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EXPERIMENTAL INVESTIGATION OF FIBER-FOAM RHEOLOGY IN ADVANCED MULTIPHASE FORMING SYSTEMS

SF17: Surfactants, Foams, and Emulsions

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Society of Rheology Annual Meeting, Chicago IL

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U.S. DEPARTMENT OF ENERGY

NNSA

FOAM FORMING OF FIBER PRODUCTS

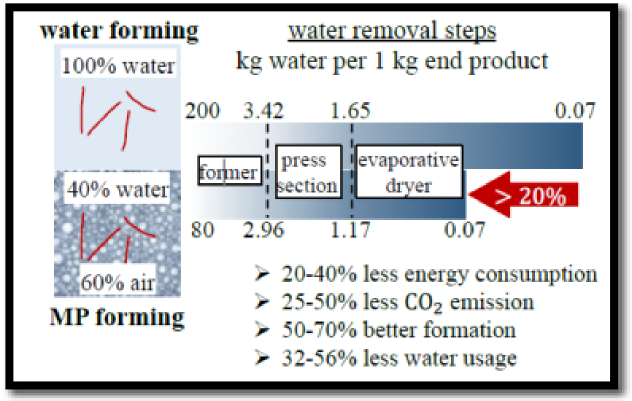
Foam forming pilot plant
Hjelt et al., 2021, *J. Dispersion Sci. and Tech*.

Paper industry is the 3rd largest consumer of energy in the USA (Brueske 2015)

2/3 of the energy is consumed in evaporative drying

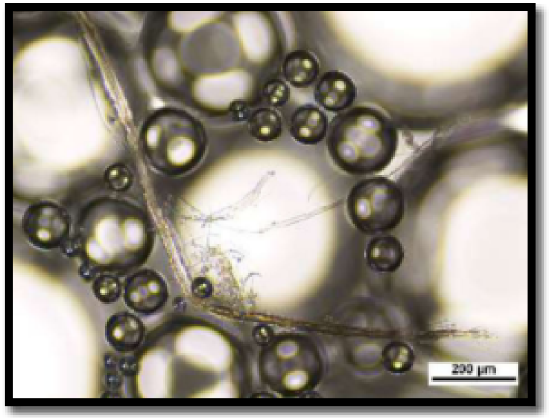
Fiber forming includes paper, specialty paper (wallpaper), filters, insulation…

Aqueous foam as a transfer medium for fiber products results in:



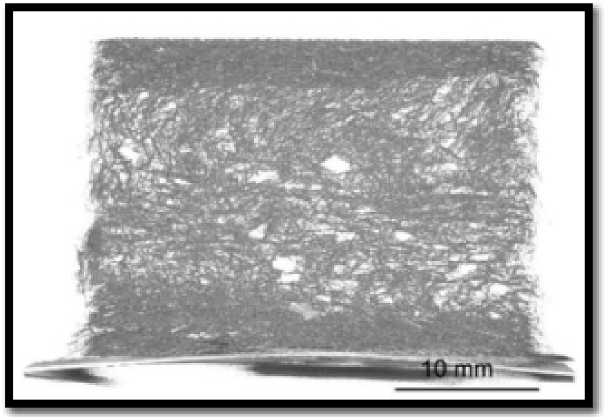
Cost and energy savings
30% reduction in drying section
Less material / water / additive costs

Wood fiber in foam
Koponen et al., 2018, *Nord Pulp Paper Res. J.*



Flexibility in fiber composition
Increased fiber lengths for specialty papers

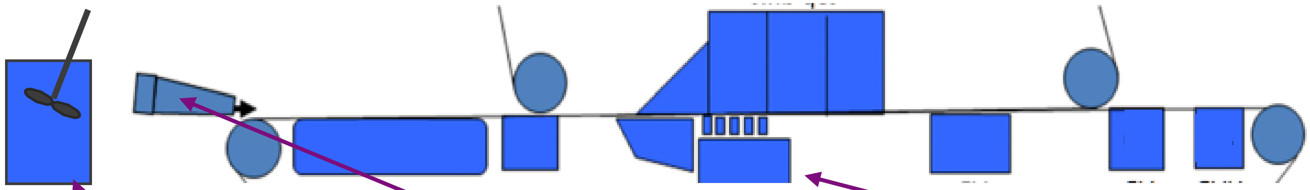
Bubble structure persistent in fiber network
Pohler et al., 2020, *Cellulose*

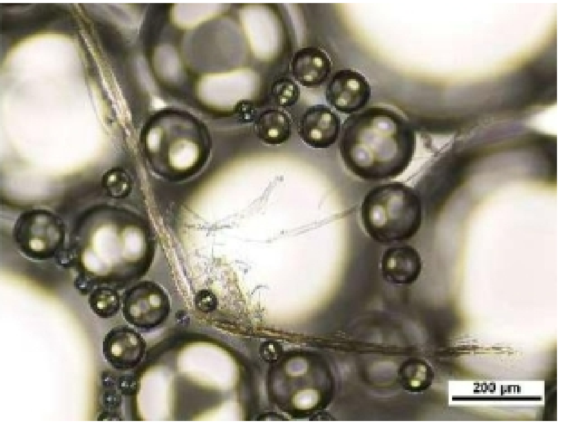


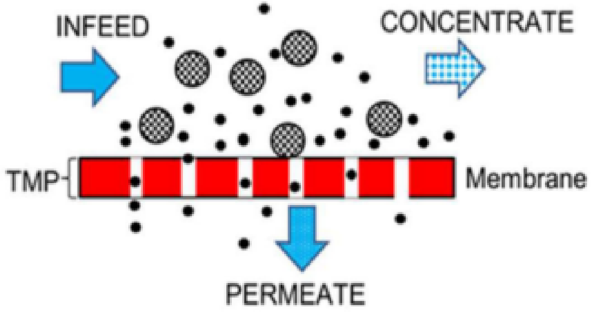
Independent control over porosity
Lightweight tissues and filters at low cost

ADAPTATIONS OF PROCESS FOR FOAM FORMING

Aging coating lines can be retrofitted to process foam for specialty papers







Foam composition greatly influences printability and product quality

Efficient and consistent generation of foams

Foams have reduced turbulence in headbox and coating nozzle

Proper vacuum conditions for dewatering foams

R+D is necessary to facilitate transitions to foam forming

Koponen 2018, *Nordic Pulp & Paper J.*
Hjelt et al., 2021, *J Dispersion Sci and Tech*

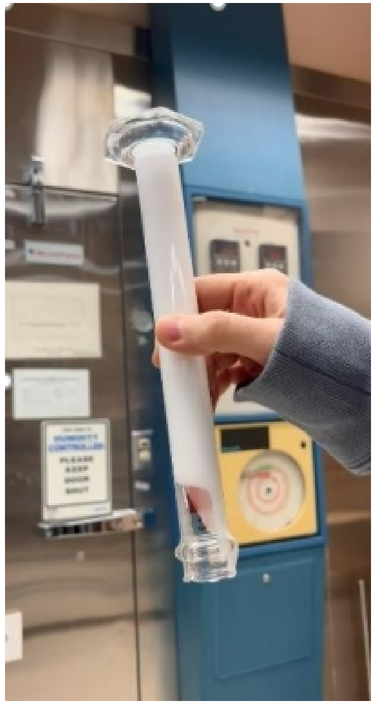
RHEOLOGY OF FIBER-LADEN FOAMS

Surfactant choice: SDS or others
Fiber content: 1 – 3 wt%
Air content: $\Phi = 0.30 – 0.80$
Bubble size: $D = 50 – 150\ \mu m$

Small changes in foam composition drastically influence foam rheology

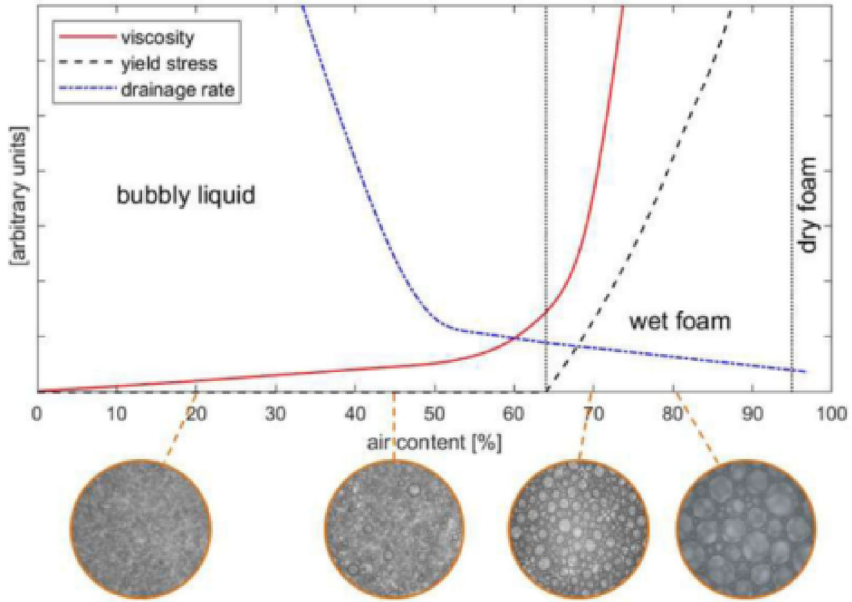
$\Phi = 0.7 – 0.72$

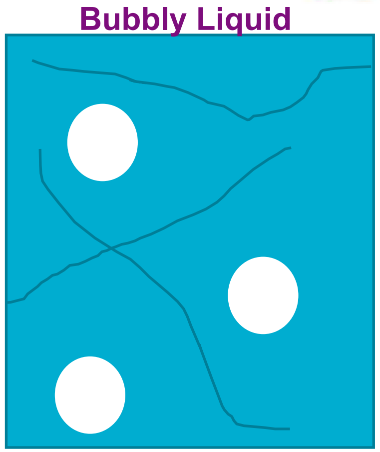
$\Phi = 0.75$



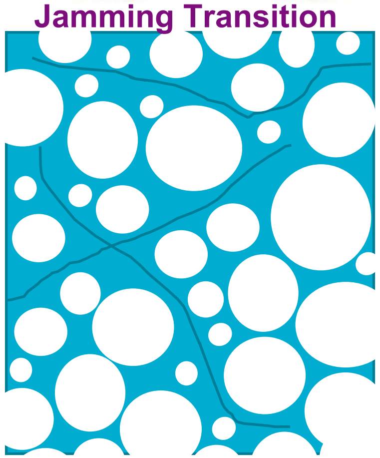
Ian Kohli, Georgia Tech

Hjelt, et al., 2021, *J. Dispersion Science and Technology*

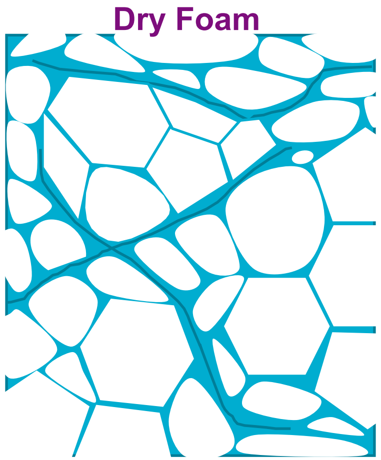




Low viscosity
No yield stress
Fibers dominate rheology



Viscosity starts increasing
Yield stress develops
Bubbles + fibers influence rheology



High viscosity
Strong yield stress
Bubbles dominate rheology

RHEOLOGY OF FIBER-LADEN FOAMS

Surfactant choice: SDS or others
Fiber content: 1 – 3 wt%
Air content: Φ = 0.30 – 0.80
Bubble size: D = 50 – 150 μm

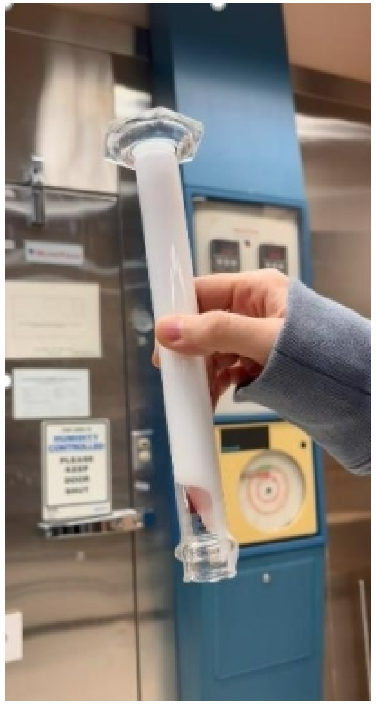
Goal: Understand fiber-filled foam rheology for future design of coating operations

