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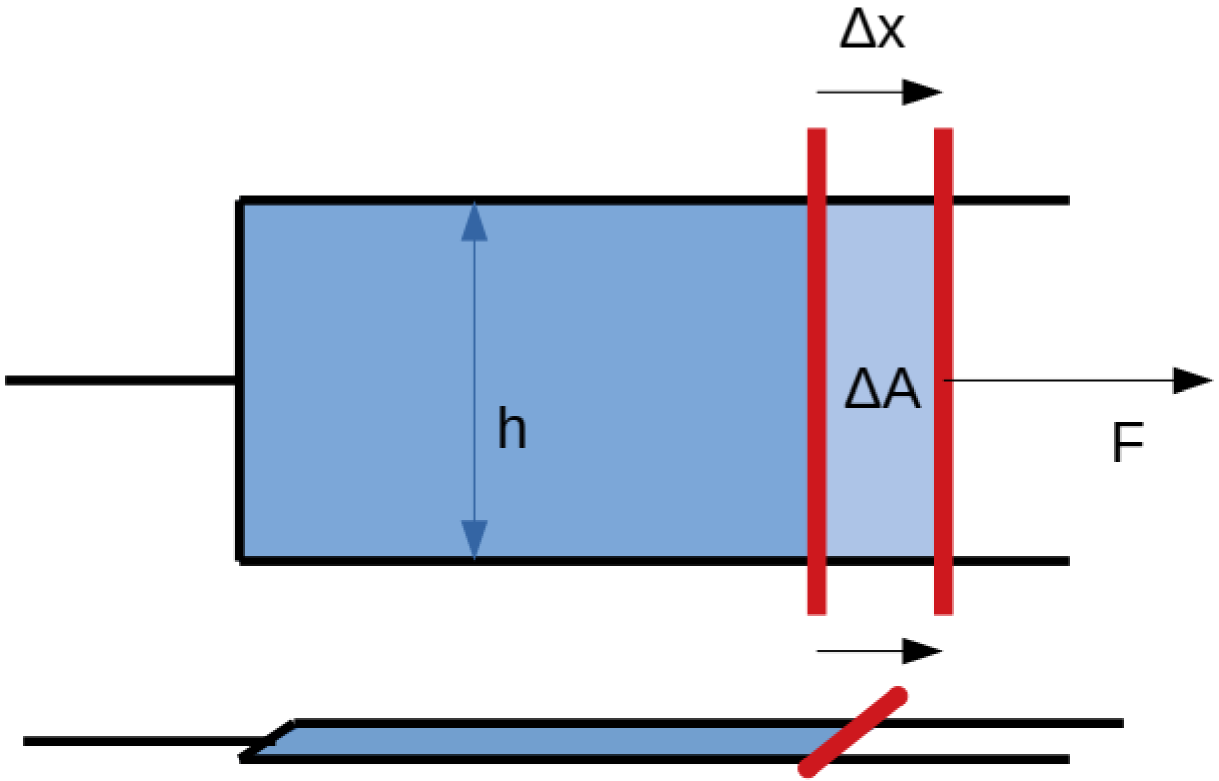
Lecture 3: Bubble generation

Structure

- Review lecture 2
- Bubble generation
- Nozzle
- Sparger
- Microfluidic
- Rayleigh-Plateau instability
- Bubble size measurement

Surface tension

- Generation of surface requires additional energy
- Counteracting force tries to minimize surface area



$$\frac{F}{h} = \frac{F\,\Delta x}{h\,\Delta x} = \frac{\Delta E}{\Delta A} = \gamma \qquad \gamma = \frac{Energy}{Surface\ Area}$$

$$\frac{F}{2h} = \frac{F\,\Delta x}{2h\,\Delta x} = \frac{\Delta E}{2\,\Delta A} = \gamma$$

