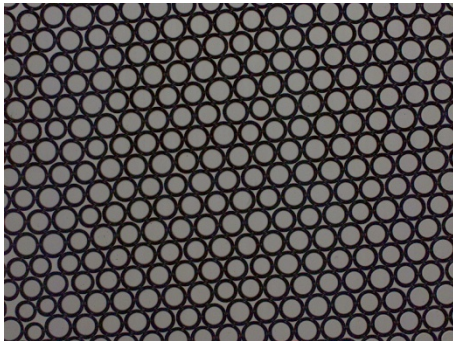
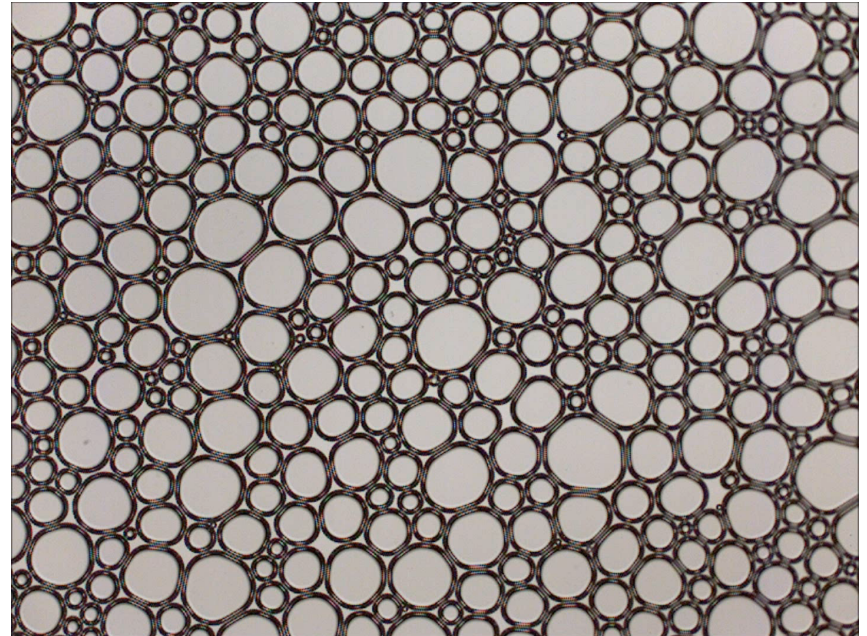
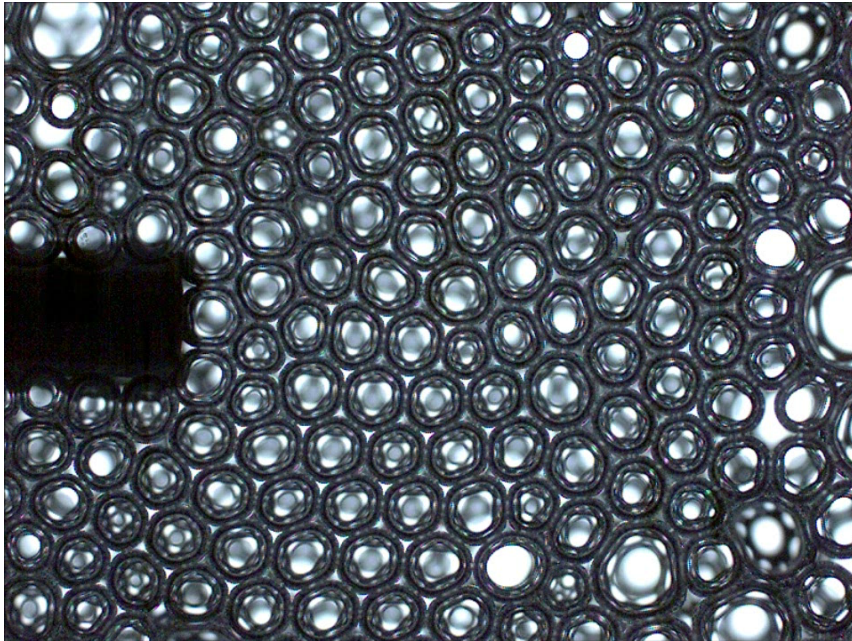
Foam Generator





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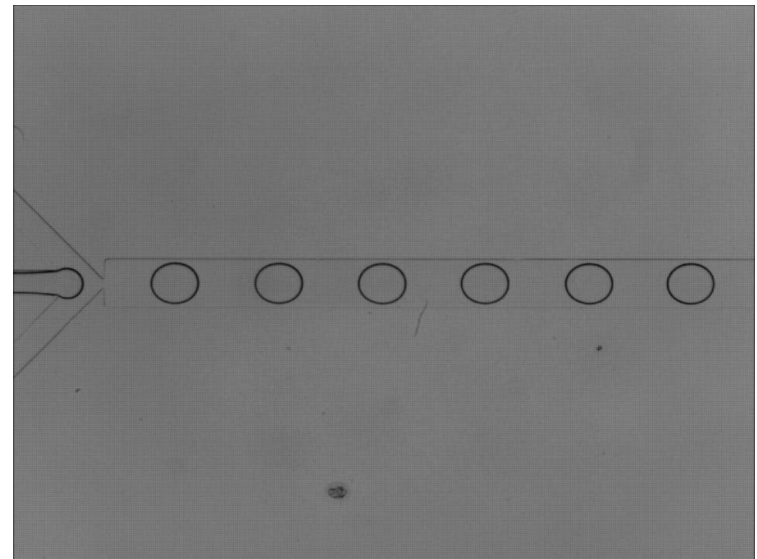
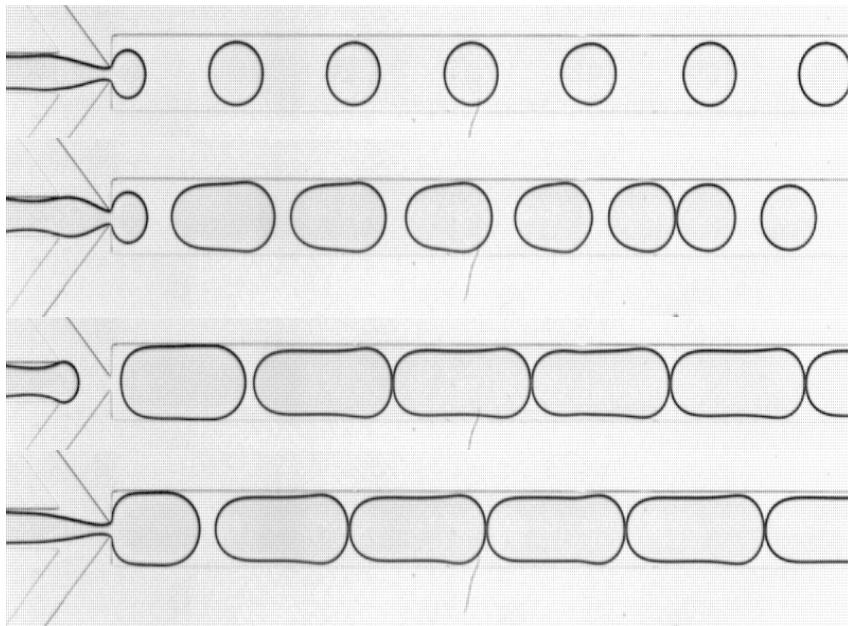
Foam Visualization