Shear rate: 0.1 – 1000 s^{-1}
Effect of air (0.3 – 0.8), fiber content (1-3 wt%)
Microstructure analysis

Small changes in foam composition drastically influence foam rheology

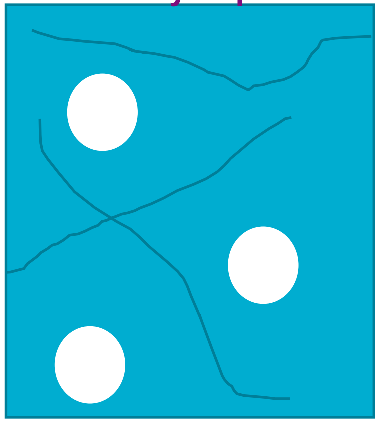
Φ = 0.7 – 0.72

Φ = 0.75



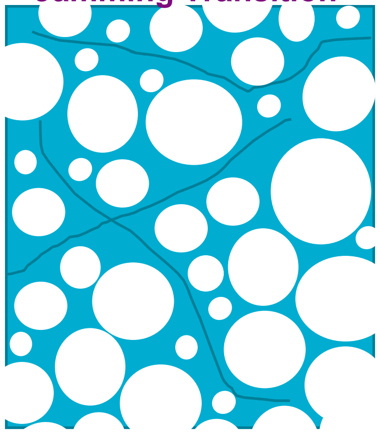
Ian Kohli, Georgia Tech

Bubbly Liquid



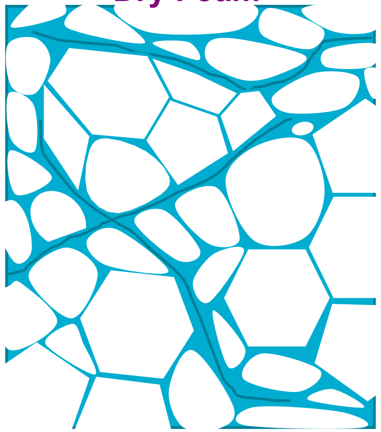
Low viscosity
No yield stress
Fibers dominate rheology

Jamming Transition



Viscosity starts increasing
Yield stress develops
Bubbles + fibers influence rheology

Dry Foam

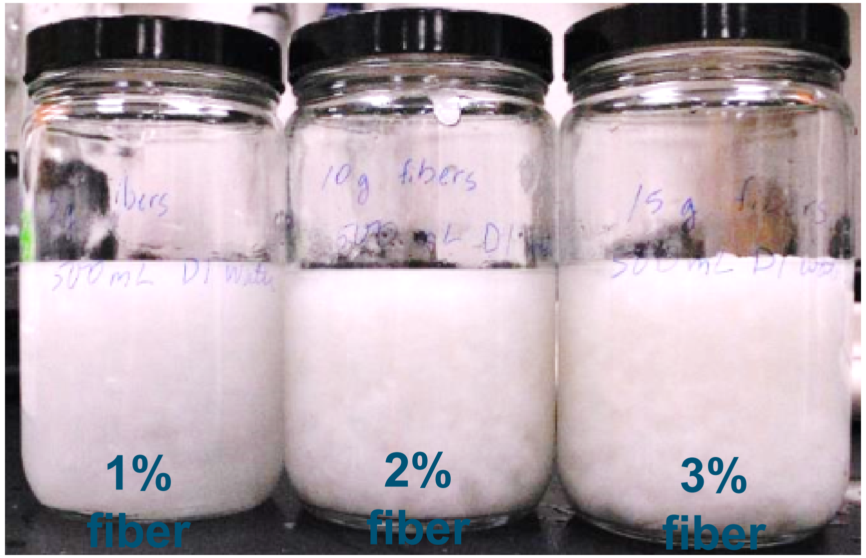


High viscosity
Strong yield stress
Bubbles dominate rheology

FIBER-FILLED FOAM PRODUCTION

Hardwood kraft fiber

Fibers mixed in a blender



SDS surfactant added to fiber slurries

Foams produced in a blender

Top view of foam

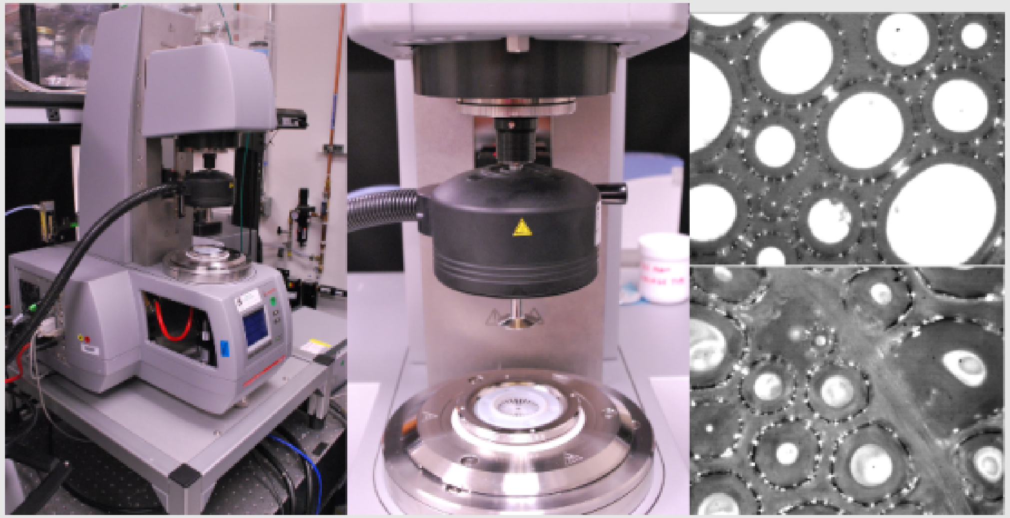
Concentration of SDS and mixer speed control air content

EXPERIMENTAL APPROACH

Goal: Rheology of fiber-laden foams (1-3 wt%) of various air concentration (**Φ = 0.30 – 0.80) and shear rates (0.1 – 1000 1/s)**

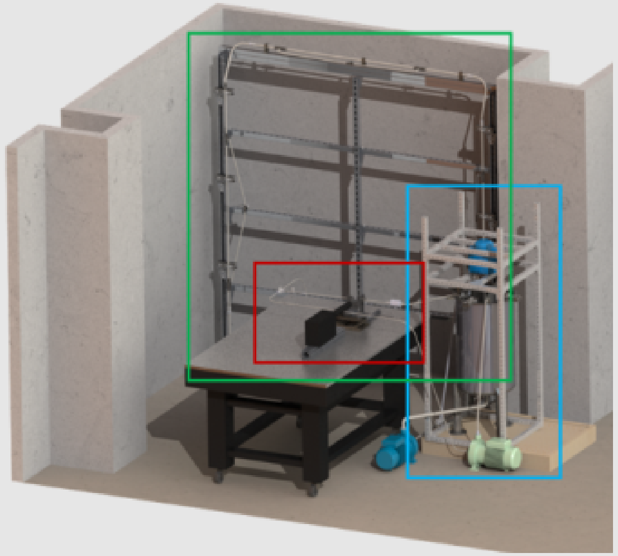
Jammed foams (Φ > ~0.70)
Foams must be stable 1 min or more

Rheometer Measurements

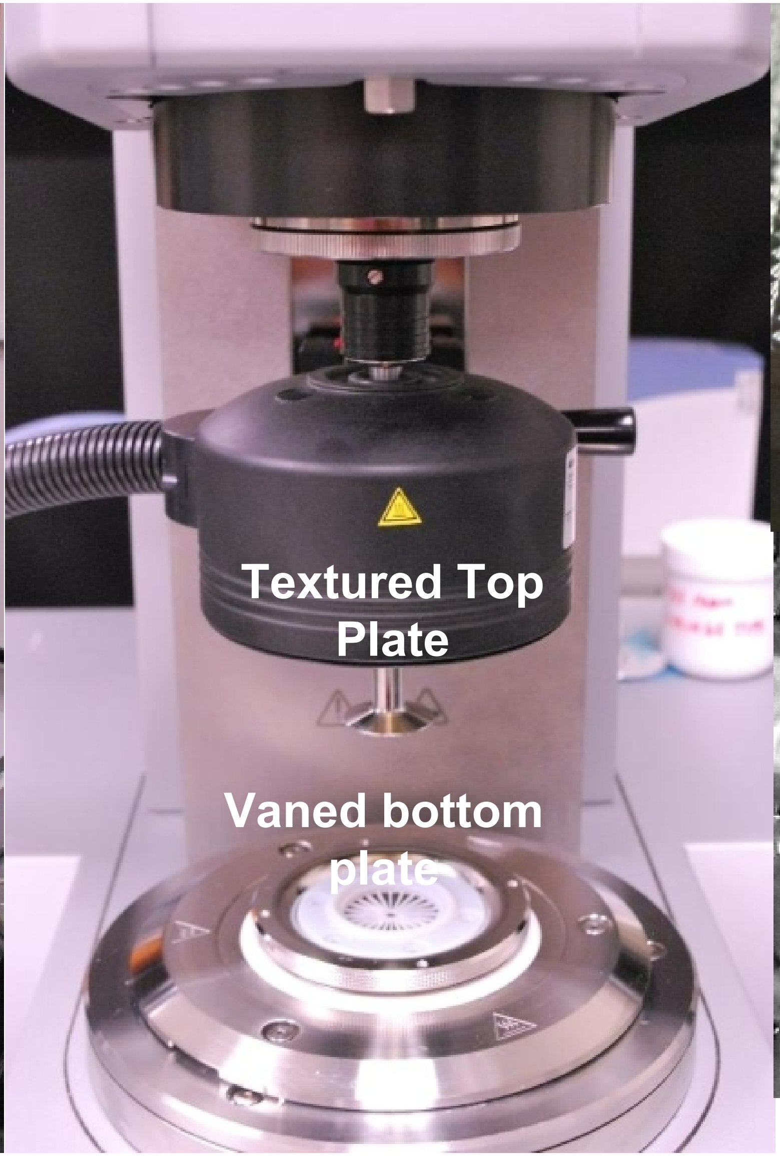


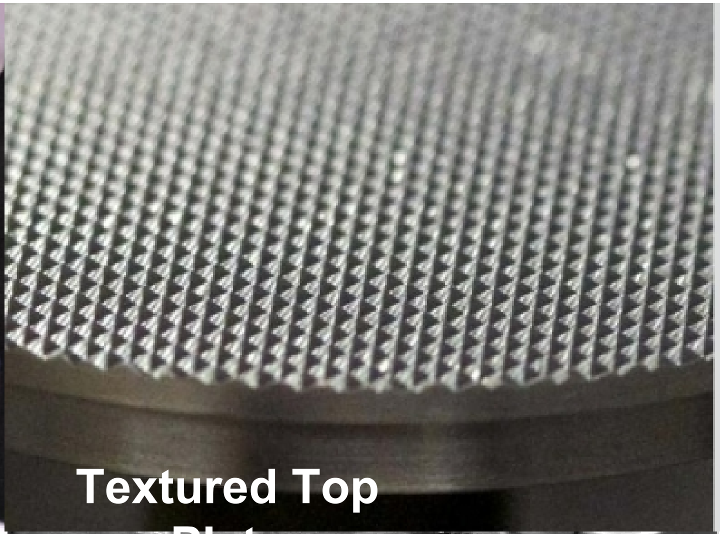
Foam stability not necessary
Less control over shear rate

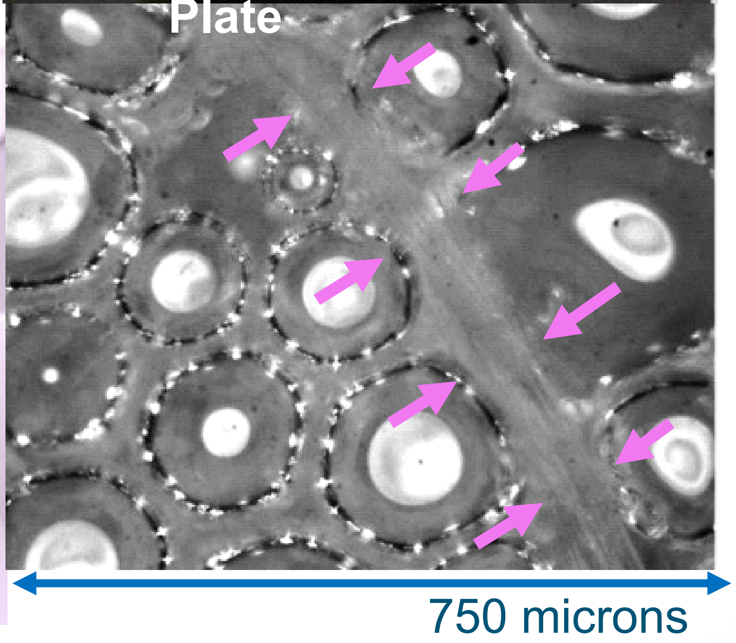
Differential Pressure Based Measurements



