

Study of foam in Fractures and Porous media for EOR process



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Experimental work:

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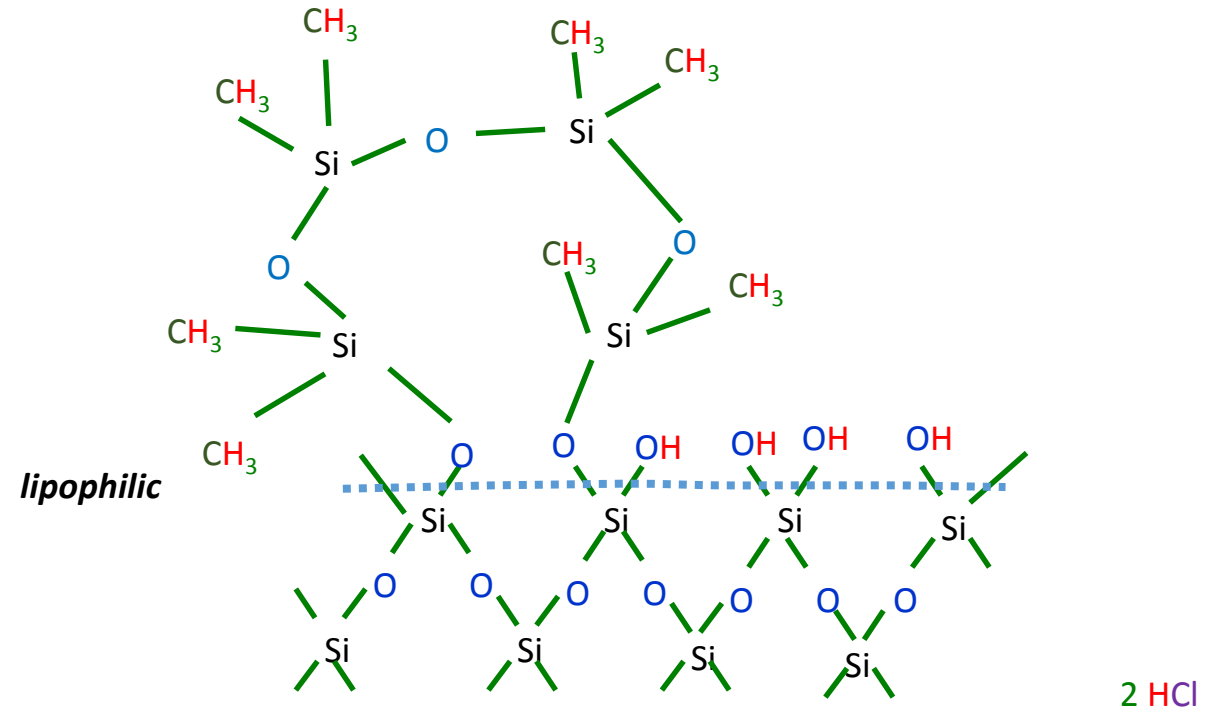
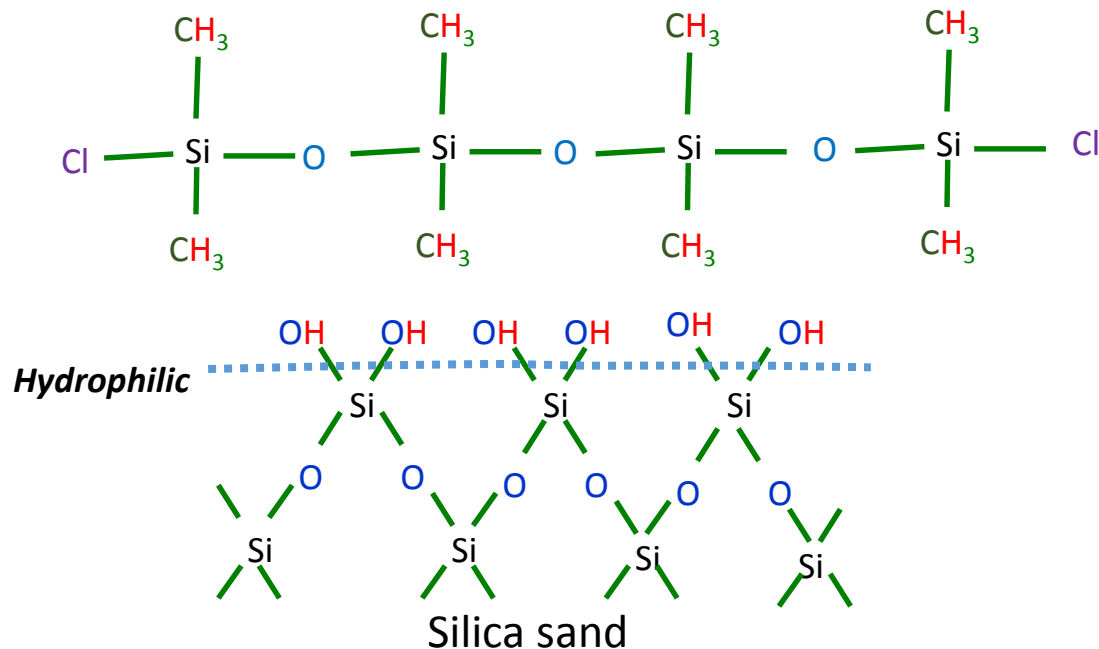
Objective:

Study of foaming properties for a surfactant blend with potential to produce ultralow IFT

Introduction:

After preliminary tests of aqueous stability, phase behavior and IFT measurements, the performance of a potential formulation was qualitatively tested. Sand was treated to be oil wet, then immersed and aged with synthetic live oil and finally contacted either seawater or Surfactant solution in seawater.

Silica sand grains were treated to be oil-wet
Using Dichloro octamethyl tetrasiloxane

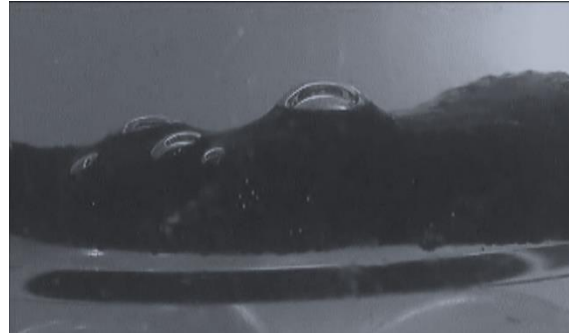


Surfactant formulation with ultralow IFT

Grains of sand covered
with synthetic live oil
70 °C



80 °C After 1 h no oil recovered

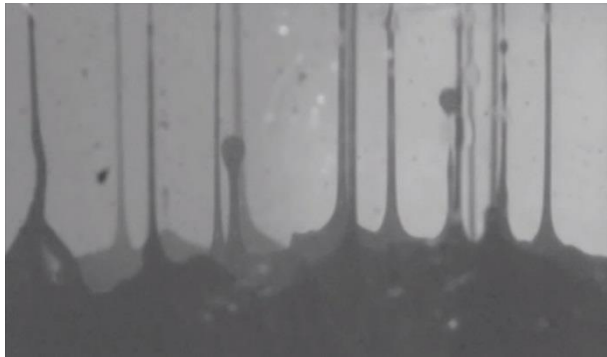


80 °C After 3 h no oil recovered

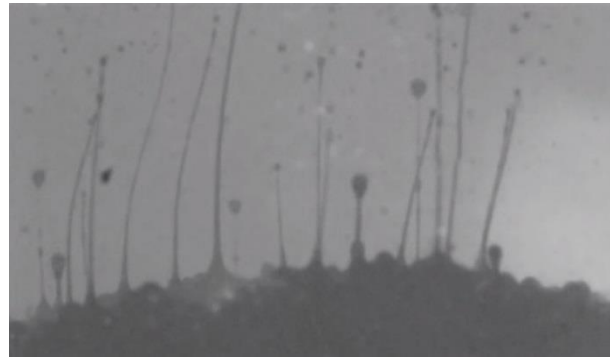


Seawater

70 °C After 2 min



80 °C After 10 min



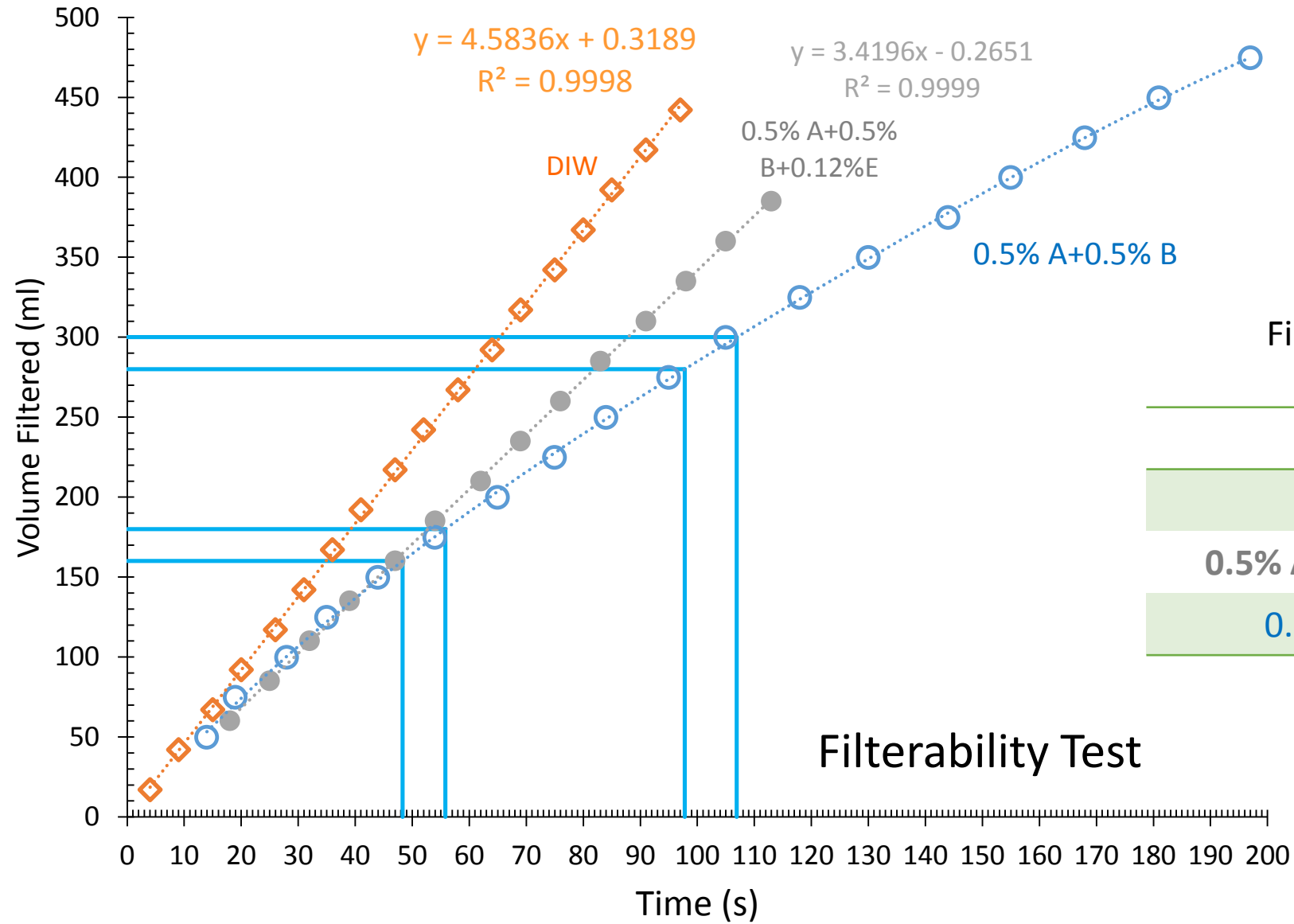
80 °C Oil being recovered



**Surfactant in
Seawater**

Silica sand was treated with 1,7-Dichloro-octamethyl tetra siloxane, then contacted with synthetic live oil

Filterability test.



Filtration Ratio = $[t_{200\text{ ml}} - t_{180\text{ ml}}] / [t_{80\text{ ml}} - t_{60\text{ ml}}]$

Solution	Filtration Ratio
DIW	1
0.5% A+0.5% B +0.12E	1
0.5% A+0.5% B	1.22

Filterability Test

Criterion $FR > 1.5$ unacceptable
Castor 1981
UT Austin $FR > 1.2$ for polymer using $0.45\text{ }\mu\text{m}$
James Sheng 2010 , Modern Chemical EOR

After verifying the potential to recover oil, a filterability test was conducted.

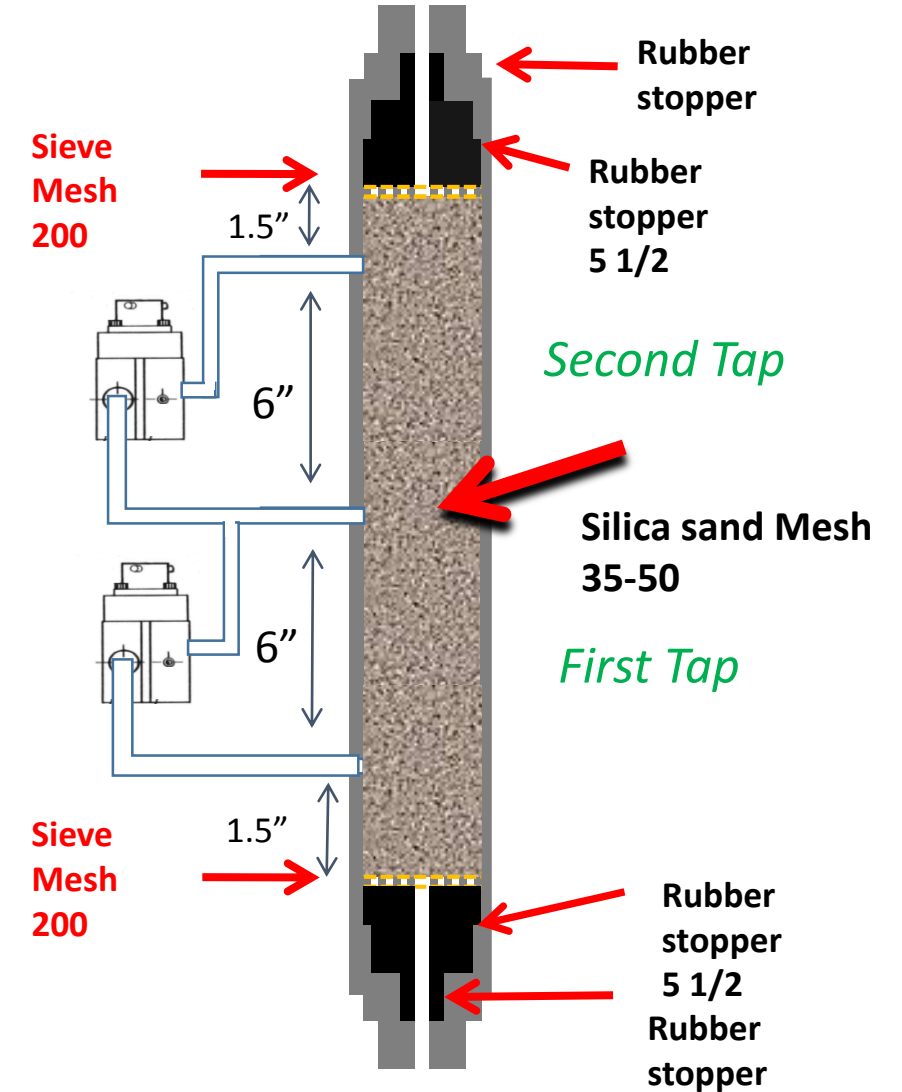
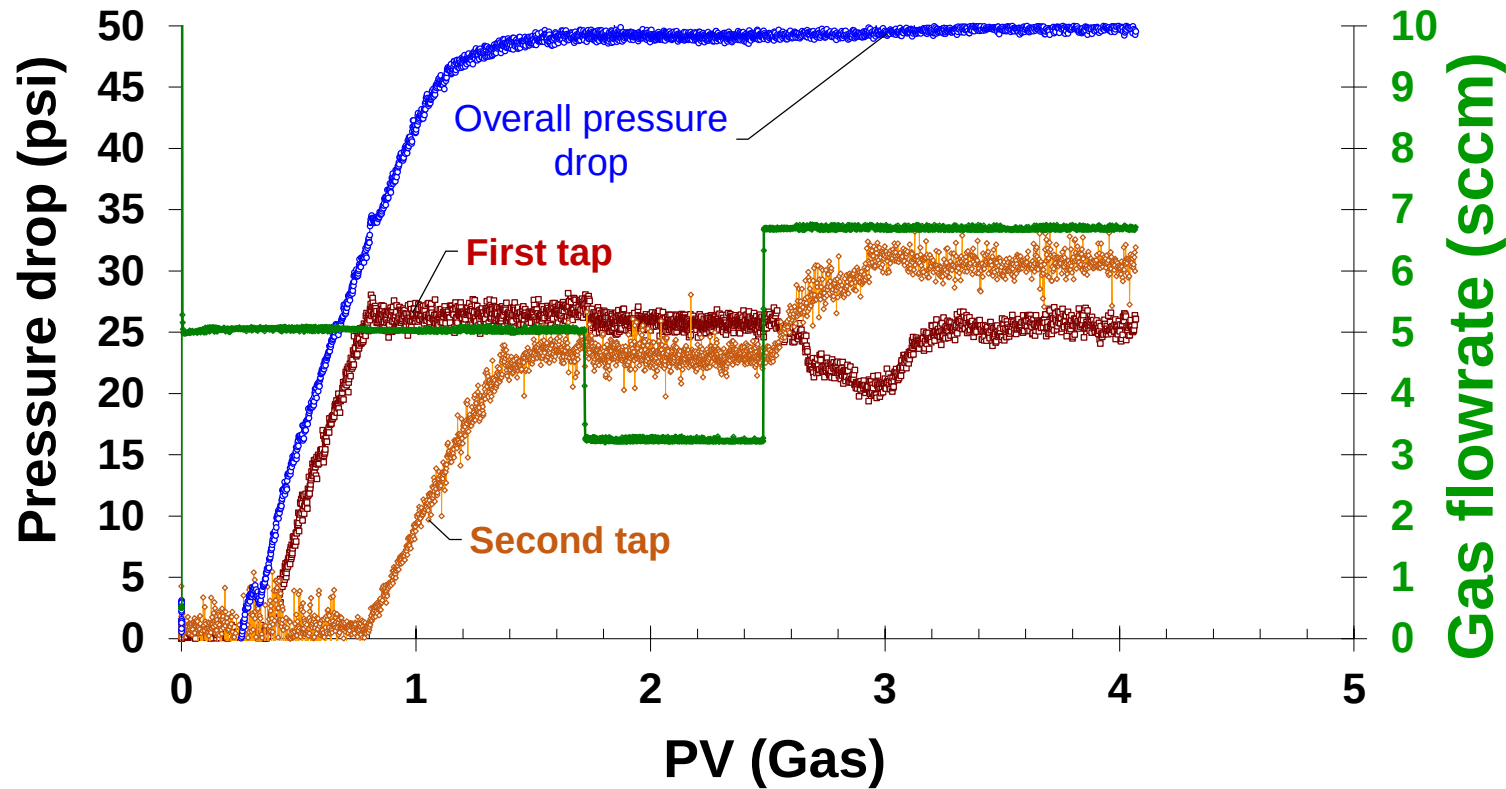
Foam experiments