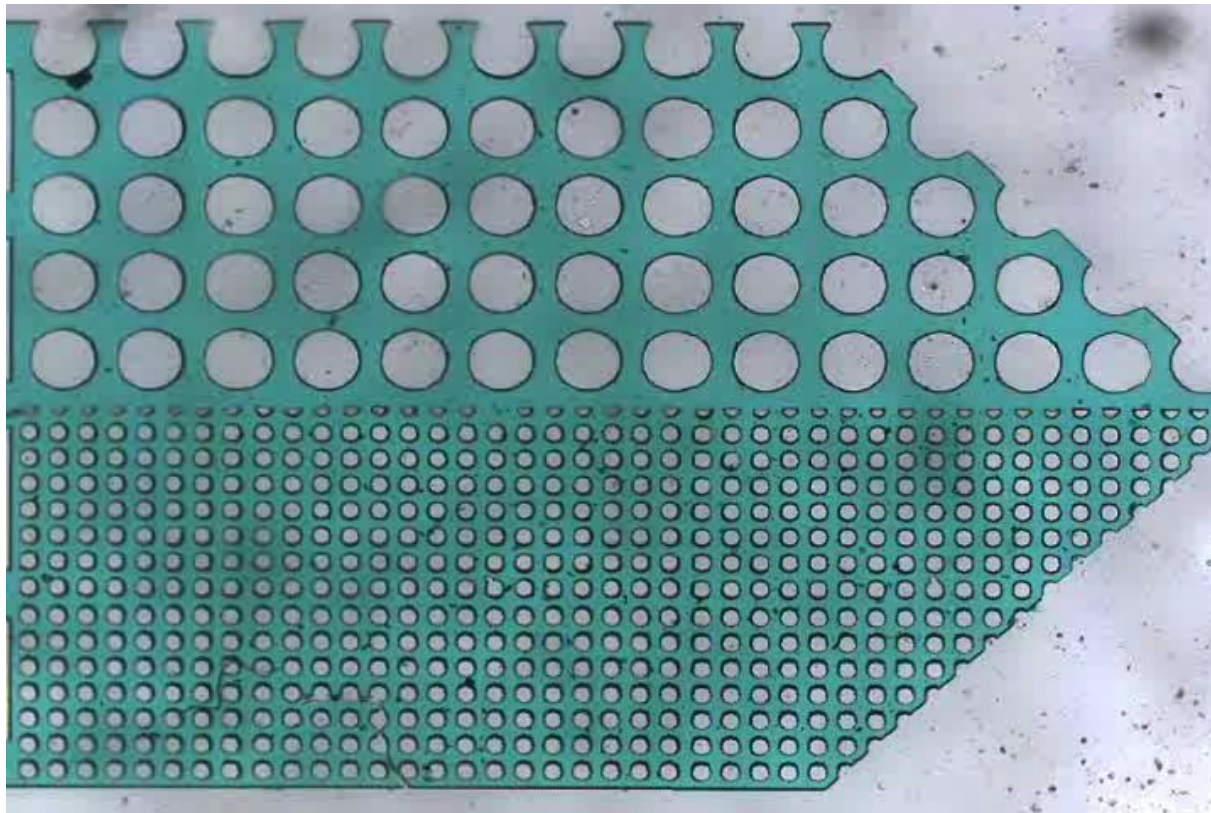
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Tuning Foam Quality



Gas Flood

Air is only able to flow through the high permeability region leaving the aqueous solution trapped in the low permeability region



Played at 1 frames per second, captured at 10 frames per second.
Injected gas flow rate 5.0 ml/hr, injected liquid flow rate 0.0 ml/hr.



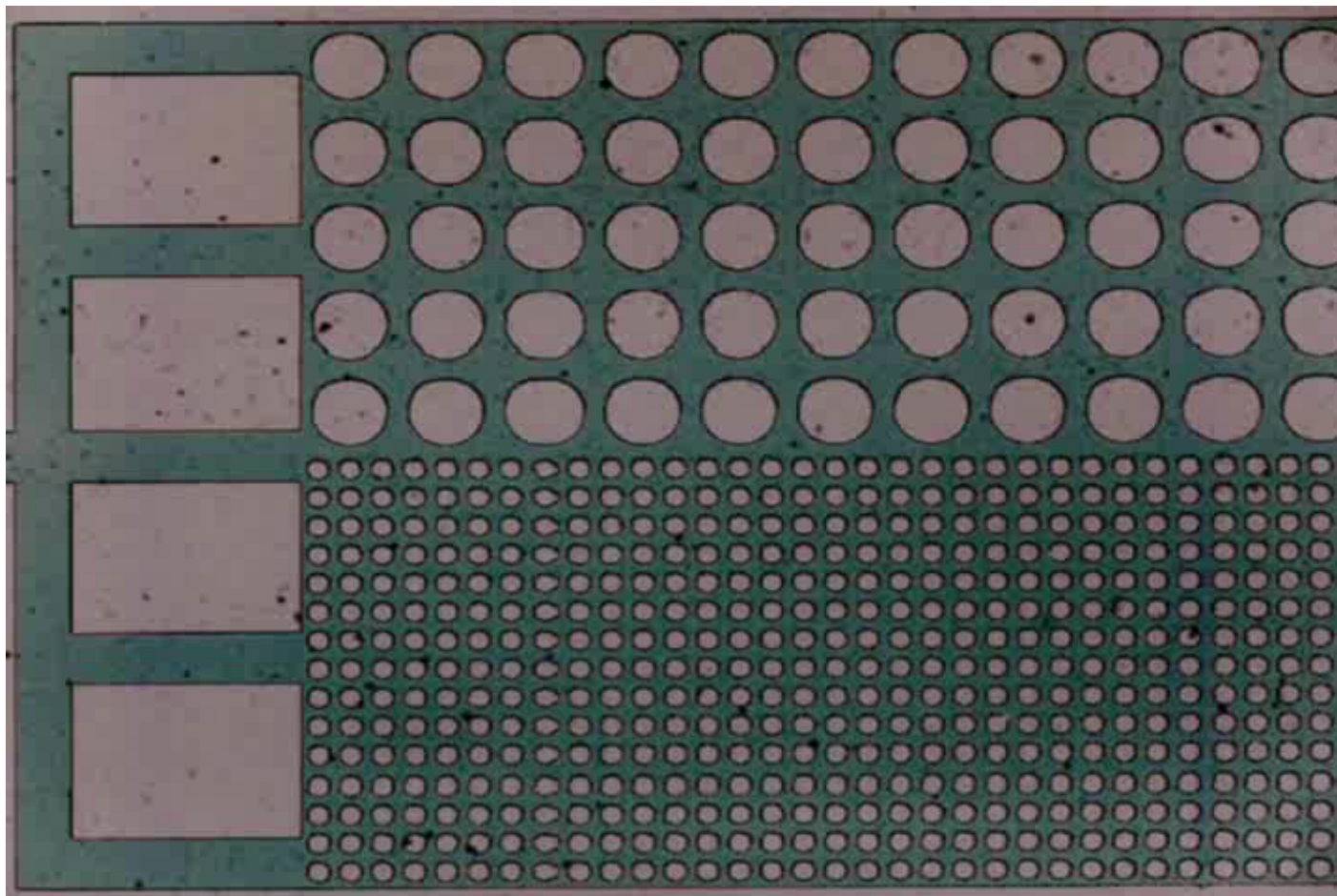
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Foam Displacement