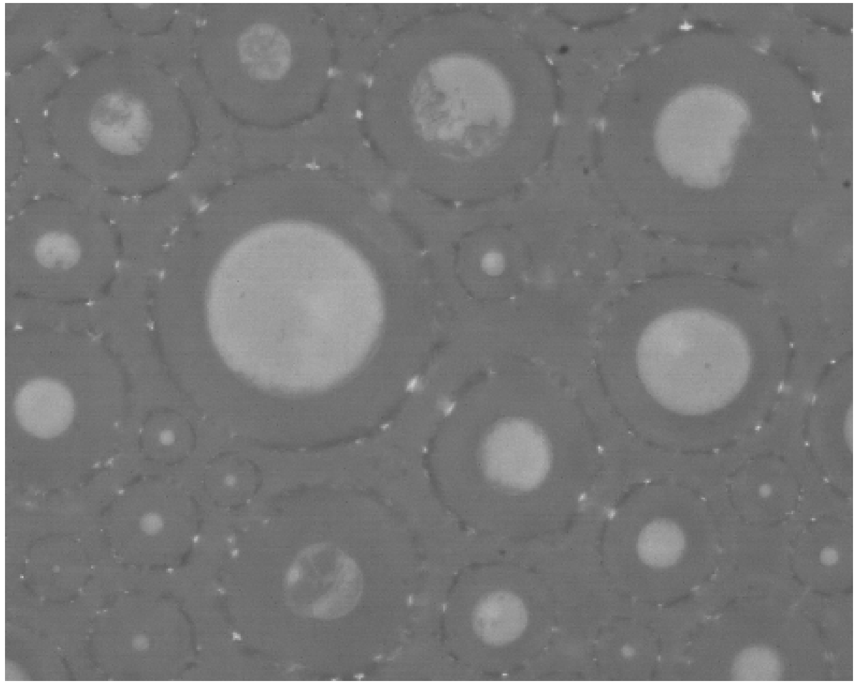
RHEOMETER EXPERIMENTAL SETUP



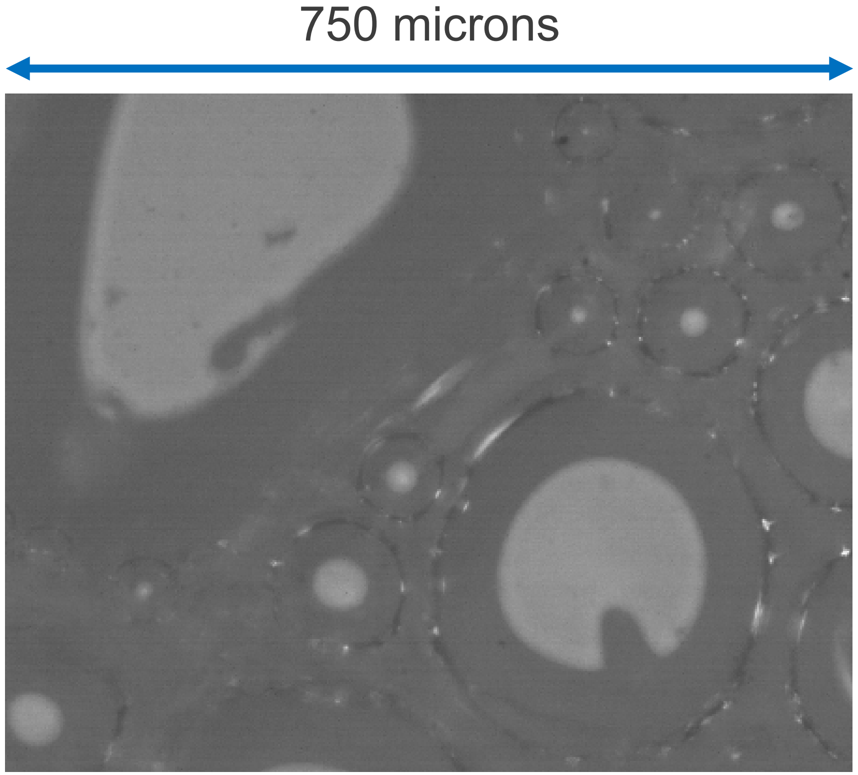




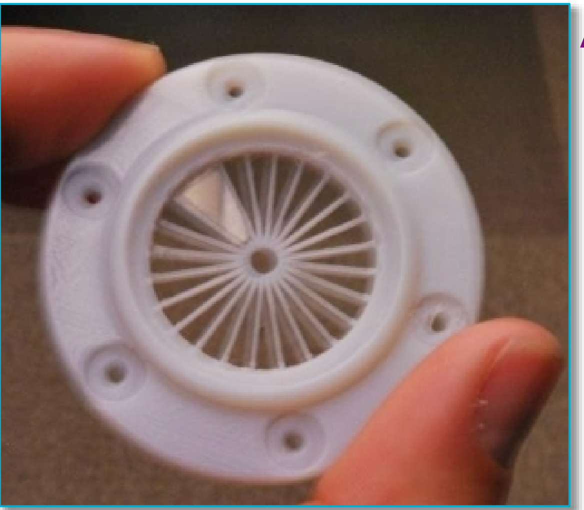
MINIMIZING SLIP



Above glass window



Between vanes



Glass window gives observation of physics within shear layer
Bubble flow prevented between vanes, confirmed up to 1000 1/s

DRAINAGE OF FIBER FILLED FOAMS

Foam drainage limits use of rheometer measurement technique

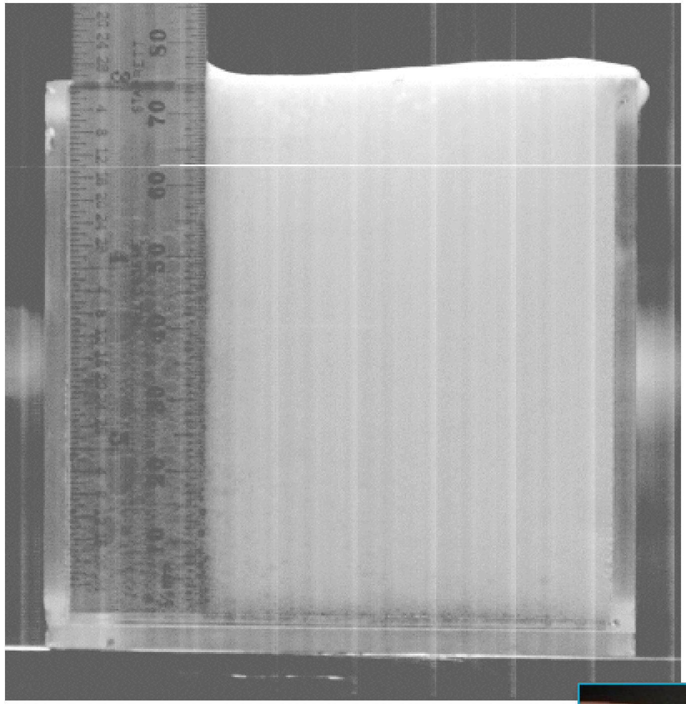
Drainage rate slows with increasing air content

Drainage rate slows with increasing fiber content. Fibers exist in liquid, between bubbles.

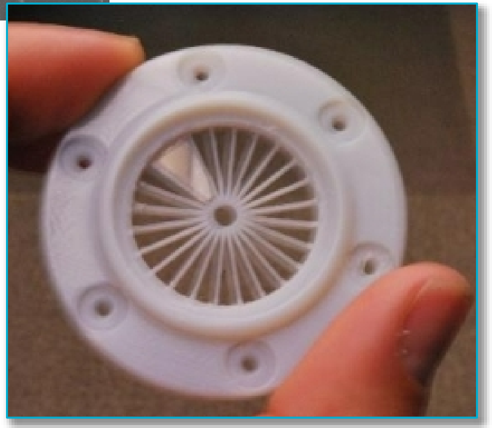
As foam drains between rheometer plate vanes, air content of foam increases

How long does it take for $\Phi = \Phi_o + 10\%$?

	1wt% fiber	2wt% fiber	3wt% fiber
$\Phi = 0.66$	~44s		~219s
$\Phi = 0.75$	~165s	~191s	[illegible]
$\Phi = 0.80$	~183s	~204s	[illegible]



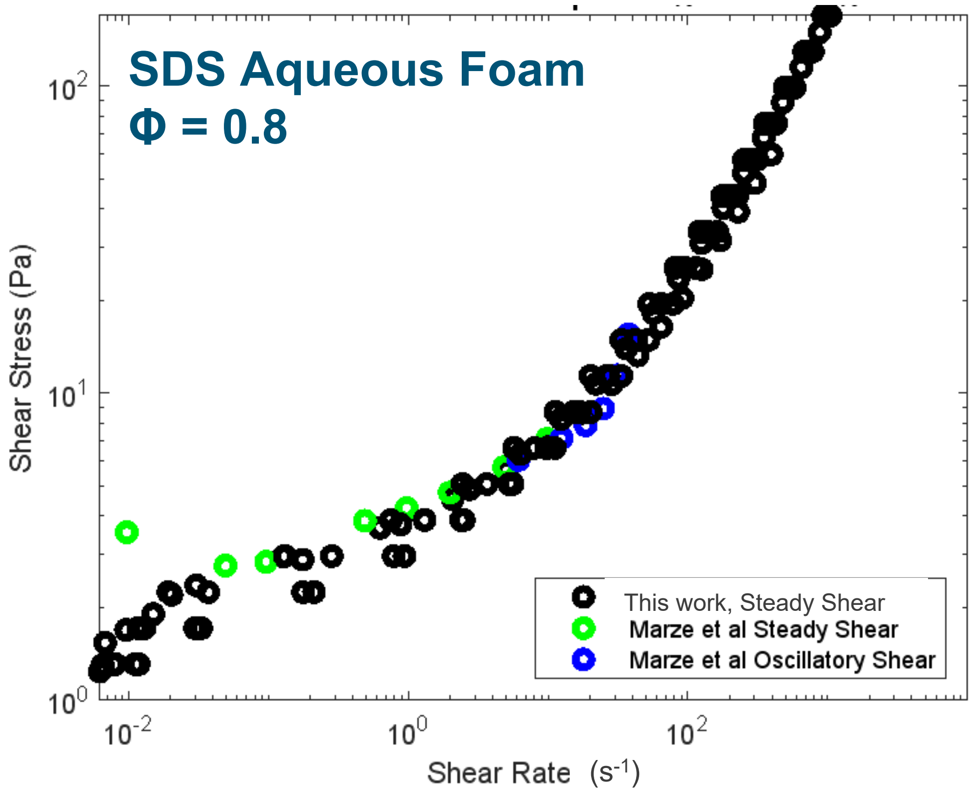
Unconfined foam drains and collapses over time



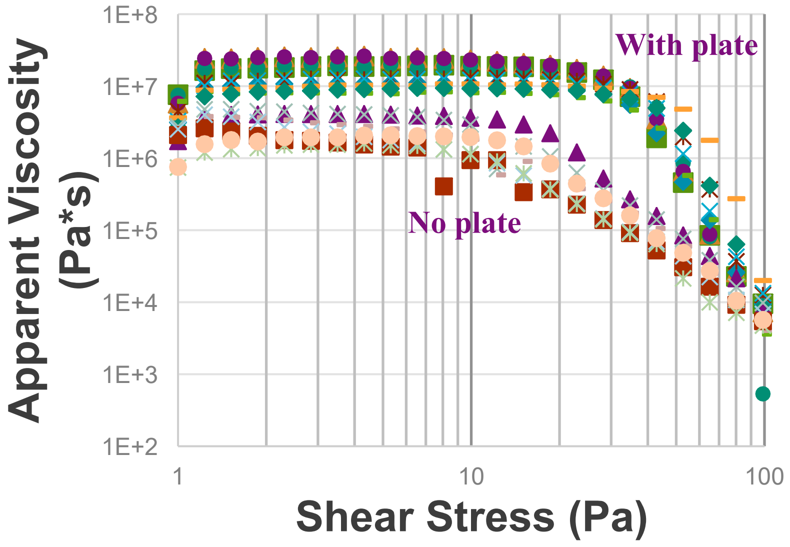
Rheology measurements require ~1 minute of time

