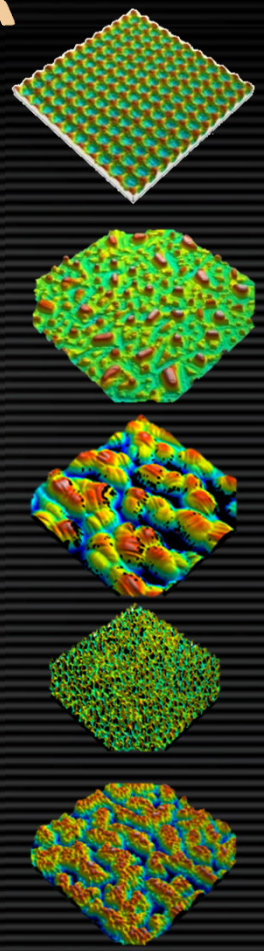
A LABORATORY STUDY OF FOAM FOR EOR IN NATURALLY FRACTURED RESERVOIRS



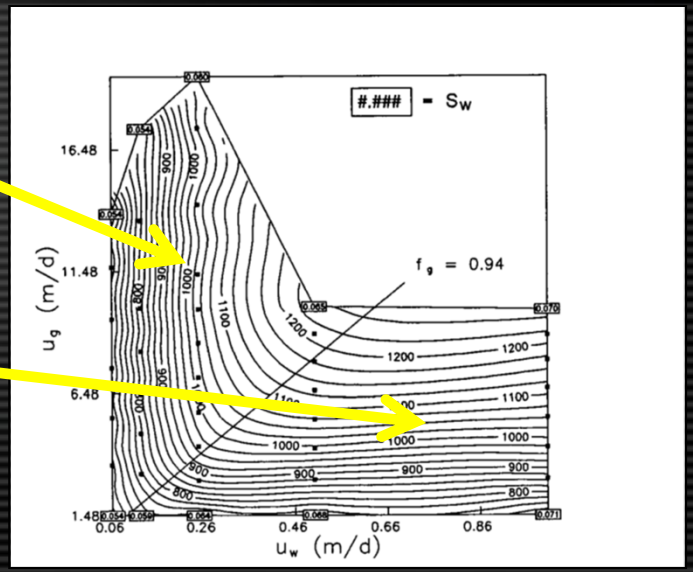
William R. Rossen

Bander. I. AlQuaimi

TU Delft

Backround

- Gas-injection EOR can displace nearly all oil contacted, but sweep efficiency is very poor, because of reservoir heterogeneity, gravity segregation and viscous instability
- Foam can help fight all three causes of poor gas sweep
- In reservoir rock, foam shows two flow regimes:
  - High-Quality regime: result of foam collapse at limiting P_c
  - Low-Quality regime: thought to reflect invariant bubble size, roughly size of pores
- Fractured reservoirs have especially poor sweep efficiency
- Foam generation in fractures is uncertain



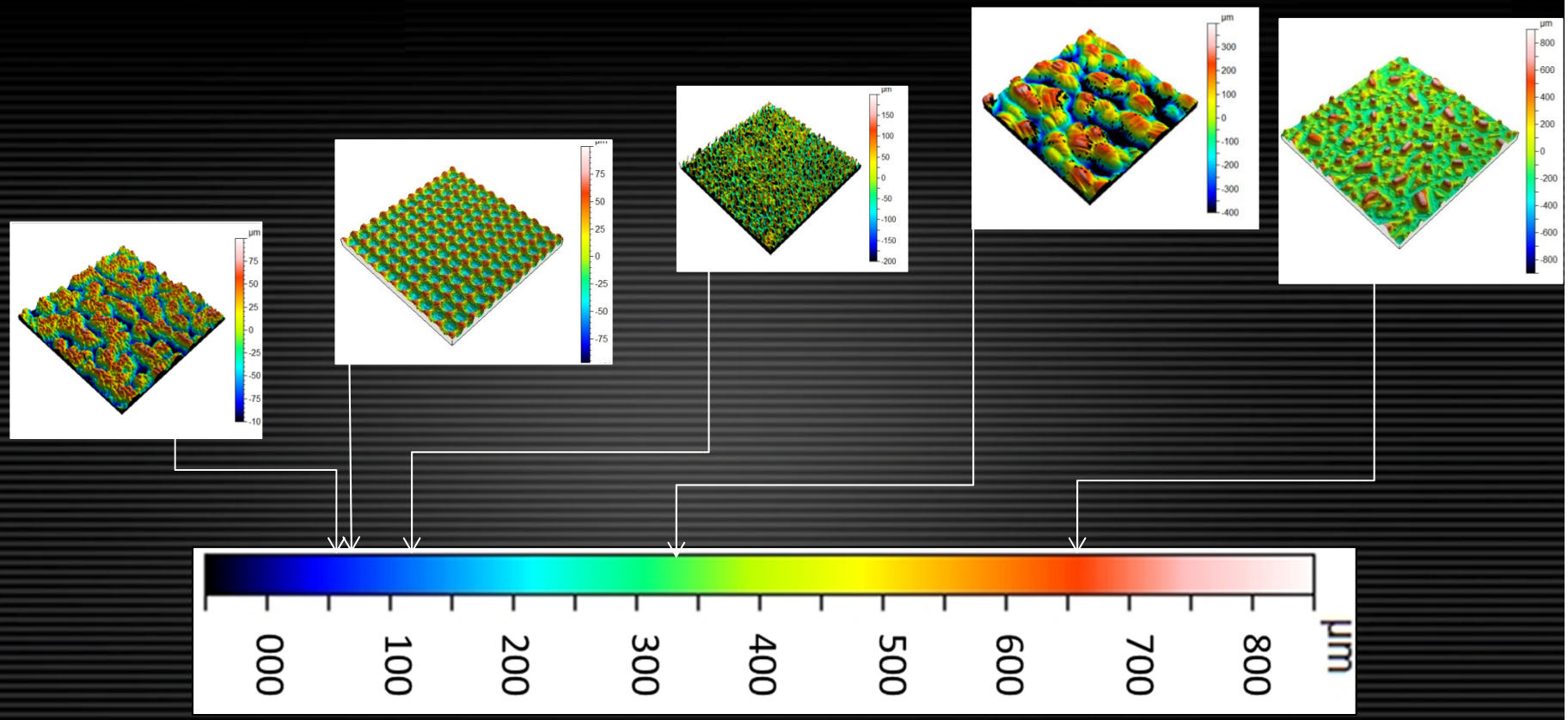
Goals and Strategy

- Develop rules for foam generation and properties in fractures that would **apply broadly to fractures of different apertures, different geometries**.
- Conduct studies in a medium where foam can be directly observed.
- Conduct experiments on samples as large as possible (avoid entrance effects).
- Obtain a variety of samples with very different fracture apertures, permeabilities, and scales of roughness

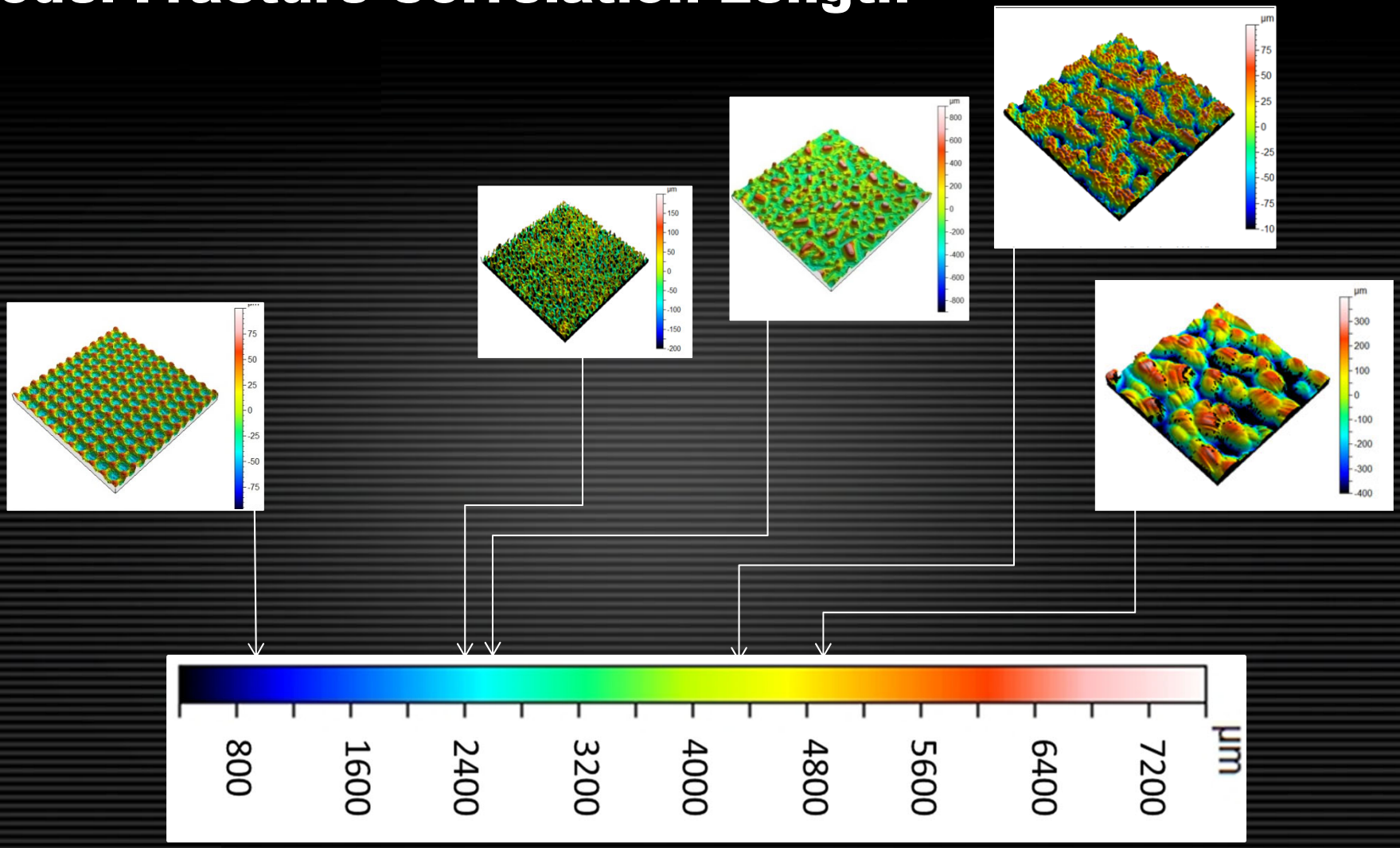
Implementation

- Conduct experiments in model fractures between glass plates, one roughened, one smooth
  - large size, cost effective, and available in different geometries