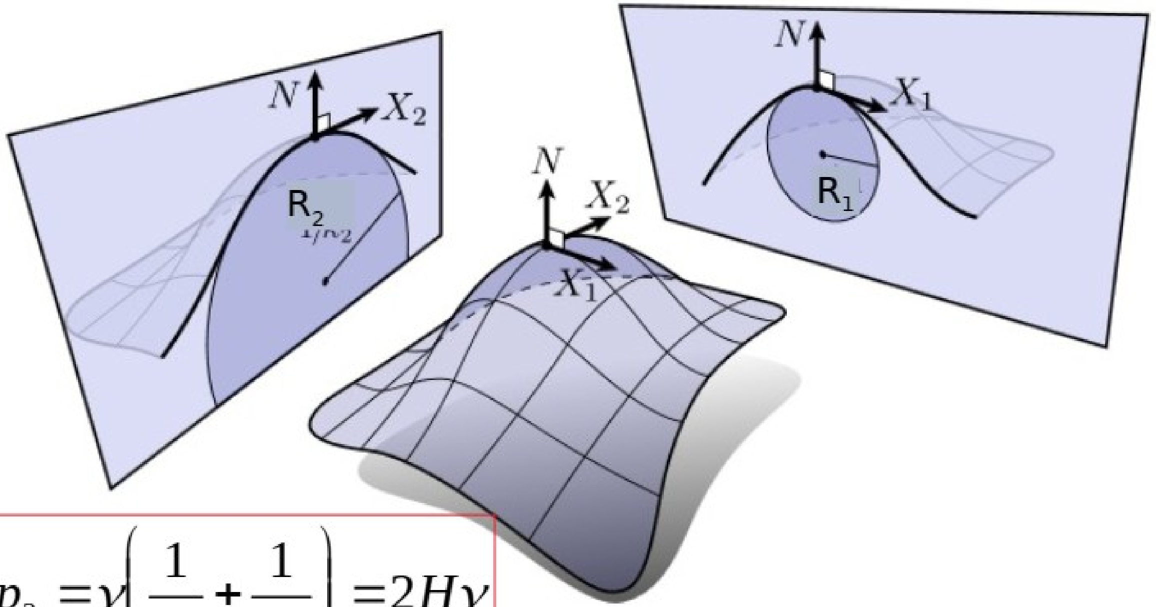
Backside!

Units: $$[\gamma] = \frac{Nm}{m^2} = \frac{N}{m} = 1000\,\frac{dyne}{cm}$$

Young-Laplace law

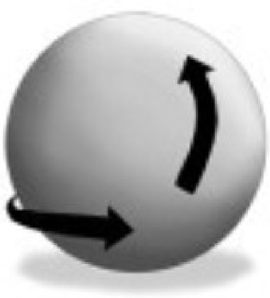
- Local „mean curvature“ H defines local pressure difference

$$H=\frac{1}{R}\rightarrow \Delta p=\frac{2\gamma}{R},$$

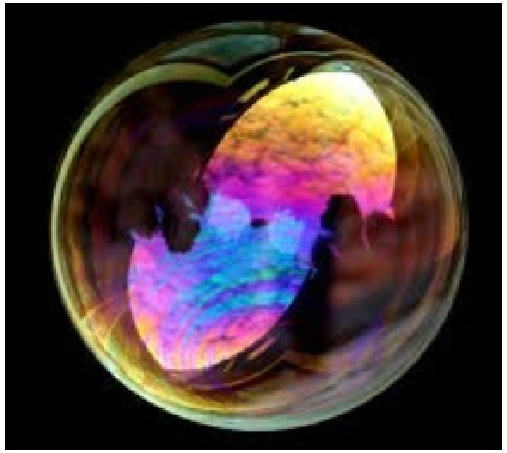


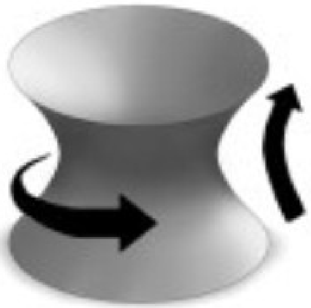
$$\Delta p = p_1 - p_2 = \gamma\left(\frac{1}{R_1}+\frac{1}{R_2}\right) = 2H\gamma$$