For Φ <= 0.66, measurements are not feasible using this approach

VALIDATION OF THE RHEOMETER APPROACH



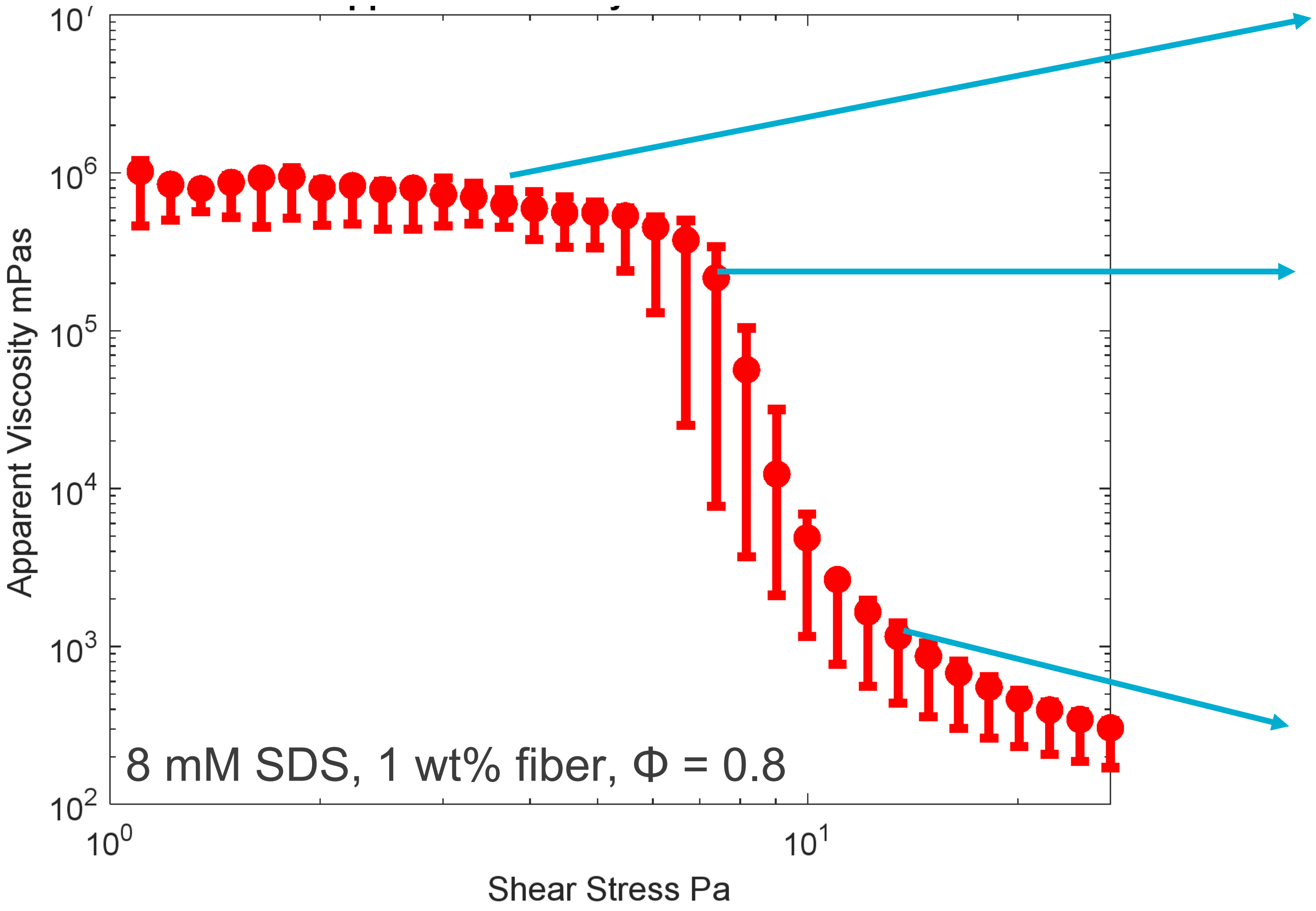
Without vaned rheometer plate, apparent viscosity is low due to slip.

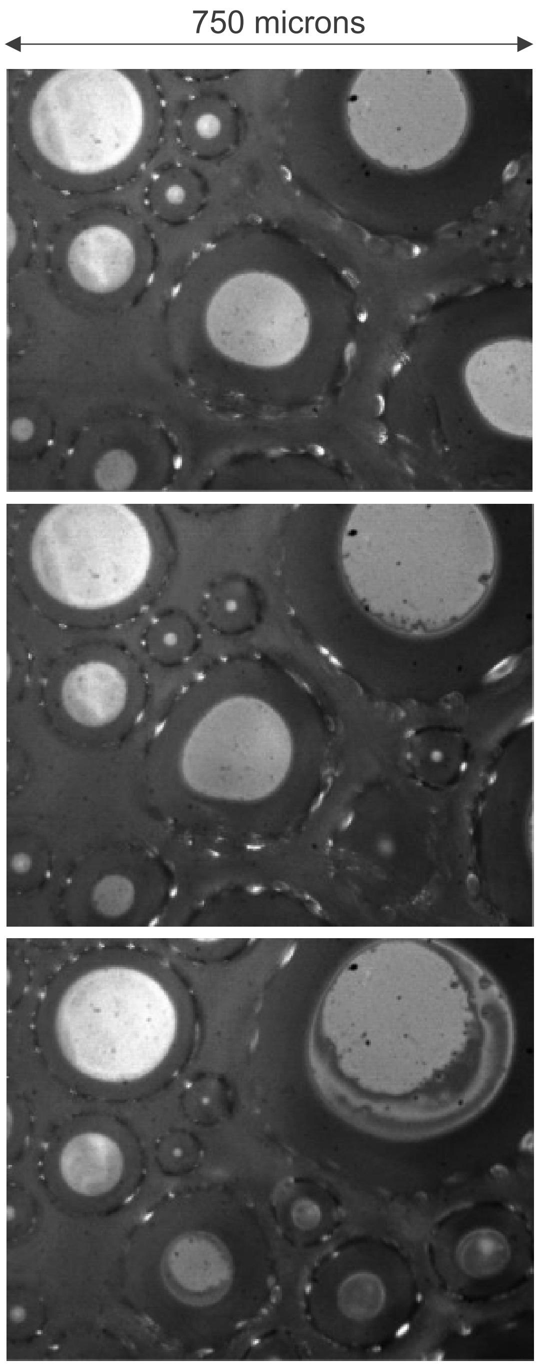


With vaned plate, successfully reproduce published rheometry for SDS aqueous foams

Marze, Sebastien, Langevin, and Saint-Jalmes. *Journal of Rheology* 52.5 (2008): 1091-1111.

QUALITATIVE FLOW OF AQUEOUS FOAMS WITH FIBERS





"Small" bubble slips through larger bubbles

Clusters of "medium" sized bubbles slip through larger bubbles

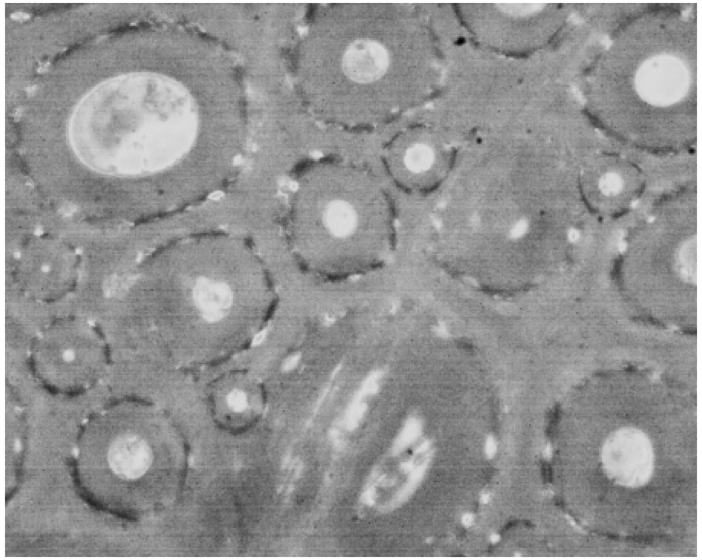
All bubbles translate, transporting fibers

Fibers lie in plateau borders, and bubbles sometimes are attached to fibers. Fibers impede bubble and water flow.

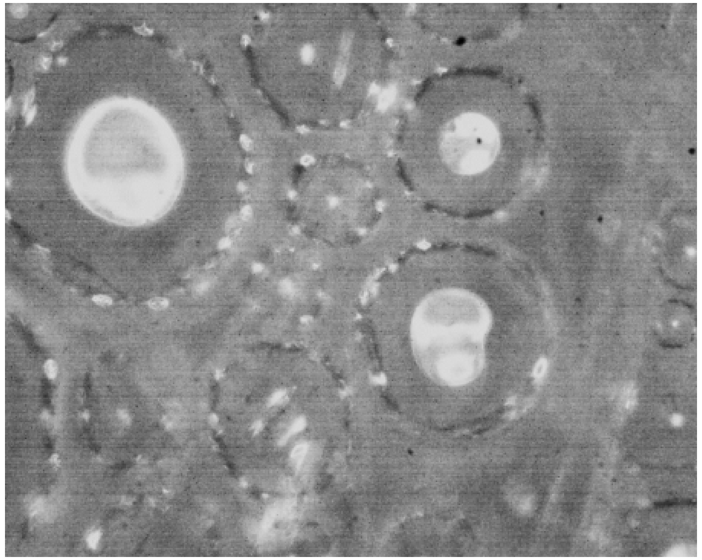
BUBBLE MOTION: INCREASING SHEAR RATE

Sample: 2% fibers, Φ = 0.8, increasing shear rate
View at surface of glass window