Experiments were conducted to study:

- Foam in porous media (unconsolidated sand pack)
 - Shear thinning properties
 - Effect of permeability
 - Temperature dependence
 - Effect of quality
 - Effect of oil
 - Effect of surfactant concentration
 - Fit parameters of a foam model (MRF Approach)
- Foam in parallel plates as a representation of fractures

Foam : Co-injection of 0.5% A + 0.5%B+ 0.12% E
In Seawater at 94° C

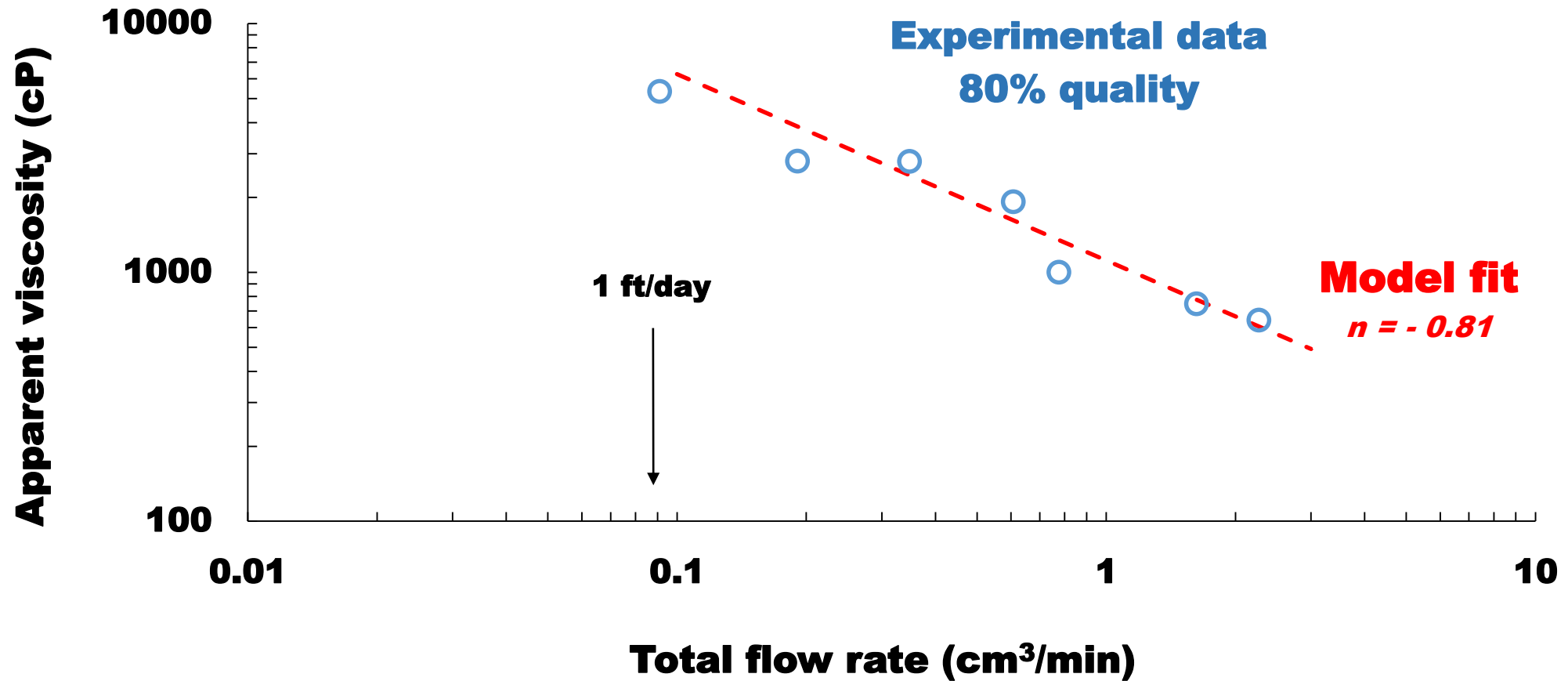
80% Foam Quality, OTTAWA Sand K = 45D



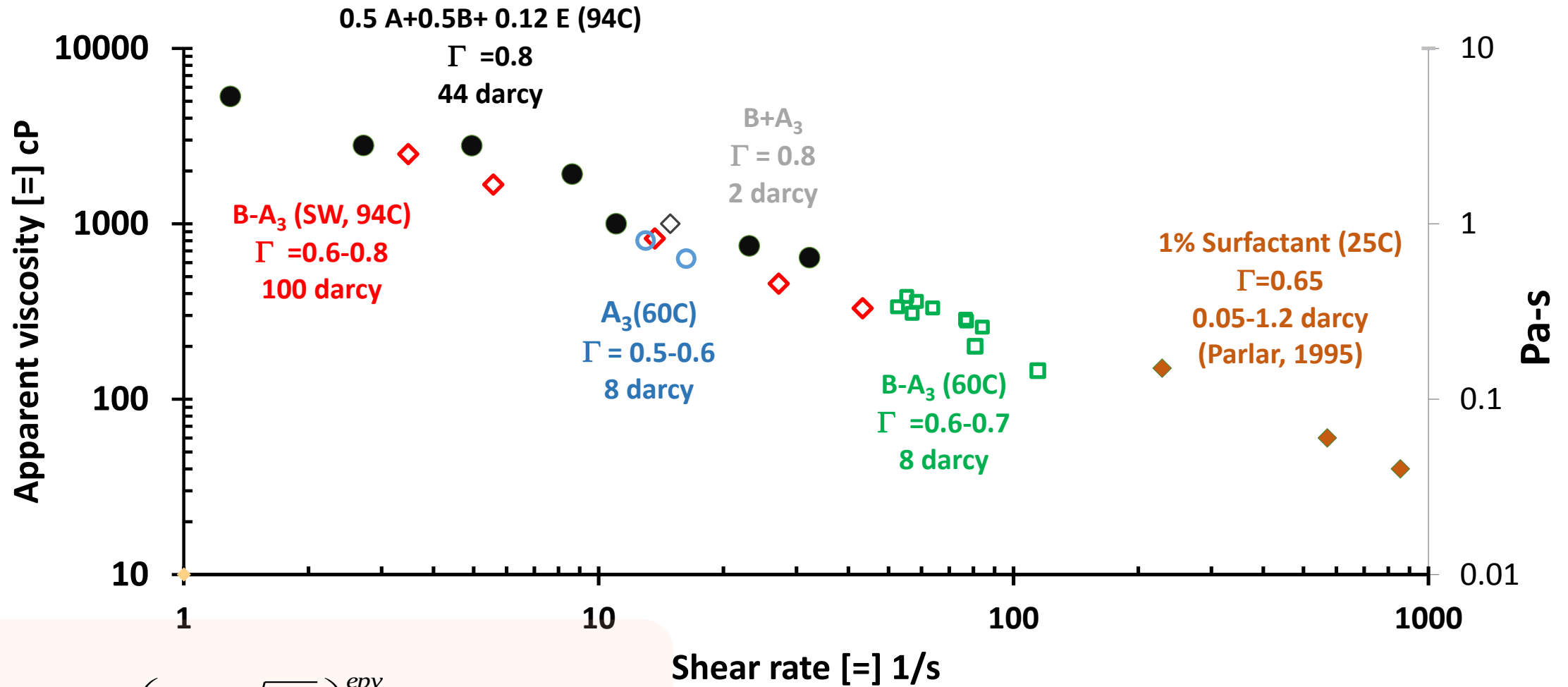
Sand pack Internal-Tap Locations

Foam : Co-injection of **0.5% A + 0.5%B+ 0.12% E**
In Seawater at 94° C

Shear thinning effect



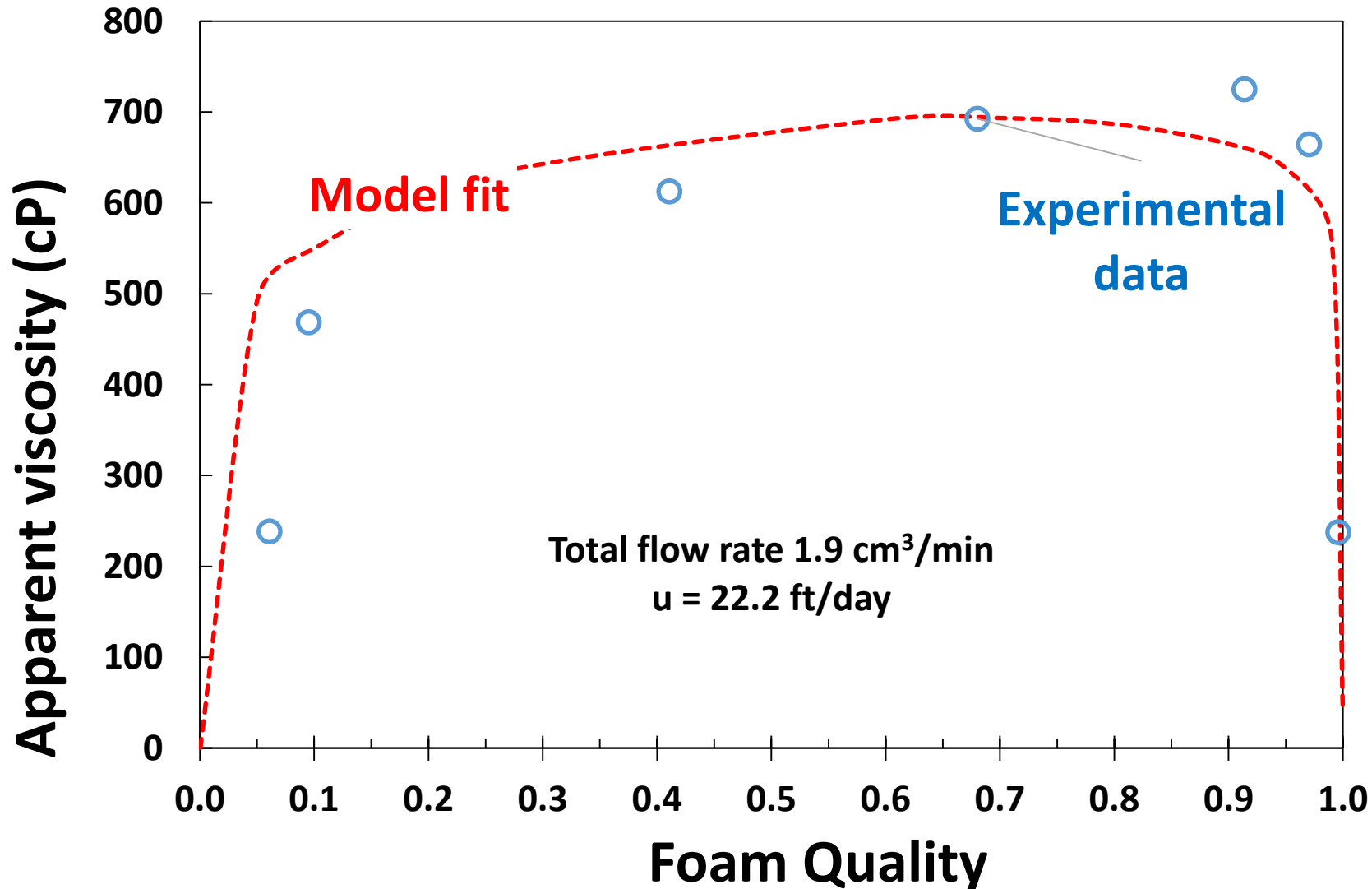
Effect of permeability



$$F_4 = \left(\frac{u_g / \sqrt{k\phi}}{1.53 \text{ s}^{-1}} \right)^{epv}$$

Foam : Co-injection of **0.5% A + 0.5% B + 0.12% E**
In Seawater at 94° C

Effect of foam Quality



Parameters for the model

D	2.29	cm
L	36.195	cm
k	44	darcy
ϕ	0.36	
ΔL	15.24	cm

S_{cw}	0.1
S_{rg}	0.05
n_w	5
ng	2
k_w^0	1
k_g^0	1

Porous media and fluids properties

μ_w	0.3	cP
μ_g	0.02	cP

$$k_{rw} = k_{rw}^0 \left(\frac{S_w - S_{cw}}{1 - S_{rg} - S_{cw}} \right)^{nw}$$

Parameters for the model after fitting

$epdry$	100
$fmdry$	0.15
$fmmob$	140500
epv	-0.81
$U_{ref}(m/s)$	1.00E-05

$$F_2 = \frac{1}{2} + \frac{1}{\pi} \arctan[epdry(S_w - fmdry)]$$

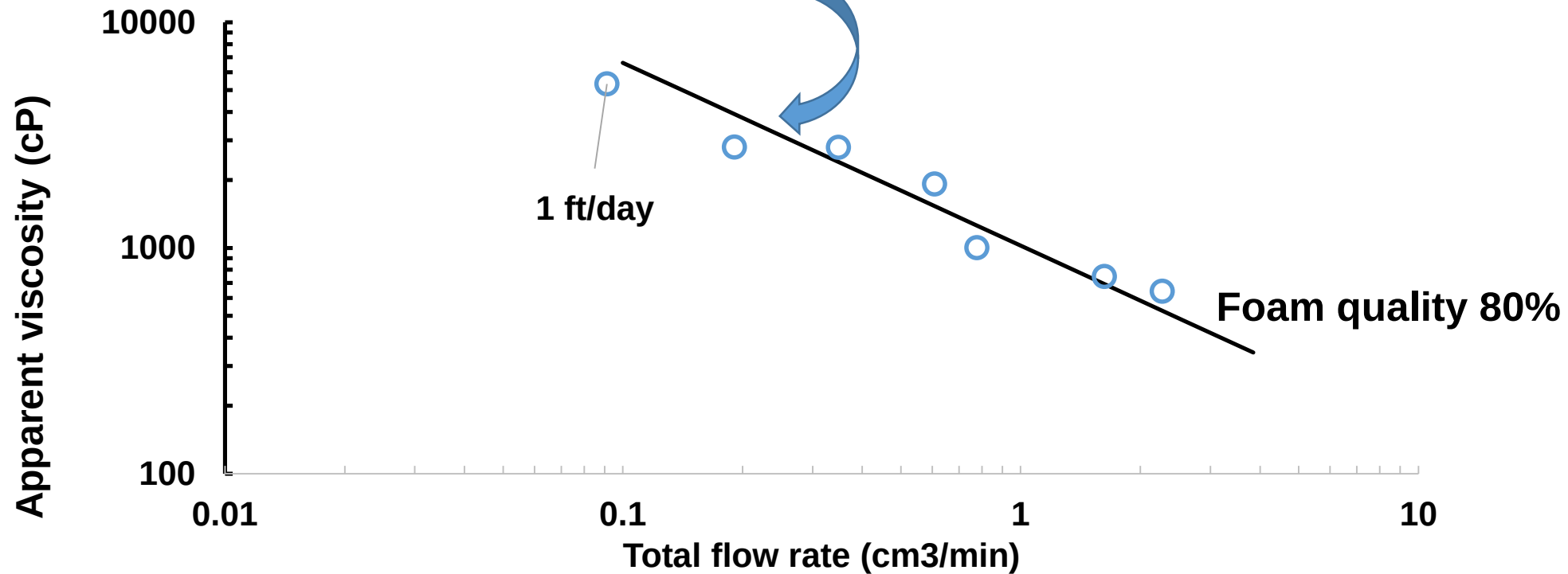
$$k_{rg}^f = \frac{k_{rg}}{\left(1 + fmmob \prod_{i=1}^6 F_i \right)}$$

$$F_4 = \left(\frac{u_g}{u_{gref}} \right)^{epv}$$

Parameters for the model : observation comparison and suggestion

Comparison of Foam strength at same shear rate with previous recommended formulation: B+A₂ 2:1

Shown as continuous black line



$$F_4 = \left(\frac{u_g / \sqrt{k\phi}}{1.53 \text{ s}^{-1}} \right)^{epv}$$

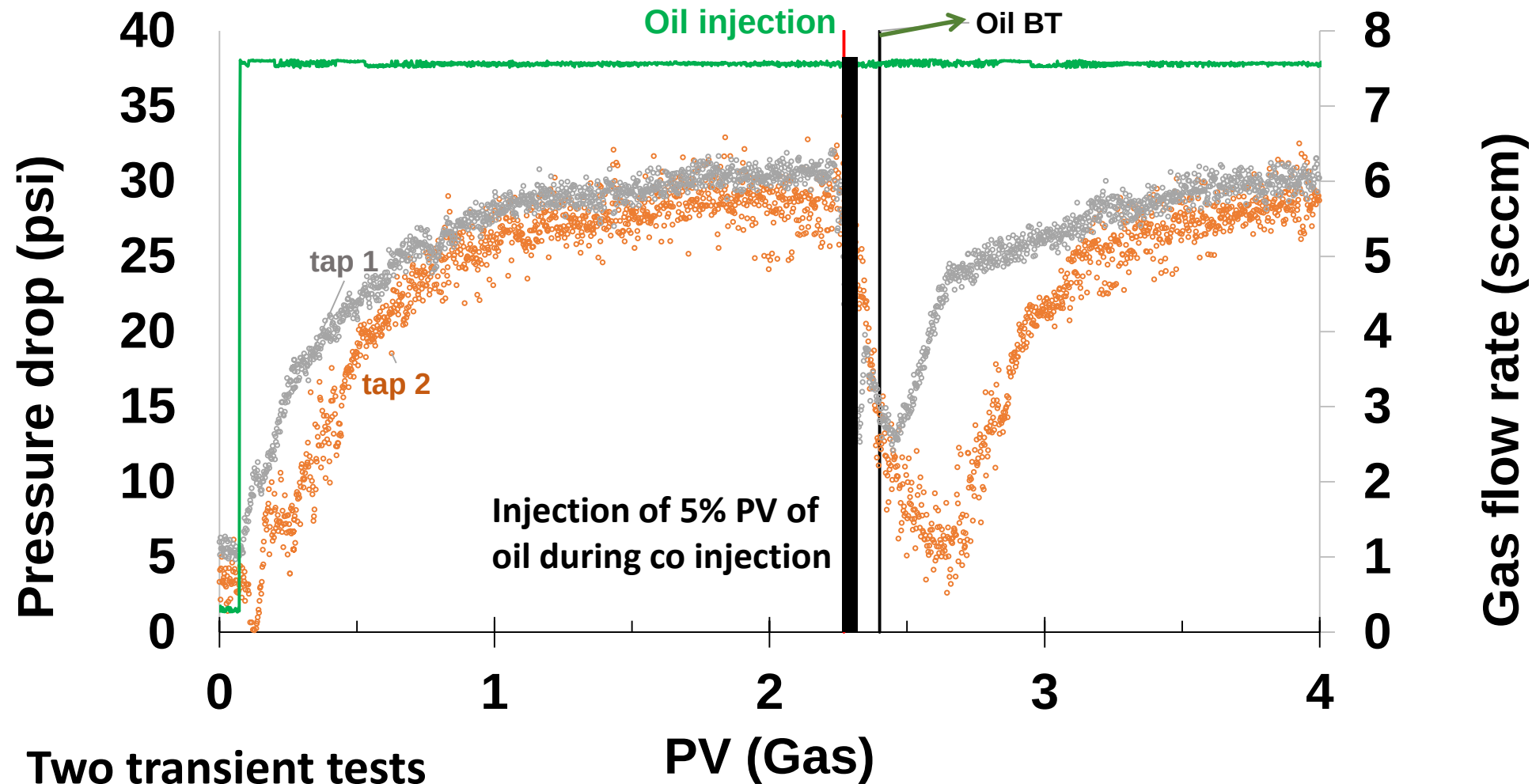
Fits to all values of permeability studied
100 , 44 , 8 and 2 darcy