98% Gas Injection

injected gas flow rate= 4.90 mL/hr

Injected surfactant flow rate = 0.10 mL/hr

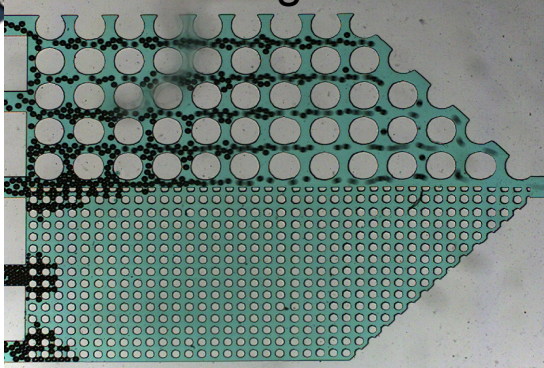




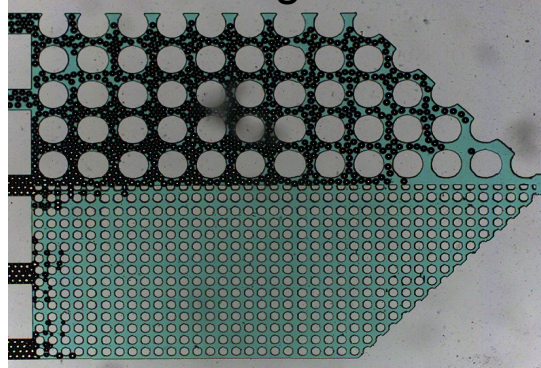
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Screening conditions