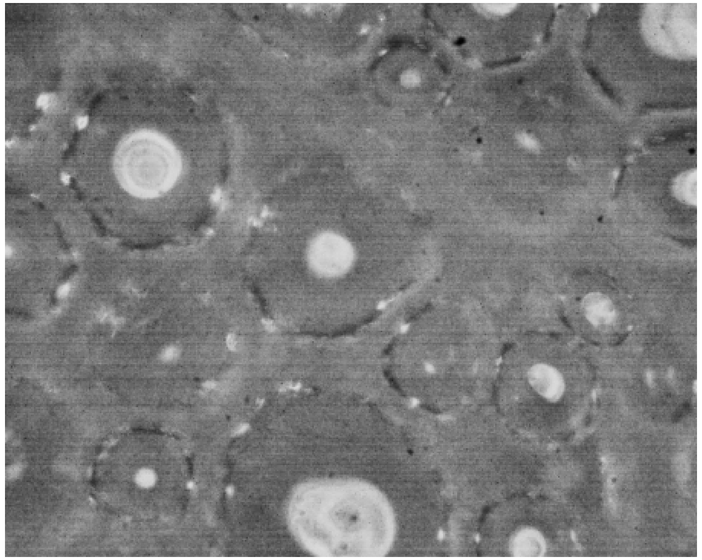
750 microns



"Small" bubble slips through larger bubbles

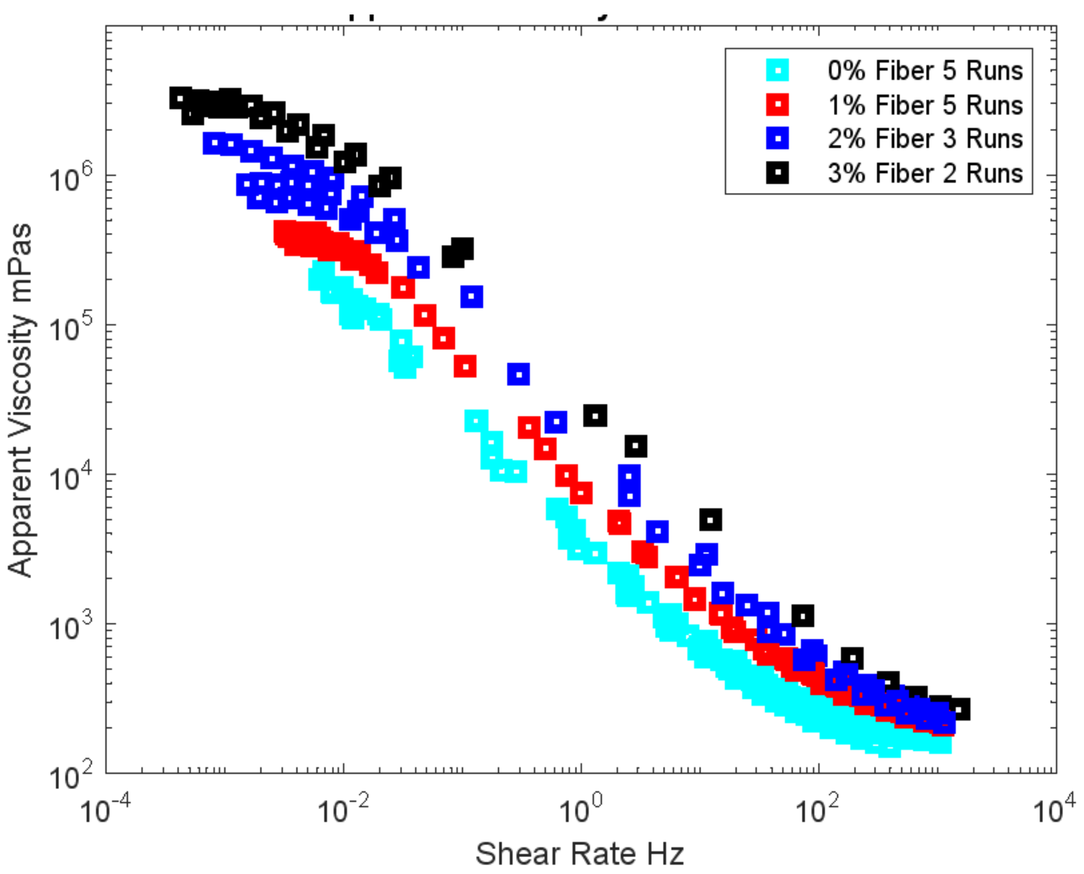


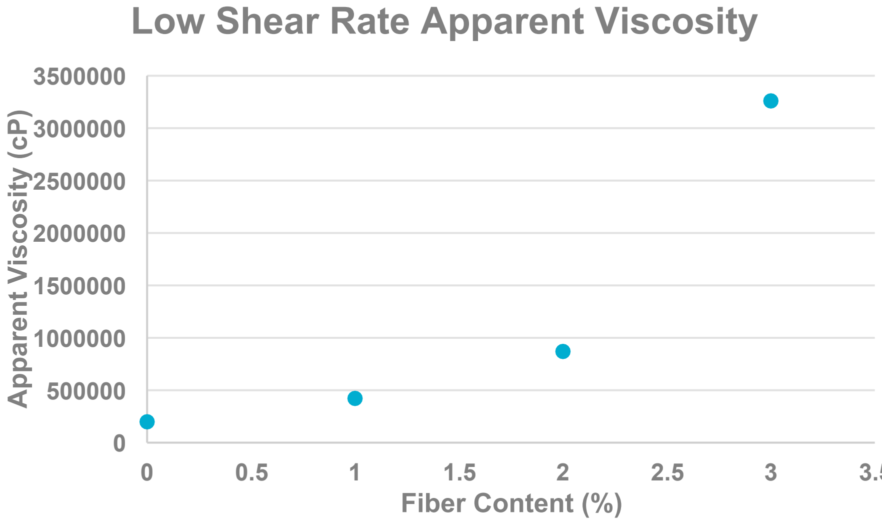
Clusters of "medium" sized bubbles slip through larger bubbles



All bubbles translate, transporting fiber

VISCOSITY OF AQUEOUS FOAMS CONTAINING FIBERS

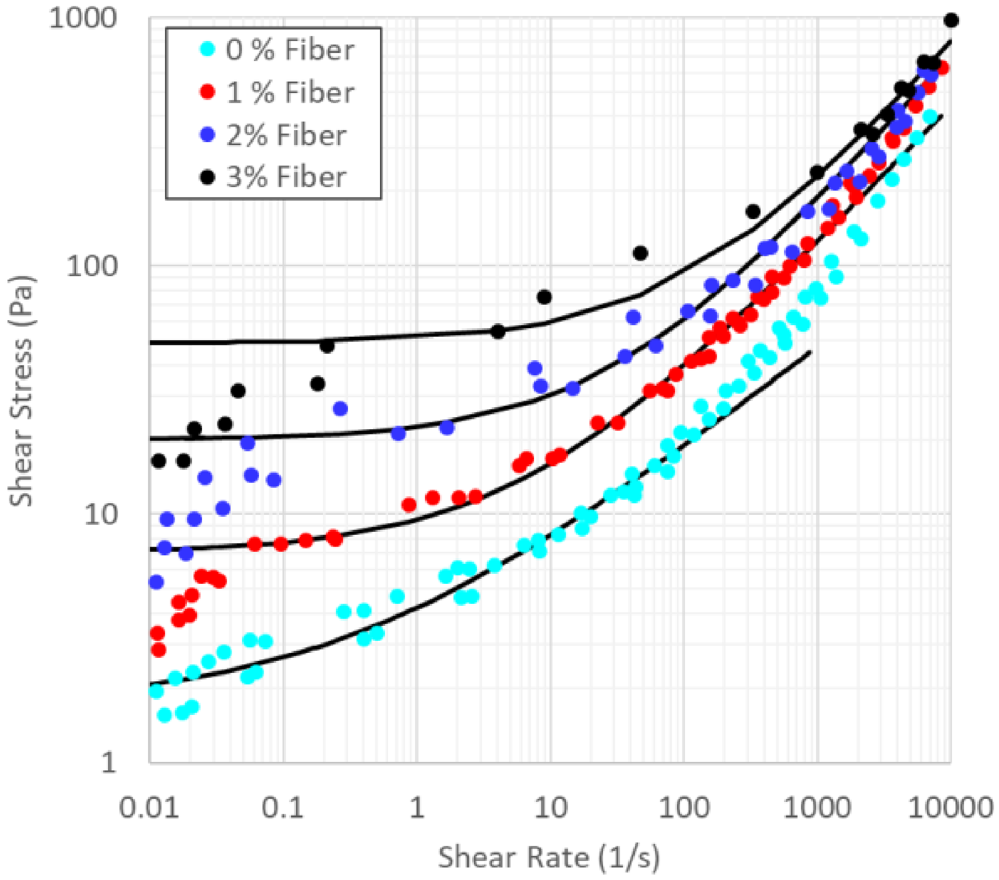


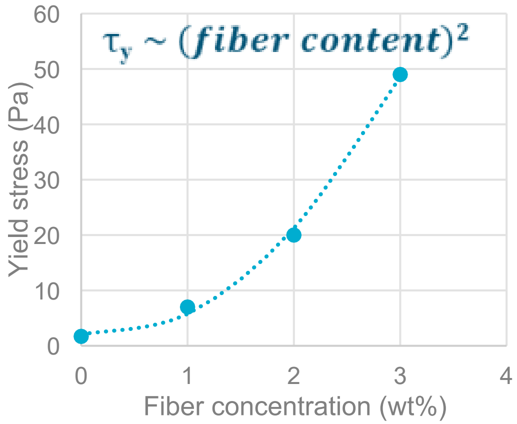


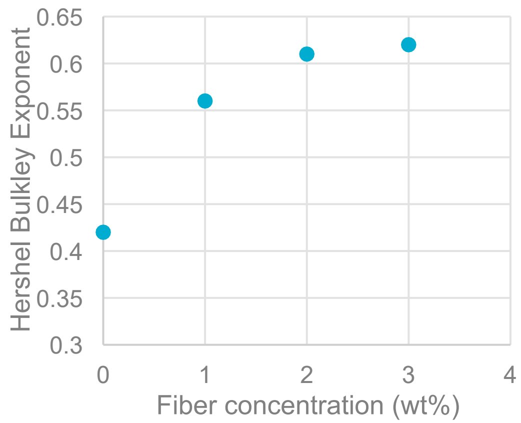
HERSCHEL-BULKLEY MODEL FIT

Jammed foam exhibits Hershel-Bulkley behavior with a yield stress τ_y :

$$\tau = \tau_y + \alpha\dot{\gamma}^{\beta}$$







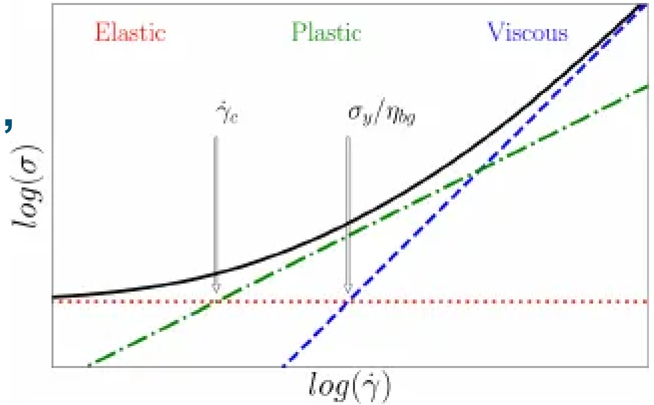
At 0% fibers, reproduce fit by Marze 2008

Fibers increase the yield stress and HB exponent

As bubbles are sheared at higher rates, microstructural changes lead to an increase in the exponent, not captured by the HB form.

Exploring alternative models, such as Caggioni 2019:

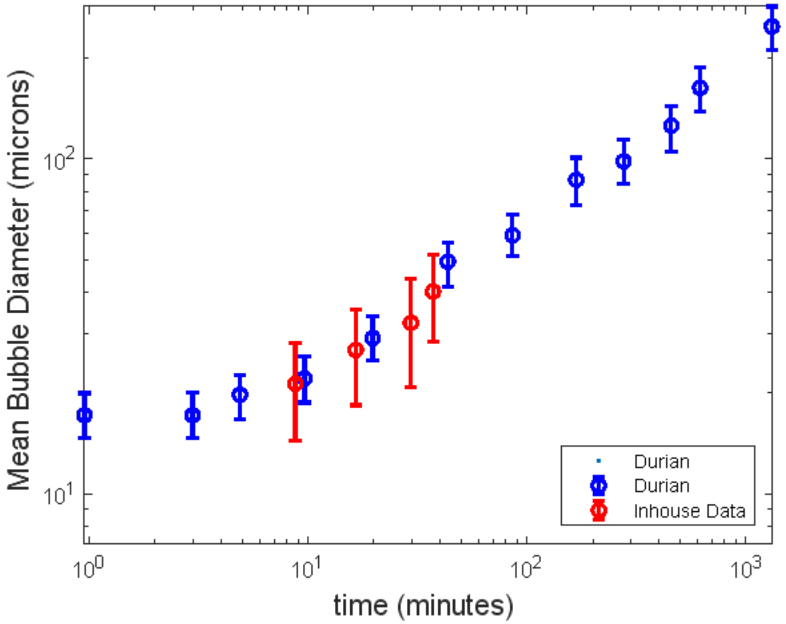
$$\sigma = \sigma_y + \sigma_y \cdot \left(\frac{\dot{\gamma}}{\dot{\gamma}_c}\right)^{1/2} + \eta_{bg} \cdot \dot{\gamma}.$$

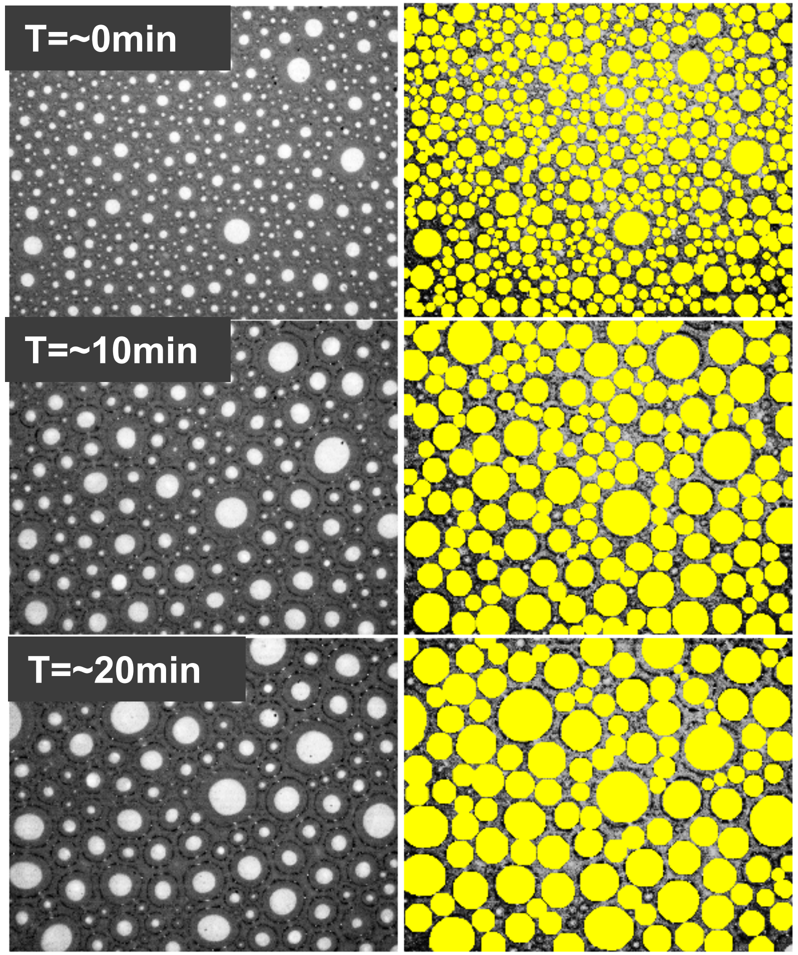


Caggioni, Trappe, Spicer. *Journal of Rheology* 64(2) (2020): 413.