Apparent shear rate (Carreau, 1997)

$$\dot{\gamma} = 12 u_g / \sqrt{75 k\phi} \approx 1.385 u_g / \sqrt{k\phi}$$

$$F_4 = \left(\frac{1.385 u_g / \sqrt{k\phi}}{3.505 \text{ s}^{-1}} \right)^{epv}$$

Effect of Oil on Foam Strength at 70% quality

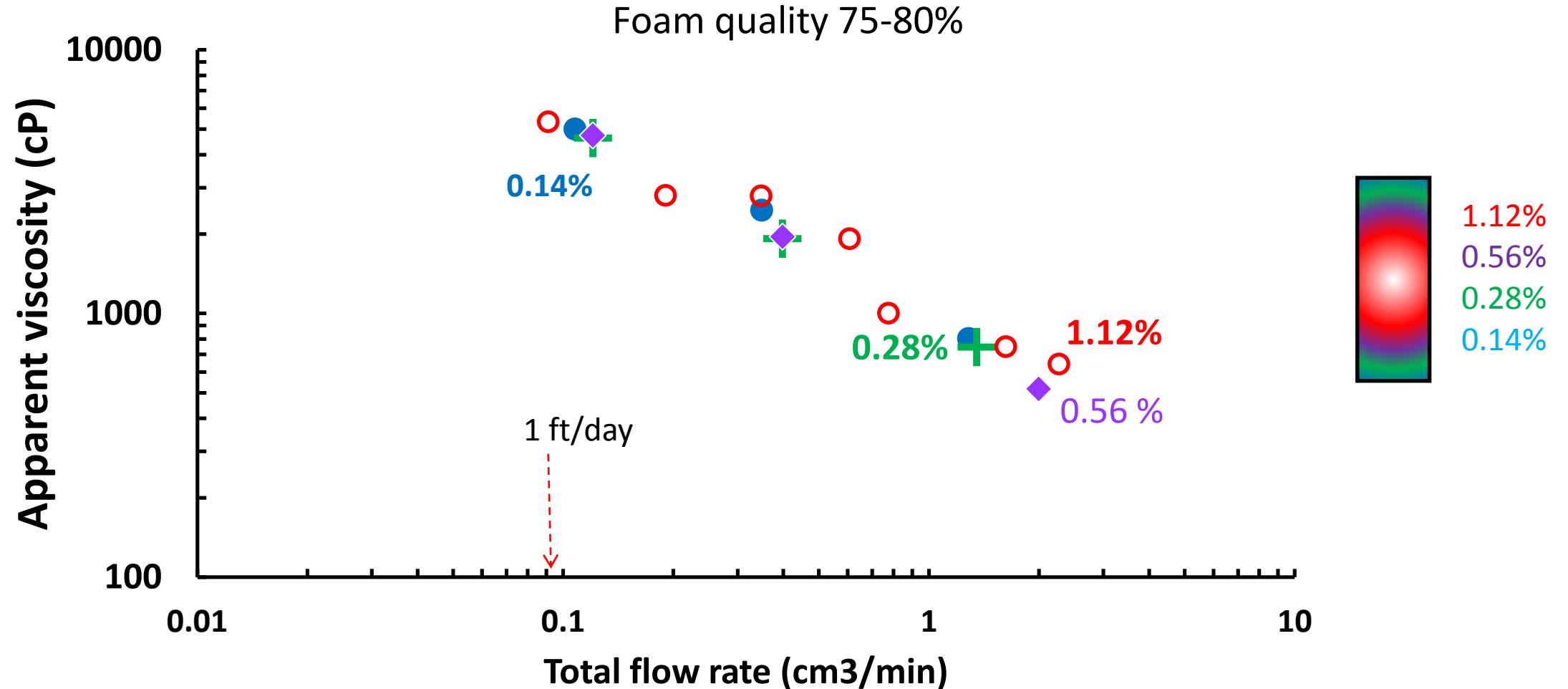


Two transient tests

Flow increased at 0.1 PV of gas from 0.12 cm³/min to 1.87 cm³/min

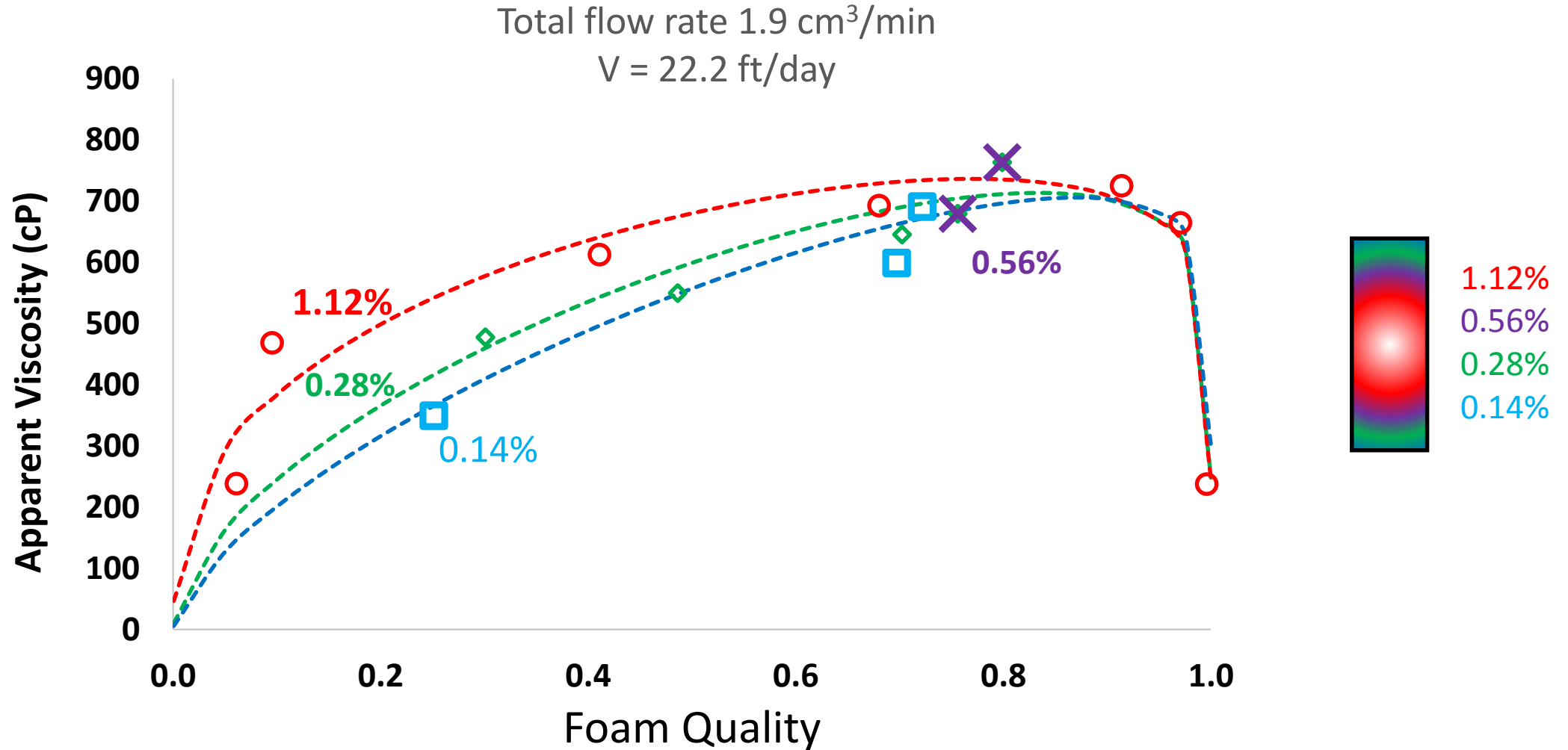
- foam recovered its strength in less than 1PV of gas
- oil injection at 2.27 PV of gas, took close to 0.1 PV of gas injection to see the oil BT

Effect of surfactant concentration on shear thinning effect.



The surfactant concentration in the range from 0.14% m/v to 1.12 % has no effect on the foam strength at steady state for quality between 75% and 80%.

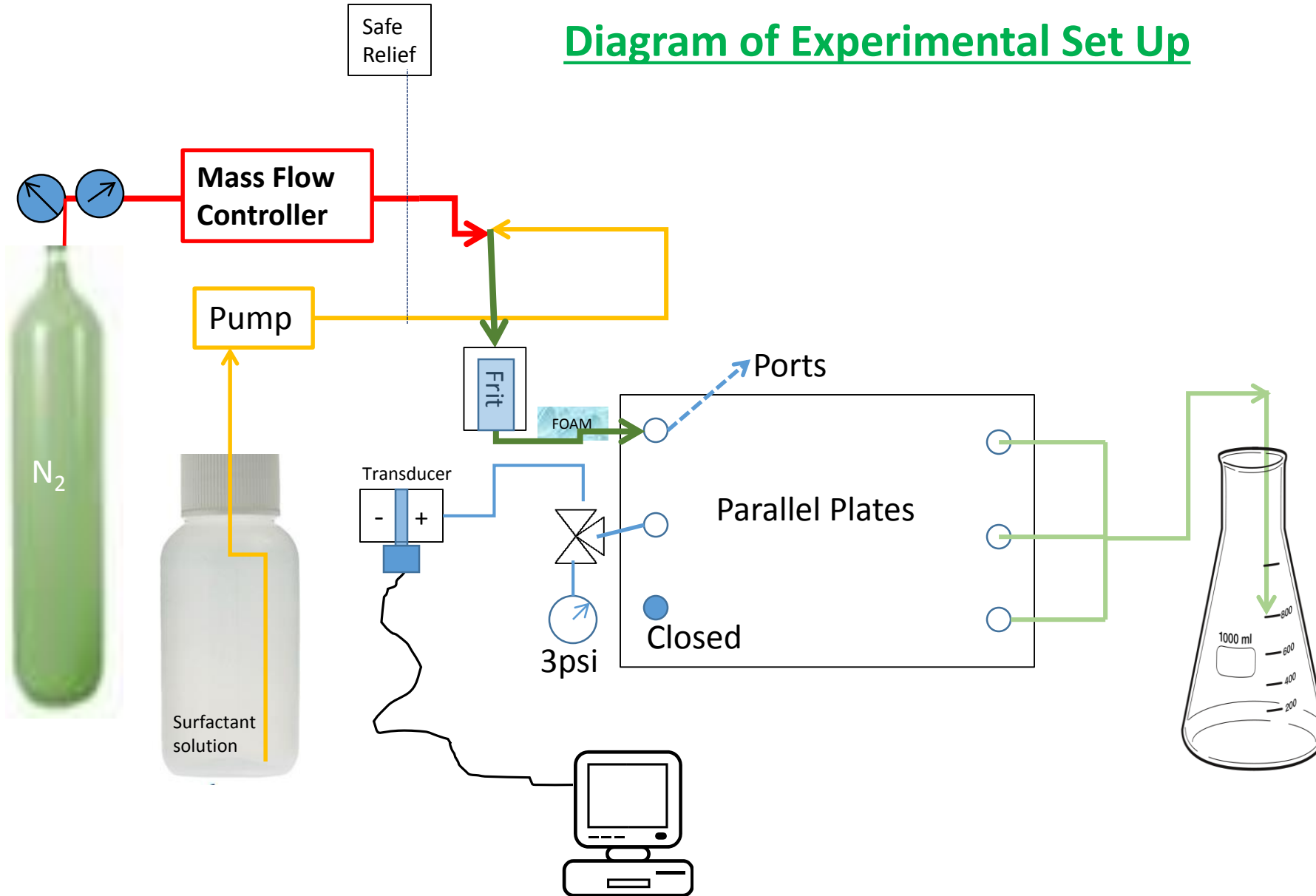
Effect of surfactant concentration



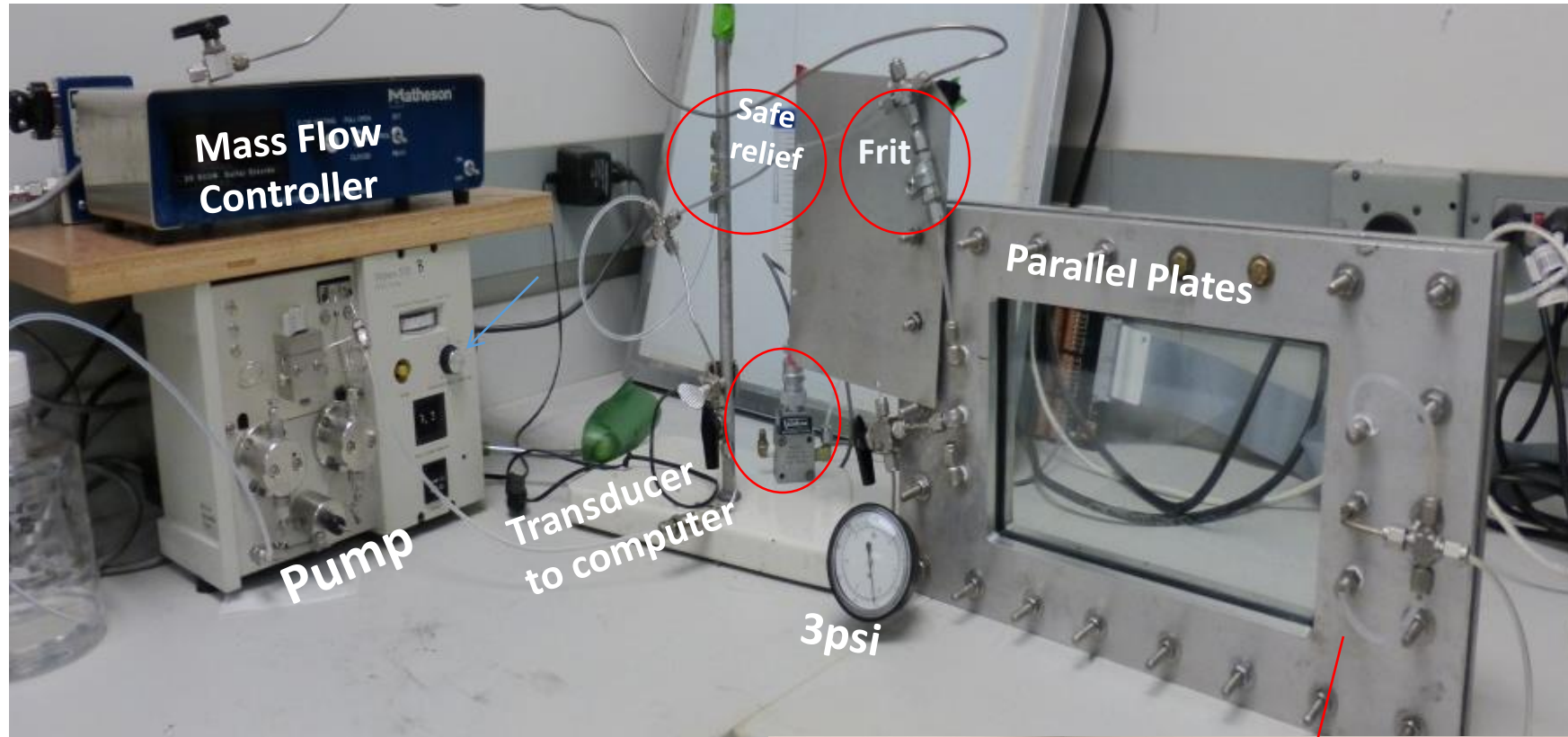
The dependence of foam strength with surfactant concentration is stronger when the quality is less than 80%.