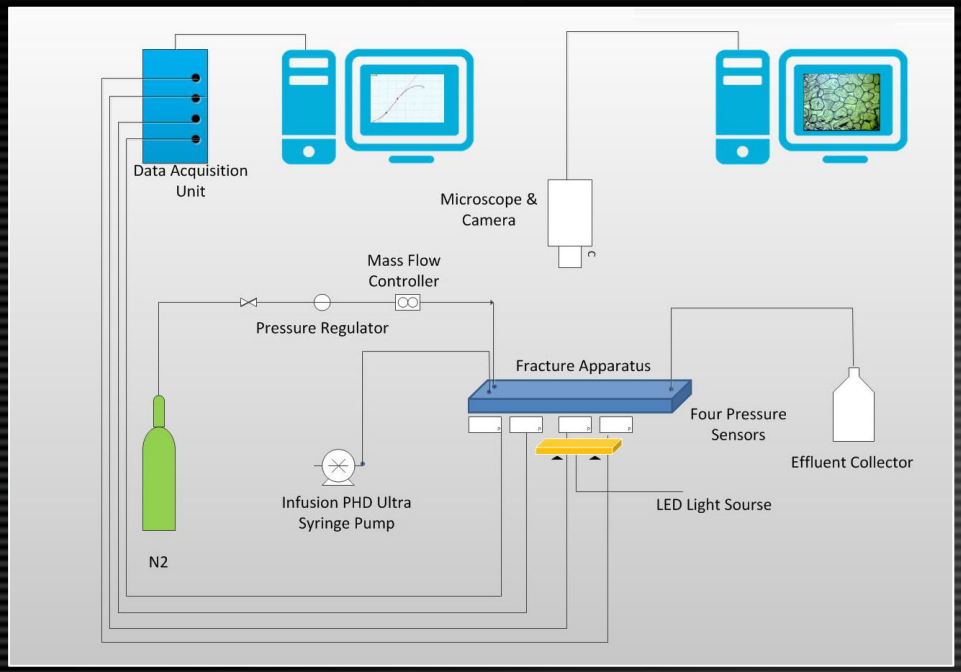
Model Fracture aperture size

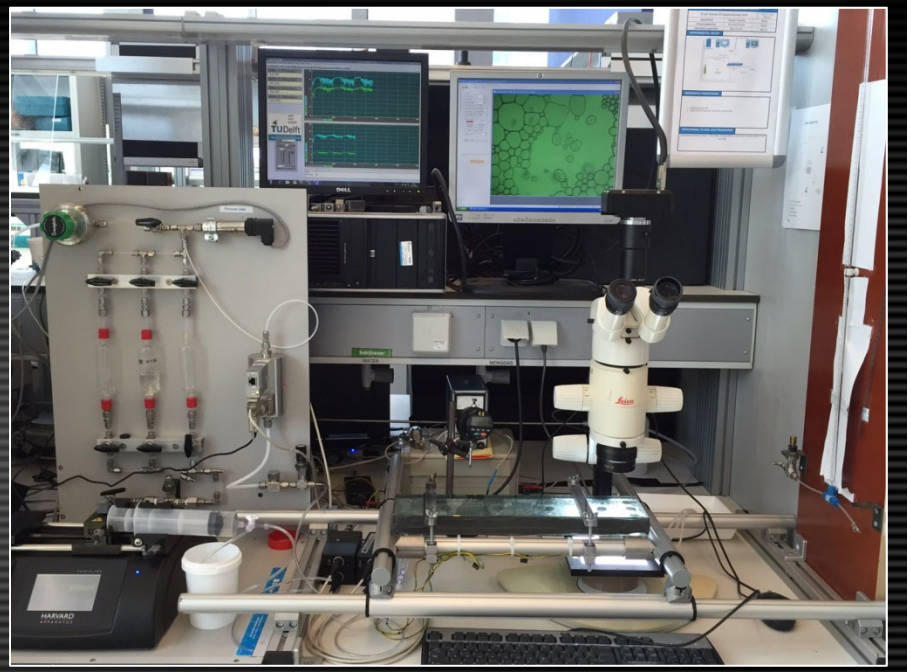


Model Fracture Correlation Length



Experimental Setup



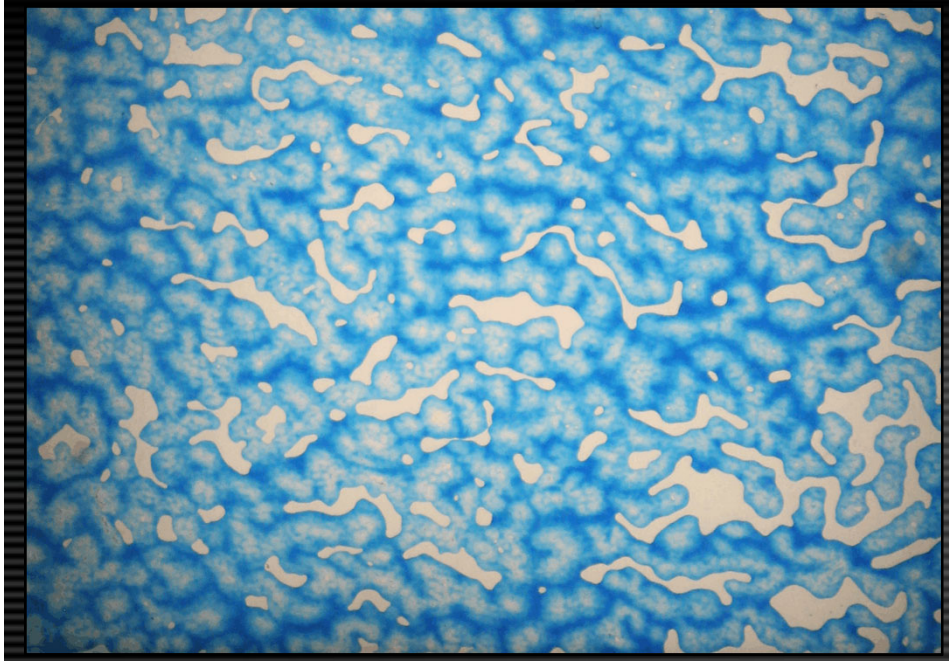


Initial Study: Trapping and Mobilization in Fractures

- Trapping and mobilization of bubbles is a key to foam mobility.
- Trapping and mobilization of non-wetting phase in rock is represented as function of capillary number, $[k\nabla p/\sigma]$
- In fractures, permeability k is primarily a function of average aperture, but trapping depends on roughness
- What is best definition of capillary number for trapping in fractures?

TUDelft

Trapping and Mobilization of gas (no foam)



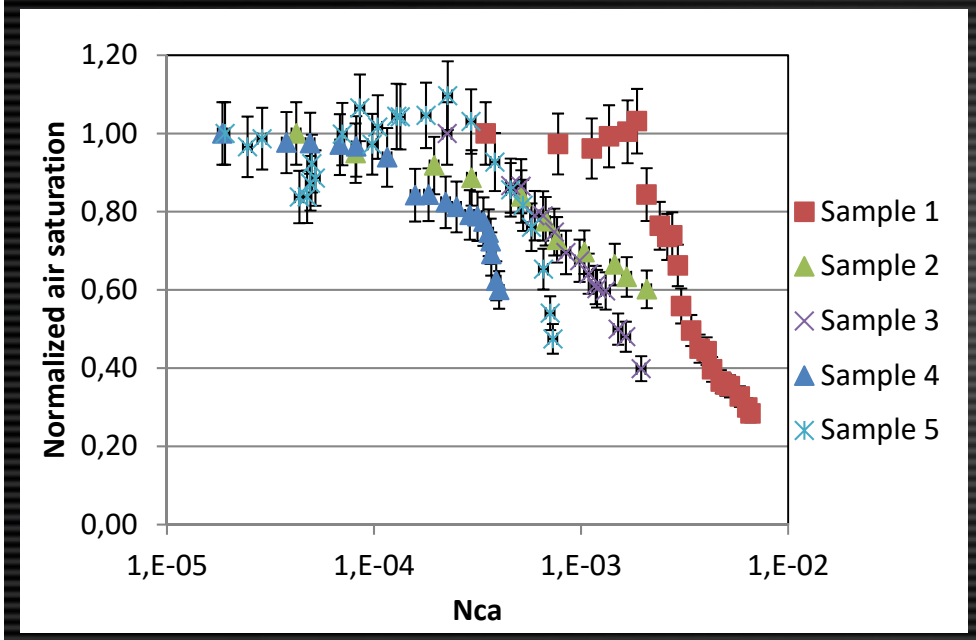
Desaturation-experiment example (16x10 cm image)

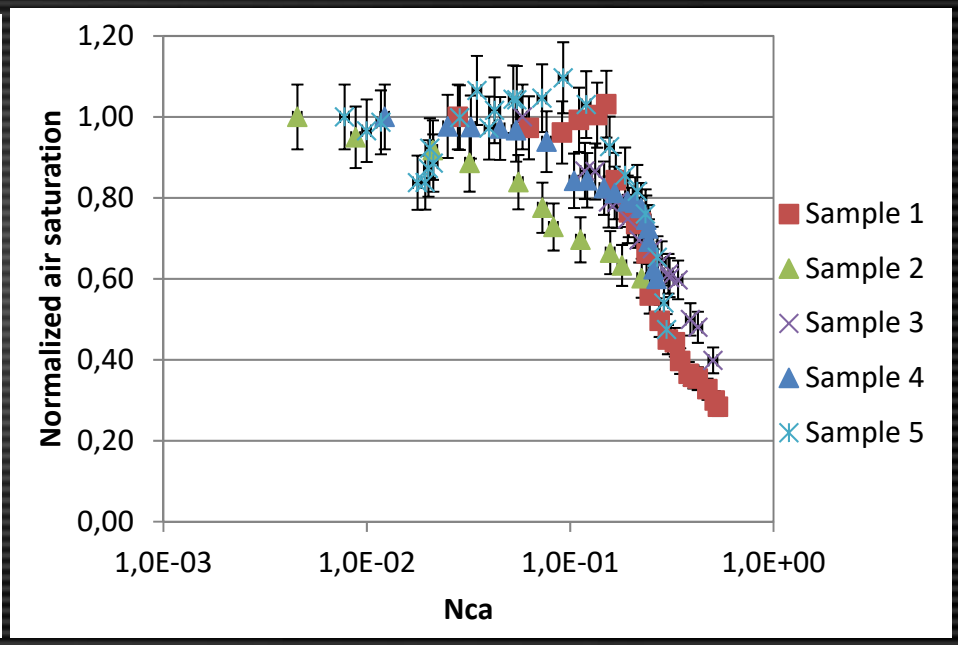
Trapping and Mobilization

Conventional Nca $$N_{ca} = \frac{k|\nabla P|}{\gamma cos\theta}$$

New N_{ca}

$$N_{ca} = \left(\frac{\nabla P k_f}{\gamma}\right)\left[\left(\frac{12}{2}\right)\left(\frac{d_t}{d_H}\right)^2\left(\frac{L_g}{d_t}\right)\left(\frac{1}{\left(1-\left(\frac{d_t}{d_b}\right)\right)}\right)\right]$$



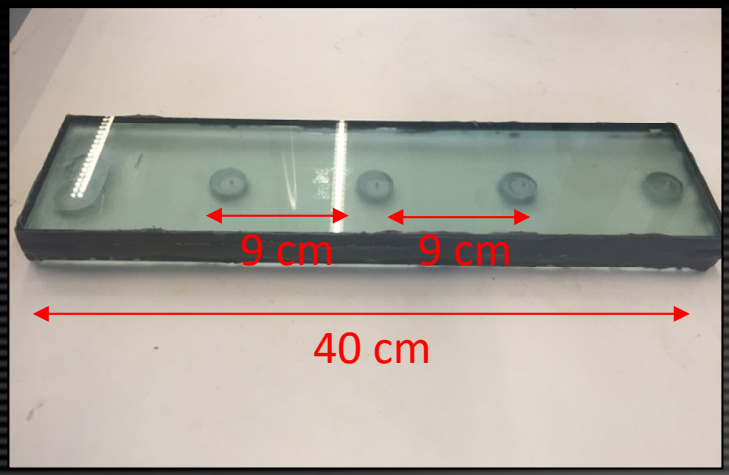


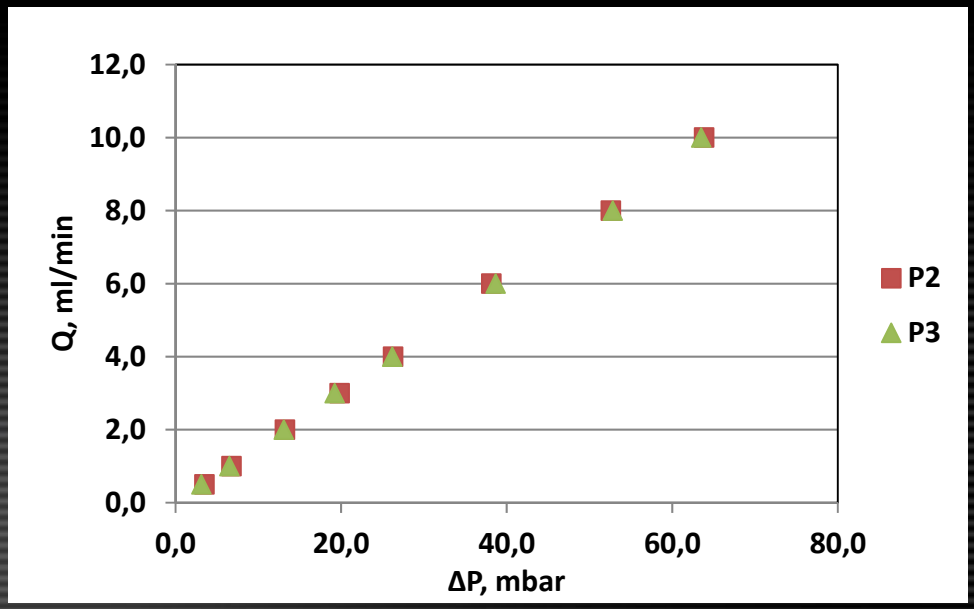
Force balance on trapped ganglion leads to new N_{ca} for fractures

Foam Generation and Propagation

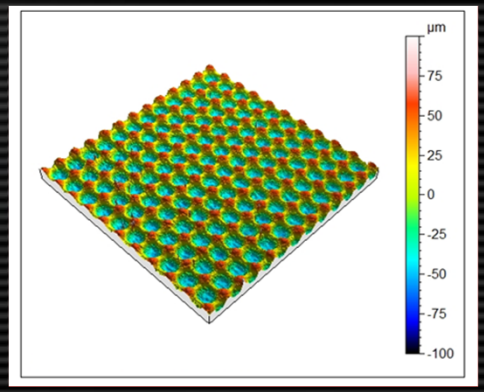
1. In-situ Foam Generation

2. Pre-generated Foam





- First model : narrow aperture, regular pattern
- Single-phase water injection to determine hydraulic aperture
- Two inner ports used for pressure gradient
- The hydraulic aperture estimated to be 66 µm



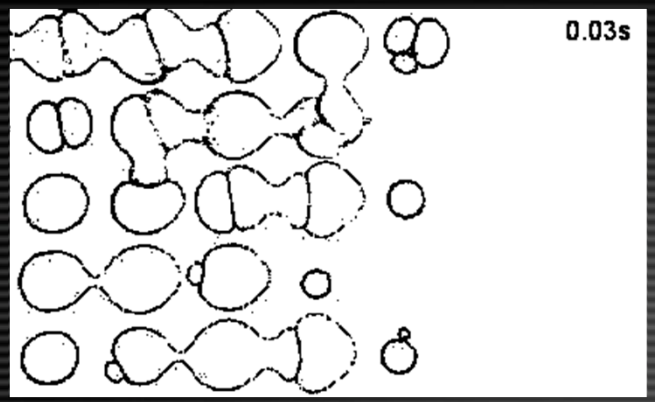
1. In-situ Foam Generation

- **Can we generate foam, in-situ, in a fracture?**
- **How effective is it in reducing gas mobility in the fracture?**