IMAGE ANALYSIS FOR BUBBLE SIZE MEASUREMENTS

Bubbles are imaged through the bottom plate using a high speed camera (Phantom)

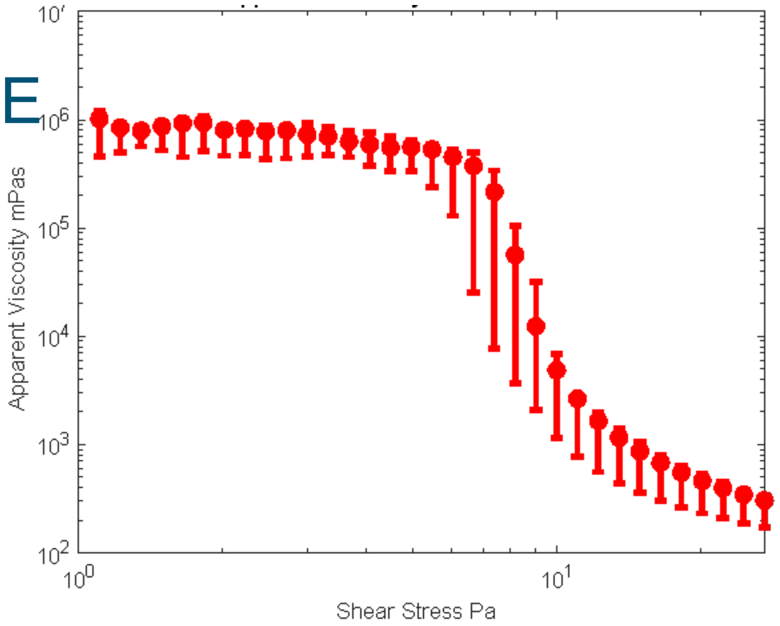




Successfully reproduced stagnant foam coarsening scaling behavior published by Durian et al. for Gillette Foamy shaving cream

Durian, Weitz, and Pine. *Physical Review A* 44.12 (1991): R7902.
Pierre, Juliette, et al. *The European Physical Journal E*36.10 (2013): 1-10.

PURE AQUEOUS FOAMS: BUBBLE APPEARANCE

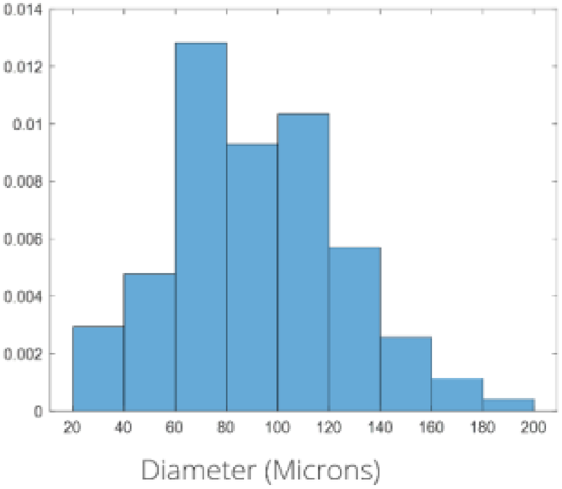


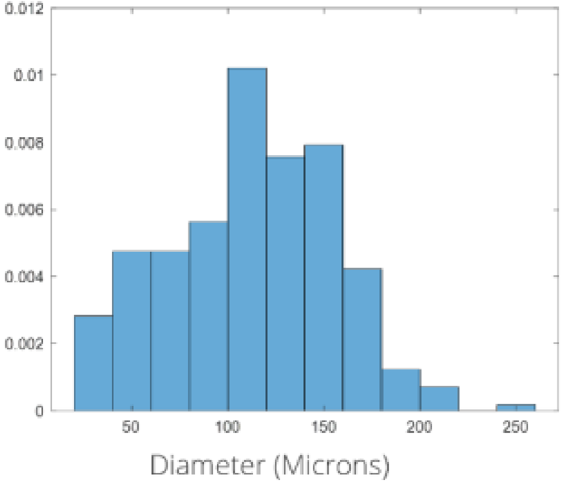
Target bubble size: D = 50 – 150

Low shear rate

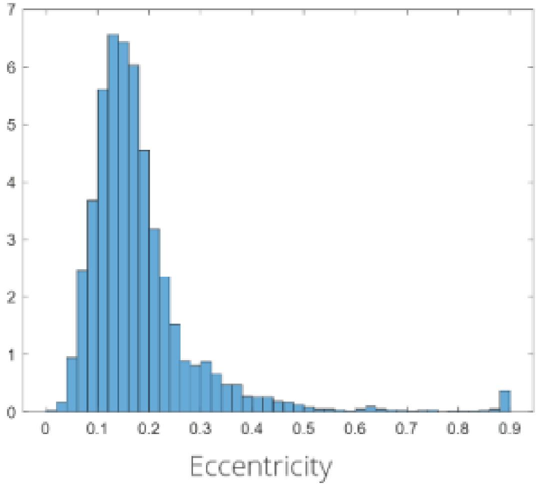
High shear rate

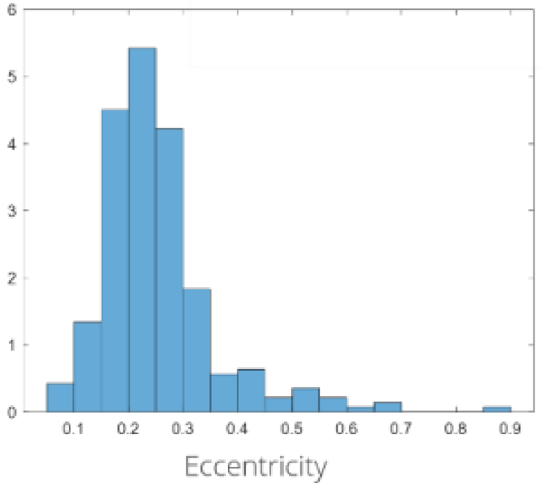
Bubble size





Bubble shape

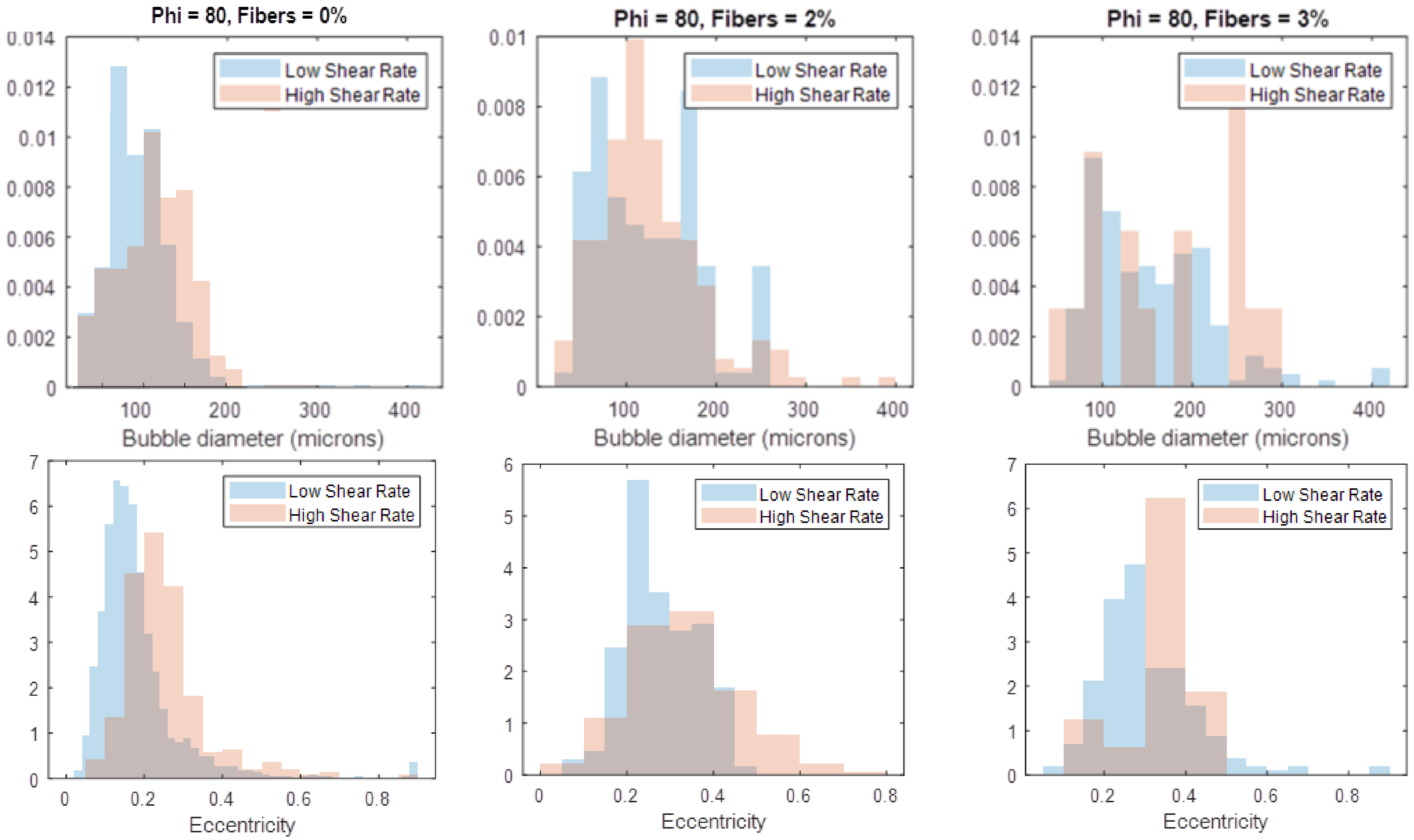




At low shear rate, bubbles are spherical.

Increasing shear rate above yield creates eccentric bubbles and larger bubbles through coalescence.

BUBBLE APPEARANCE VS FIBER CONCENTRATION



Fibers stabilize large bubbles and encourage eccentricity

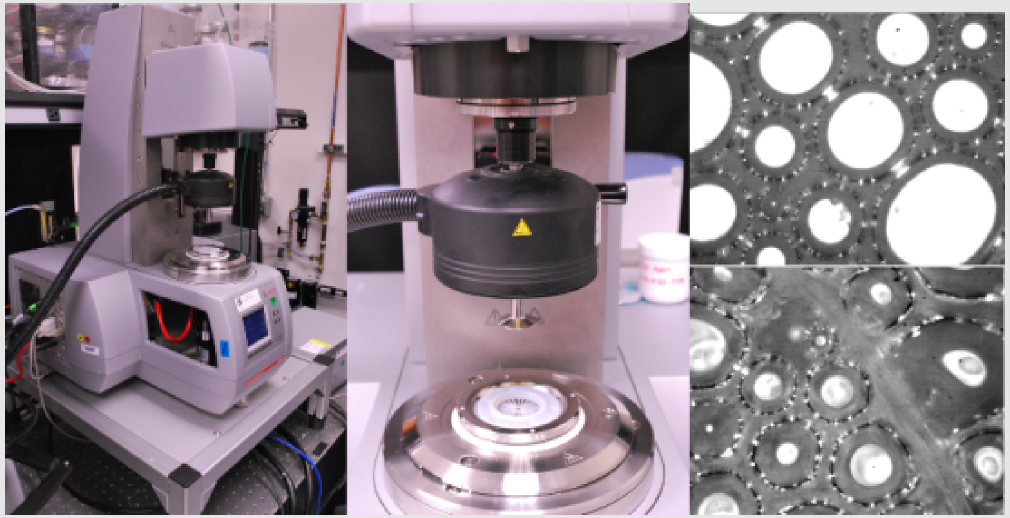
EXPERIMENTAL APPROACH

Goal: Rheology of fiber-laden foams (1-3 wt%) of various air concentration (**Φ = 0.30 – 0.80) and shear rates (0.1 – 1000 1/s)**