Foam in fractures

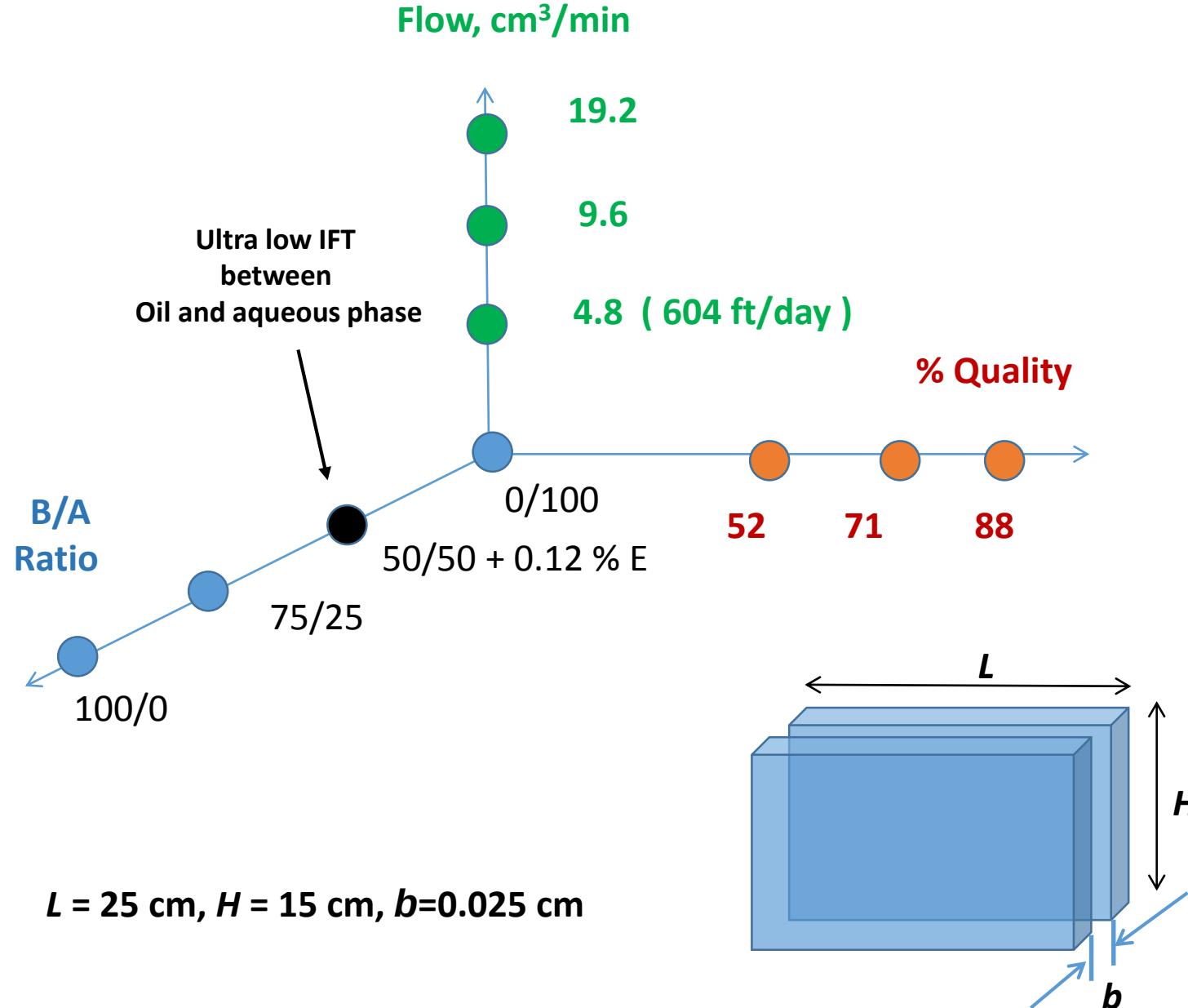
Diagram of Experimental Set Up



Picture of Experimental Set Up for Foam Testing



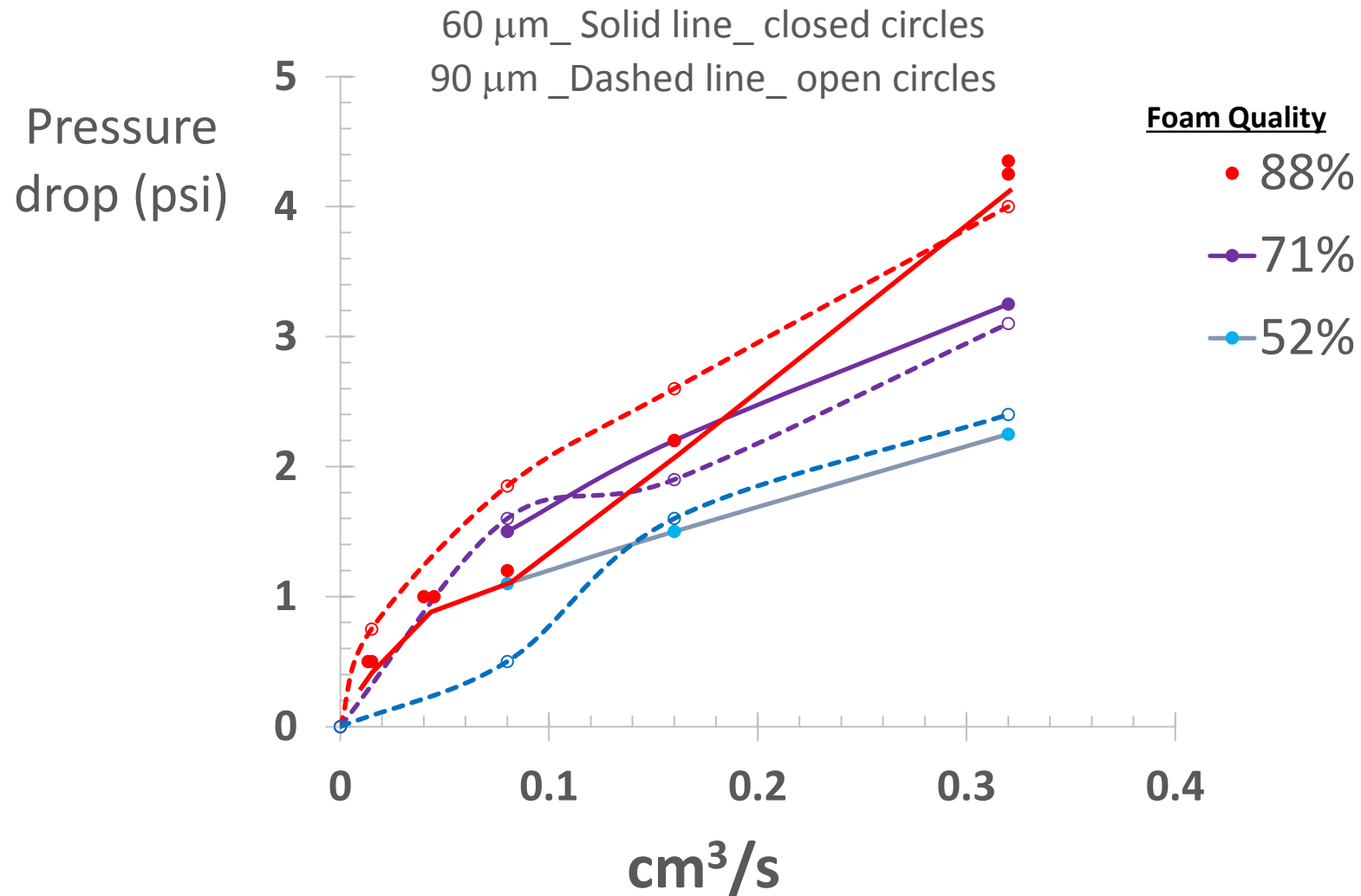
Experimental variables



Effect of frit size to pre-generate foam

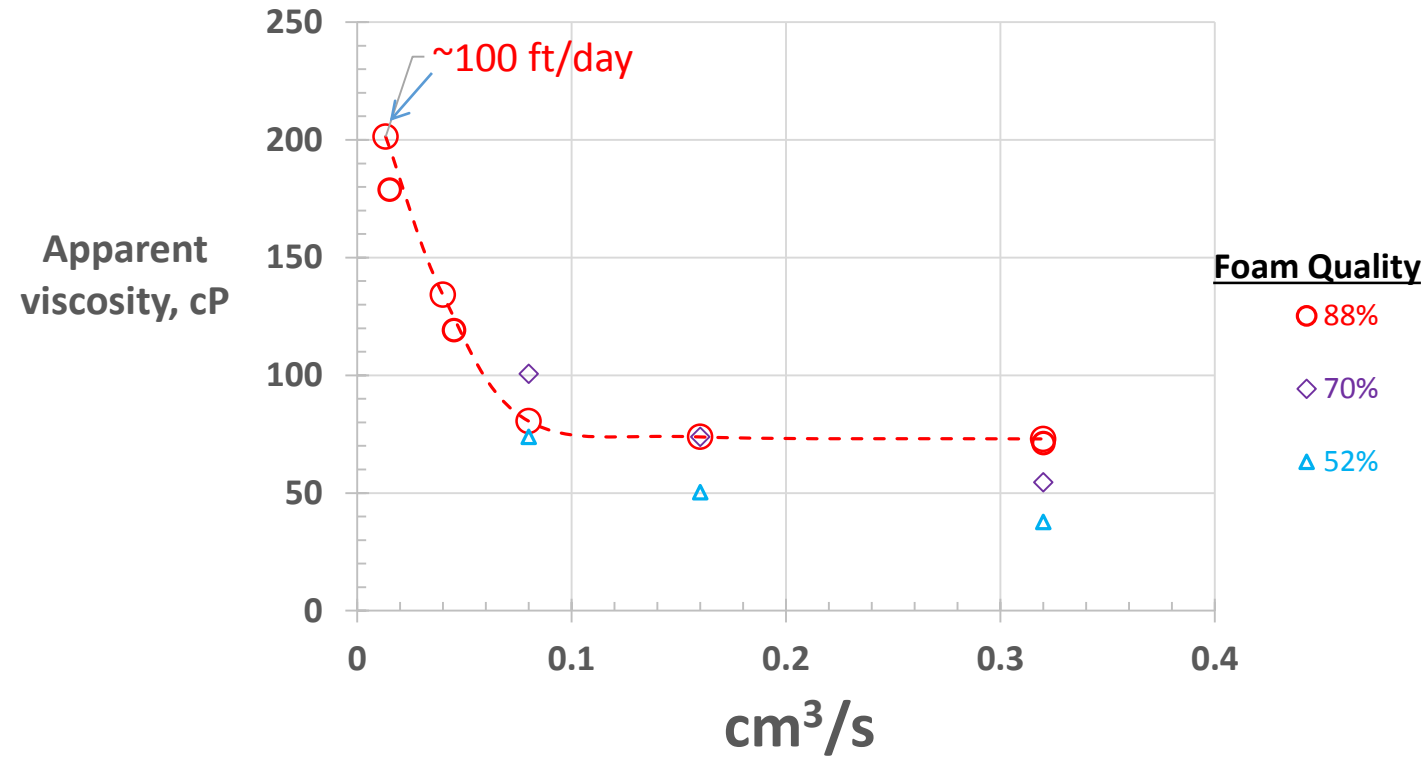
Foam in 250 μm aperture parallel plates 25° C

7.5B: 2.5 A



Apparent viscosity

7.5 B : 2.5 A



$$\mu = k A \frac{\nabla p}{q}$$

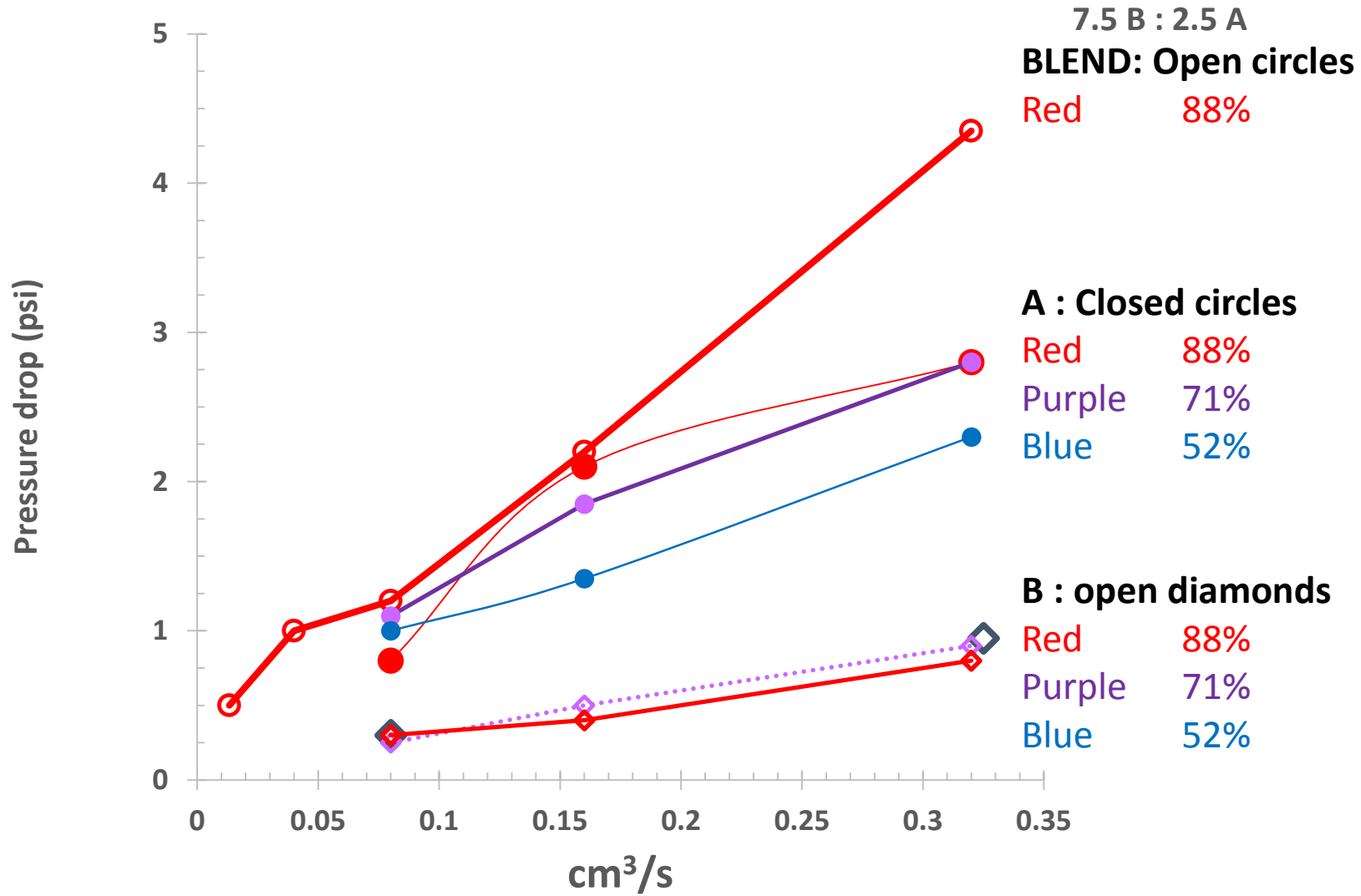
$$k = \frac{b^2}{12}$$

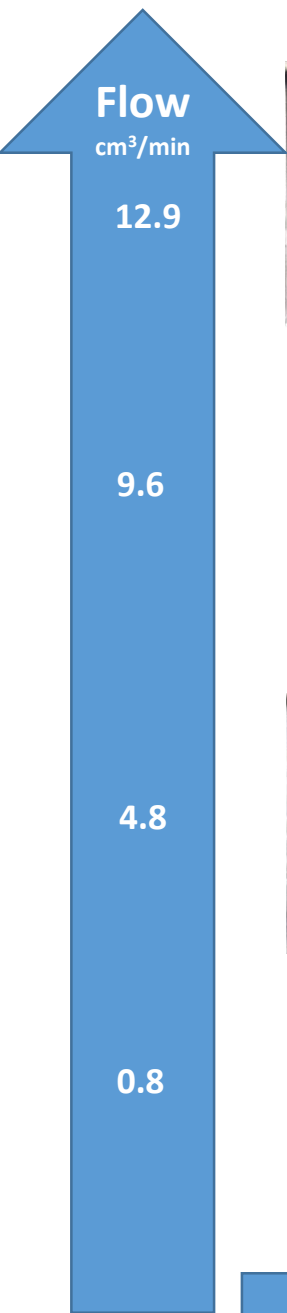
b = fracture thickness = 250 μm

k = 5260 Darcy

Comparison of Surfactants (1)

Pre-generated foam (60 μm frit)





1% B



Quality

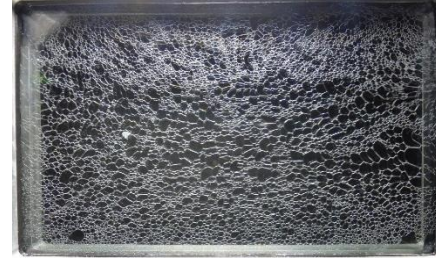
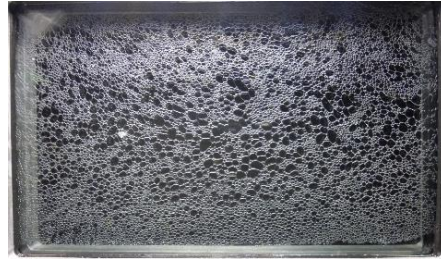
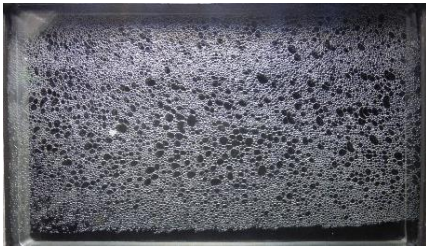
50 %

70%

90%

1% A

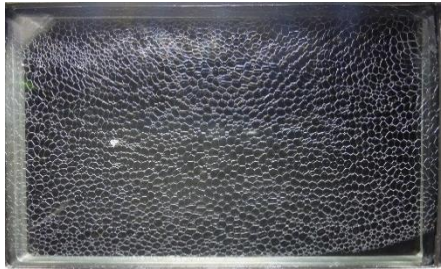
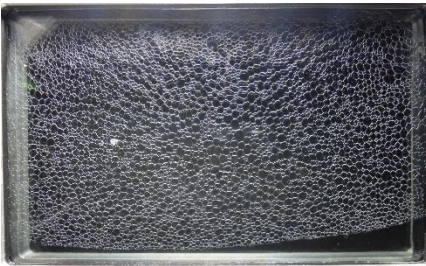
Flow
cm³/min
12.9



9.6



4.8



0.8



Quality

50 %

70%

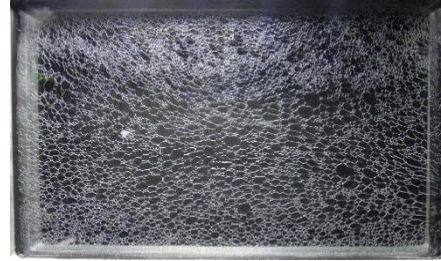
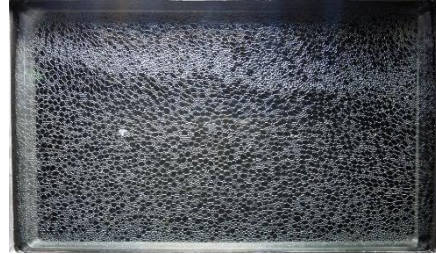
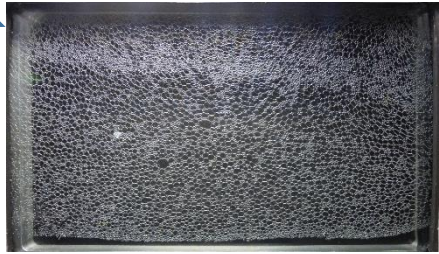
90%