$$H = \frac{1}{2}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$$

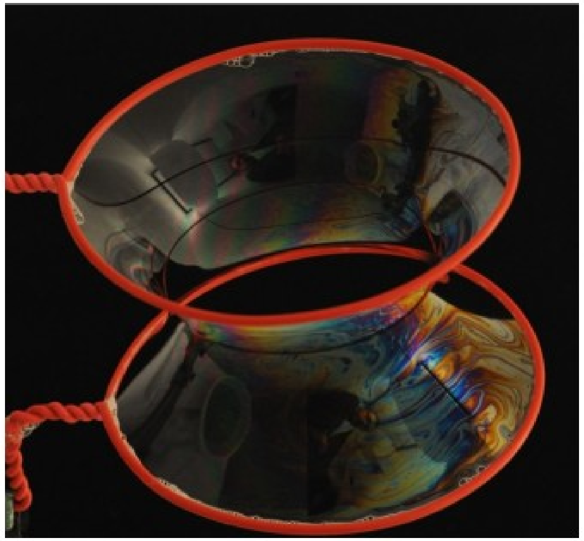


H>0



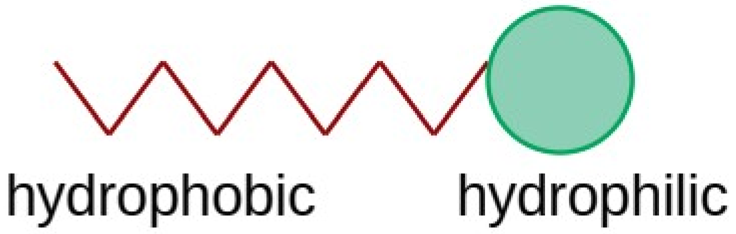


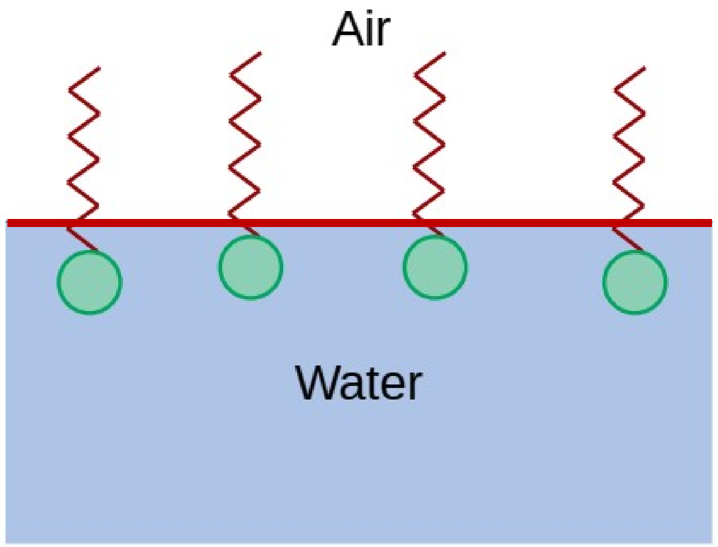
H=0



What are surfactants?

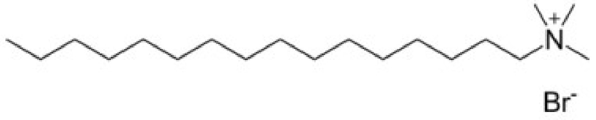
- Surfactants = SURFace ACTive AgeNTS
- Adsorb at interfaces, decreasing surface tension

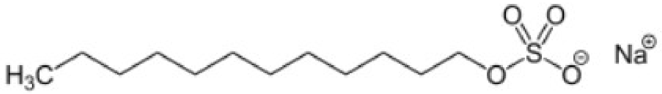


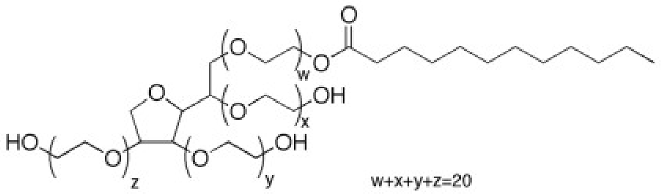


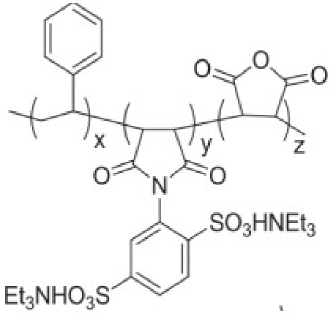
Types of surfactants

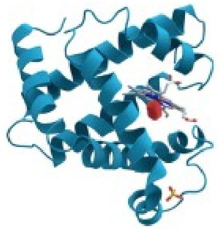
- Small molecules (mass up to 1000 g/mol)
  - – Ionic surfactants
    - ● Cationic surfactants CTAB, TTAB
    - ● Anionic surfactants SDS
  - – Non-ionic surfcatants Tween
- Large Molecules
  - – Polymers
  - – Proteins (Enzymes)
- Particles