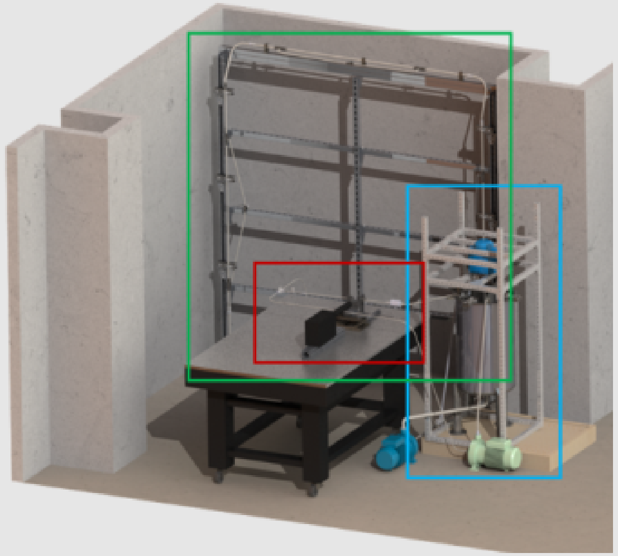
Foams above jamming transition
Stable foams

Foam stability less necessary
Less control over shear rate

Rheometer Measurements

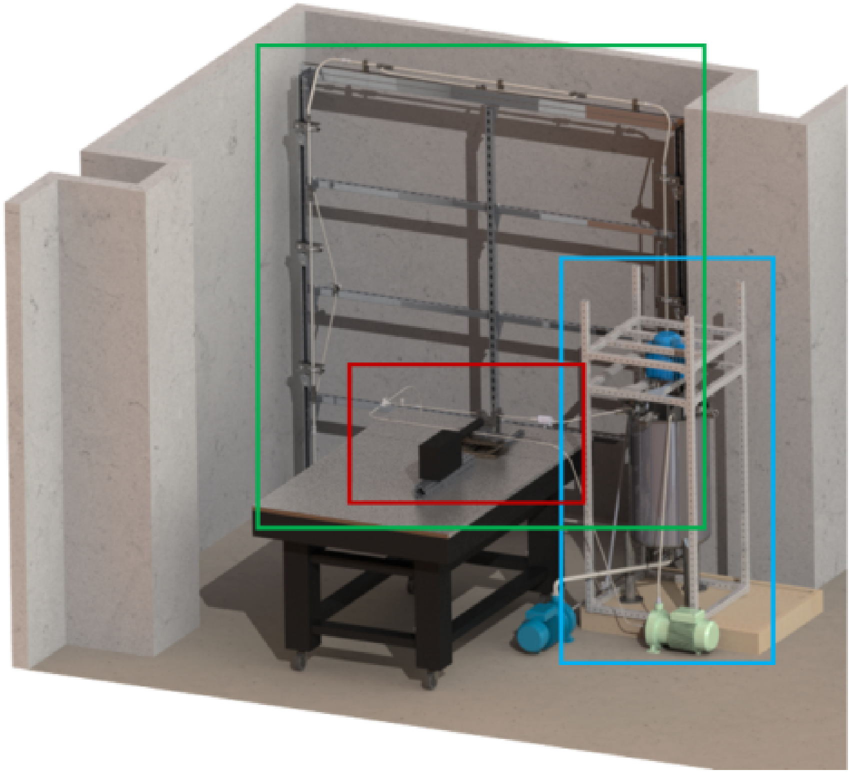


Differential Pressure Based Measurements



DIFFERENTIAL PRESSURE BASED MEASUREMENTS

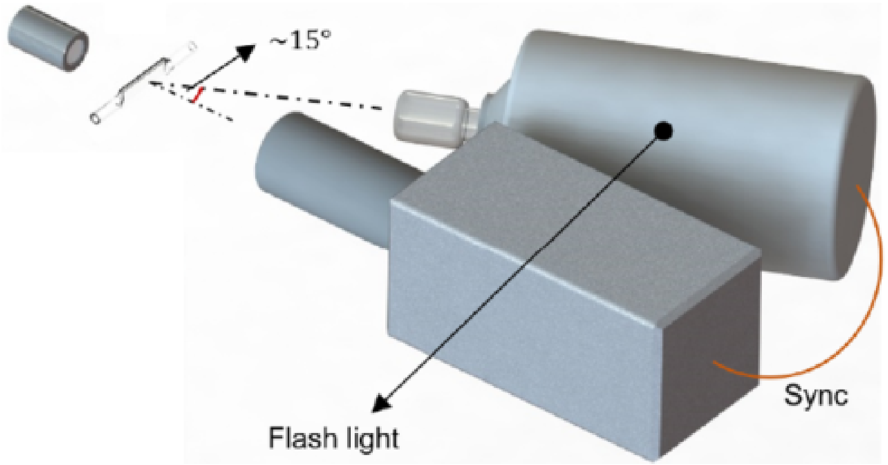
Foams less than Φ = ~0.66 cannot be interrogated through rheometer due to coarsening.

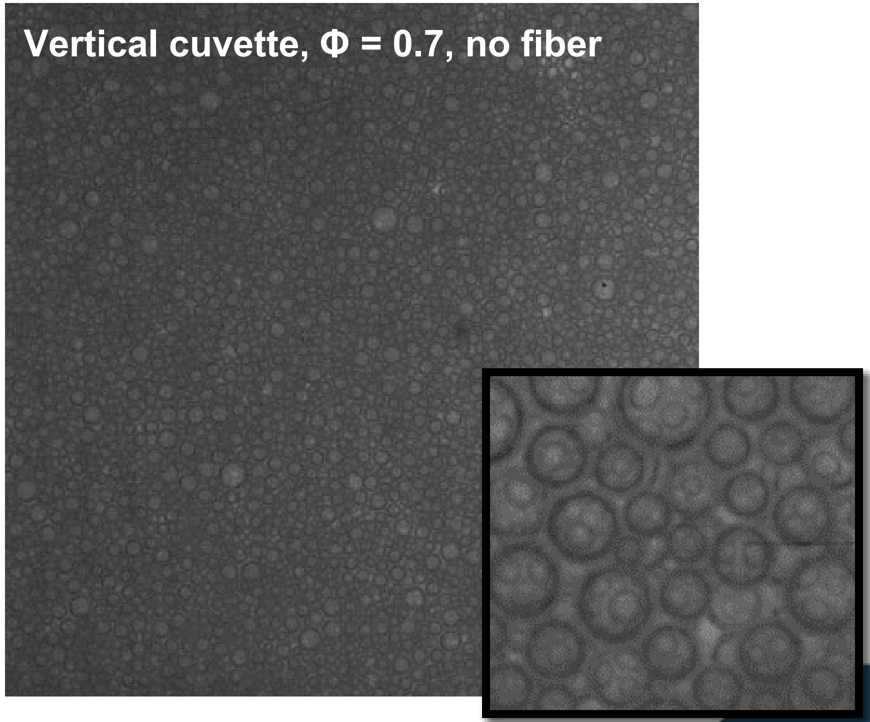


1. Mixing section

2. Three pipe rheometers

3. Bubble size analysis



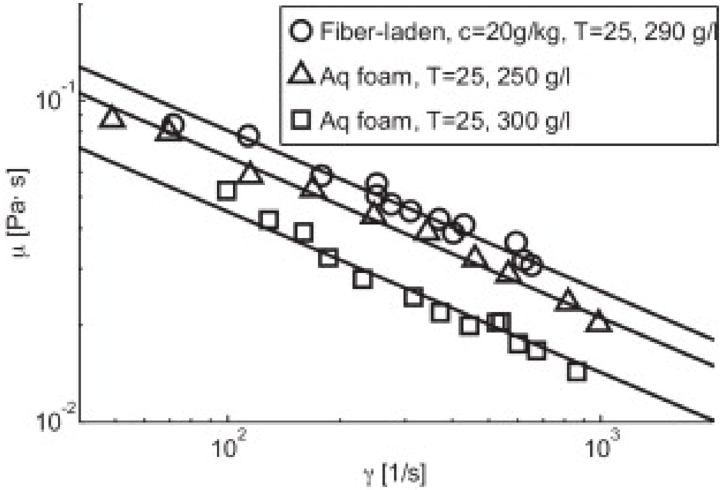


Measure pressure drop of foam as it is pumped through a pipe to obtain estimation of viscosity.
Simultaneous high speed imaging.

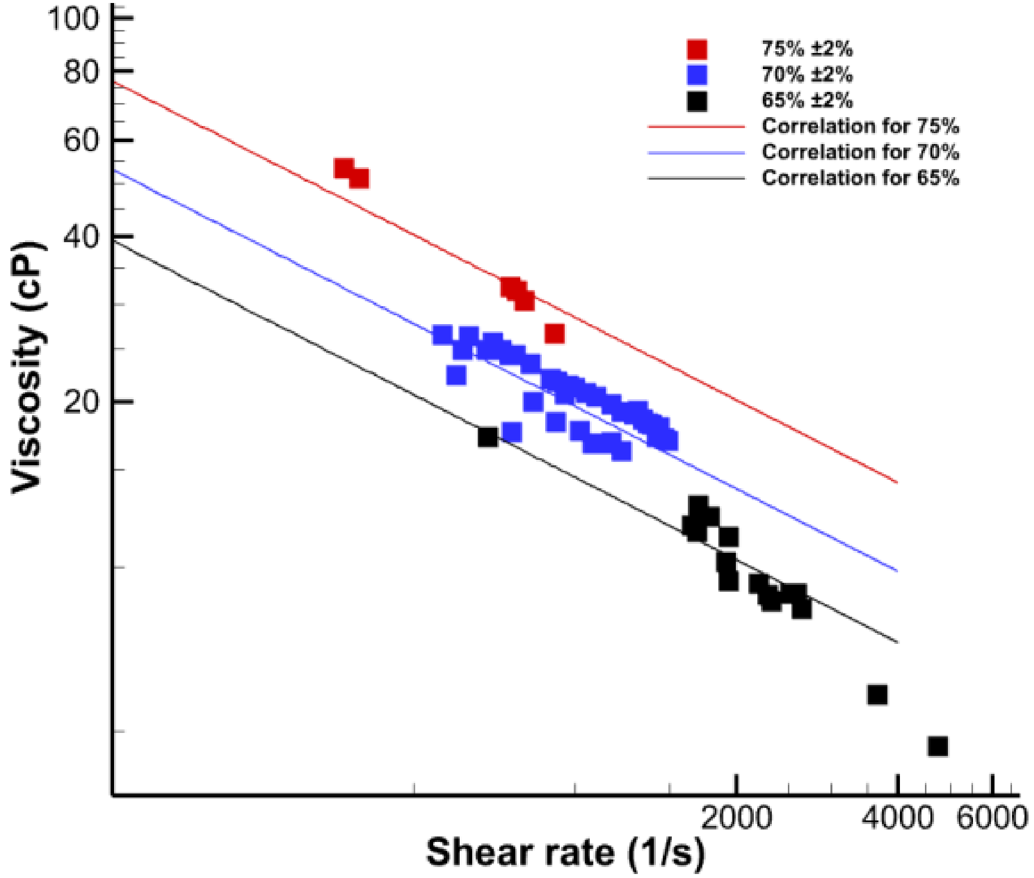
FLUID LOOP RHEOLOGY

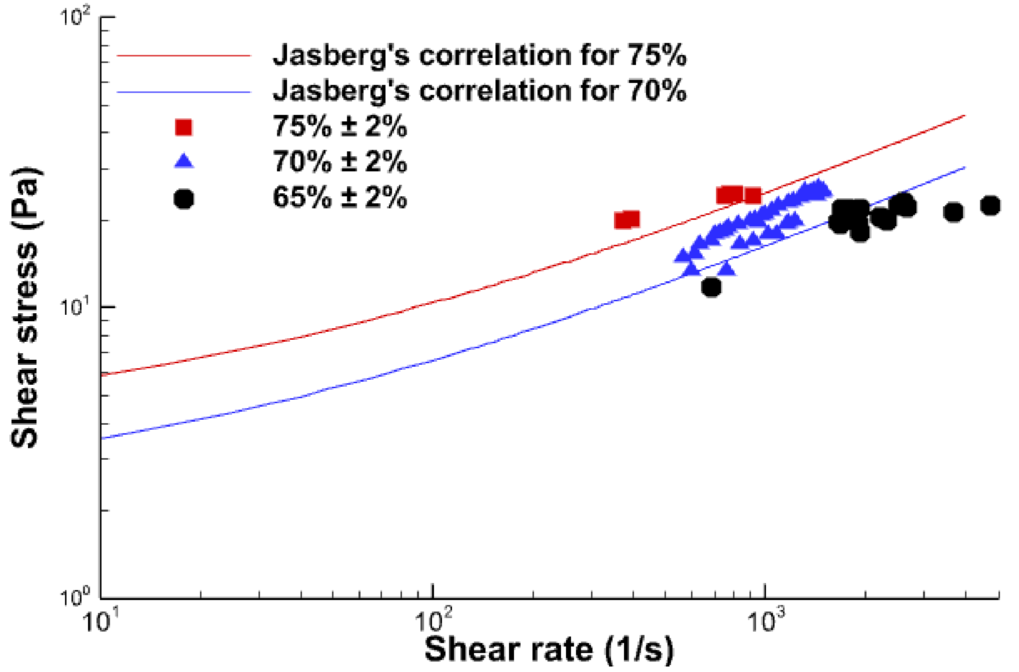
Jäsberg studied fiber-foam rheology up to 10^3 1/s