1% 7.5 B/2.5 A

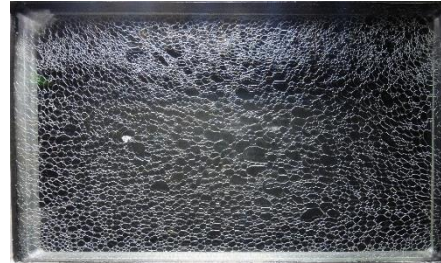
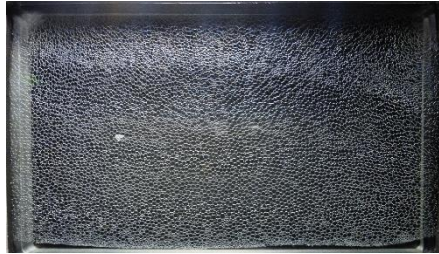
Flow

cm³/min

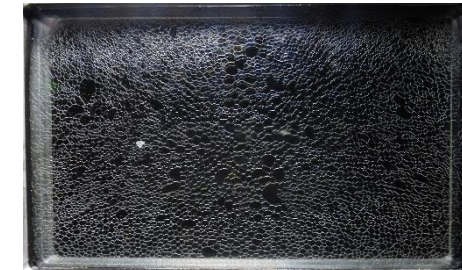
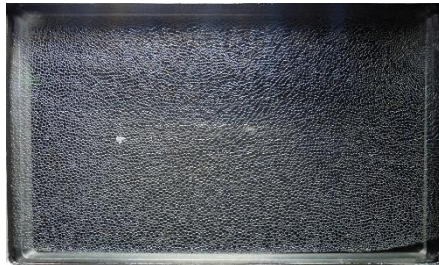
12.9



9.6



4.8



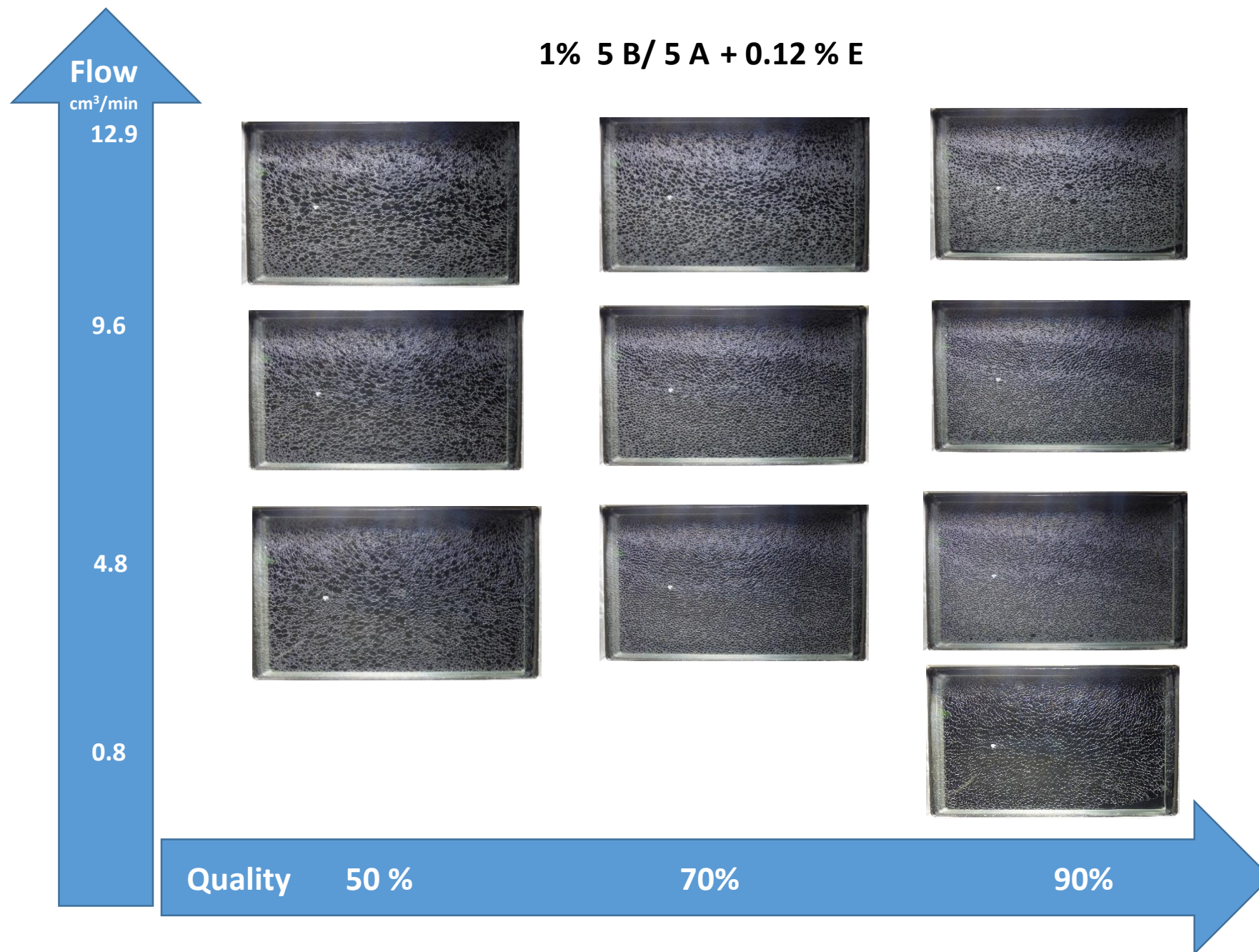
0.8



Quality 50 %

70%

90%



Remarks:

- N₂Foam of blended **B:A** is stronger than B or A
 - **B** creates weaker foam, more segregation than **A**.
 - **A** creates stronger foam than **B** but weaker than blend
- 1% 5/5 B/A + 0.12% E - of ultra low tension- creates strong foam, and no segregation under studied conditions.
- The sizes of frit studied produced practically insignificant differences among test results

Porous media vs parallel plate

According to Falls *et al.* (1989) four components of viscosity can be listed:

- (1) Newtonian viscosity of any liquid slugs between gas bubbles
- (2) Resistance of interface deformation, viscous resistance of liquid between the foam bubbles and capillary wall
- (3) Surface traction from surface tension gradient in surfactant concentration
- (4) Pore constrictions resistance

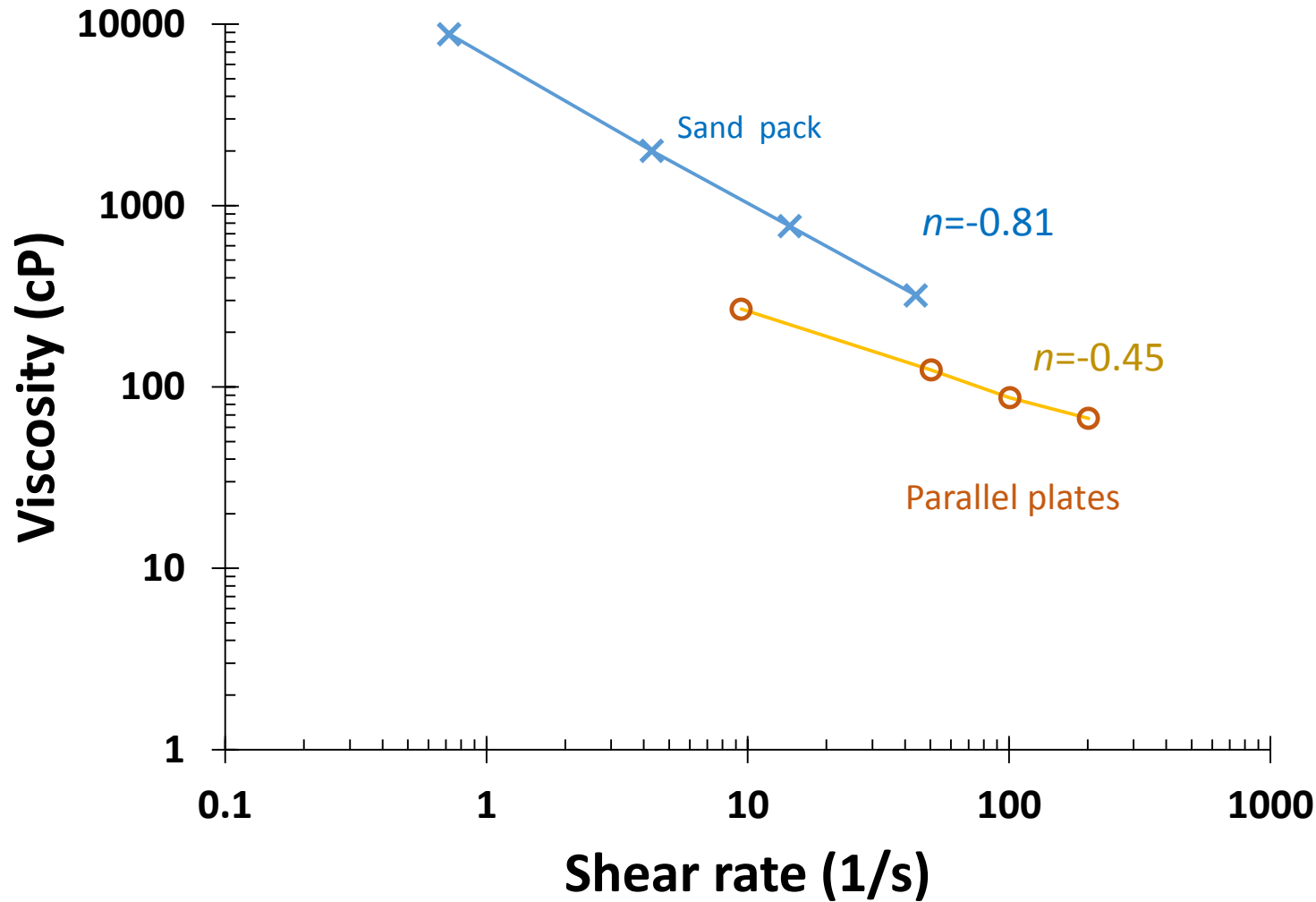
Zhang et al. (2009) Suggested the most important terms are (2) and (4)



Test results from Foam Generation in parallel plates and sand packs are consistent with work done by Falls et al .:

The contribution of pore constrictions to the viscosity of foam was observed when Porous media and Parallel plate test results were compared

Porous media vs parallel plate : Sand pack and glass plates



Apparent shear rate
in sand pack

$$\dot{\gamma}_{SP} = 12 u / \sqrt{75 k \phi}$$

Silica sand:
44 darcy
Foam quality 80%
By Andres

Apparent shear rate
in parallel plates

$$\dot{\gamma}_{PM} = 6 u / (\Delta x)$$

Parallel plates:
Aperture 250 μm
Frit: 90 μm
Foam quality 88%
By Angelica

Shear thinning including pore constriction $-1 < n = -0.81 < -1/3$

Shear thinning without pore constriction $-2/3 < n = -0.45 < -1/3$

Falls *et al.* (1989)

Conclusions

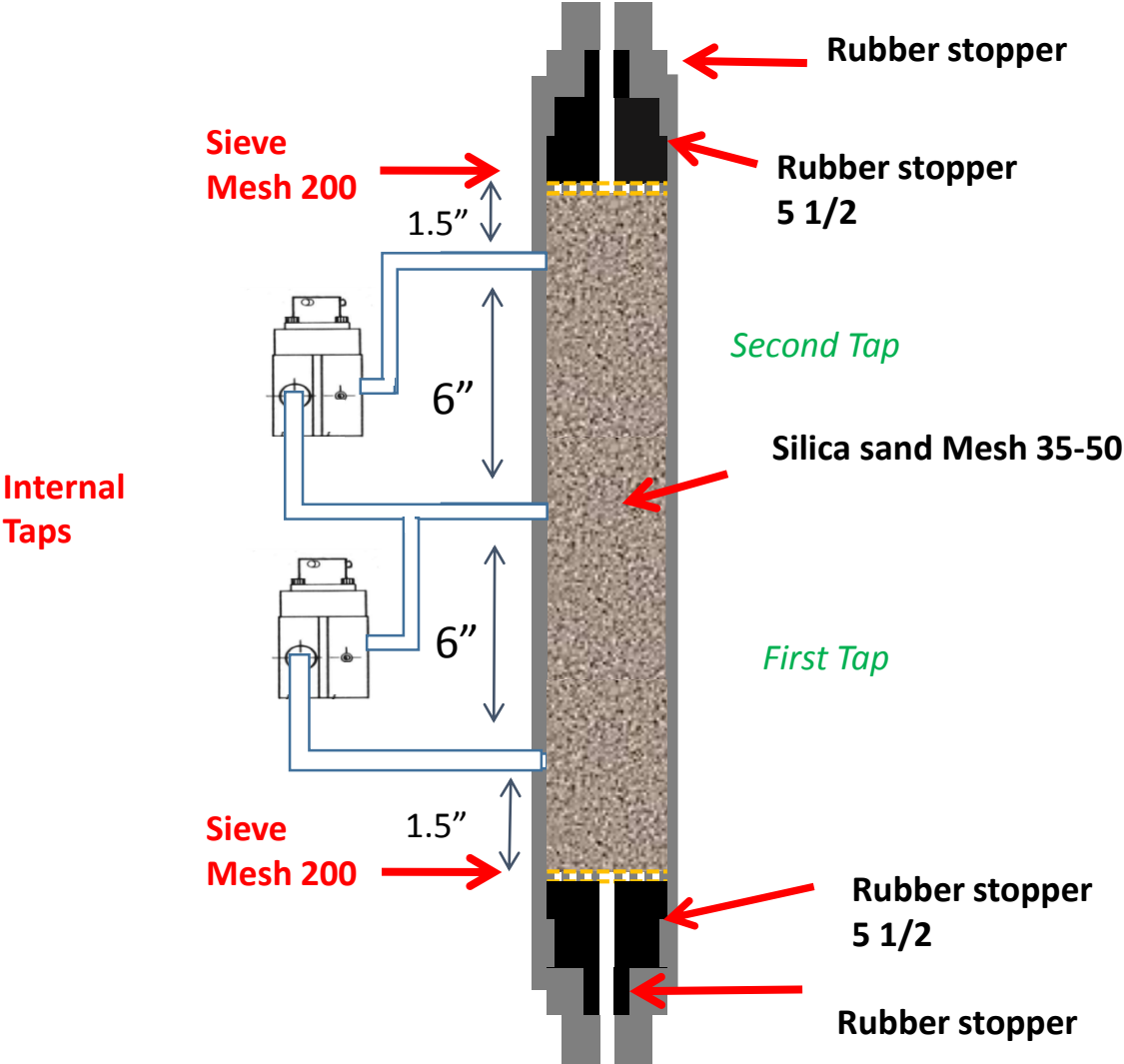
- Surfactant with potential to recover oil produced strong foams in sand packs at reservoir temperature.
- The formulation is robust in concentrations from 0.14 to 1.12% in seawater.
- Foam strength is recovered after recovering all the crude oil.
- Parameters of a foam model were fitted using experimental data in a wide range fractional flows, permeabilities and flow rates
- The foam is strong not only in porous media, but fractures represented by parallel plates.

Future studies

- Foam in parallel plates should be evaluated in presence of oil, different temperatures and concentrations.
- The modeling of foam in porous media and fracture should be combined to simulate the performance of foam in the field.

Acknowledgements : PEMEX
End of Presentation

Sandpack Internal-Tap Locations

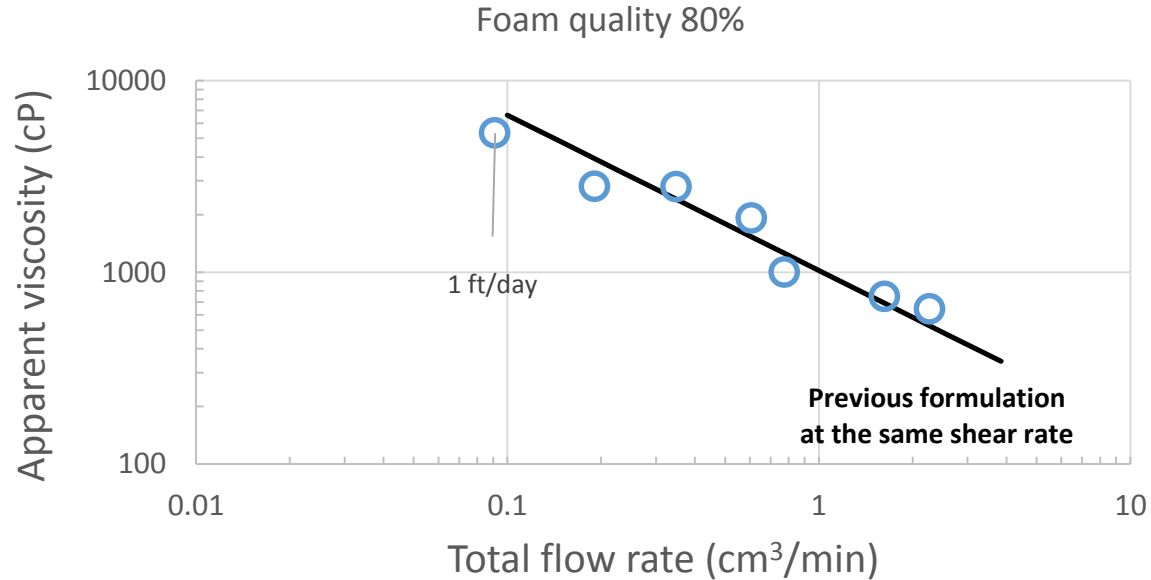


$$k_{rg}^f = k_{rg}^0 \left[1 - \frac{S_w - S_{wc}}{1 - S_{gr} - S_{wc}} \right]^{ng}$$

Parameters for the model (observation comparison and suggestion)

Foam strength comparison with previous formulation (B+A₁ 2:1)