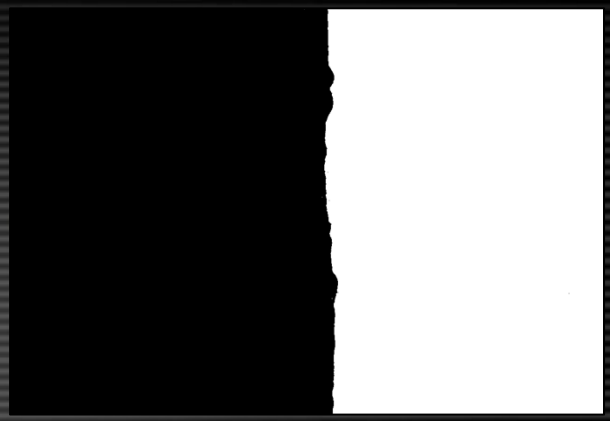
1. In-situ Foam Generation

- **Can we generate foam, in-situ, in a fracture?**

  Foam generated in our model fracture by mechanisms similar to “3D” porous media



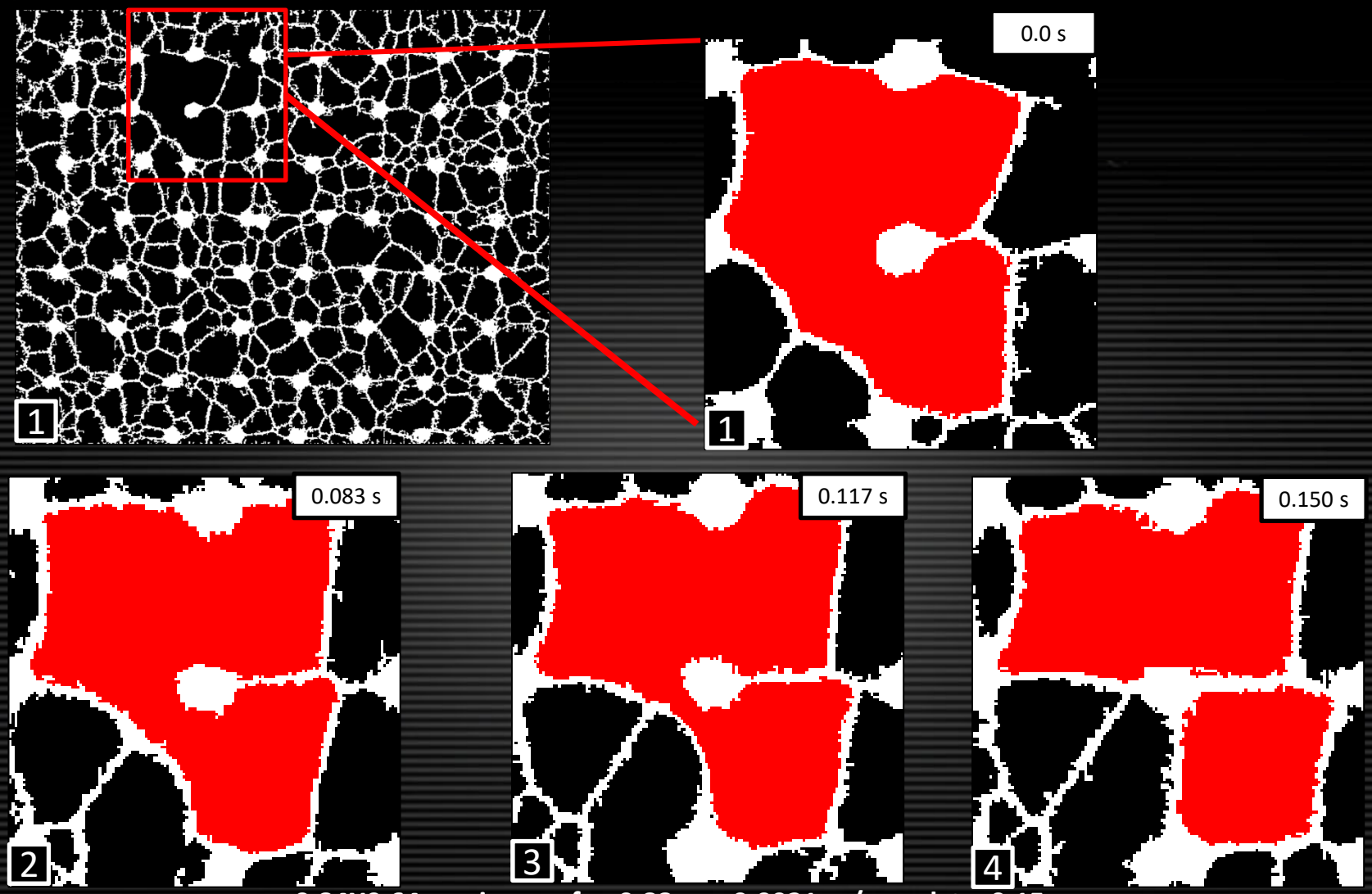
0.65X0.40 cm image, f_g = 0.37, and u_t = 0.0021 m/s



2.2X1.5 cm image, f_g = 0.25, and u_t = 0.0021 m/s

Snap-off

Leave-Behind



0.84X0.64 cm image, f_g = 0.88 u_t = 0.0021 m/s, and t = 0.15s

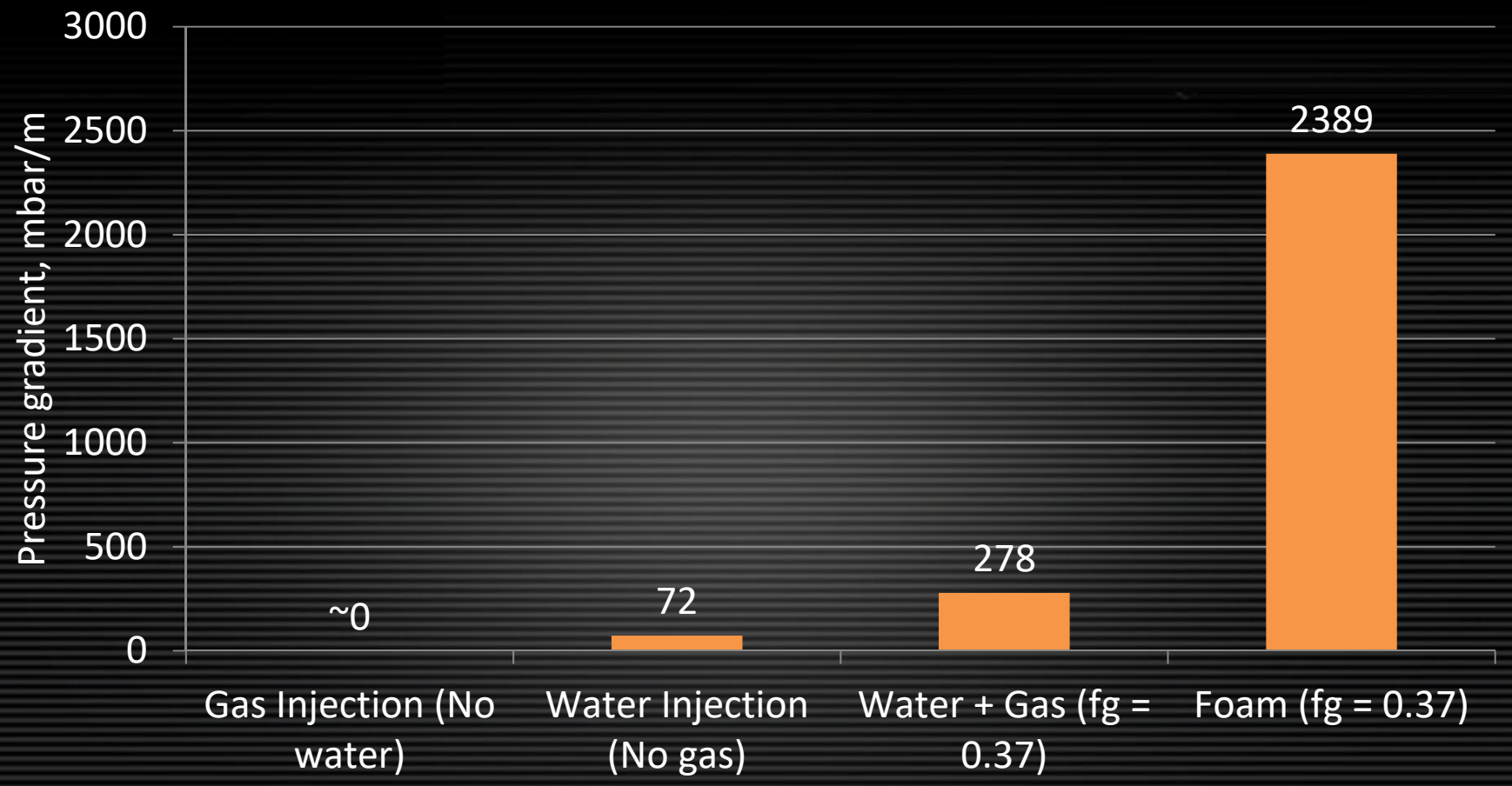
Lamella Division

1. In-situ Foam Generation

- **Can we generate foam, in-situ, in a fracture?**

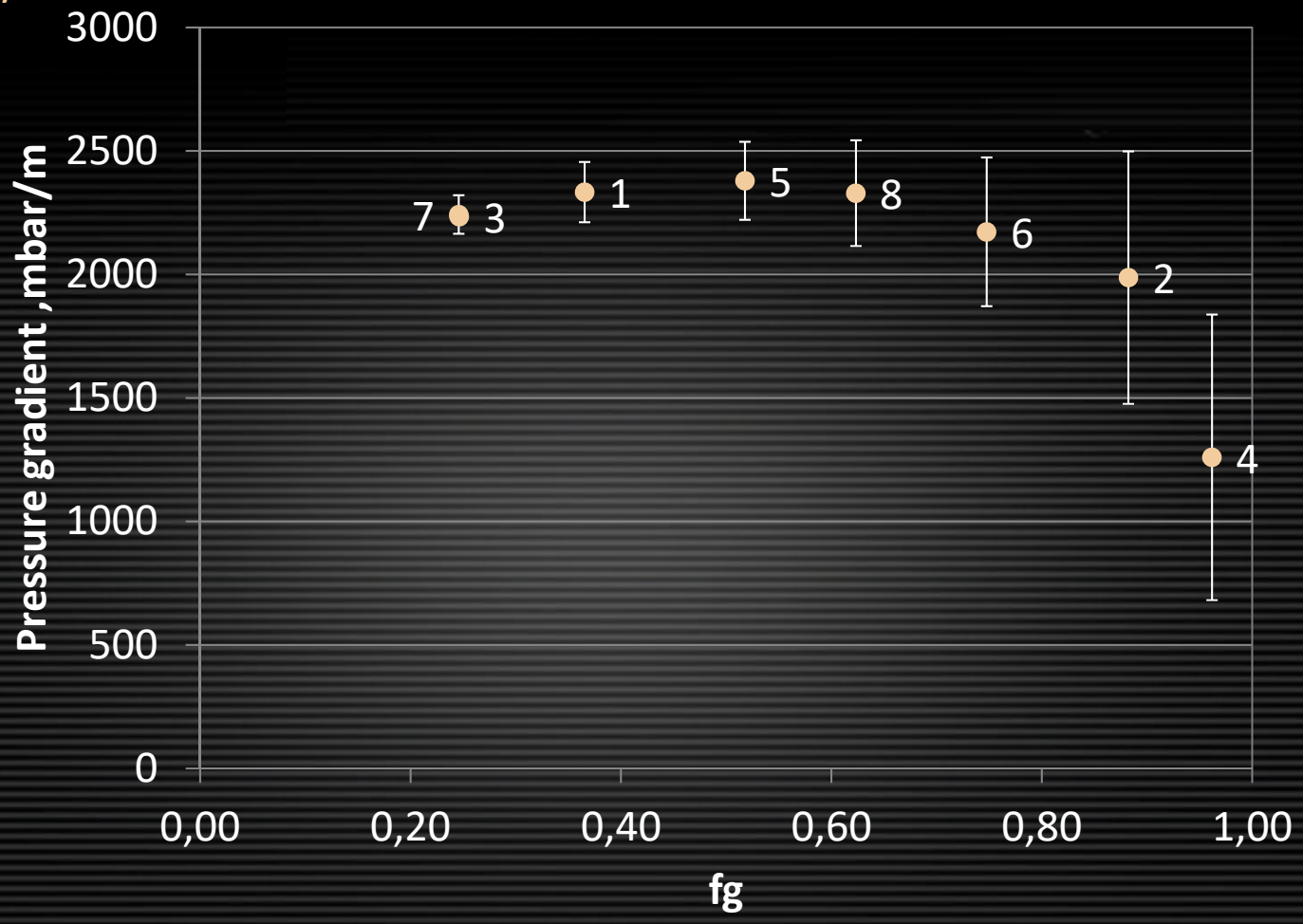
- **How effective is it in reducing gas mobility in the fracture?**

Foam Injection Benchmark



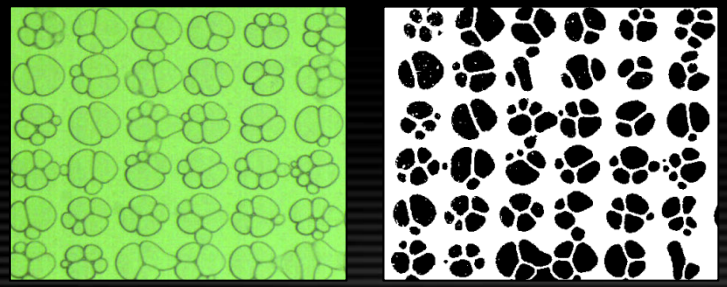
ut = 0.0021 m/s

Foam Quality Scan

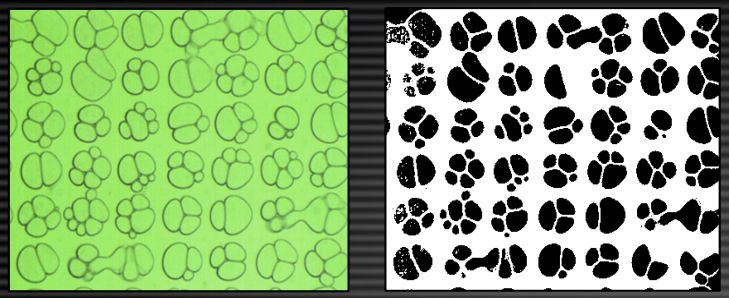


(Fixed u_t = 0.0021 m/s)