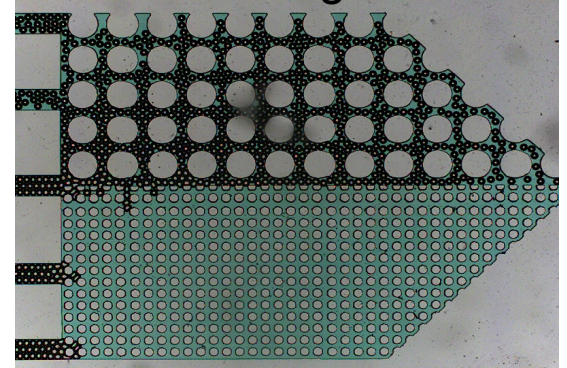
90% gas



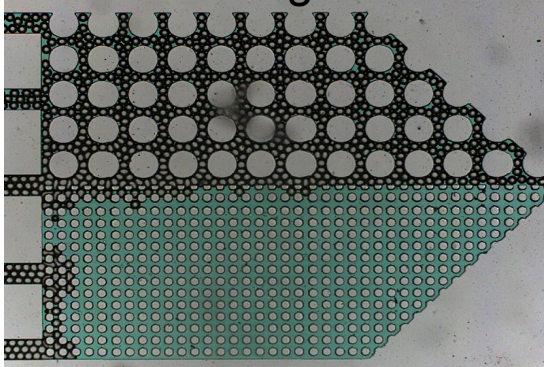
91% gas



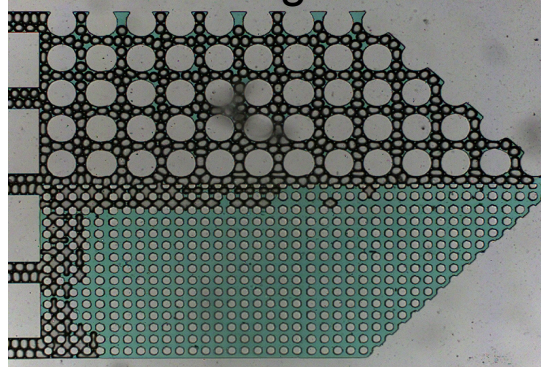
92% gas



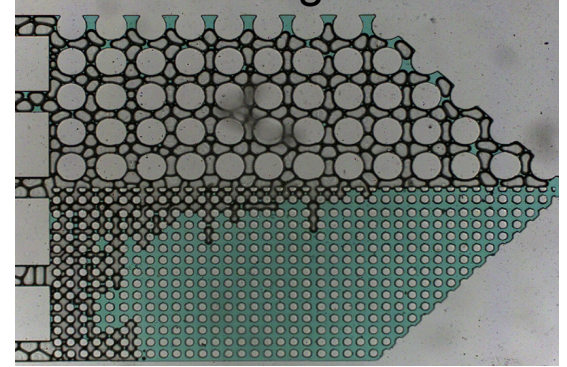
93% gas



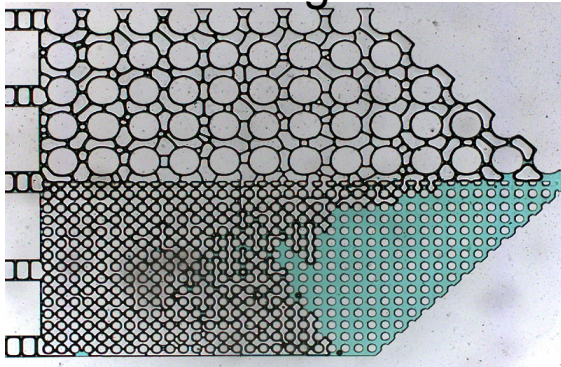
94% gas



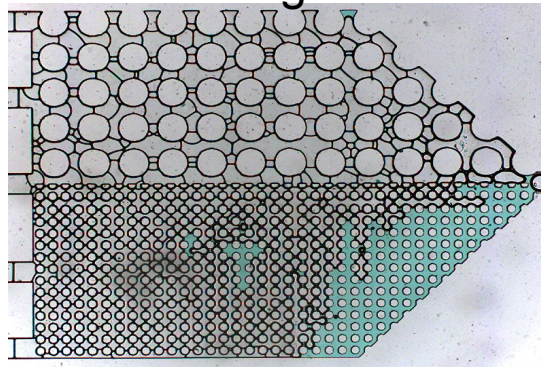
95% gas



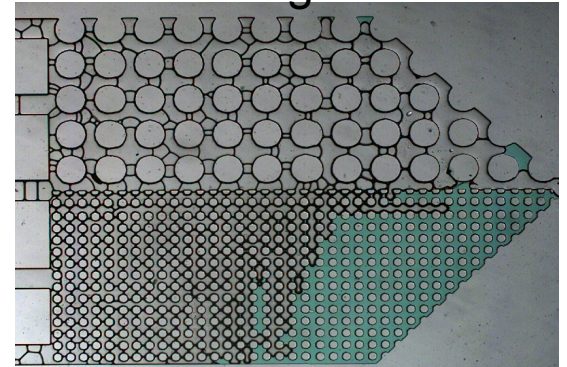
96% gas



97% gas



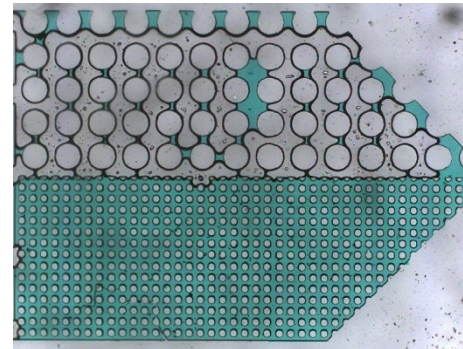
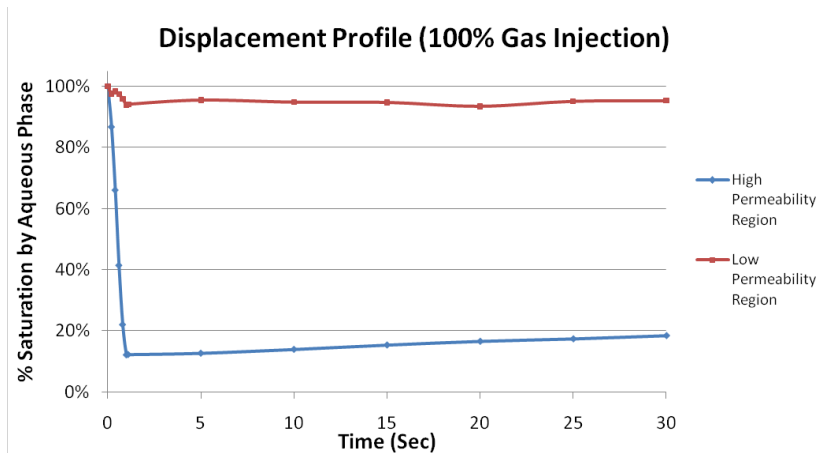
98% gas





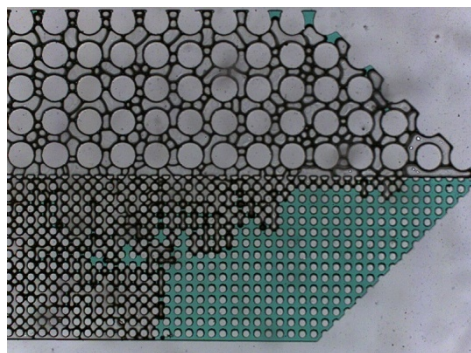
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Breakthrough Times

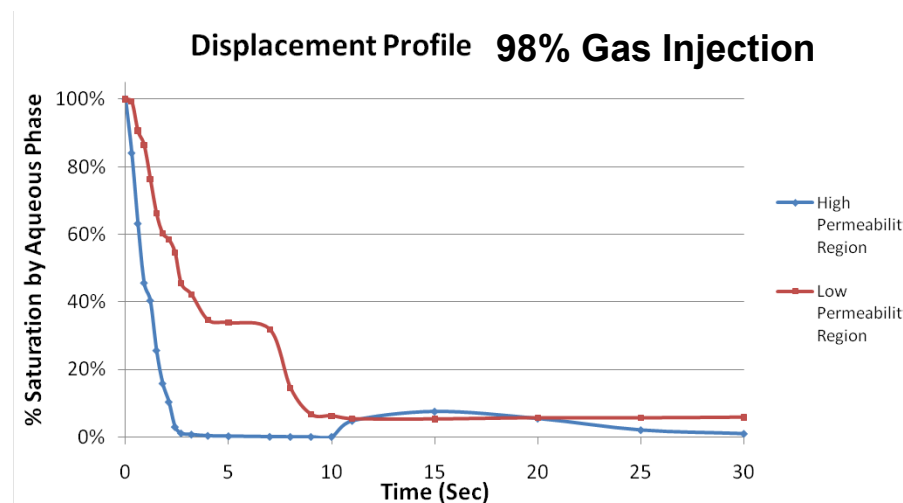


1.1 sec
(gas breakthrough)

$$t_b = \frac{V_{swept}}{u_g A} = \frac{V_{swept}}{\frac{kk_{rg} \nabla P}{\mu_g} A} = \frac{V_{swept} \mu_g}{kk_{rg} A \nabla P}$$



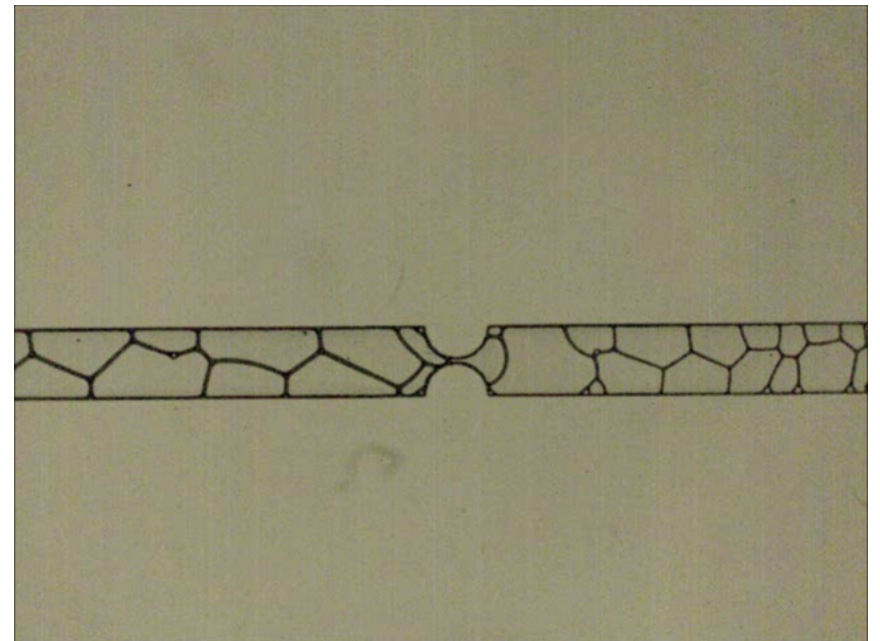
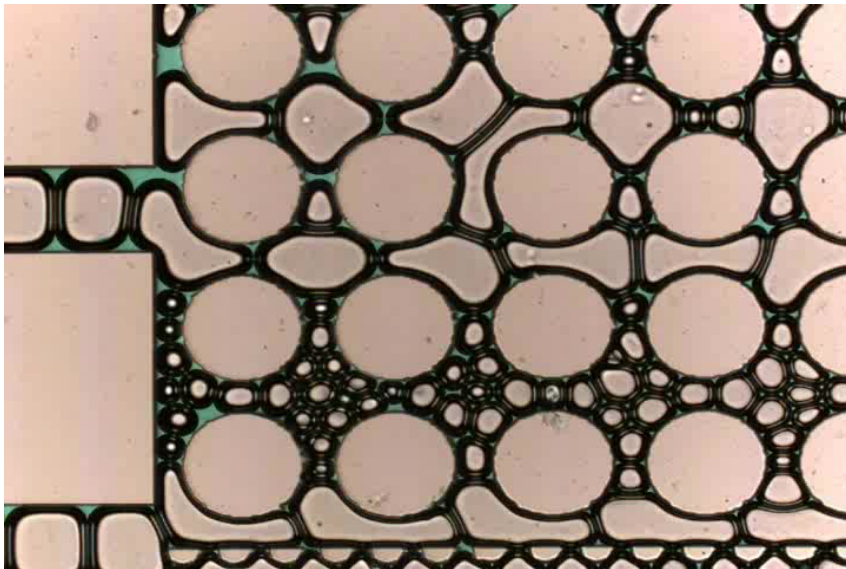
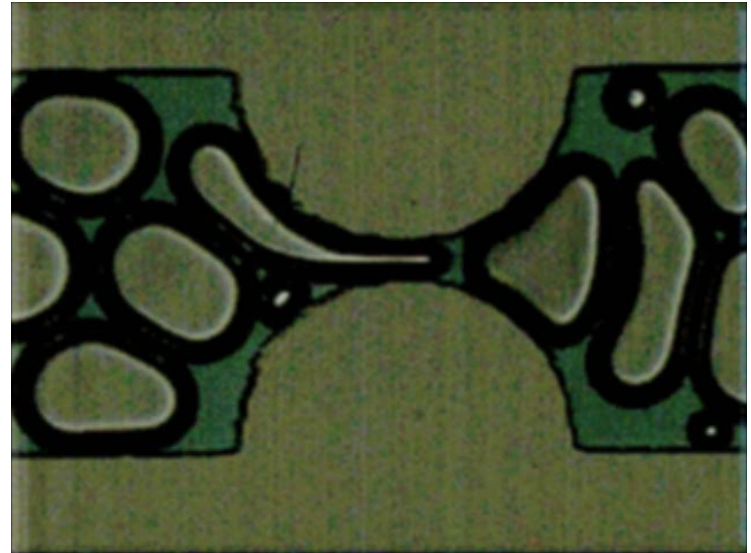
2.7 sec (gas breakthrough)