Shown as continuous black line



$$F_4 = \left(\frac{u_g / \sqrt{k\phi}}{1.53 \text{ s}^{-1}} \right)^{epv}$$

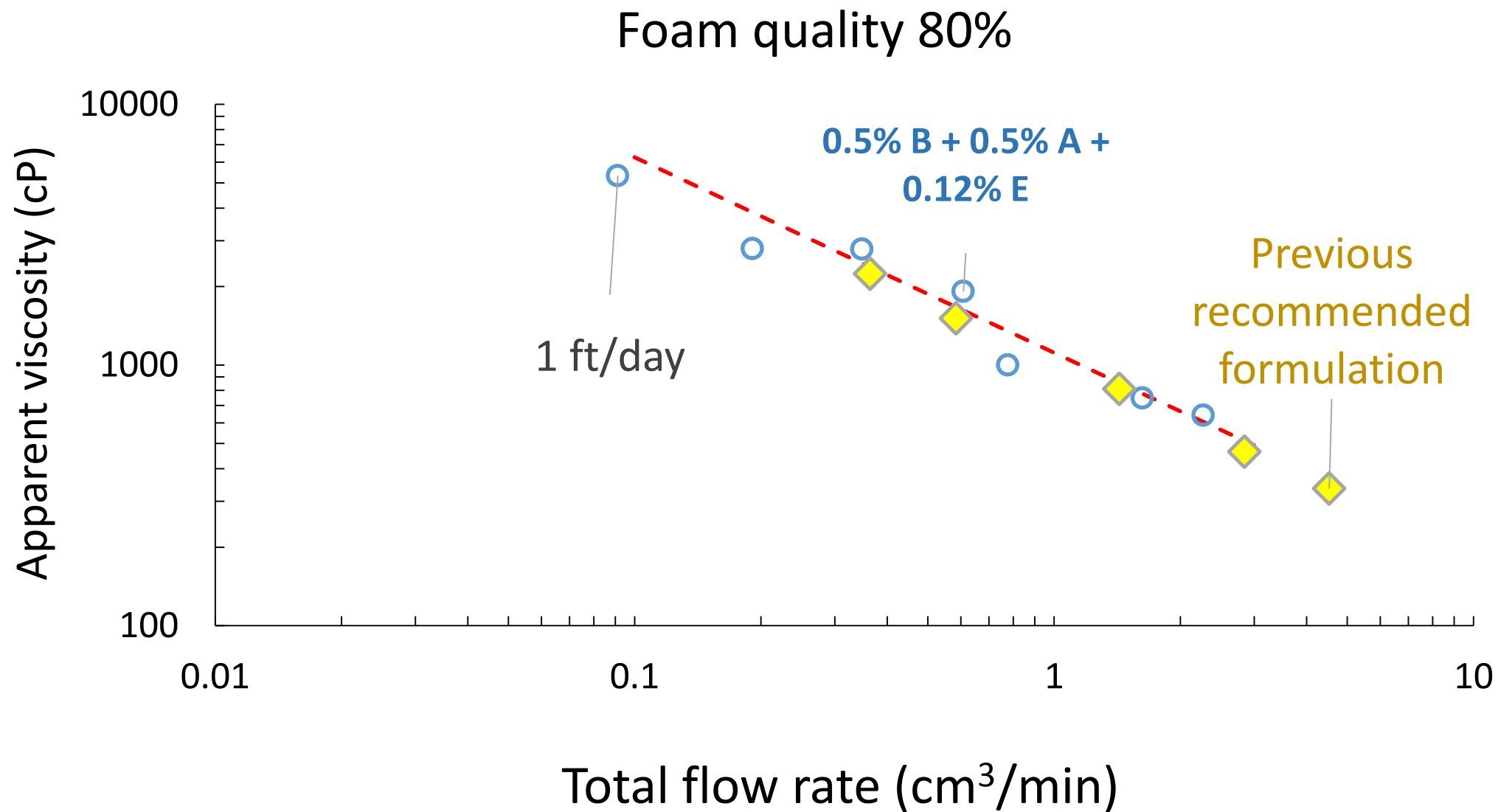
This function fits to all the values of permeability studied
100 darcy, 44 darcy, 8 darcy and 2 darcy

See Appendix A

Apparent shear rate (Carreau, 1997)

$$\dot{\gamma} = 12 u_g / \sqrt{75 k\phi} \approx 1.385 u_g / \sqrt{k\phi}$$

$$F_4 = \left(\frac{1.385 u_g / \sqrt{k\phi}}{3.505 \text{ s}^{-1}} \right)^{epv}$$



Shear thinning including pore constriction $-1 < n = -0.81 < -1/3$

Shear thinning without pore constriction $-2/3 < n = -0.45 < -1/3$

Falls *et al.* (1989)

Sample	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
SS in SW	100	90	80	70	60	50	40	30	20	10	0
FB	0	10	20	30	40	50	60	70	80	90	100

Surfactant solution
in seawater
Formation Brine

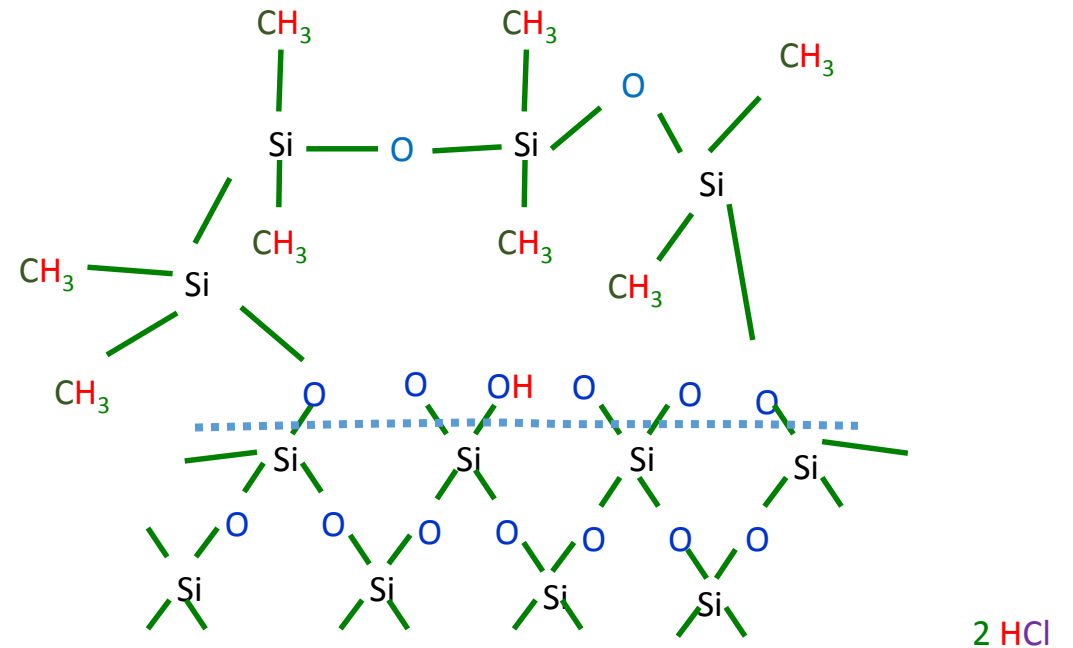
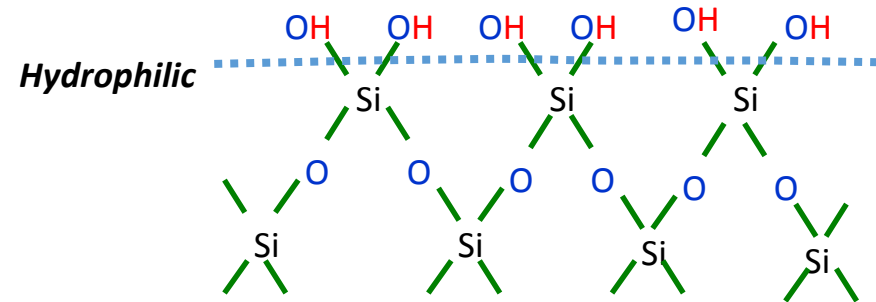
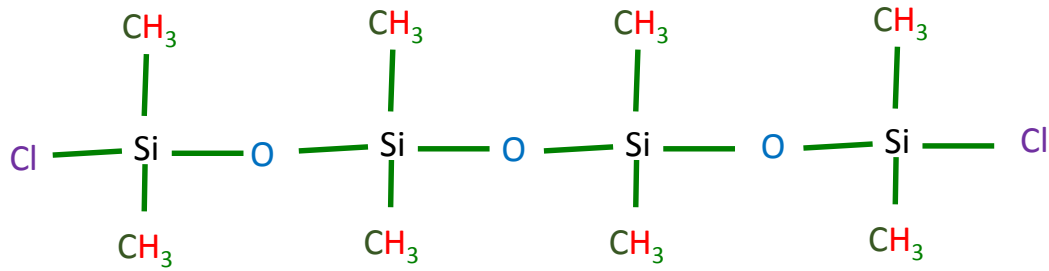


Abstract:

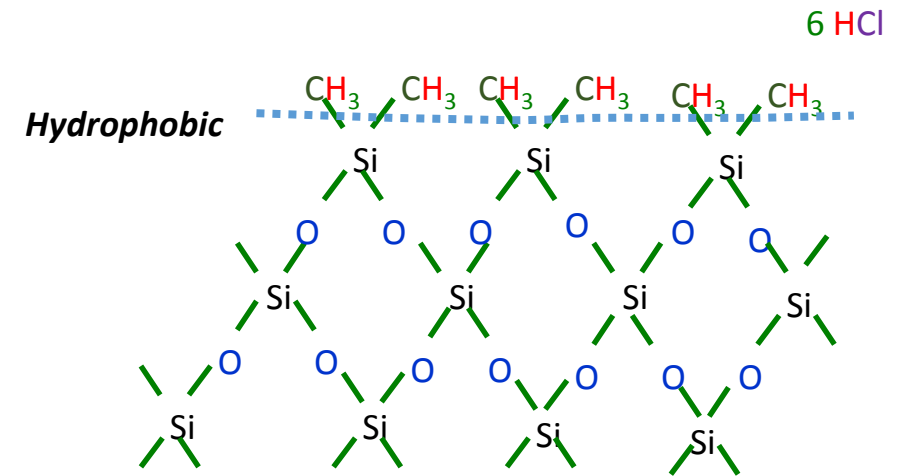
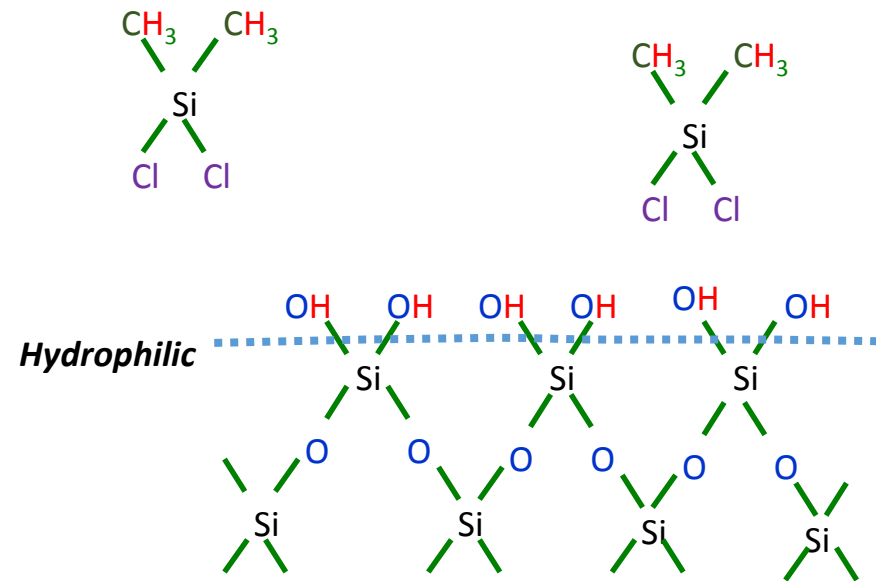
A formulation to obtain ultralow IFT for EOR application is evaluated to be transported as a foam in a fractured porous media. The evaluation process includes tests from room up to reservoir temperature 120°C in sandpacks, rubblized porous media and parallel plates. Surfactant solutions used were prepared in seawater. Experimental results were used to fit parameters of a mathematical model to describe the foam using the mobility reduction factor approach. The experimental study includes, shear thinning effect, dependence on quality, temperature, permeability, presence of oil and surfactant concentration.

Sand was treated to be oil wet, then equilibrated with synthetic live oil for couple of days and then contacted either formation brine or Surfactant solution in sea water

Silica sand grains were treated to be oil-wet
Using Dichloro octamethyl tetrasiloxane

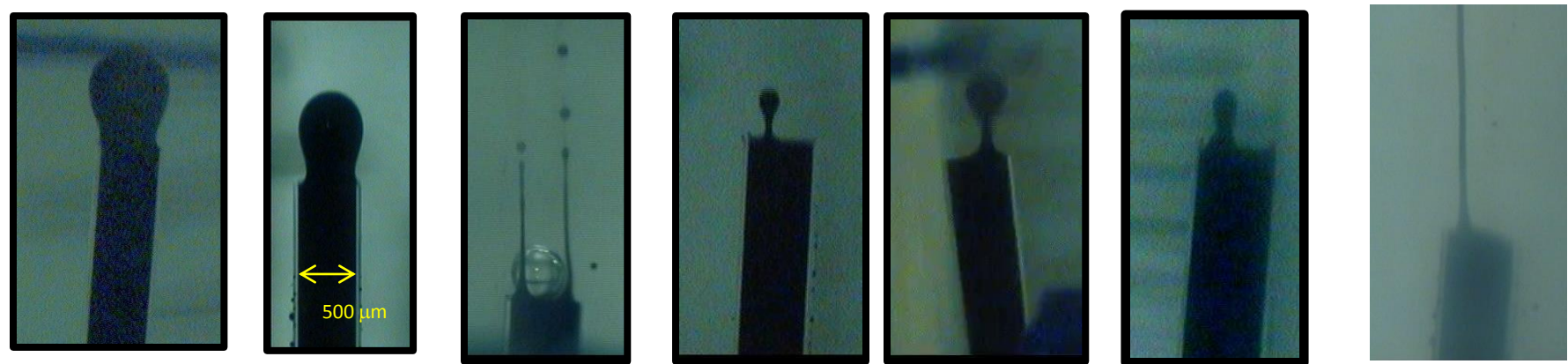


Glass micro channels were treated to be oil-wet
Dichlorodimethylsilane



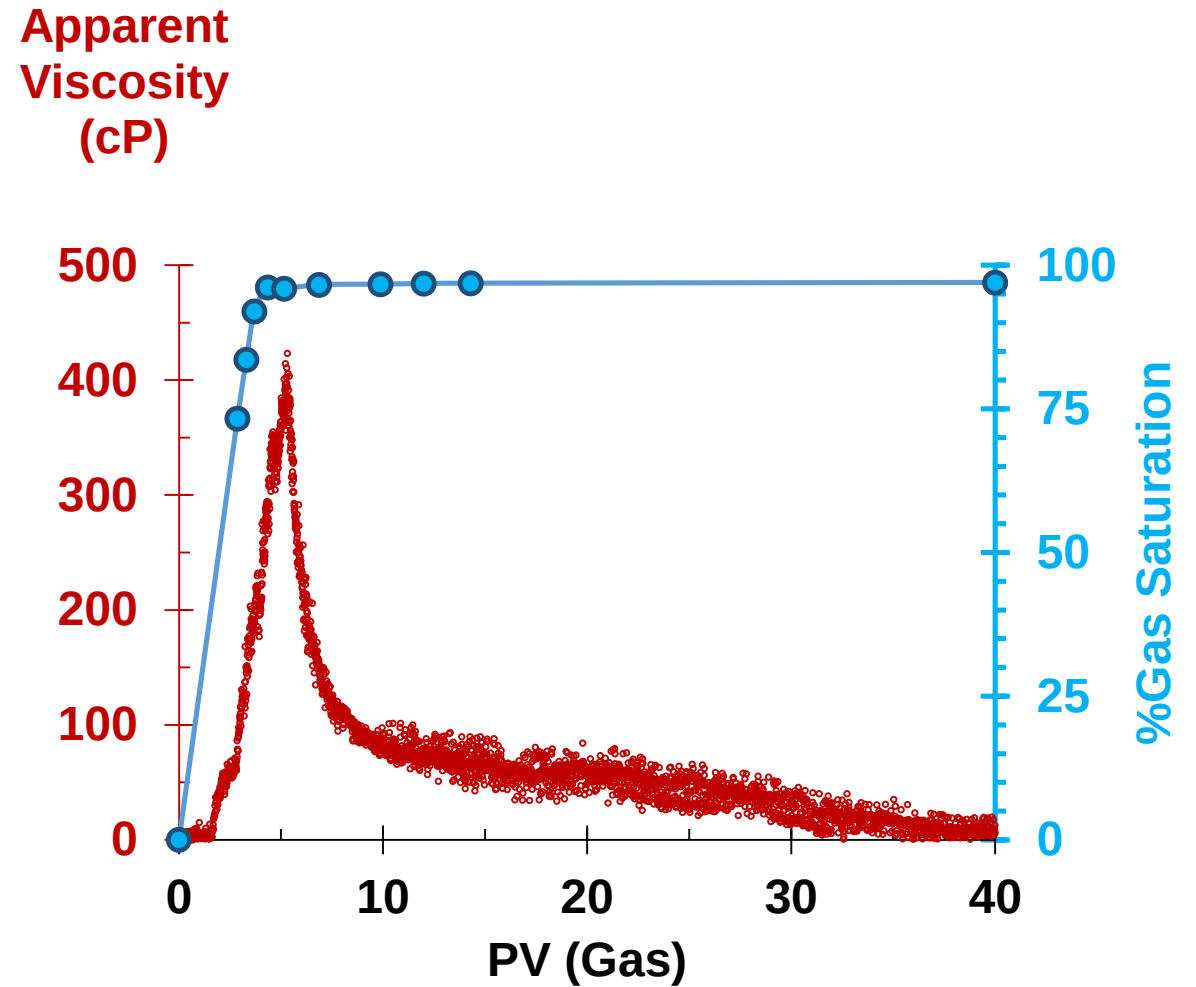
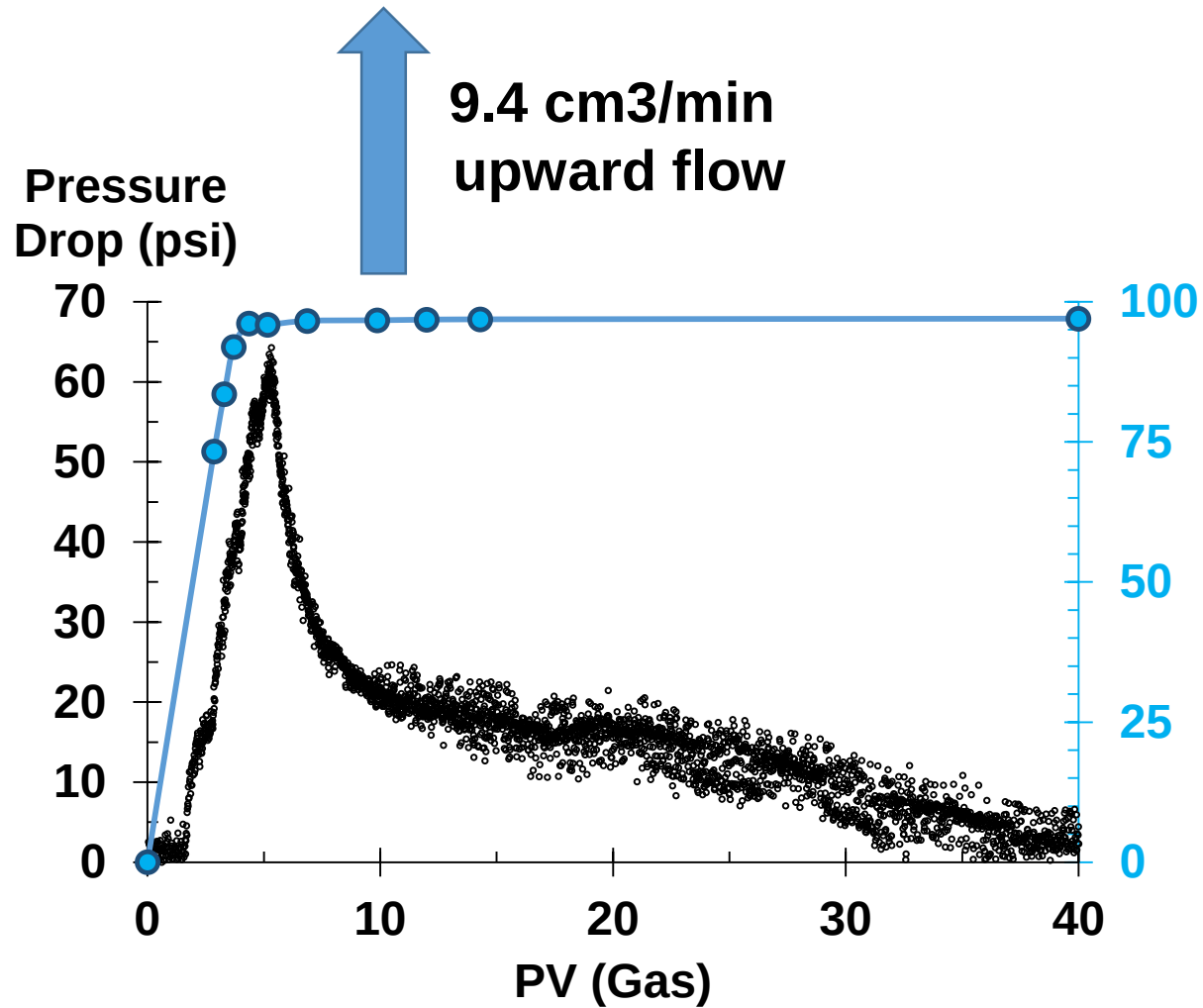
- Screening of Surfactants for foam applications
 - Surfactant blend should be tolerant to divalent ions.
 - Should be stable in the range of Temperature of interest (25°C-120°C)
 - In tests of front dilution should not precipitate.
 - Filterability test must demonstrate unplugging.