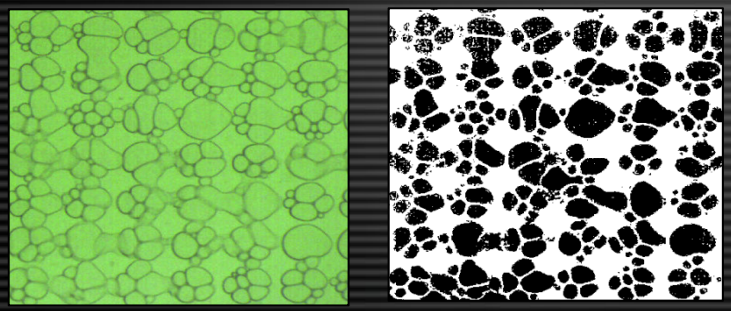
fg = 0.25



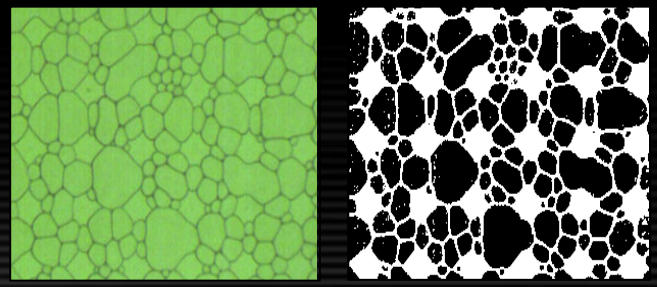
0.37



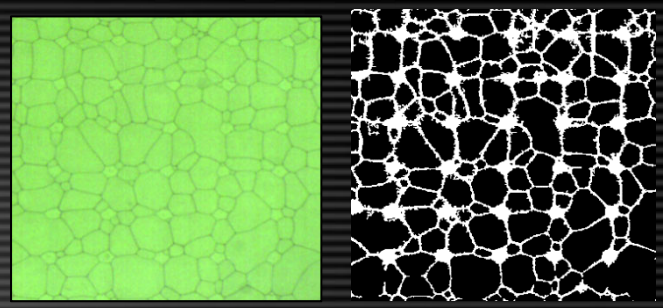
0.52



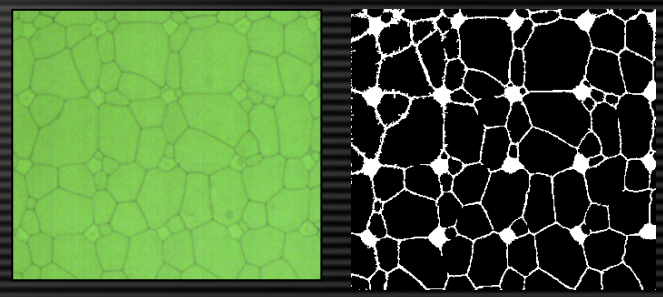
0.75



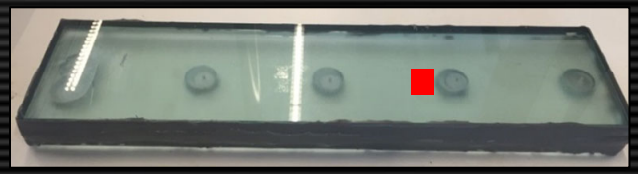
0.88



0.96



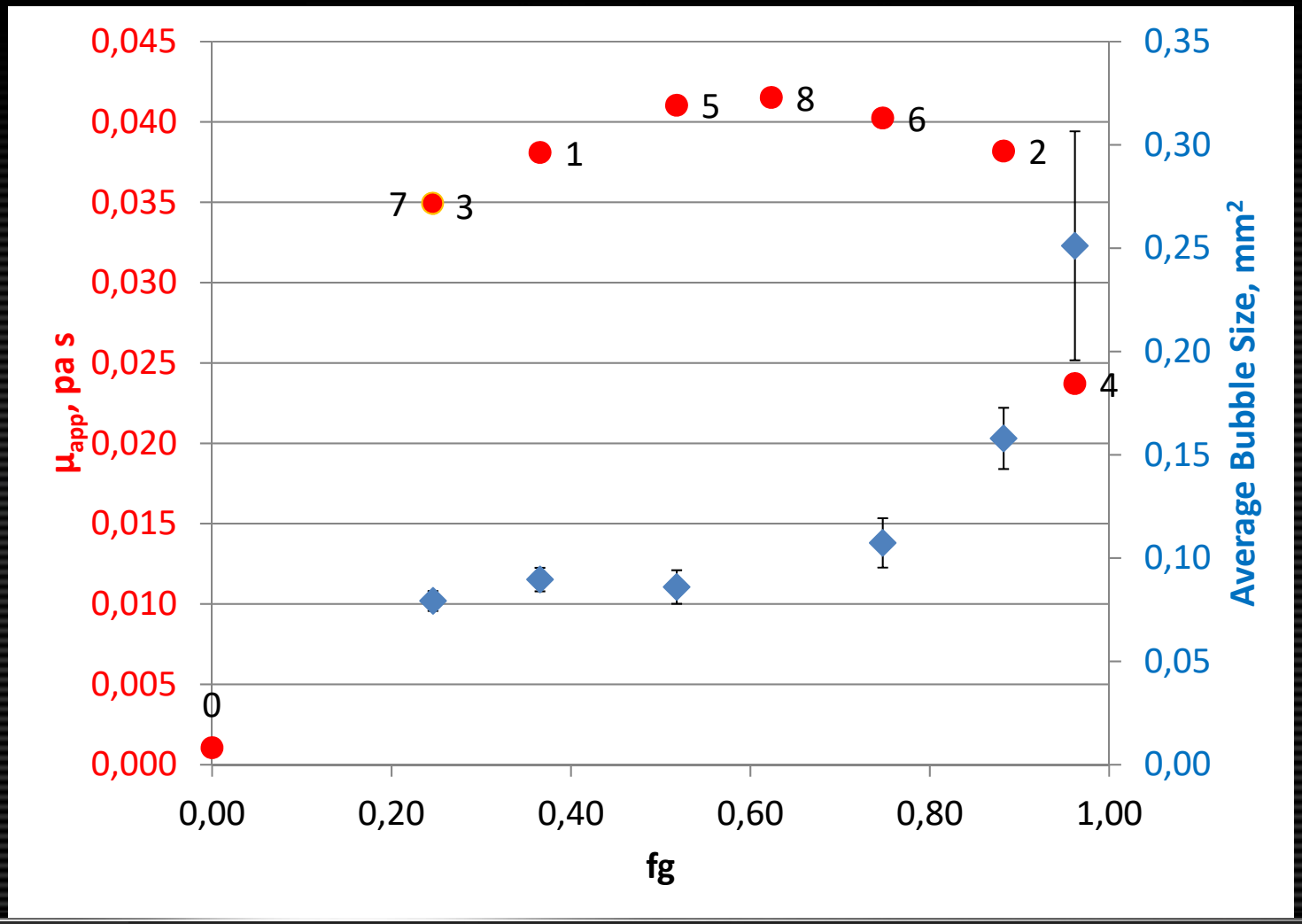
Images captured during stabilized pressure drop 27 cm from injection port



Gas
water

Effect of Gas Fraction (Foam Quality)

Foam Bubble Size Analaysis (fixed u_t = 0.0021 m/s)

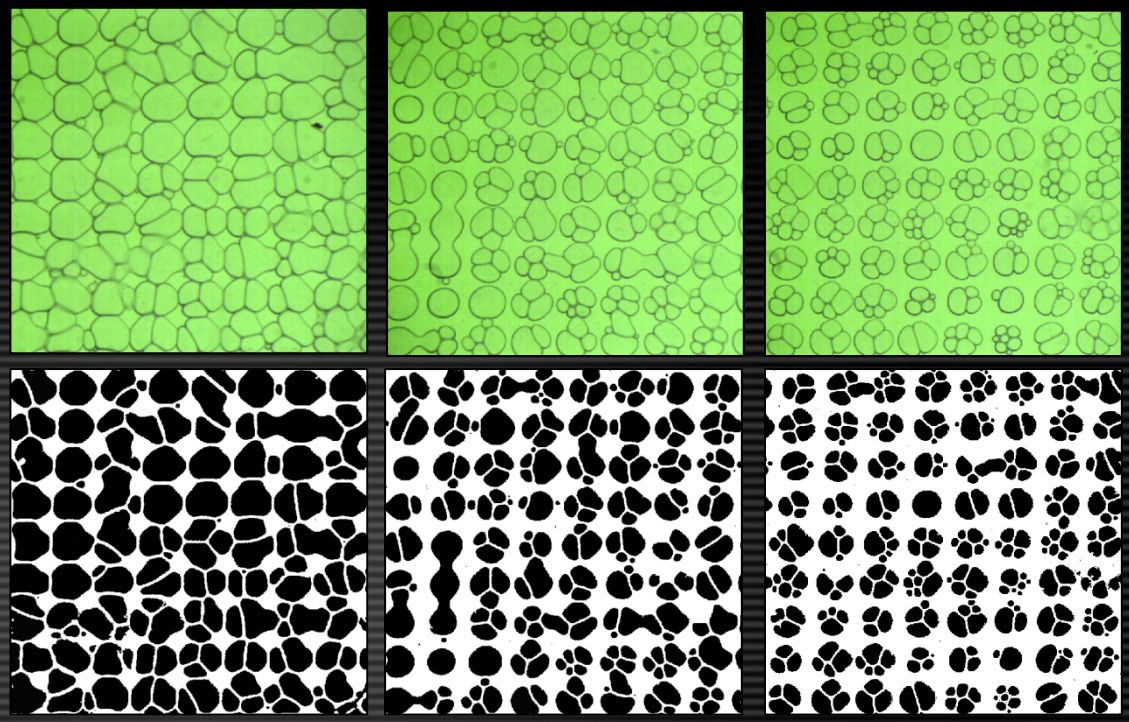


Foam mobility inversely related to bubble size

Foam Bubble Size Analaysis

fg = 0.37
vt = 0.0021 m/s
Surfactant Concentration 1% wt

Inlet Outlet



0.8 X 0.77 cm Images

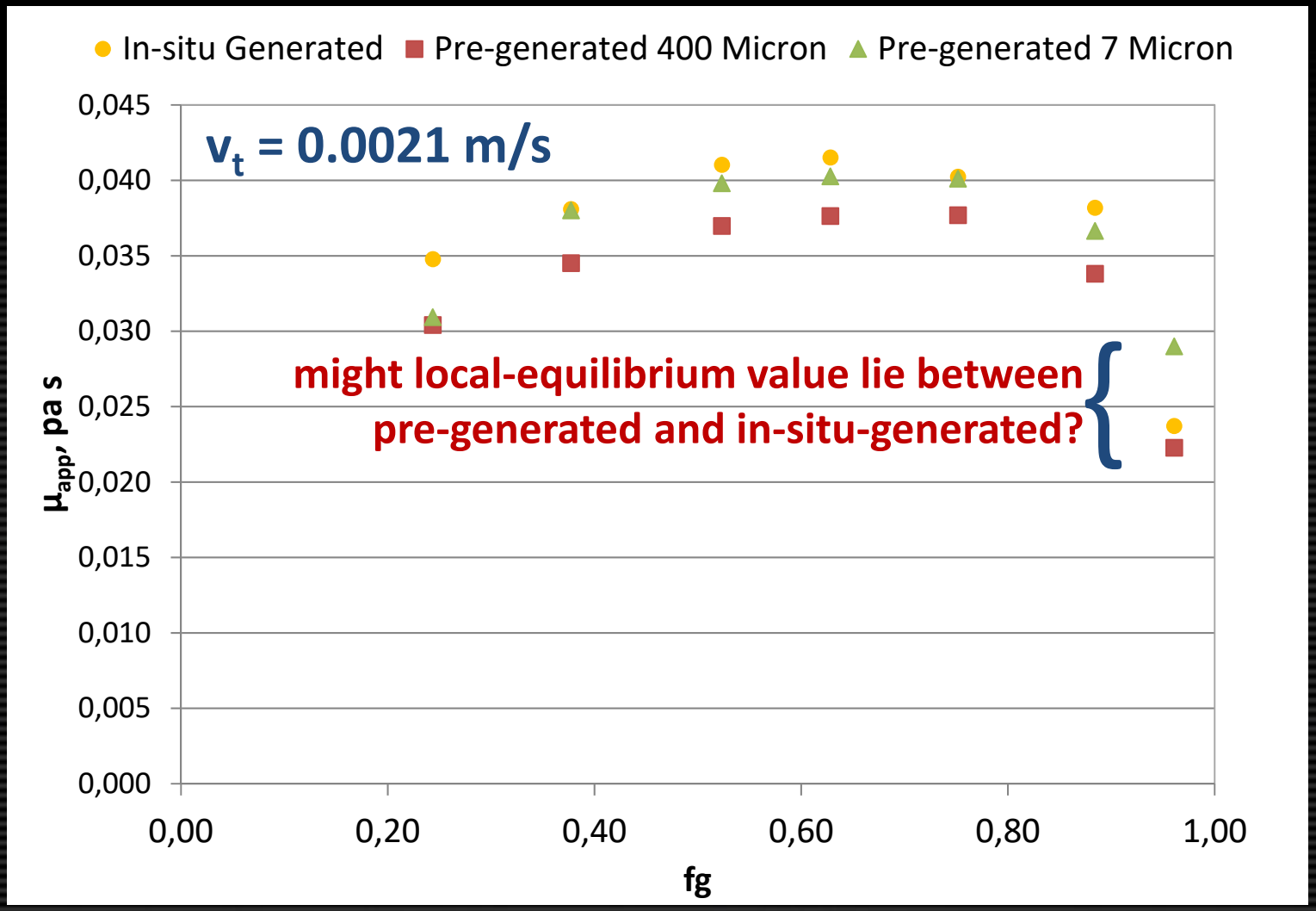
Distance from in let, mm	20	120	270
Average bubble size, mm^2	0.250	0.138	0.081
Bubble size, std. dev. , mm^2	0.205	0.125	0.056
Number of bubbles	165	217	303