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Pore Level Visualization and Manipulation of Foam

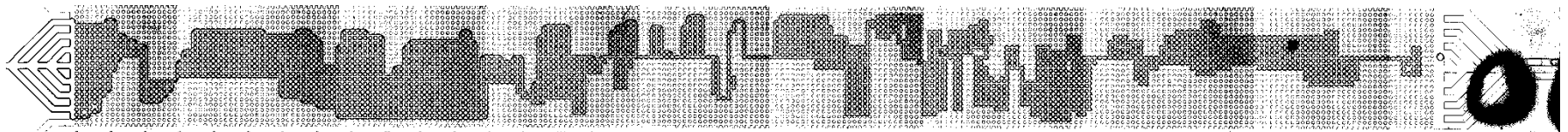
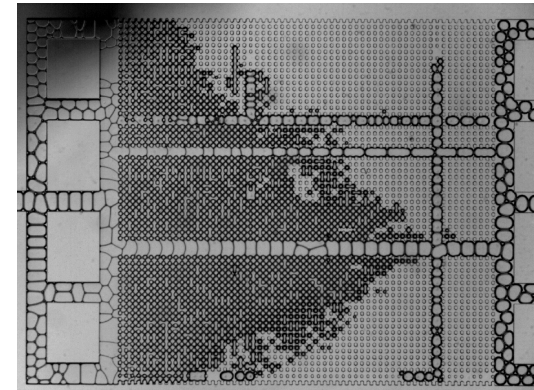
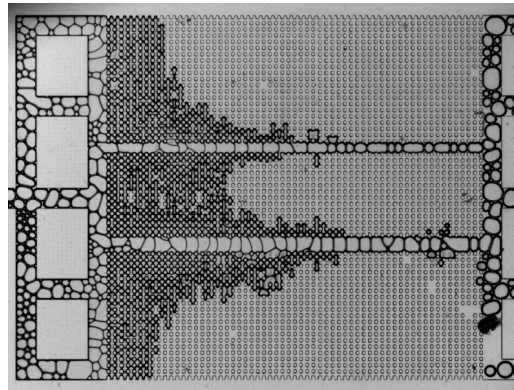
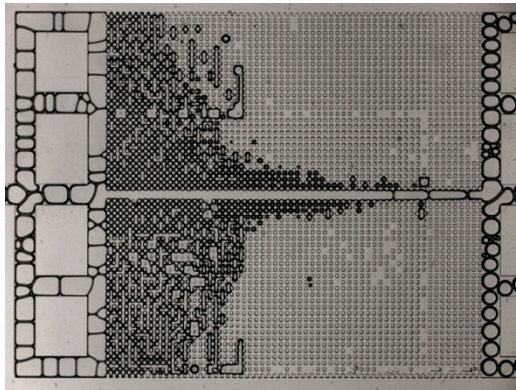
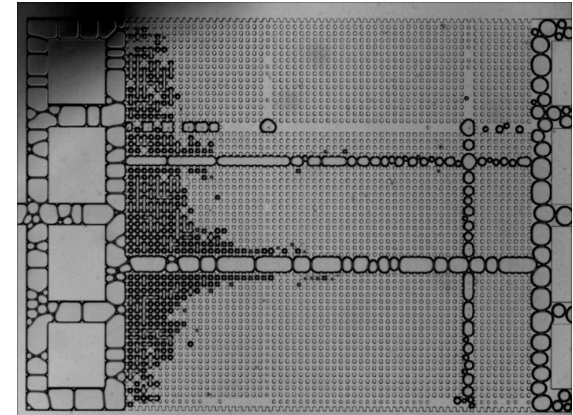