IFT of formulations with added N and L { surface active}



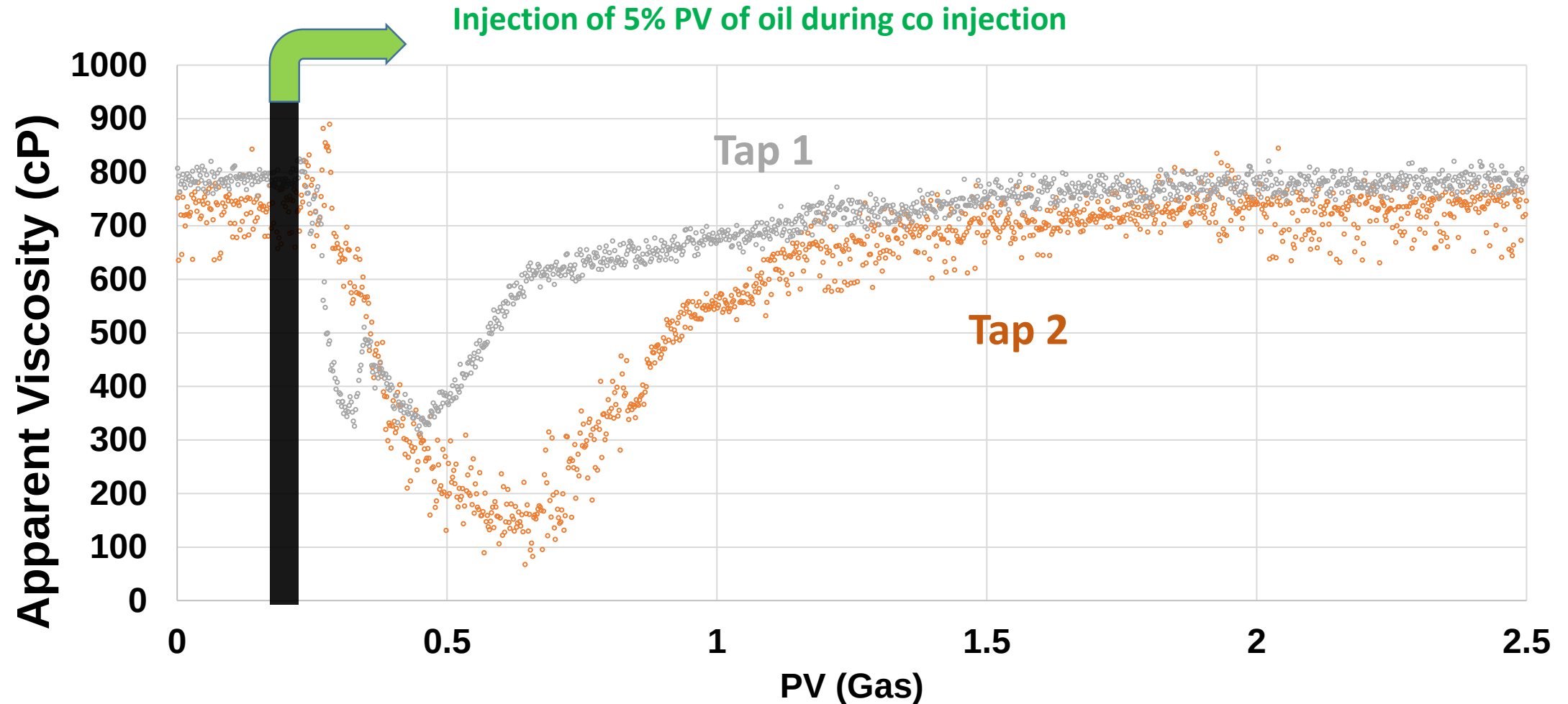
$\frac{7.5}{0.15\%}$ B/ $\frac{2.5}{S61}$ A	$\frac{7.5}{0.04\%}$ B/ $\frac{2.5}{N58}$ A	$\frac{5}{0.04\%}$ B/ $\frac{5}{N58}$ A	$\frac{5}{0.11\%}$ B/ $\frac{5}{N58}$ A	$\frac{5}{0.3\%}$ B/ $\frac{5}{A_{6.4}}$ A	$\frac{5}{0.3\%}$ B/ $\frac{5}{A_{6.4}}$ A	$\frac{5}{0.12\%}$ B/ $\frac{5}{L38}$ A
*IFT in Dynes/cm in Seawater at 100°C						
4.3E-1	3E-1	2E-3	2E-2	3E-2	2.2E-2	1E-3

Transient experiments (qualitative)



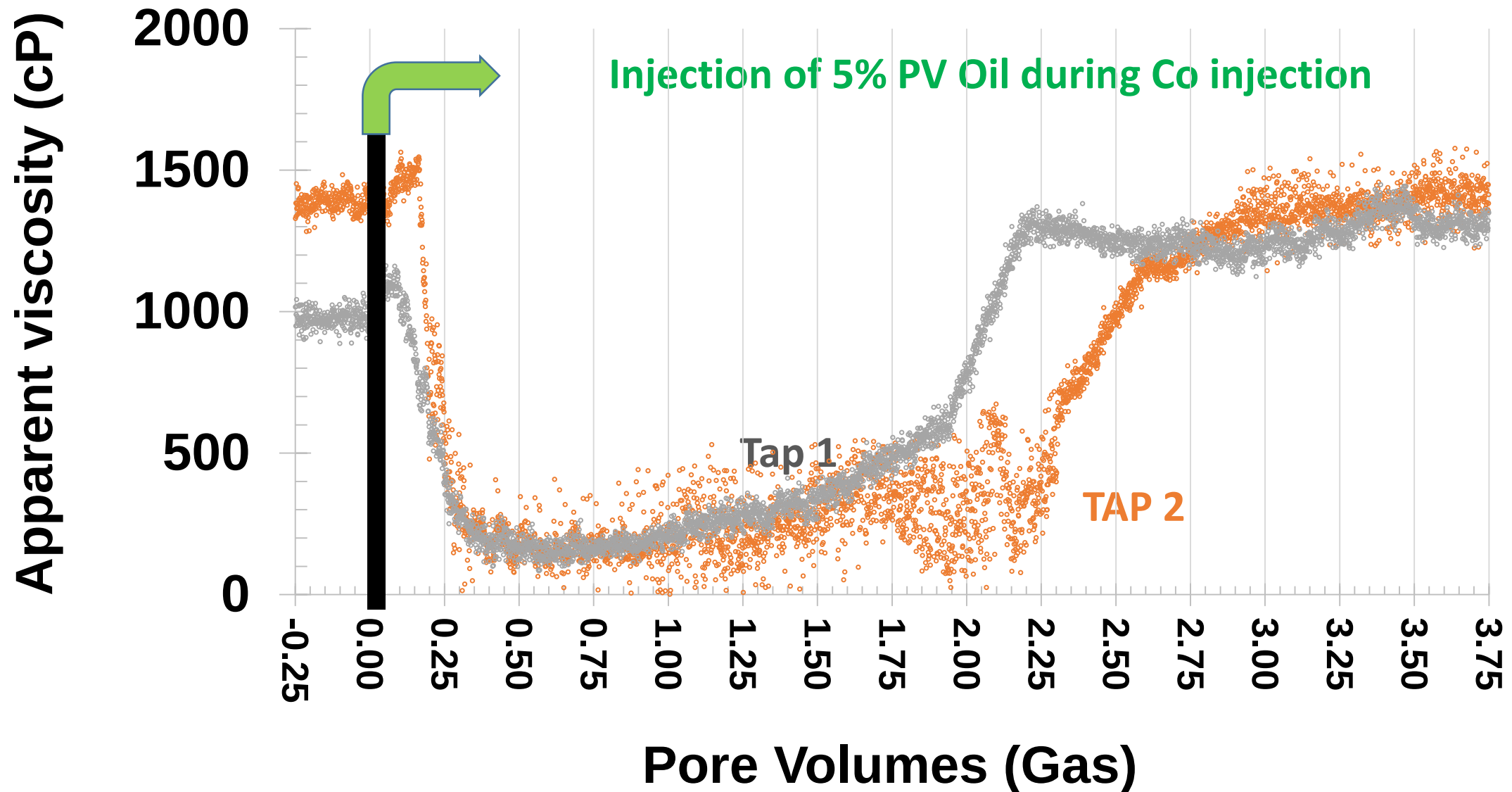
Effect of Oil on Foam Strength at 70% quality, 94°C_Part 2 of 3

Total flow rate 1.87 cm³/min (ca 19.4 ft/day)

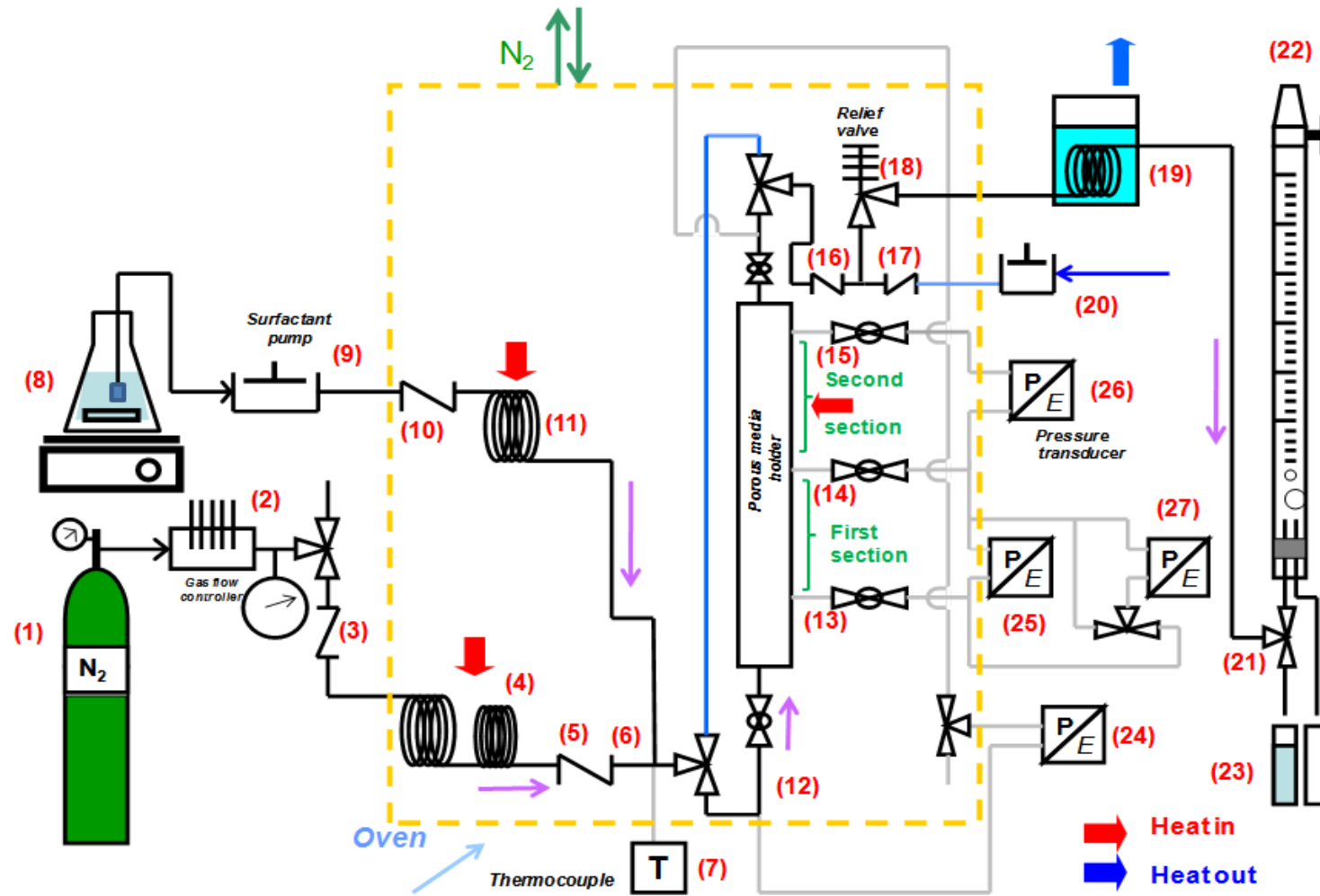


Effect of Oil on Foam Strenght at 75% quality, 94°C _Part 1 of 3

Total flow rate 0.78 cm³/min (ca 8 ft/day)

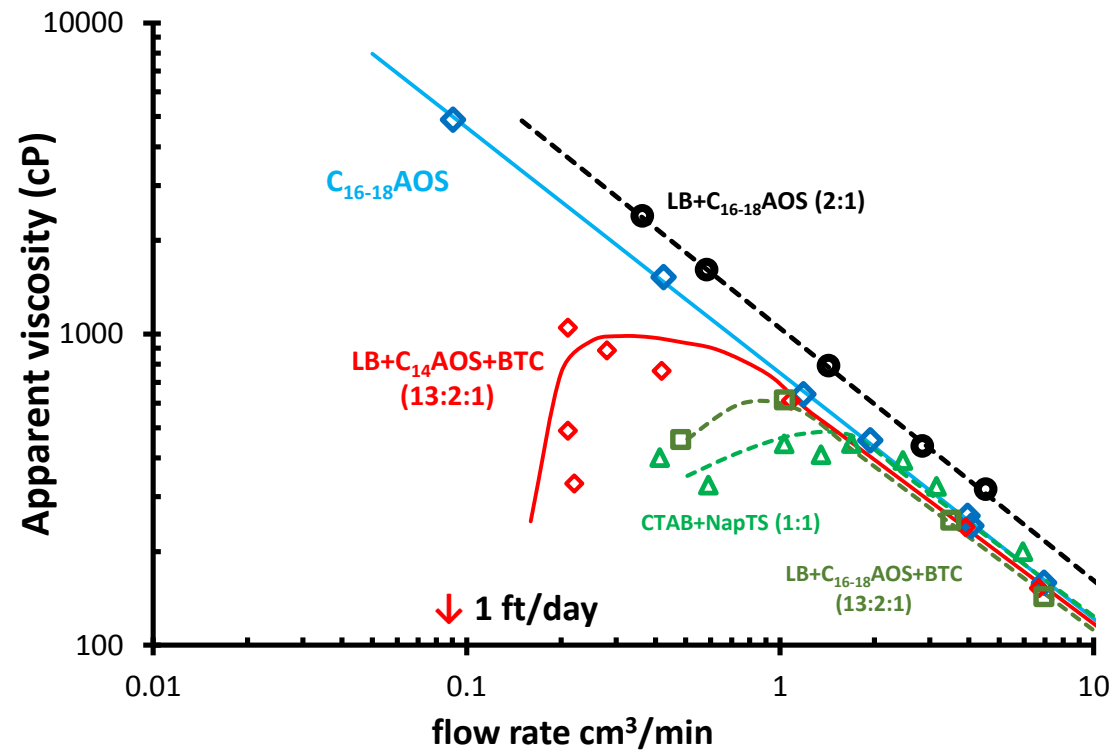


Foam experimental set up for high temperature



Foam Strength

Shear thinning effect



Comparison of foam strength for different surfactants at 94°C and 1% total surfactant concentration in a sand pack, using qualities between 60 -70%. Straight lines are for power law fit ($n \approx -0.8$)

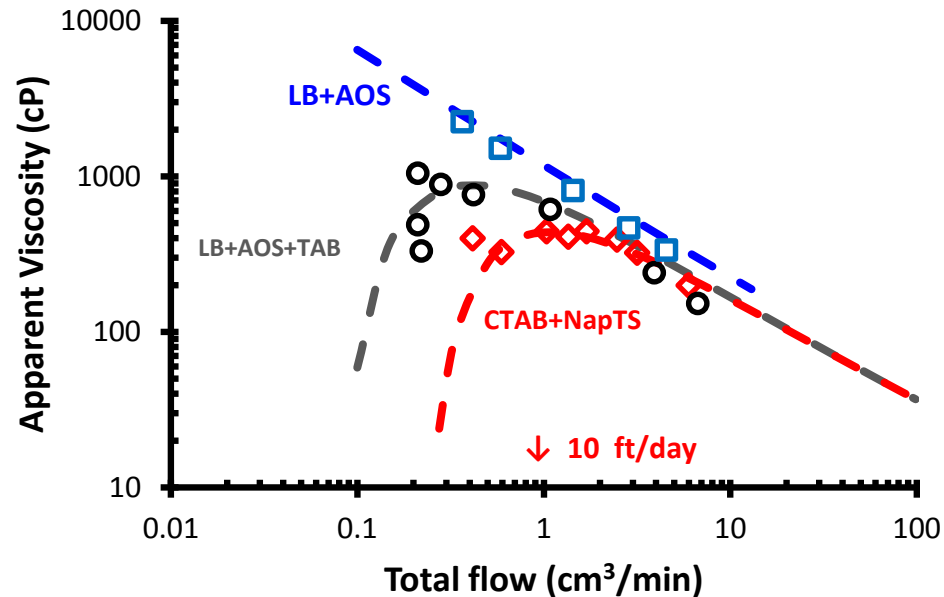
Minimum velocity to foam

$$F_5 F_6 \approx k_1 \left(\frac{u}{u_{ref1}} \right)^{epcap - epn} \left(1 - \frac{u_{ref}}{u} \right)^{epn}$$

Assumption:

$epcap = epn$.

using a value for $epcap=3$



Results are consistent with observation done by Cheng et al (2000), where he establish a relationship with the shear thinning exponent and the parameter $epcap$

$$\sigma = \frac{1}{1 + epcap}$$

Simulation of the foam viscosity using the mobility reduction factor approach. The symbols are experimental data at gas quality close to used in the simulation of 70%.