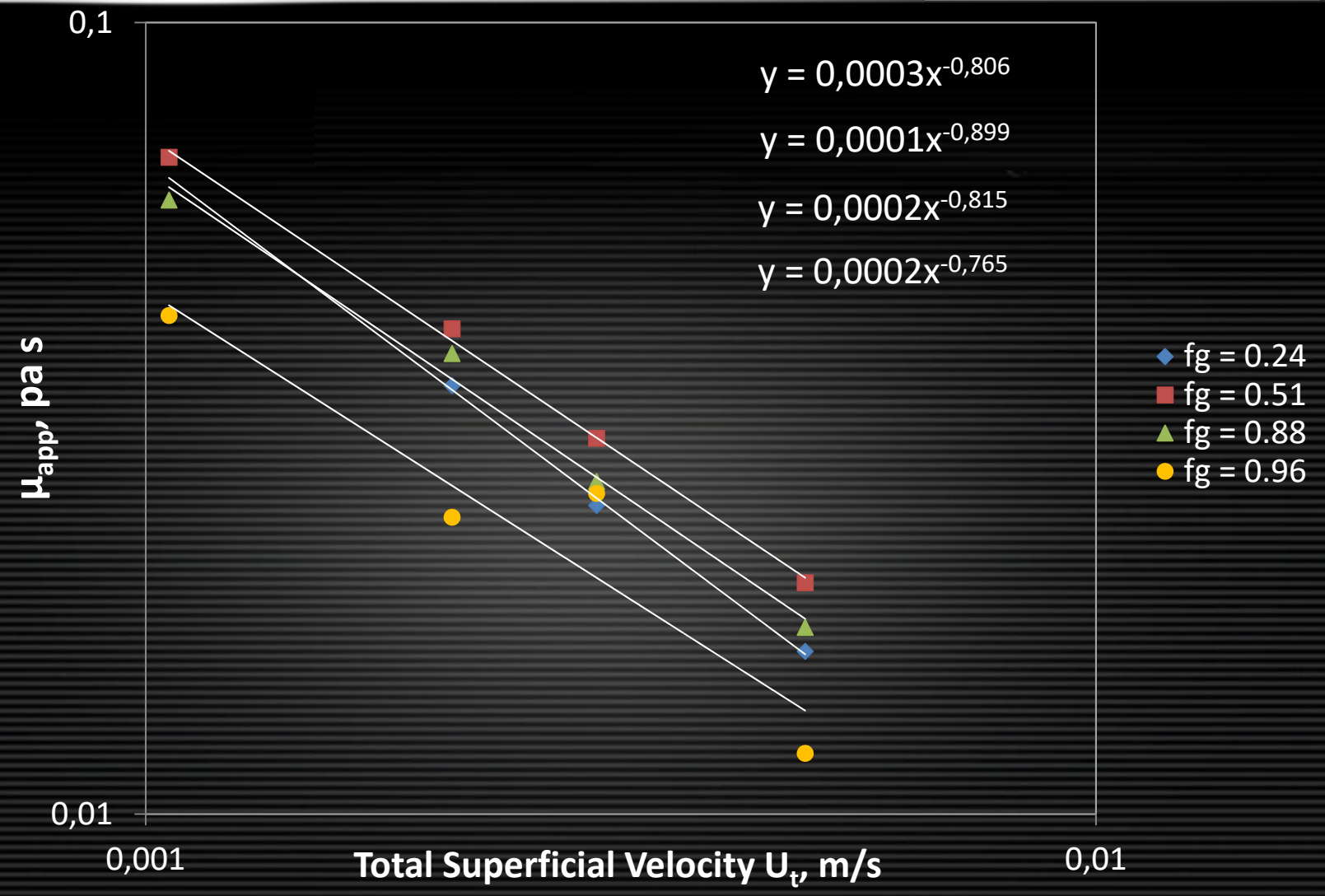
Bubble sizes evolve along fracture: “entrance effect”

2. Pre-generated Foam

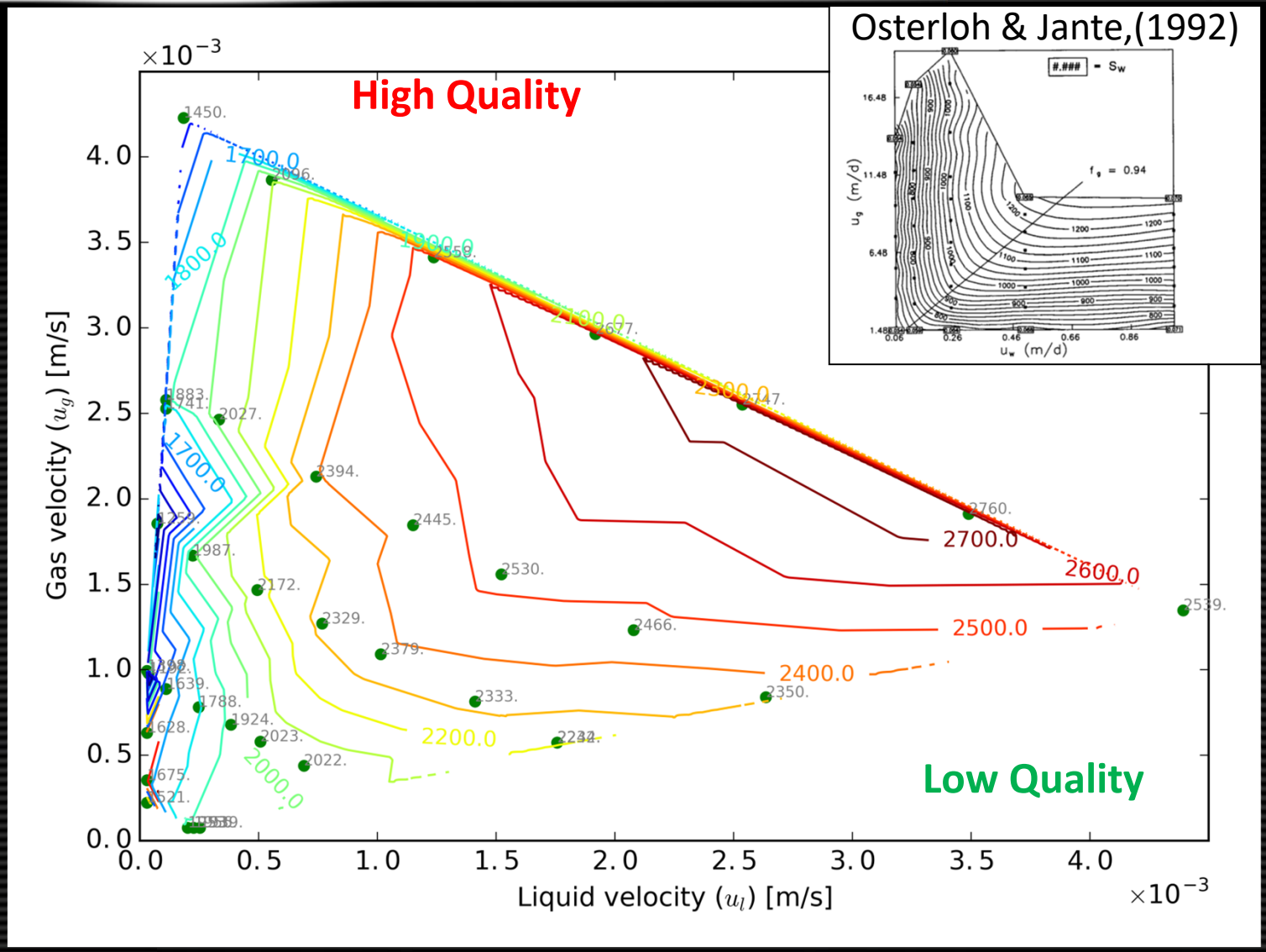
1. Fine-textured foam

2. Coarse-textured foam

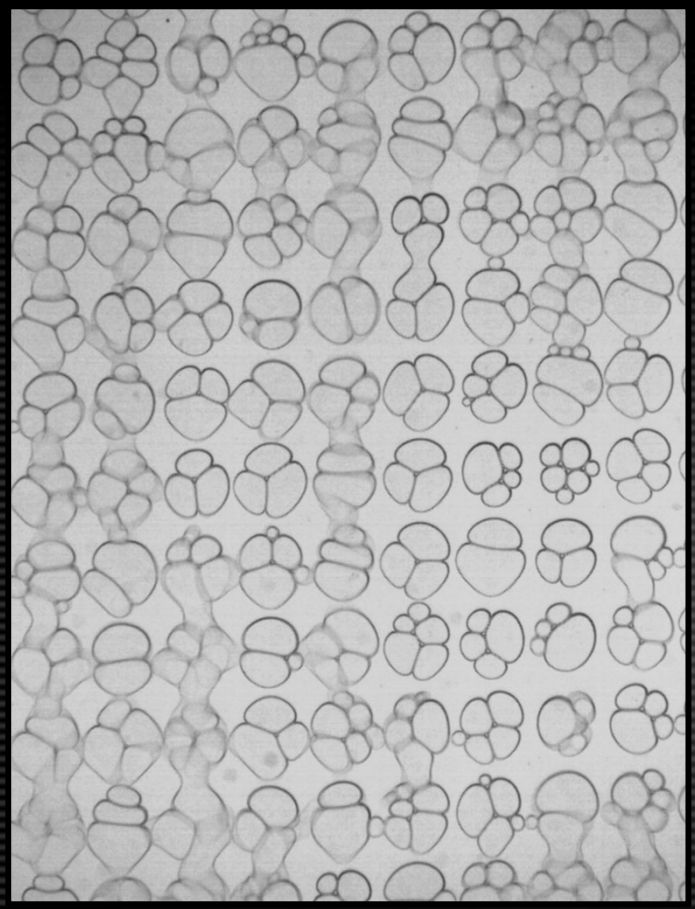

In-situ Generated
Pre-generated 400 Micron
Pre-generated 7 Micron
v_t = 0.0021 m/s
might local-equilibrium value lie between pre-generated and in-situ-generated?
μ_{app}, pa s
0,045
0,040
0,035
0,030
0,025
0,020
0,015
0,010
0,005
0,000
0,00
0,20
0,40
0,60
0,80
1,00
fg