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Micromodels with fractures

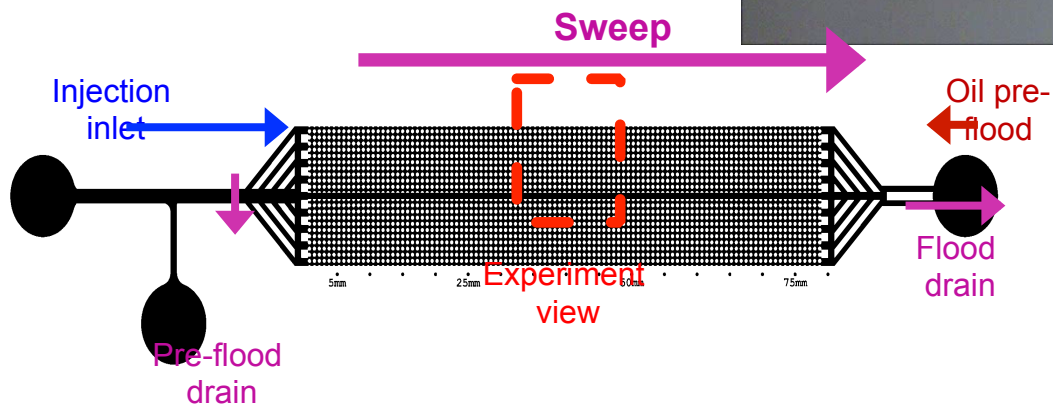
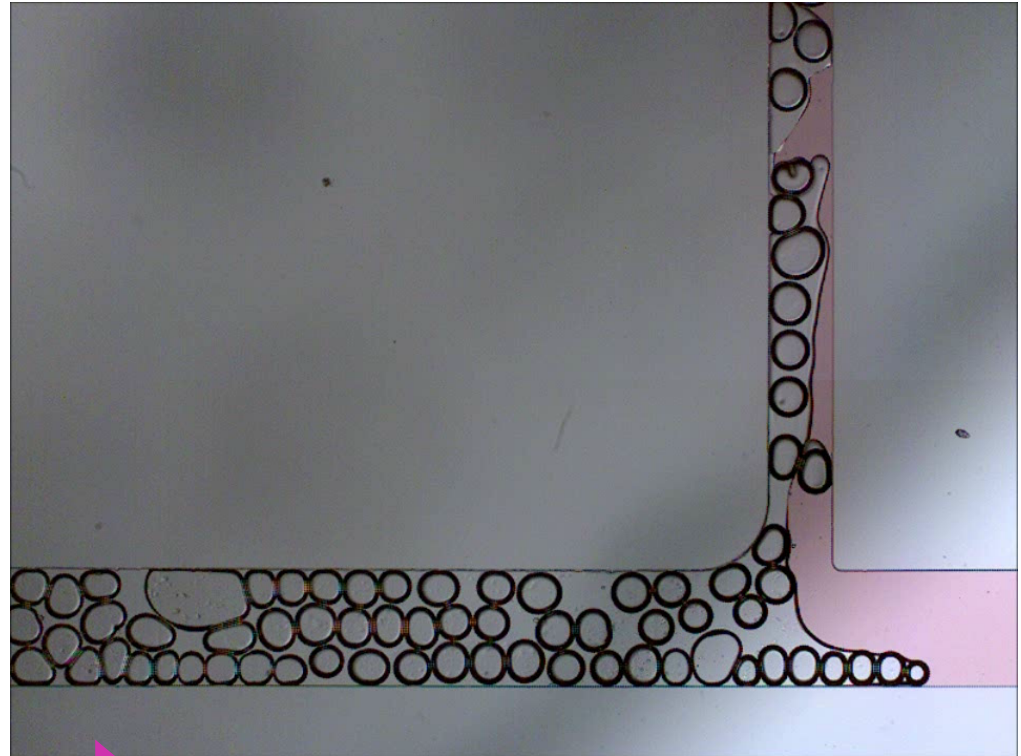
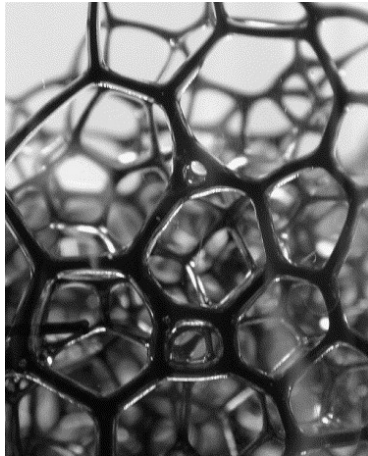
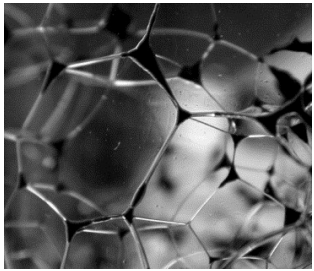
Visualization of foam in porous media micromodels, with emphasis on *fractured systems*.





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Foam Stability in the Presence of Oil

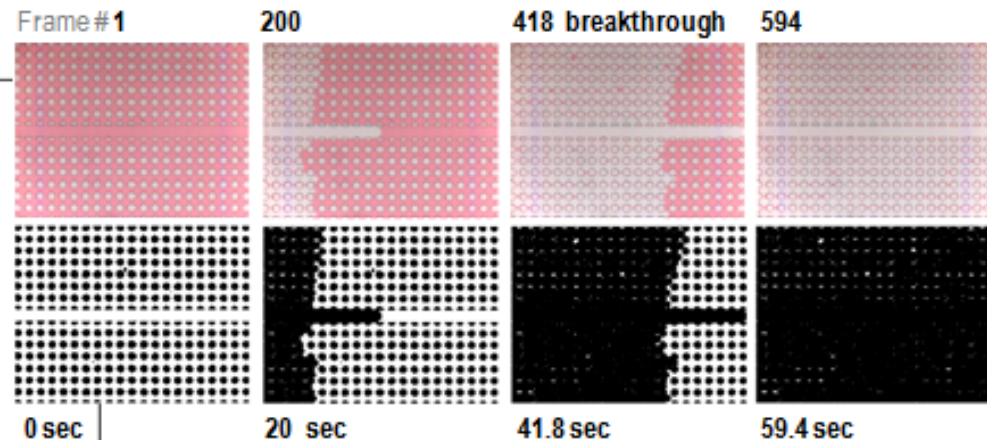
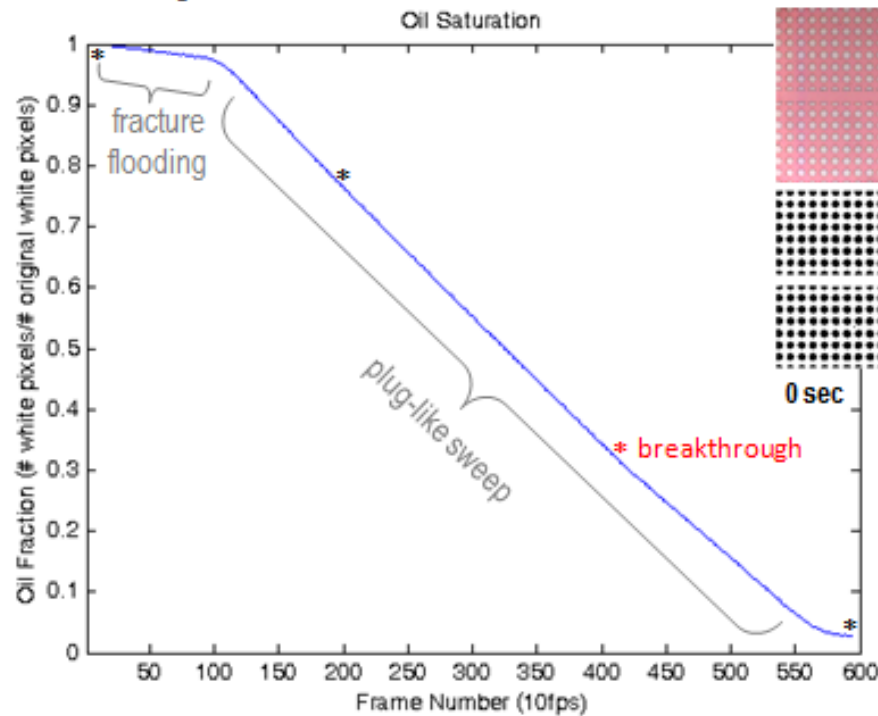