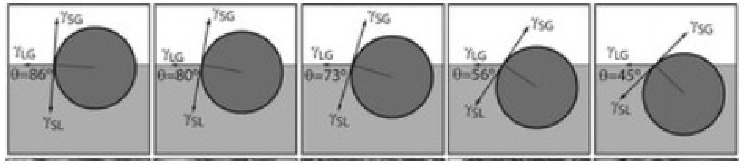






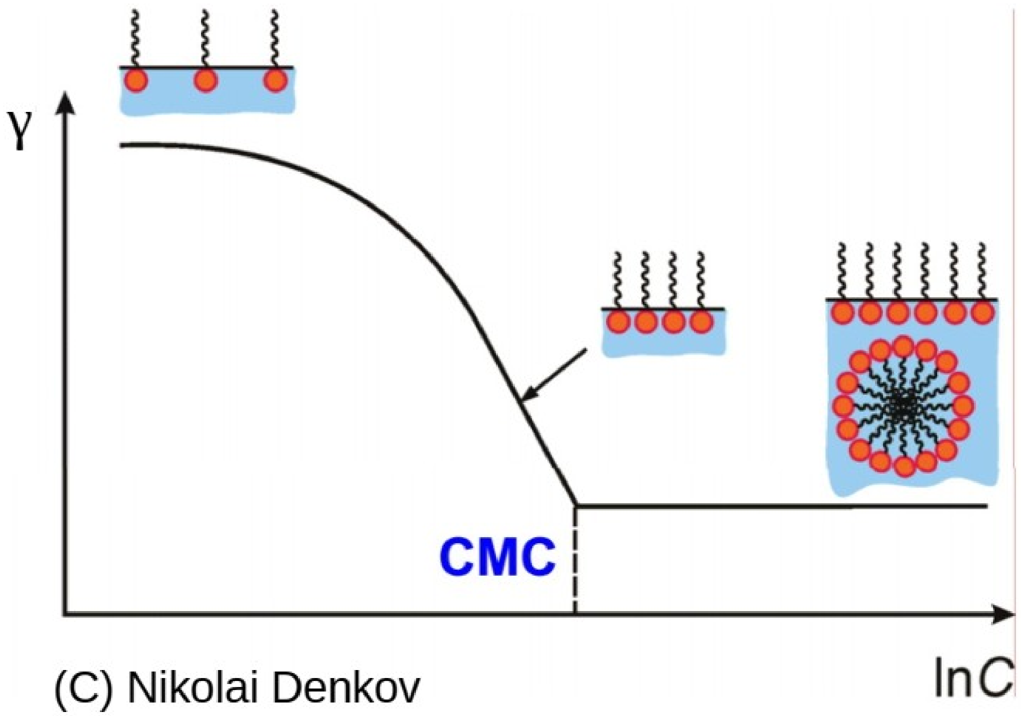


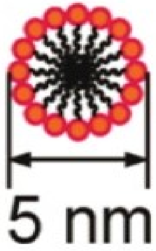


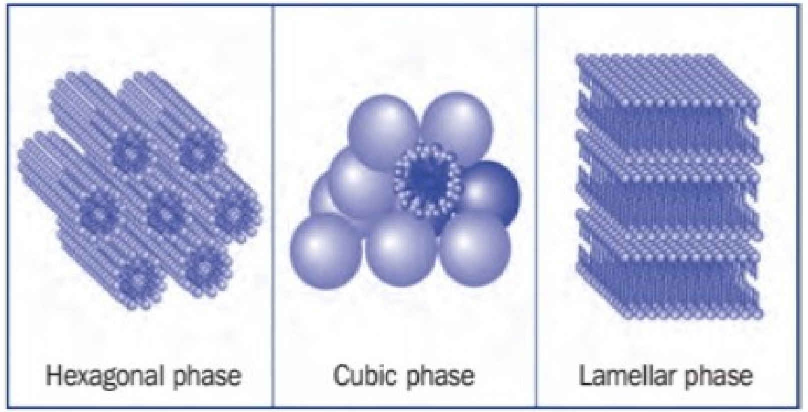


Critical Micelle Concentration - CMC

- Equilibrium between surface concentration and bulk concentration
- Below CMC surface tension is reduced with increasing bulk concentration
- Above CMC interface is fully covered and excess surfactants form micelles