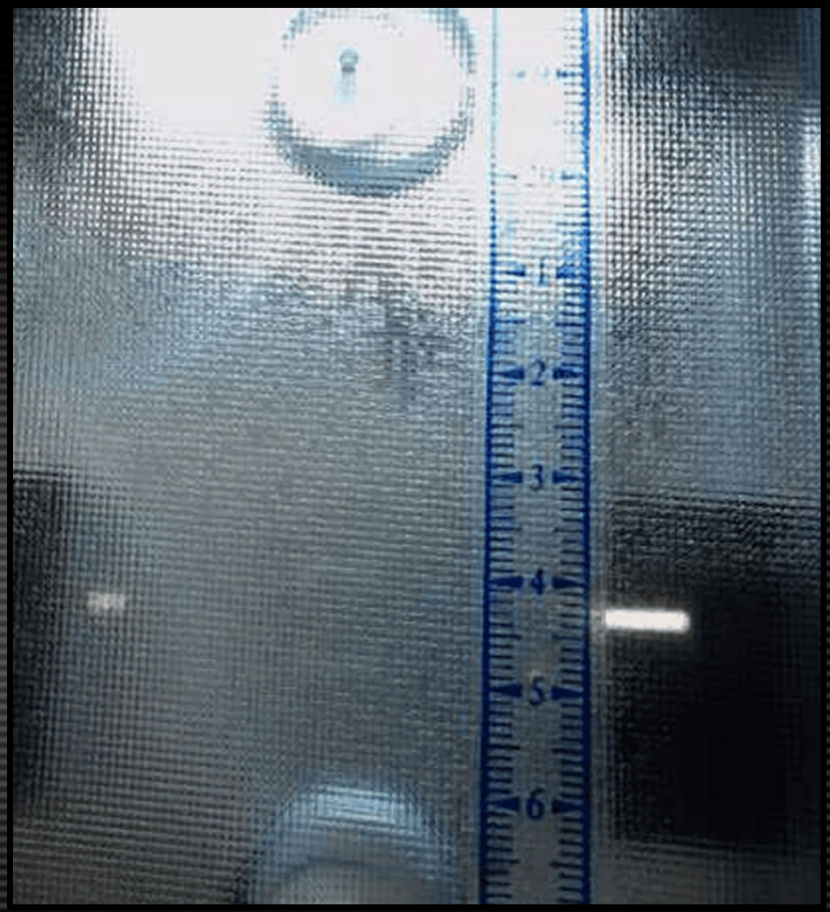


shear-thinning rheology



two flow regimes





Flow direction

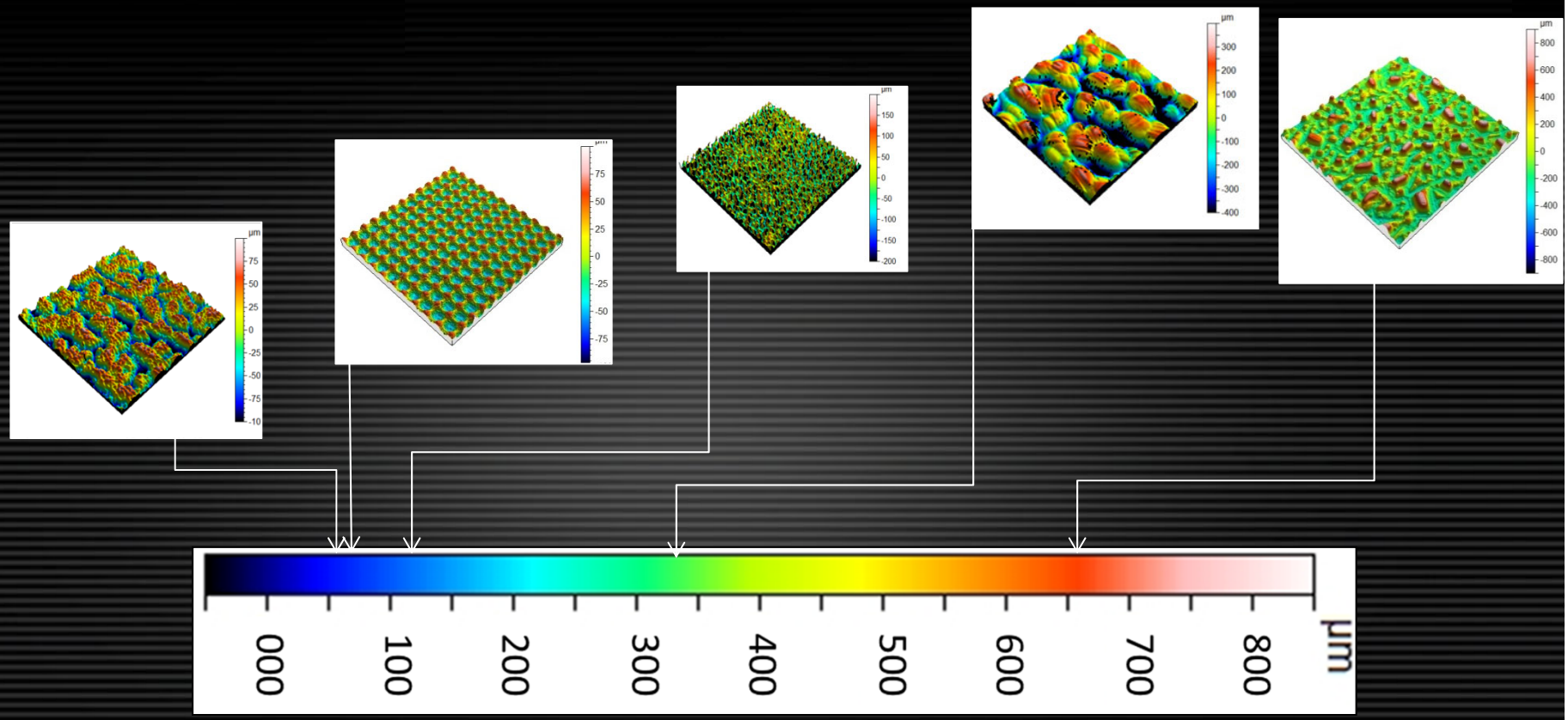
1.0X0.86 cm image, f_g = 0.37 and u_t = 0.0021 m/s

9.1X8.9 cm image, f_g = 0.92 and u_t = 0.0021 m/s

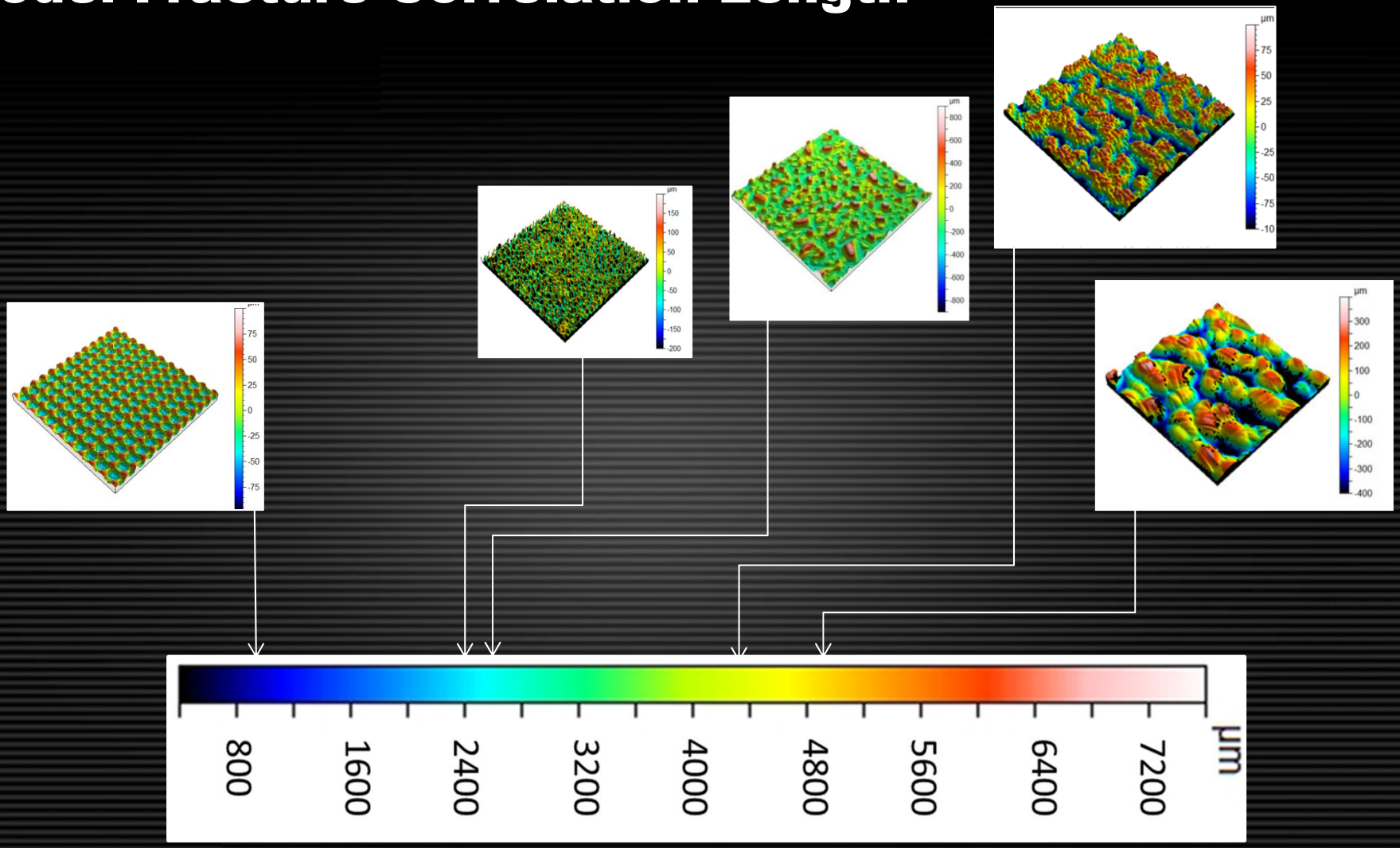
high-quality regime: caused by intermittent generation

Foam Generation and Properties in Five Different Model Fractures

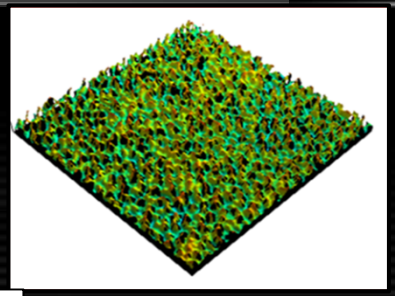
Model Fracture aperture size

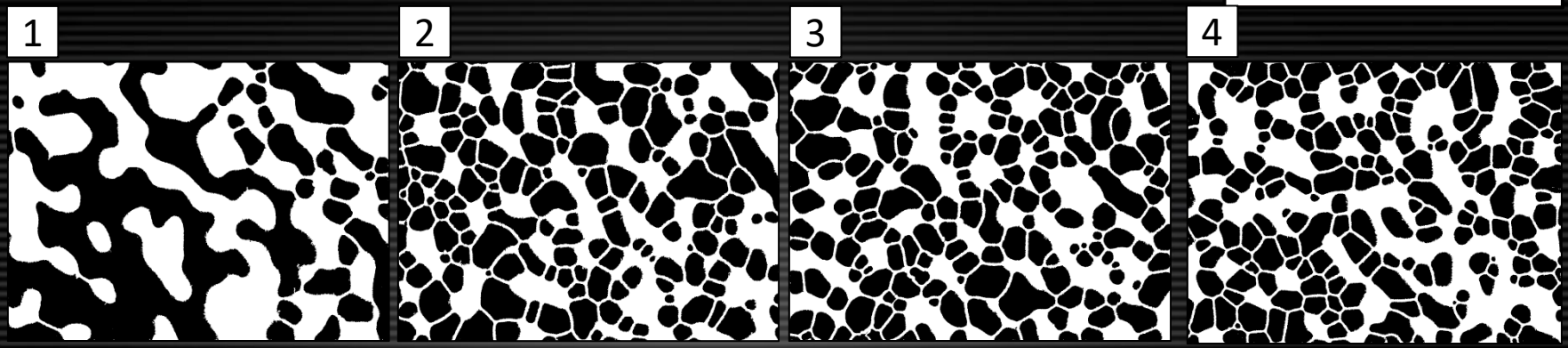


Model Fracture Correlation Length



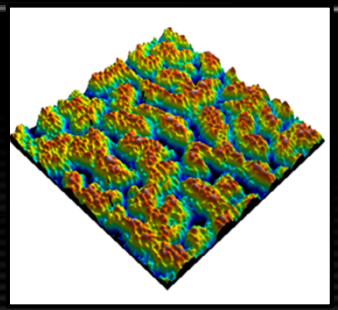
Sample 5: f_g = 0.46, u_t = 0.0007 m/s; black is gas and white is water. Image size 1.6X1.6 cm.



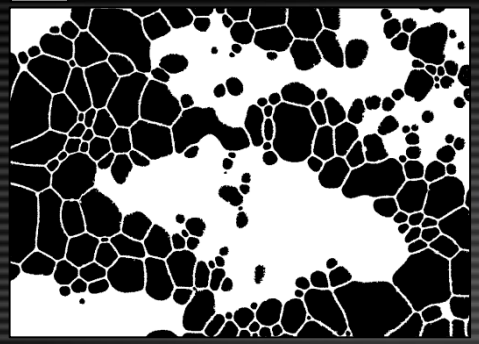


Section	1	2	3	4
Distance from inlet, mm	60	150	230	360
Average bubble size, mm^2	2.48	0.66	0.60	0.53
Bubble size, std. dev. , mm^2	7.84	0.57	0.48	0.36
Number of bubbles	37	160	176	194

Sample 4 f_g = 0.70, u_t = 0.0016 m/s; black is gas and white is water. Image size 1.4X1.0 cm.



2



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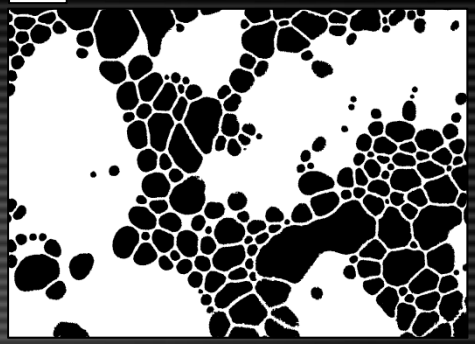
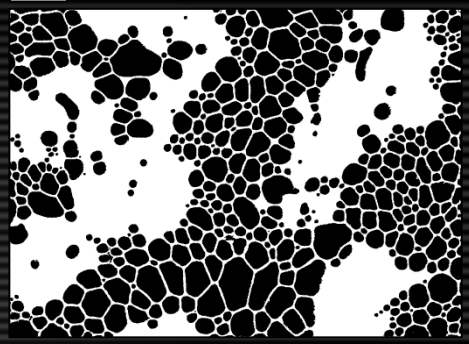
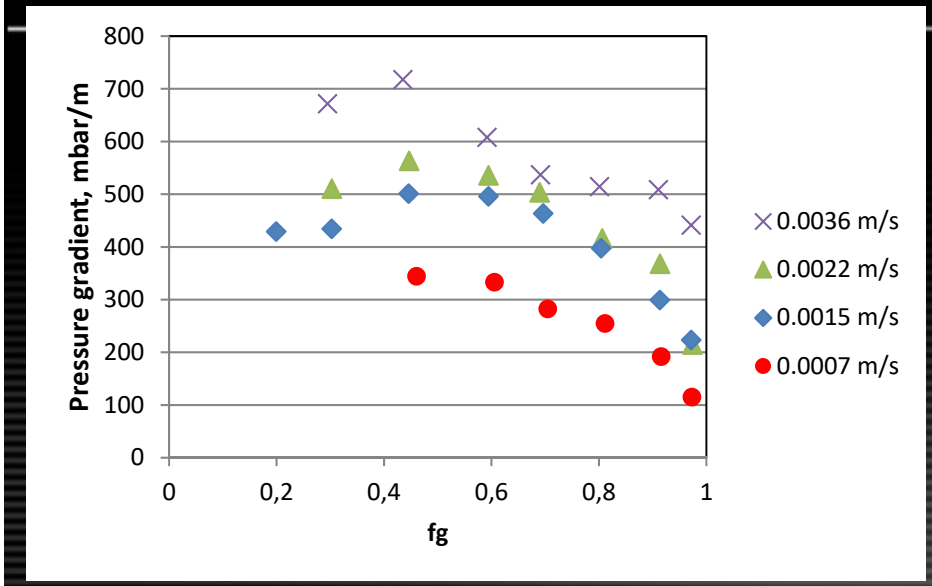
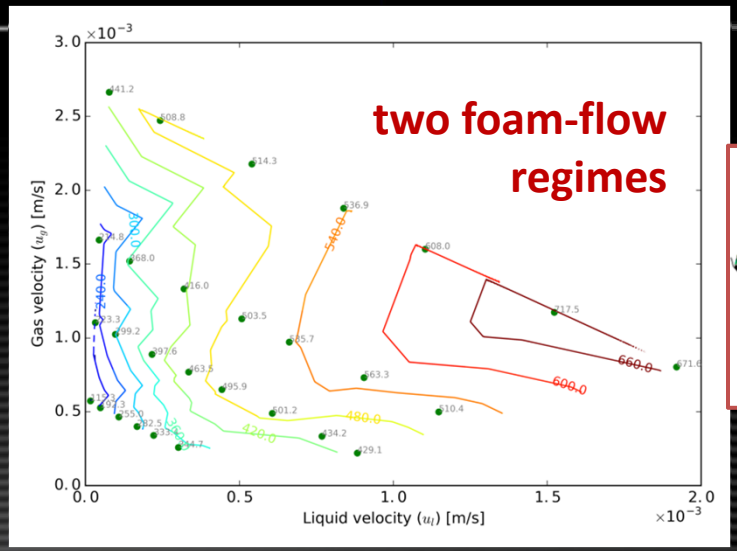