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Oil displacement with glycerol sweep

Pure Glycerol

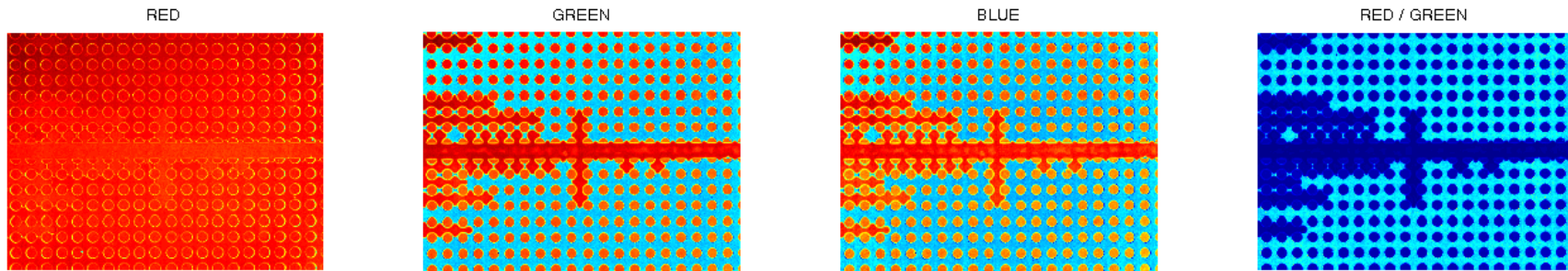


- Highly viscous injecting fluid displaces 67.5% of the oil-in-place before breakthrough in the fracture
- Most residual oil remains in the form of leave-behind lamellae (2.9% of the original oil-in-place)

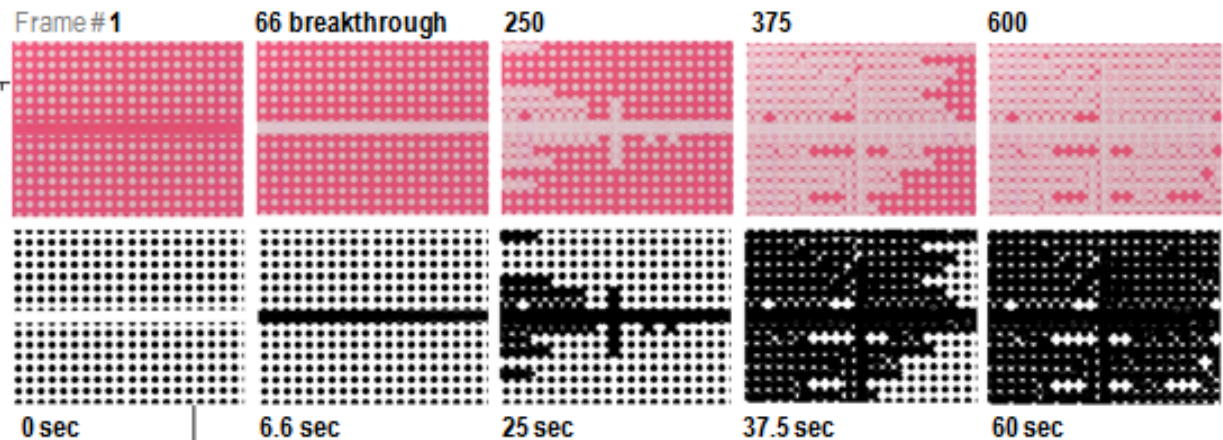
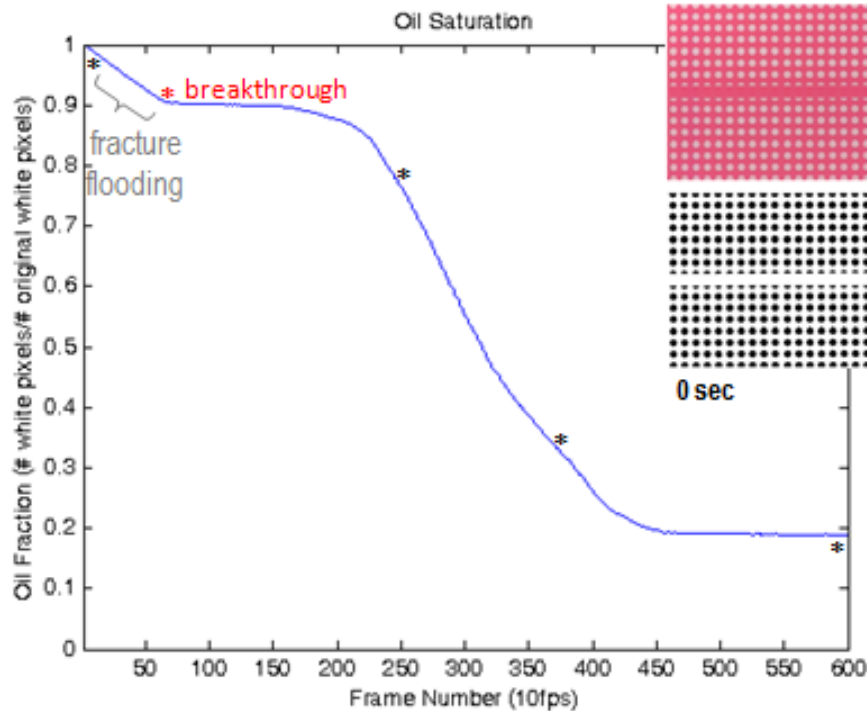