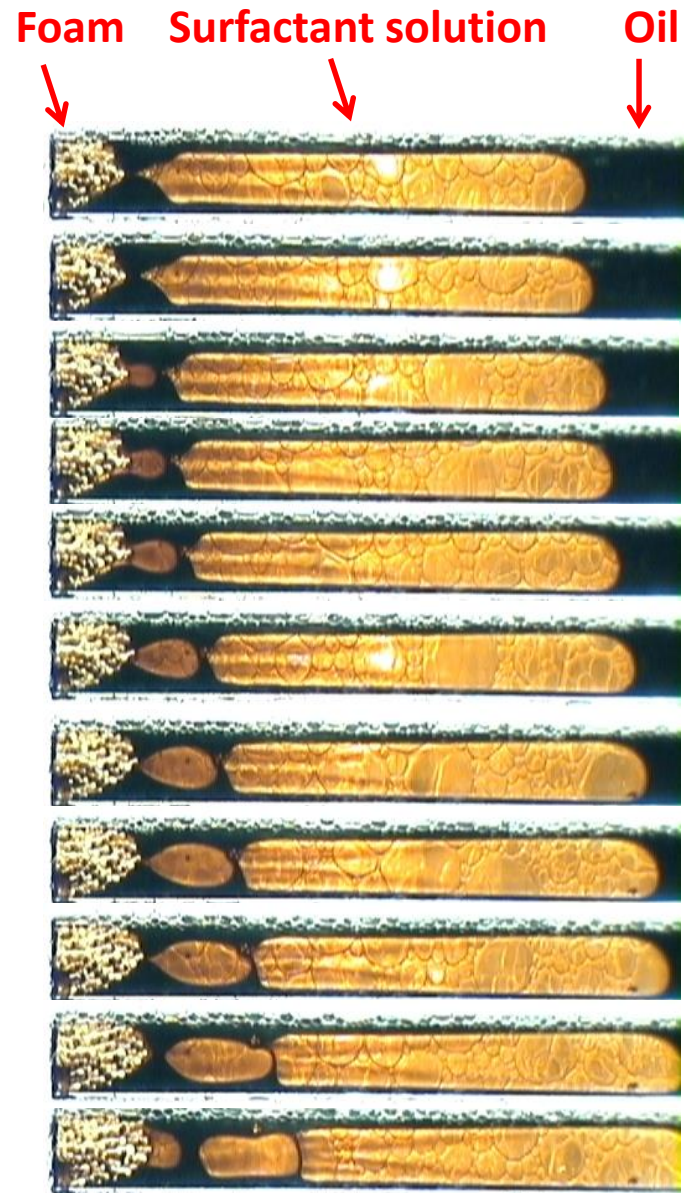
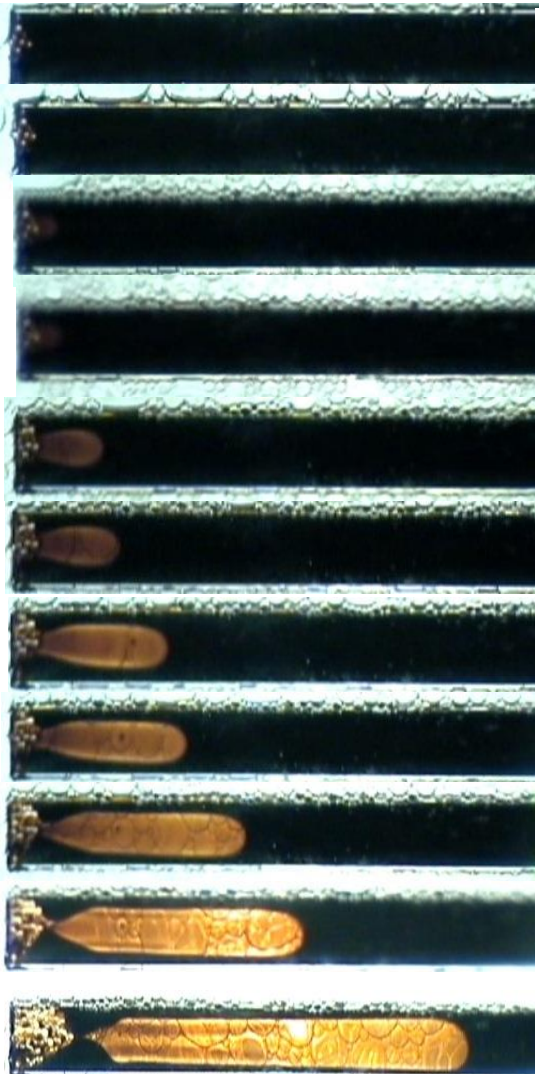
Frames from inlet section during horizontal flow

~30 Sec

time interval

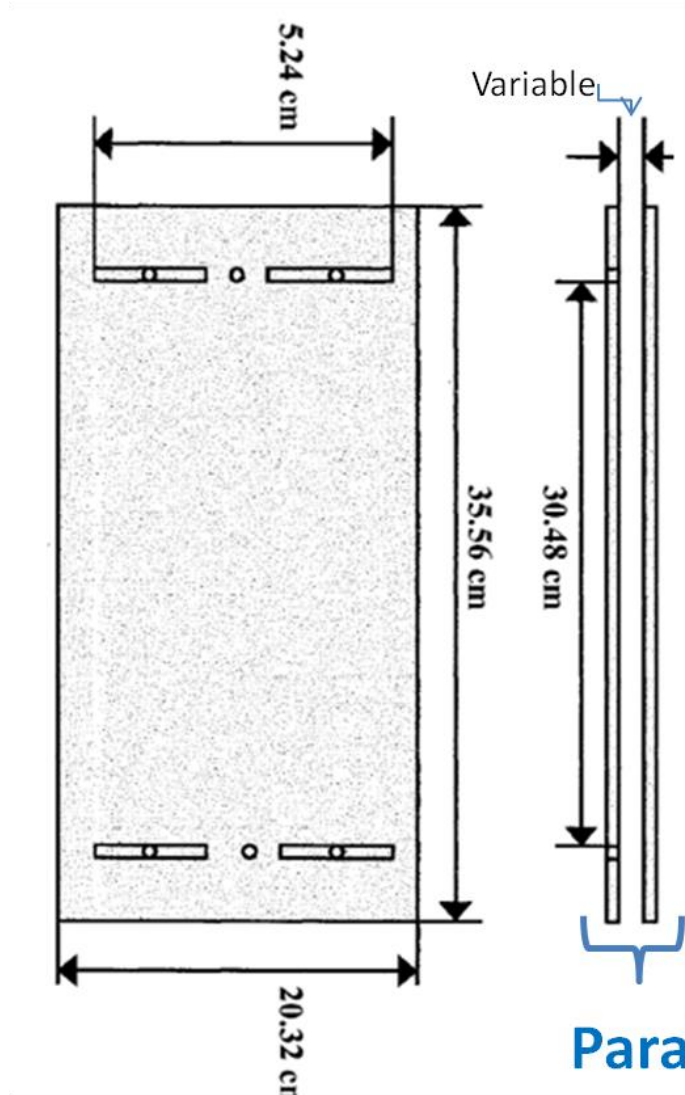
10 Sec

1000 μ
100 μ



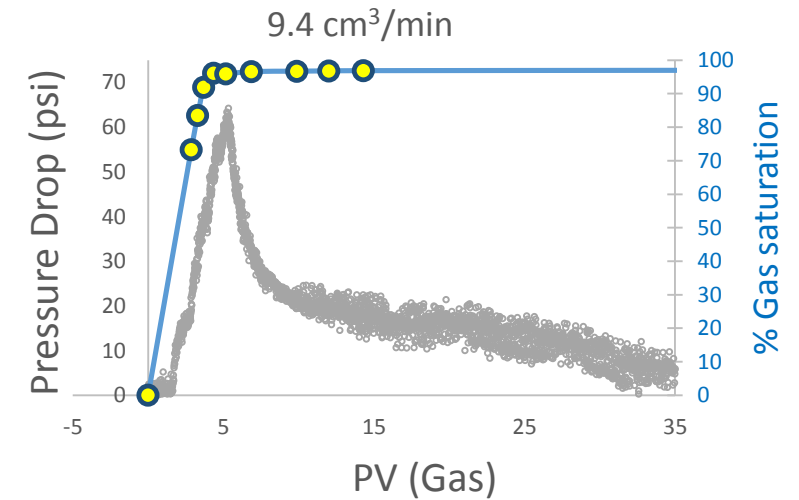
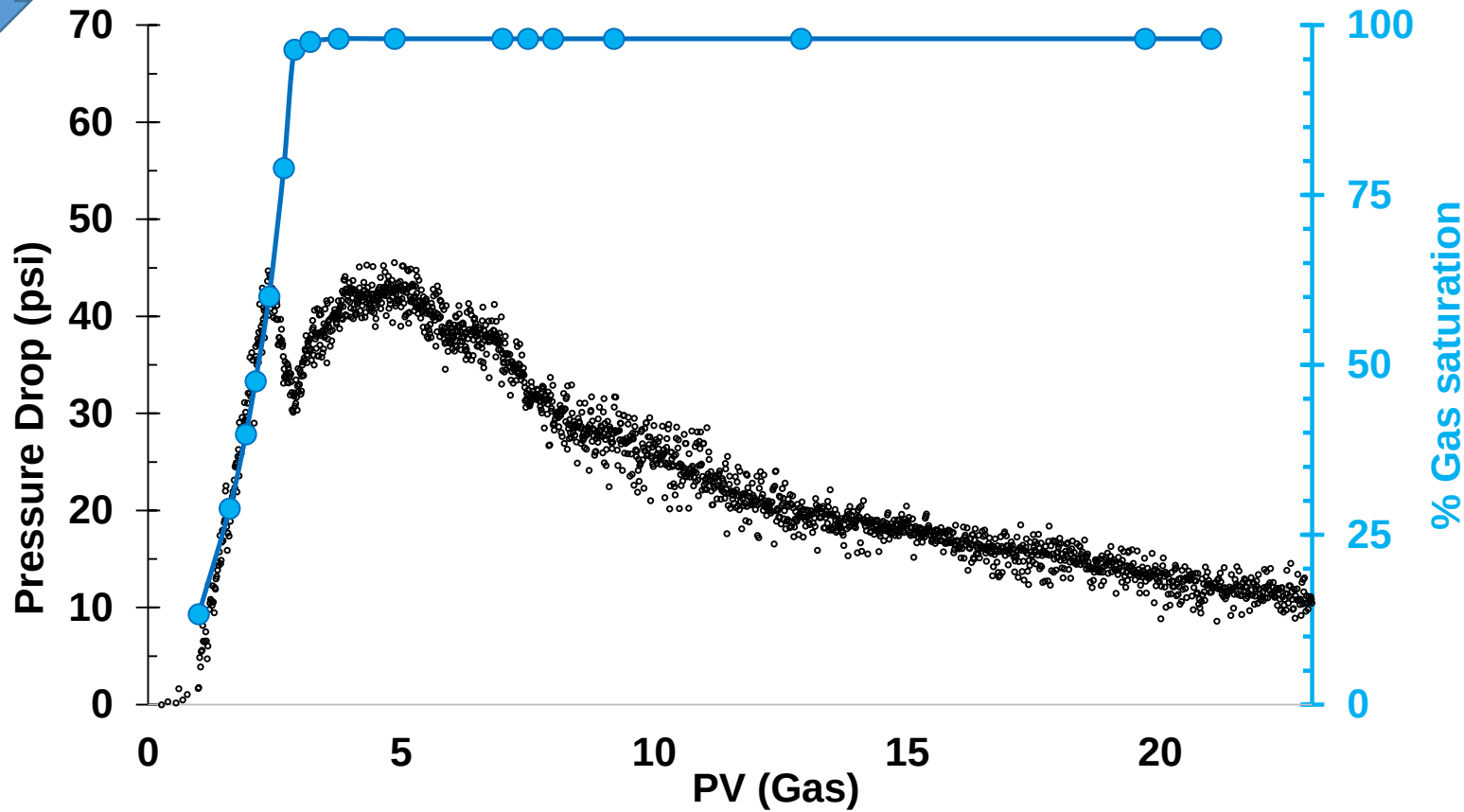
2-D Model*

Mimicking a Fracture for Study of Foam



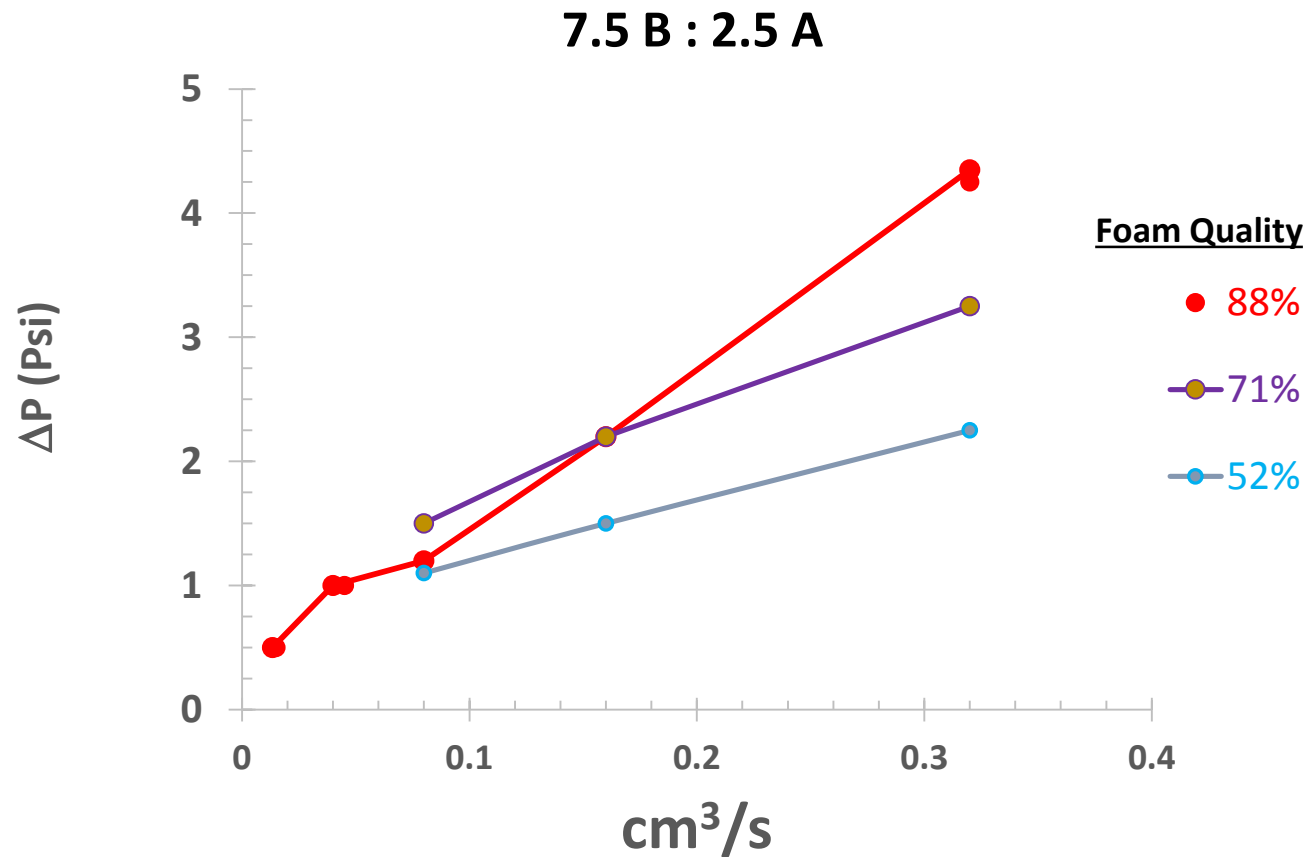
Transient experiments (upward vs downward)

9.4 cm³/min
Downward flow



Effect of Quality

Foam in 250 μm aperture parallel plates 25° C
60 μm Frit



For More Information See:

José Luis López-Salinas (Thesis, 2013)

**Transport of Components and Phases in a Surfactant/Foam
EOR Process for a Giant Carbonate Reservoir.**

**Estimation of Parameters for the Simulation of Foam Flow through
Porous Media. Part 1: The Dry-Out Effect**

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**Non-uniqueness, Numerical Artifacts, and Parameter
Sensitivity in Simulating Steady-State and Transient
Foam Flow Through Porous Media**

Kun Ma · Rouhi Farajzadeh · Jose L. Lopez-Salinas ·
Clarence A. Miller · Sibani Lisa Biswal · George J. Hirasaki

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