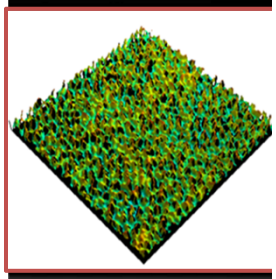
4

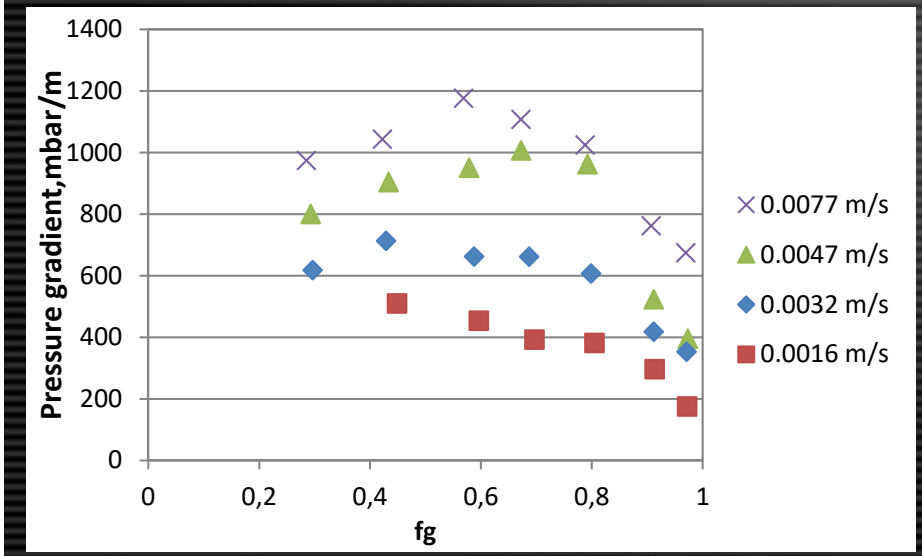


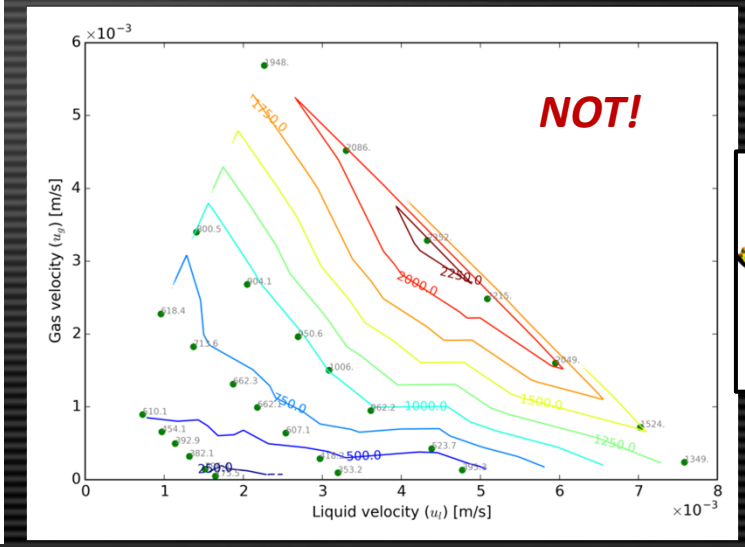
Section	1	2	3	4
Distance from inlet, mm	60	150	230	360
Average bubble size, mm^2	NA	0.36	0.26	0.14
Bubble size, std. dev. , mm^2	NA	0.47	0.40	0.16
Number of bubbles	NA	207	216	479

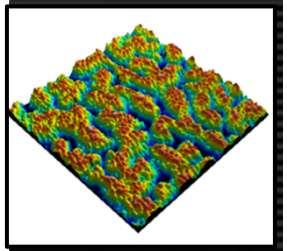

Pressure gradient, mbar/m
fg
0.0036 m/s
0.0022 m/s
0.0015 m/s
0.0007 m/s


two foam-flow regimes
Gas velocity (u_g) [m/s]
Liquid velocity (u_l) [m/s]

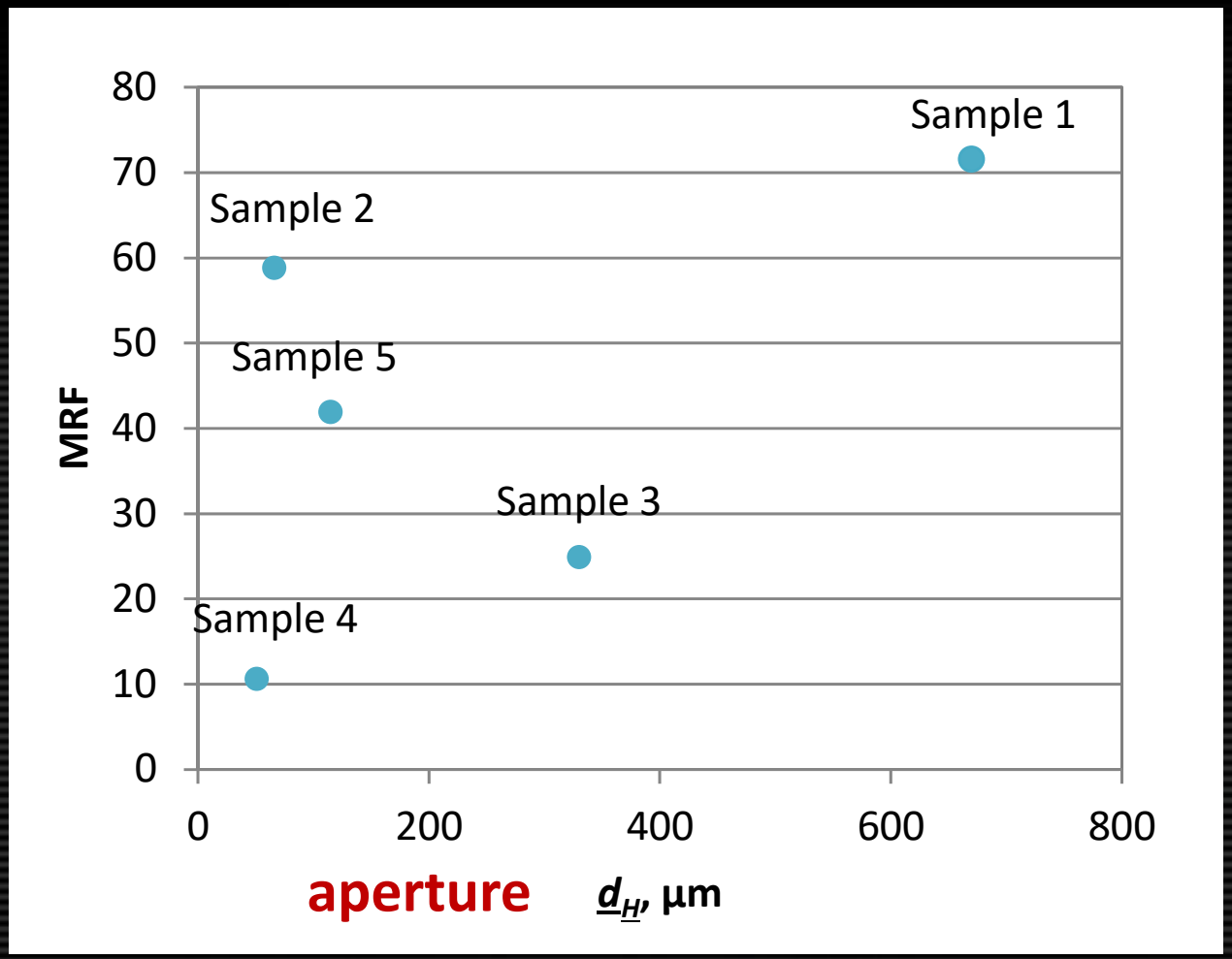



Pressure gradient,mbar/m
fg
0.0077 m/s
0.0047 m/s
0.0032 m/s
0.0016 m/s

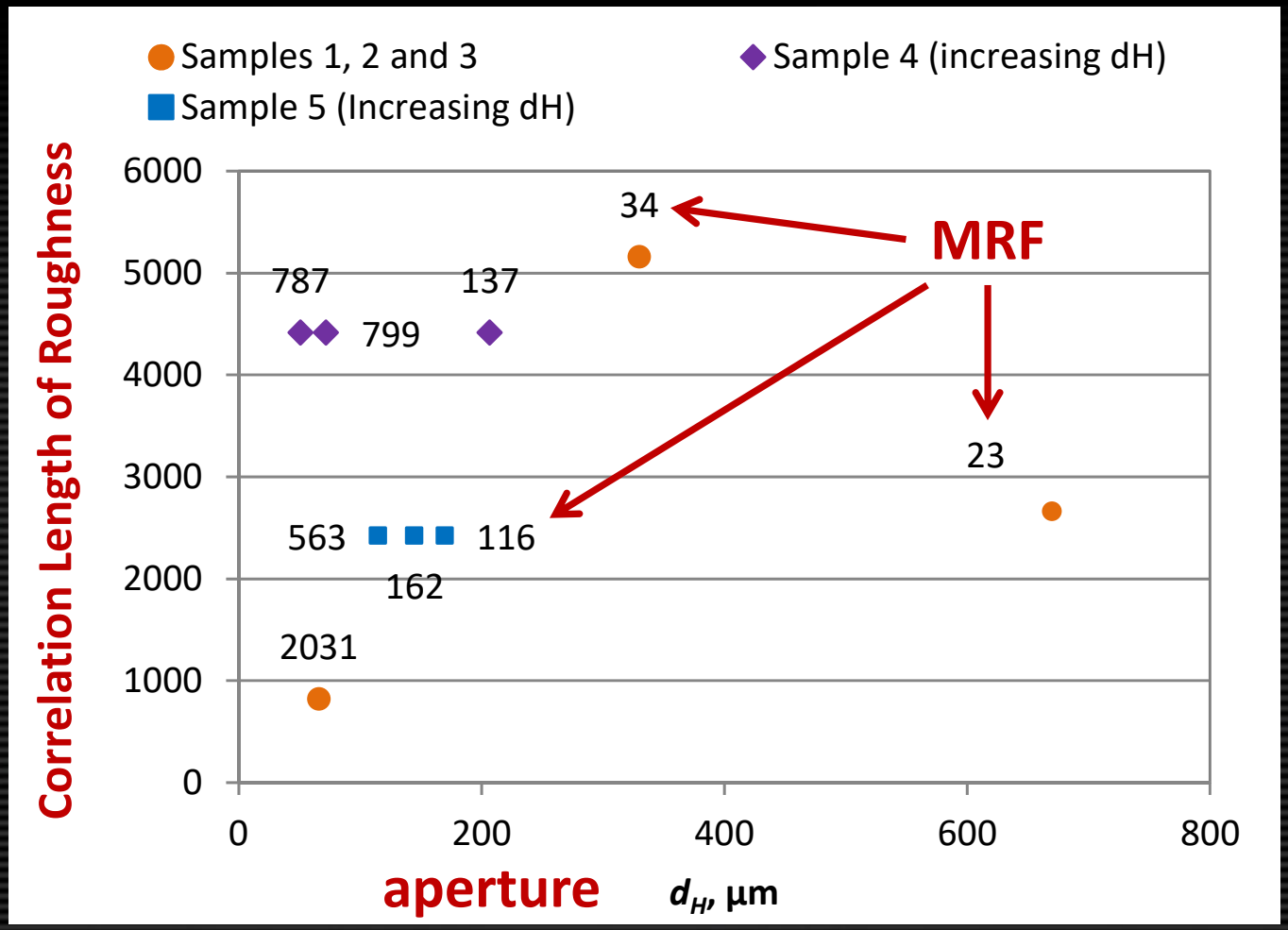

NOT!
Gas velocity (u_g) [m/s]
Liquid velocity (u_l) [m/s]



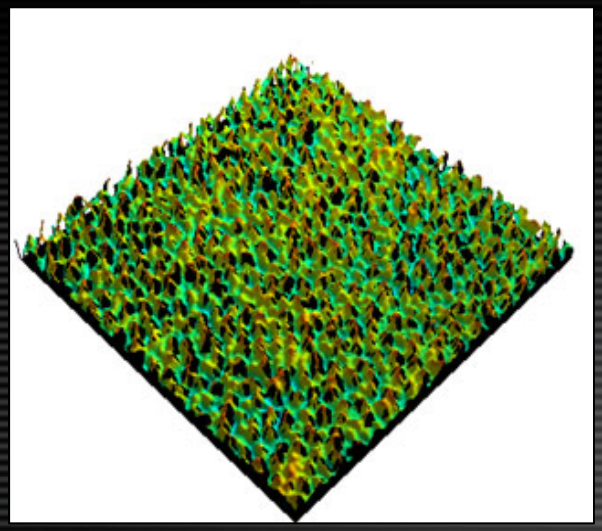
Summary of all fractures: Mobility Reduction Factors