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Viscous sweep



80 wt-% Glycerol

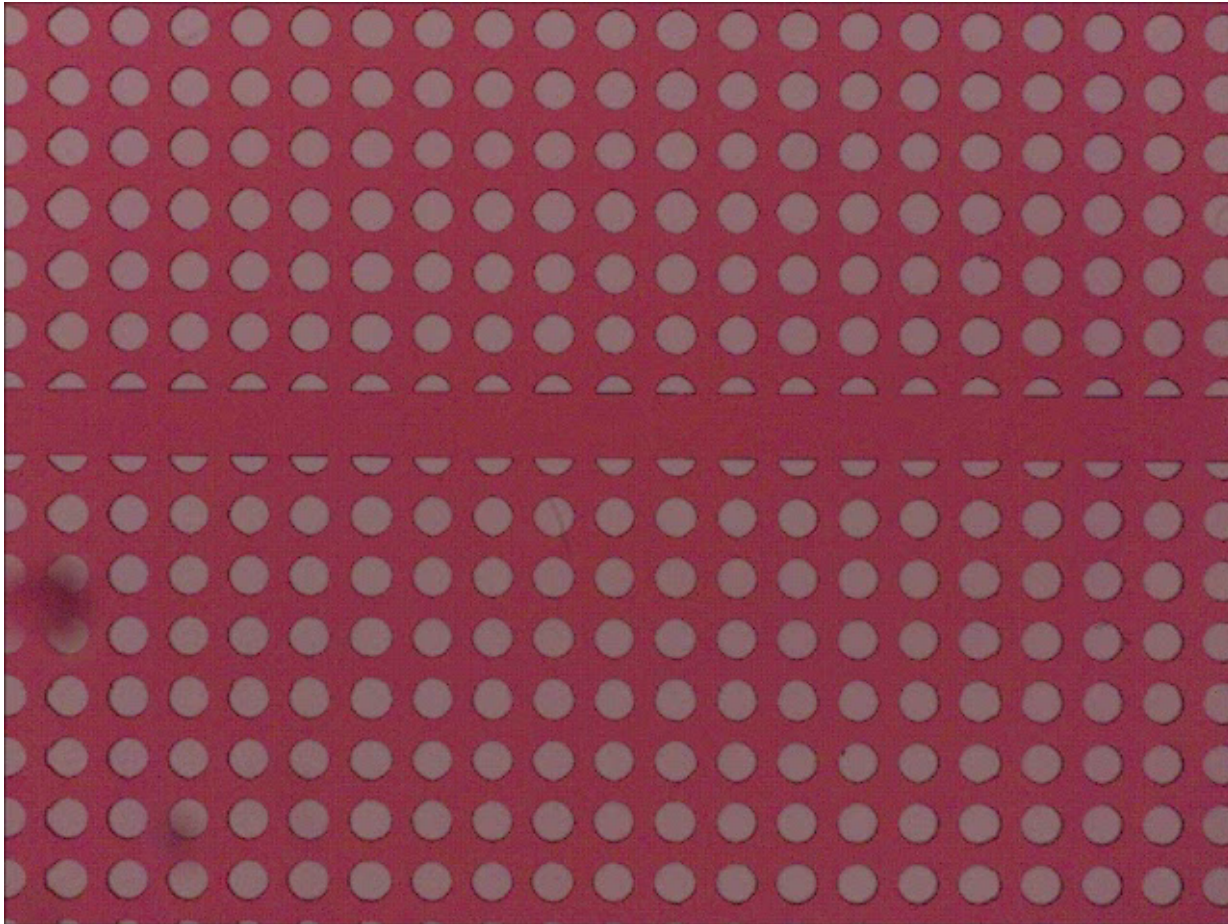


- Initial saturation of the micromodel with oil (dye red)
- Glycerol solution displaces oil first through the fracture, then into the porous media
- Threshold images indicate residual pore-trapped oil (white) after flooding



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Foam Sweep in an oil saturated porous media

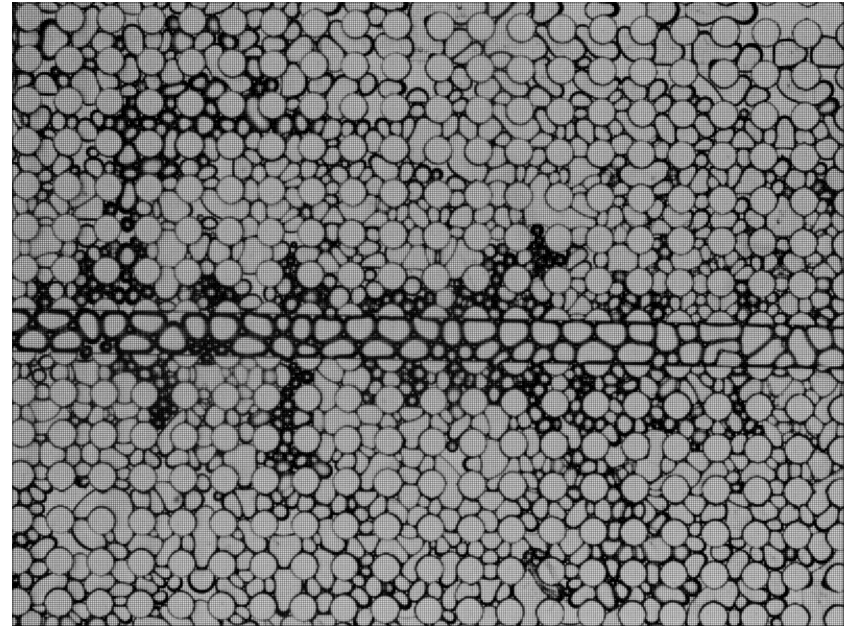


Porous media saturated with a red-dyed paraffin oil



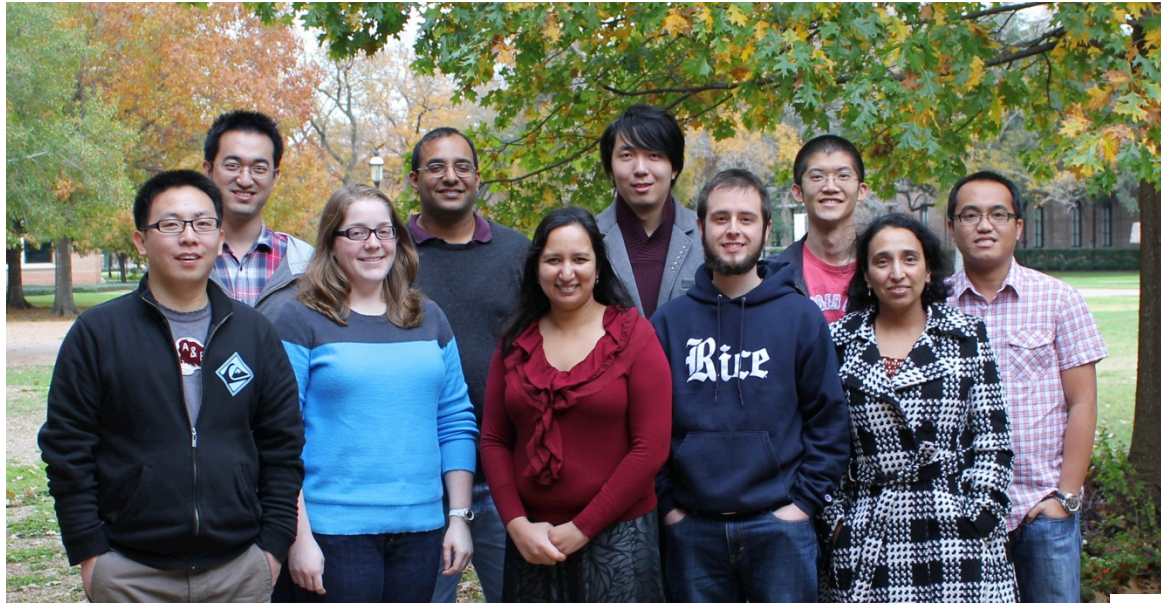
Conclusions

- Micromodels for pore-level visualization of foam propagation and stability
- Micromodels for surfactant stability evaluation
- Micromodels of fractured porous media
- Patterning and controlling surface wettability and roughness





Acknowledgments



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Rachel Liontas

www.ruf.rice.edu/biswalab