Early flow loop data corroborate data, but potentially show deviation at higher shear rates



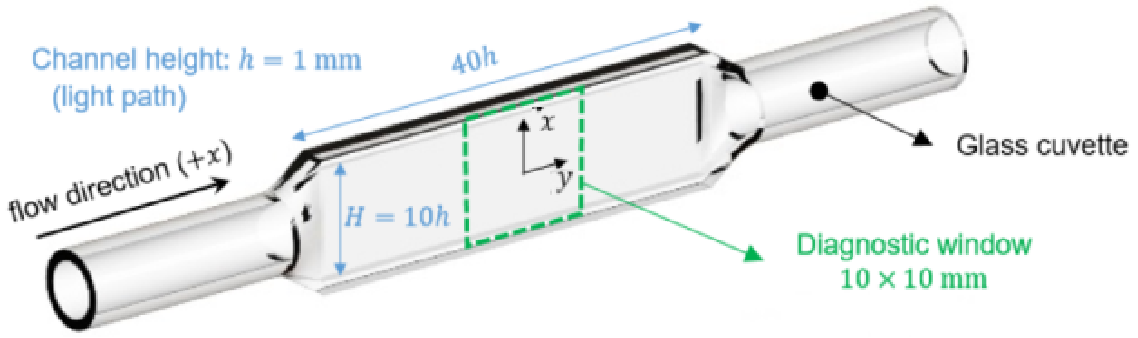
Viscosity including Weissenberg-Rabinowitsch slip correction, Jäsberg 2015

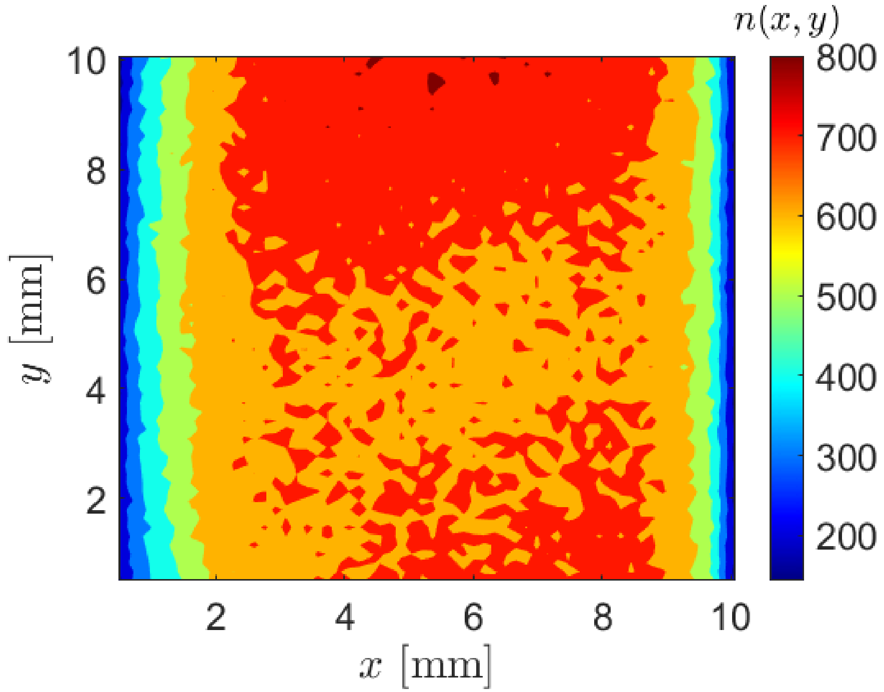




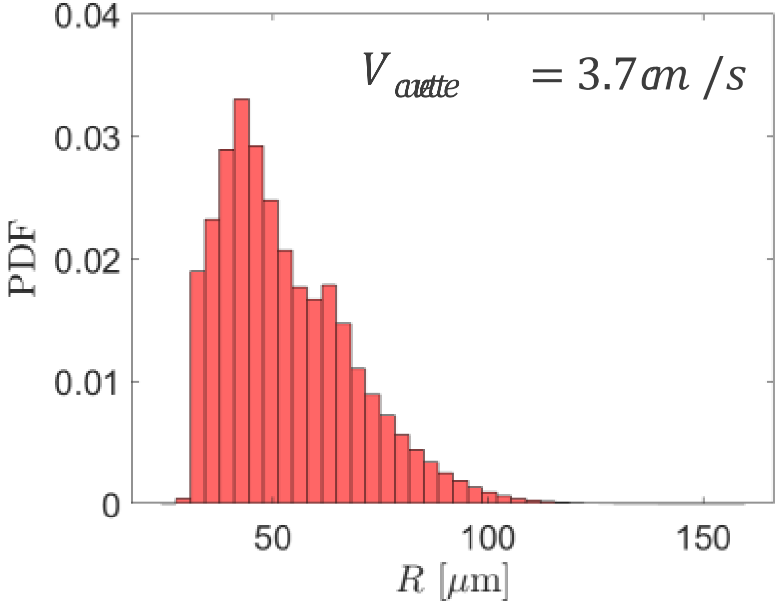
Jäsberg, A., Selenius, P., & Koponen, A. (2015). *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *473*, 147-155.

FLUID LOOP OBSERVATION OF FLOW

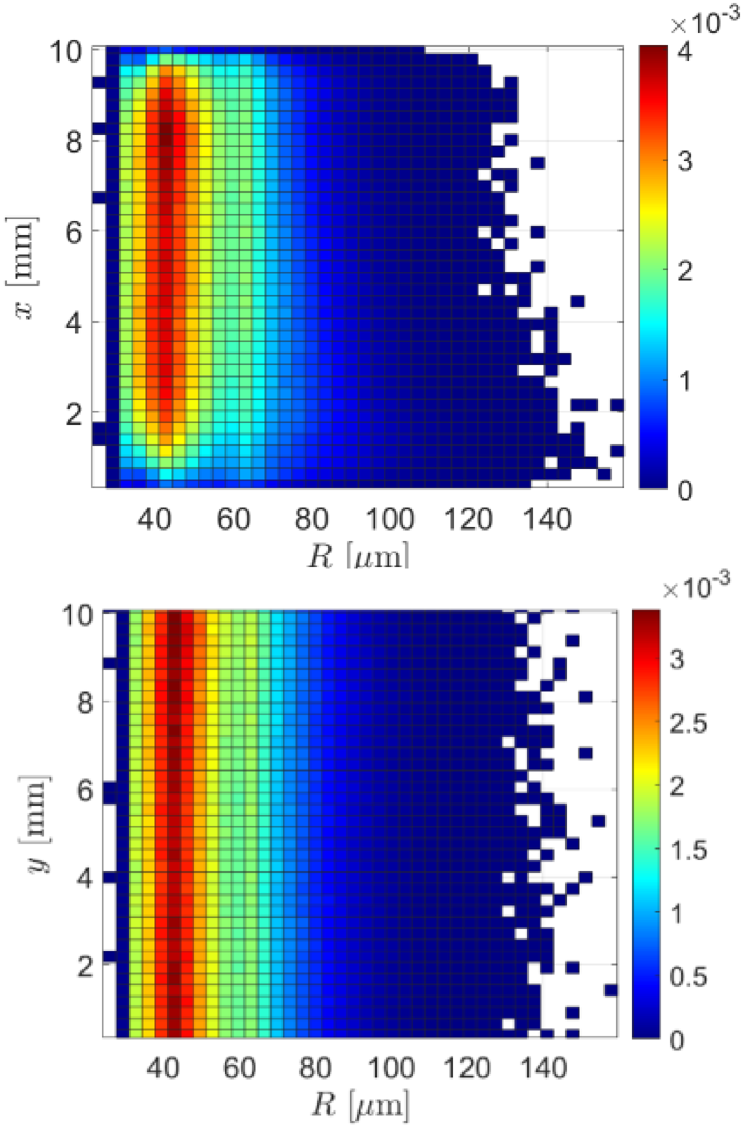




2M bubbles detected from 875 images



PDF – **Vertical** Cuvette Orientation– 70% air content, no fiber



Bubbles migrate to the center of the flow

CONCLUSIONS

Goal: Understand fiber-filled foam rheology for future design of coating operations

Shear thinning foam viscosity increases with fiber concentration

- **Yield stress is also increased**

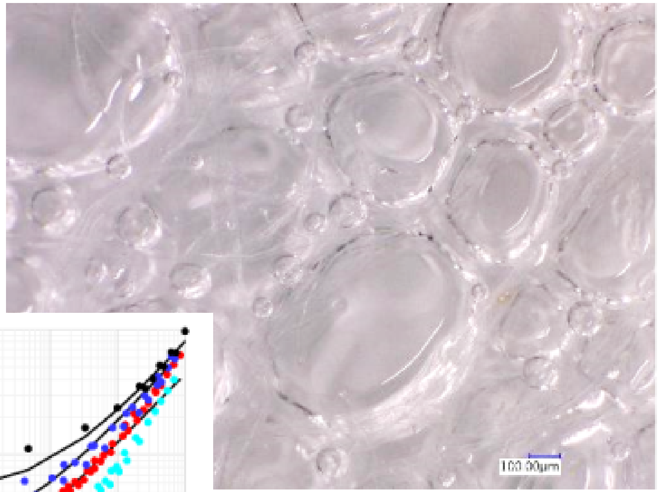
Fibers stabilize large bubbles from coalescing in shear

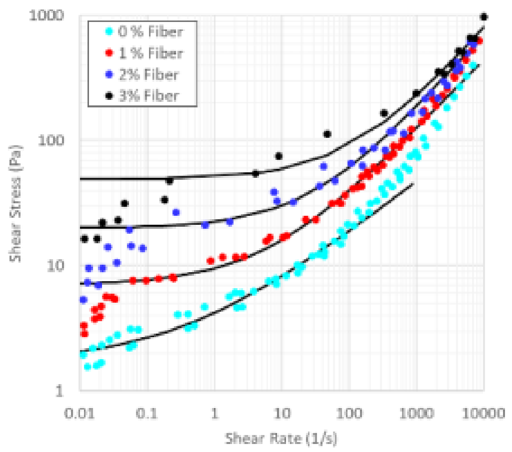
- **Opportunity for microstructured fiber mats**

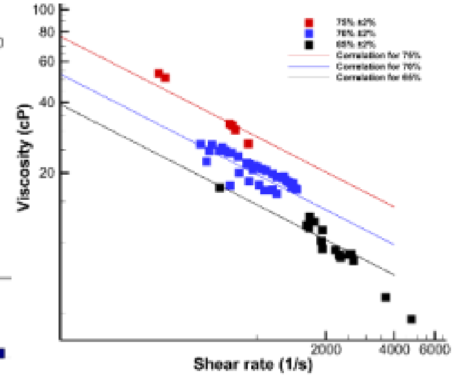
Flow loop offers process-relevant measurement method for high shear rate viscosity determination

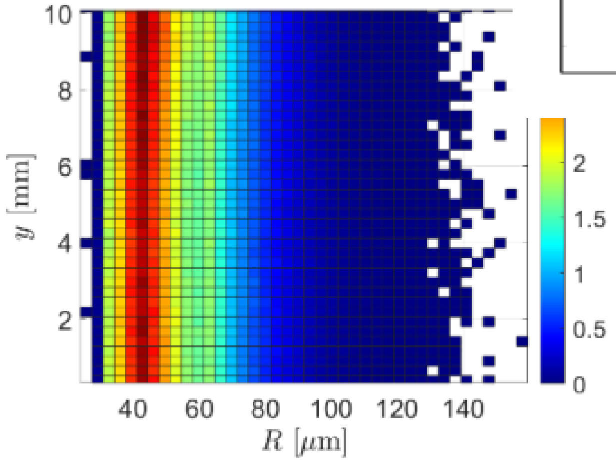
- **Design of nozzles, headboxes for coating**

Energy savings of fiber-foam processing will only be realized through understanding of fluid behavior.









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