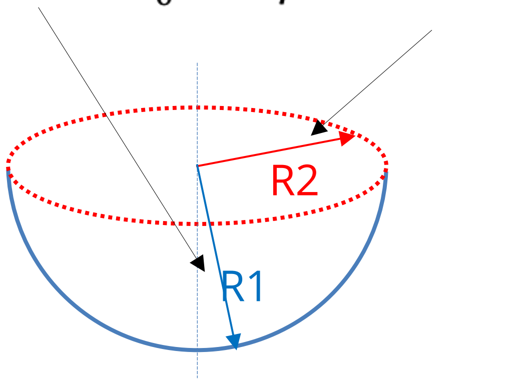


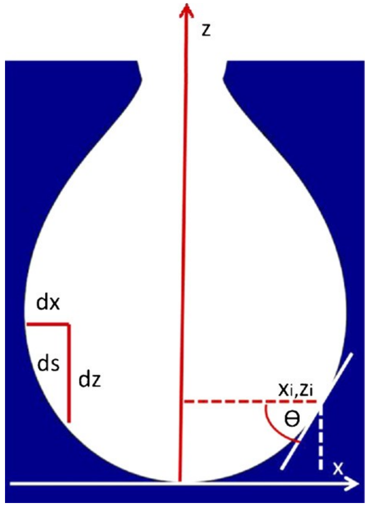
Pendant drop method

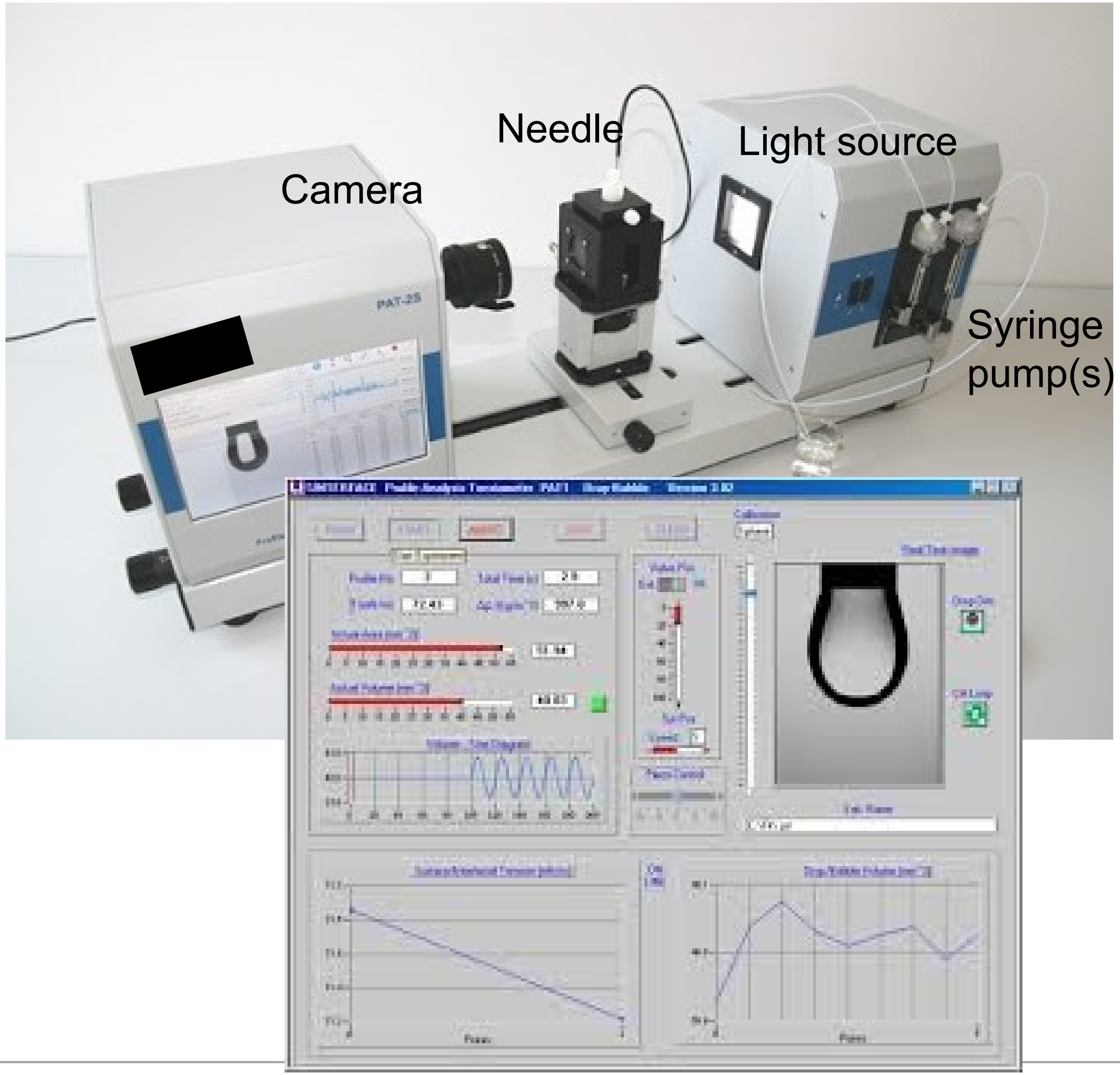
$$\frac{dx}{ds} = \cos\theta$$