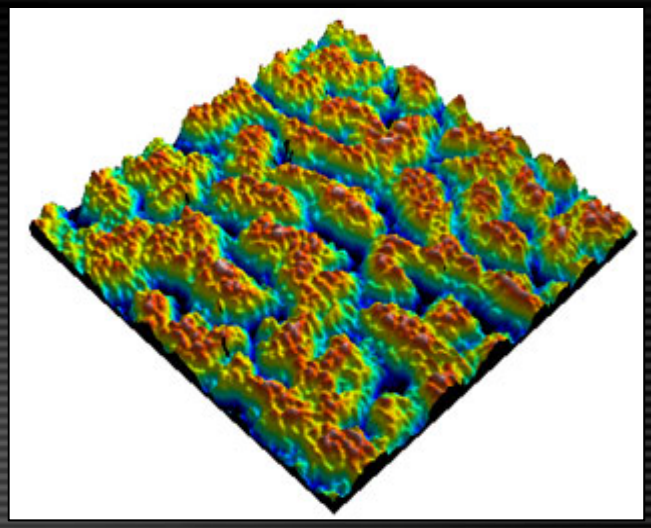


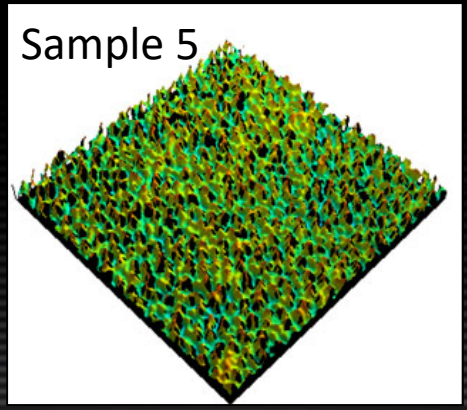
Summary of all fractures: Mobility Reduction Factors

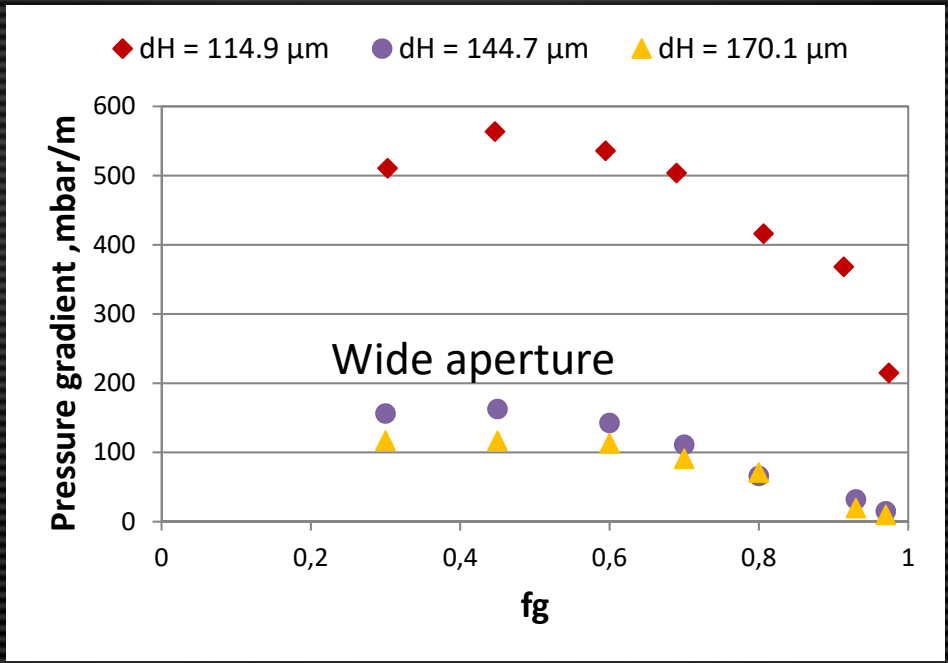


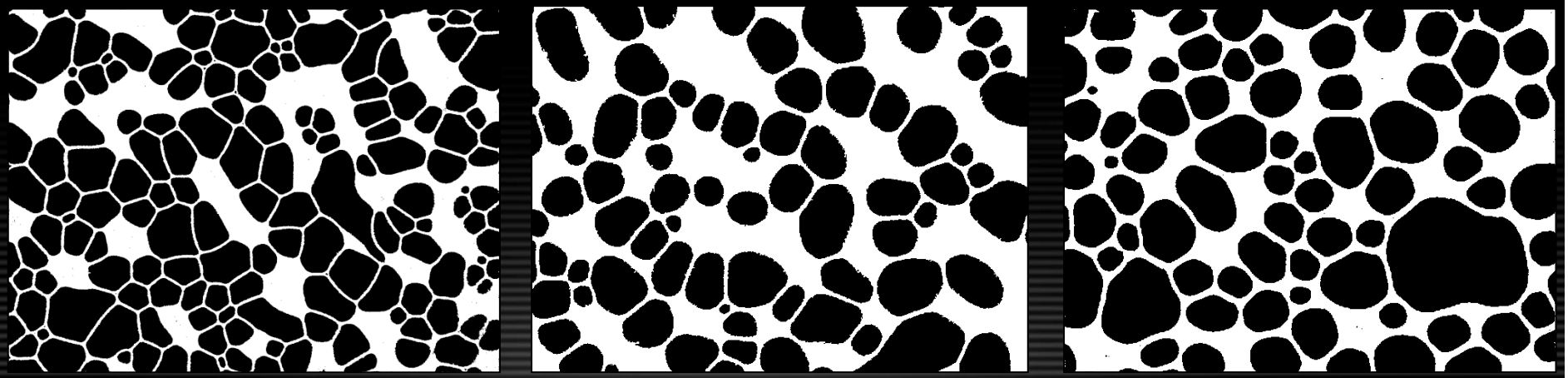
Increase aperture at fixed roughness: two cases






Sample 5


dH = 114.9 µm
dH = 144.7 µm
dH = 170.1 µm
Pressure gradient ,mbar/m
600
500
400
300
200
100
0
Wide aperture
0
0,2
0,4
0,6
0,8
1
fg

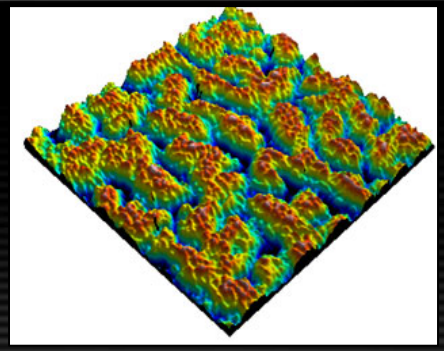


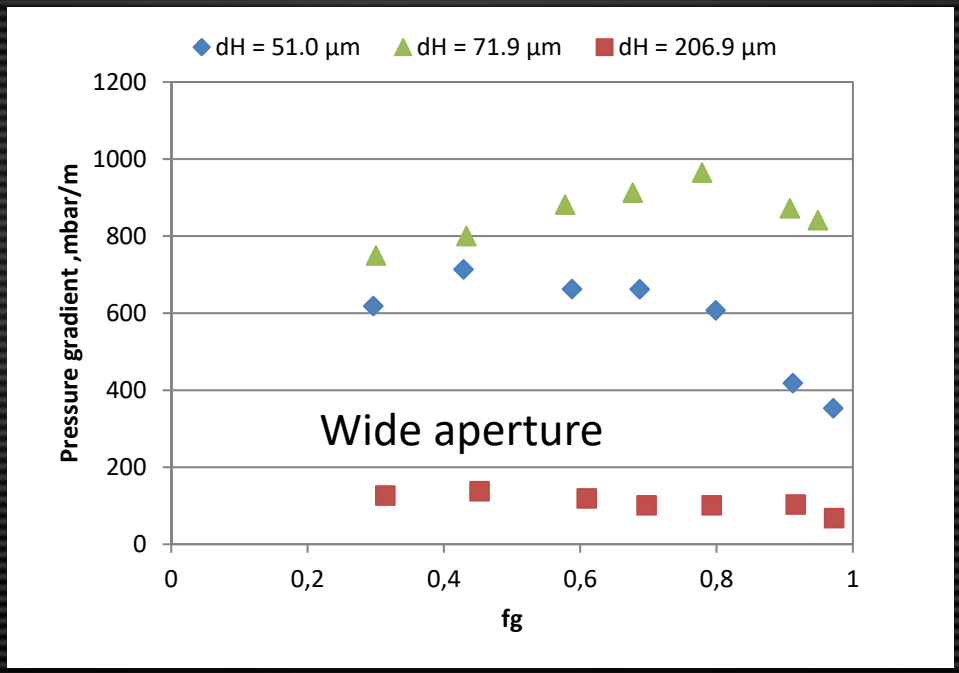
$d_{H,\ \mu m}$	114.9	144.70	170.10
Average bubble size , mm^2	0.468	0.74	0.943
Standard Deviation, mm^2	0.343	0.438	1.02
No of bubbles	120	55	54

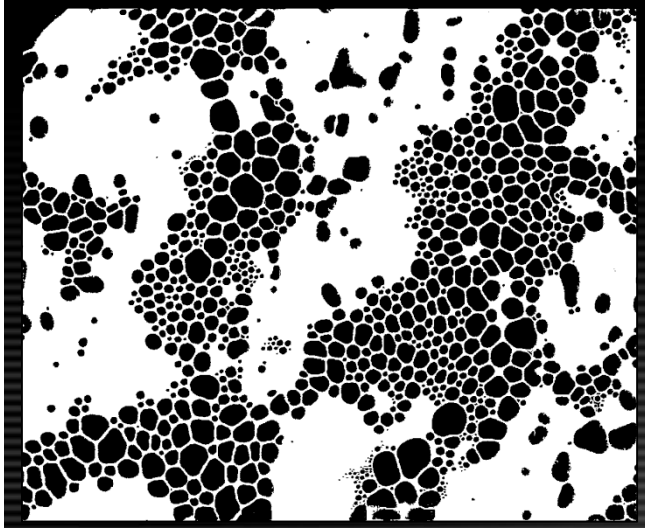
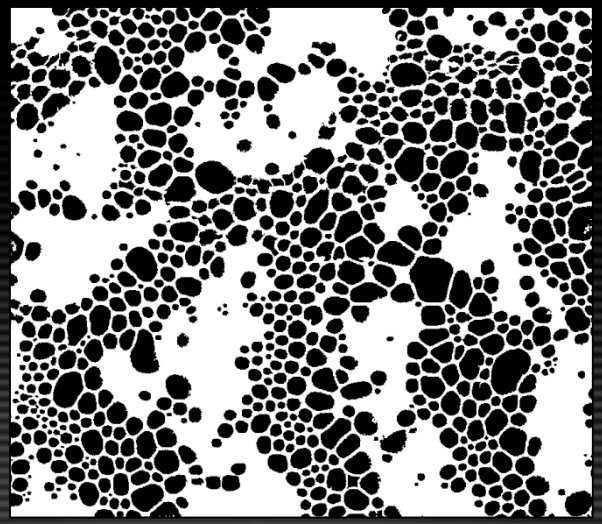
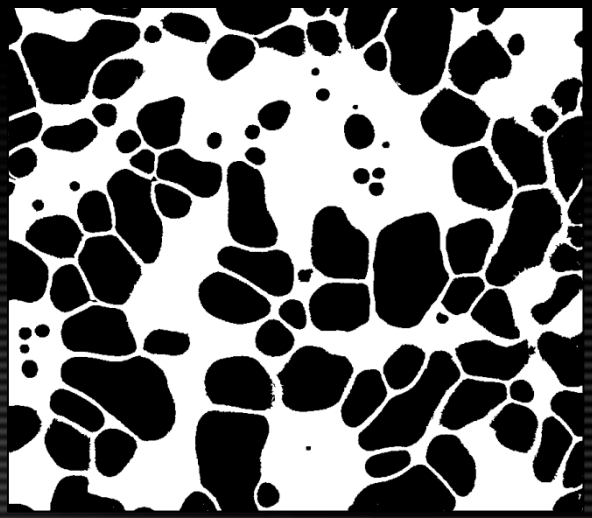
- Images are captured in section 4, fixed f_g of 0.45, and bubbles at the edges are excluded
- Images are identical in size (1.1X0.86 cm)

TUDelft

Larger aperture → bigger bubbles




dH = 51.0 µm
dH = 71.9 µm
dH = 206.9 µm
Pressure gradient ,mbar/m
1200
1000
800
600
400
200
0
0
0,2
0,4
0,6
0,8
1
fg
Wide aperture

d_H	51.00	71.90	206.9
Average bubble size, mm^2	0.097	0.148	1.37
Standard deviation, mm^2	0.114	0.133	1.32
No. of bubbles	972	750	78

- Images are captured in section 4, fixed f_g of 0.45, and bubbles at the edges are excluded
- Images are identical in size (1.7X1.5 cm)

TUDelft

Larger aperture → bigger bubbles

Summary and Conclusions

- Foam generation was observed in the model fractures, mainly by capillary snap-off and lamella division.
- Hydraulic aperture alone is not enough to determine foam-generation and mobility reduction. Roughness scale, both laterally and vertically, plays a significant role. Slit-shaped throats & wet conditions favor snap-off.
- Bubble size was inversely related to pressure gradient, as expected
- Shear-thinning behaviour was observed as velocity increases.
- Two flow regimes were observed in 2 cases out of 3. However, the high-quality regime evidently reflected reduced and fluctuating generation, not collapse of foam at limiting capillary pressure P_c*. Bubbles were smaller than pore size in low-quality regime.
- With fixed roughness, pressure gradient decreases with increasing hydraulic aperture. Foam bubbles became larger as aperture increases.

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Reports and Publications

- The dissertation has details on both the N_{ca} and foam experiments and analysis and is available online. Search for AlQuaimi at

  https://www.tudelft.nl/en/library/

- **Journal and Conference Publications**
- AlQuaimi, B. I., Rossen, W. R. (2017), New capillary number definition for displacement of residual nonwetting phase in natural fractures.Geophys. Res. Lett., 44 (11), 5368–5373.
- AlQuaimi, B. I., Rossen,W. R. (2017), Capillary Desaturation Curve for Residual Nonwetting Phase in Natural Fractures. Accepted by *SPE Journal*.
- AlQuaimi, B. I., and Rossen, W. R., "Characterizing Foam Flow in Fractures for Enhanced Oil Recovery," presented at the EAGE IOR Symposium, Stavanger , April 24-27, 2017.

Thank You
For Your Attention