$$\frac{dz}{ds} = \sin\theta$$

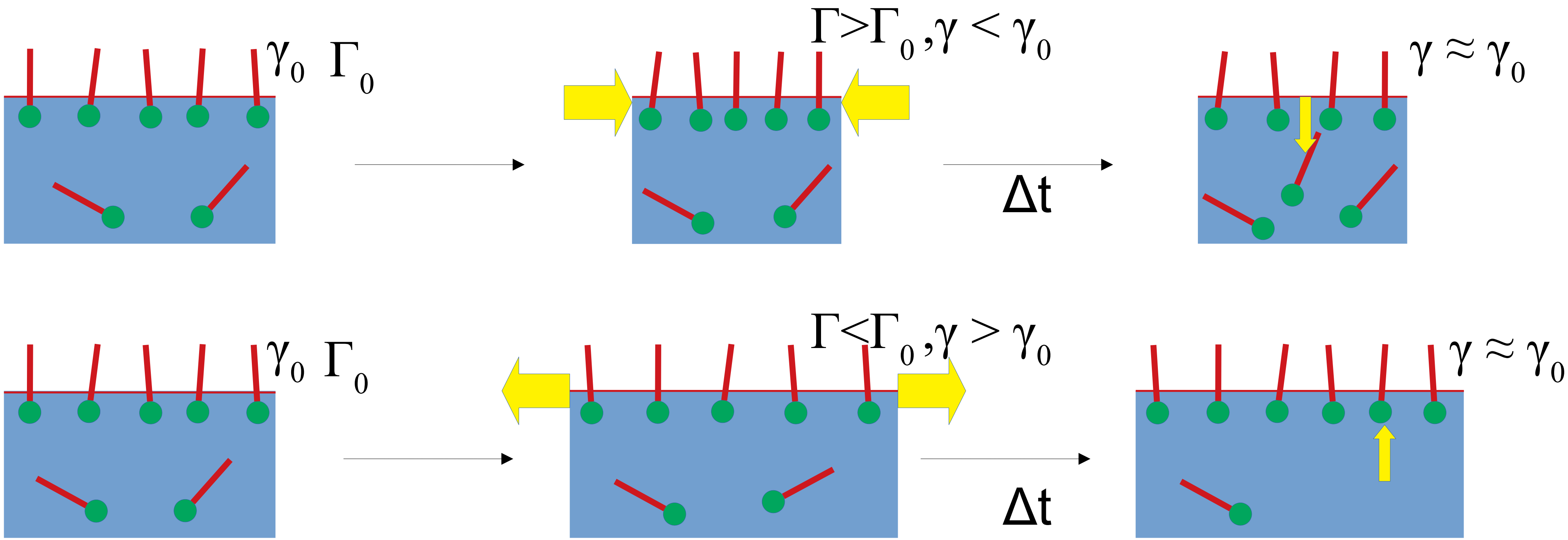
$$\frac{d\theta}{ds} = \frac{2}{R_0} - \frac{\Delta\rho g z}{\gamma} - \frac{\sin\theta}{x}$$







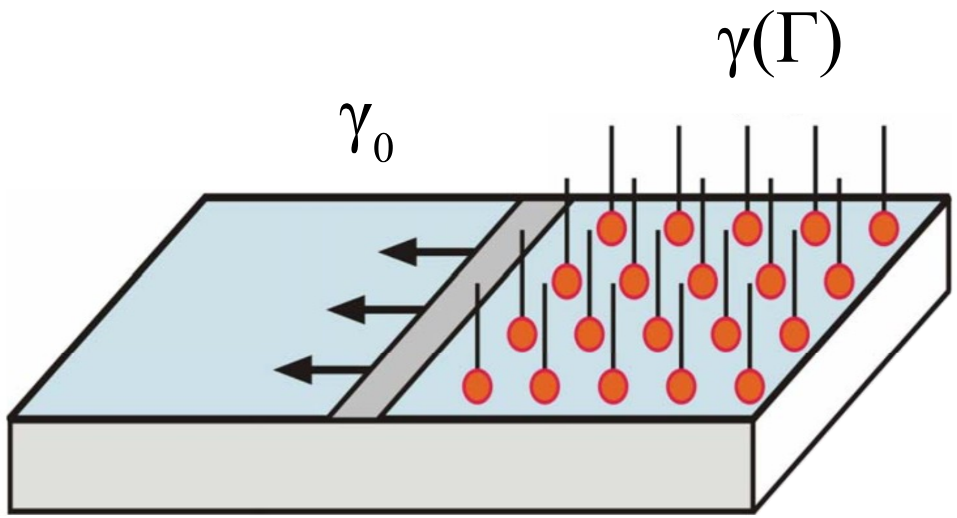
Dynamic adsorption / desorption

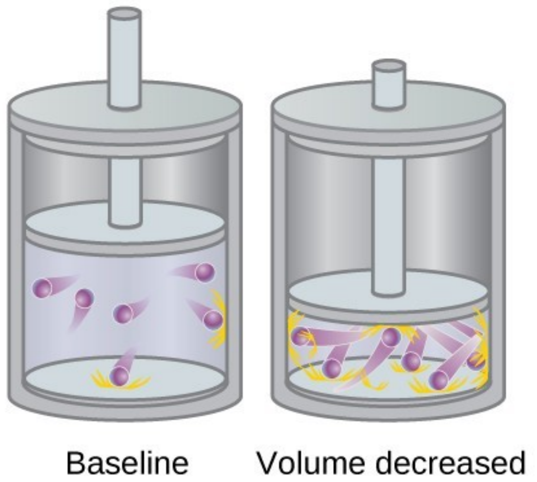


- Change of surface area leads to ad/desorption to maintain equlibrium
- Delay due to ad/desorption dynamics

Surface pressure

- Pool of water, adsorbed surfactants are shifted by mobile barrier
- Difference in surface tension exerts force on barrier
- Equivalent to gas pressure





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Suggested literature

- Lecture based on [Drenckhan & Saint-Jalmes 2015]

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Historical perspective

The science of foaming

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A R T I C L E I N F O

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Keywords:
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Liquid foam
Bubble generation
Gas/liquid interface
Foaming techniques
Bubble size distribution

A B S T R A C T

The generation of liquid foams is at the heart of numerous natural, technical or scientific processes. Even though the subject of foam generation has a long-standing history, many recent progresses have been made in an attempt to elucidate the fundamental processes at play. We review the subject by providing an overview of the relevant key mechanisms of bubble generation within a coherent hydrodynamic context; and we discuss different foaming techniques which exploit these mechanisms.

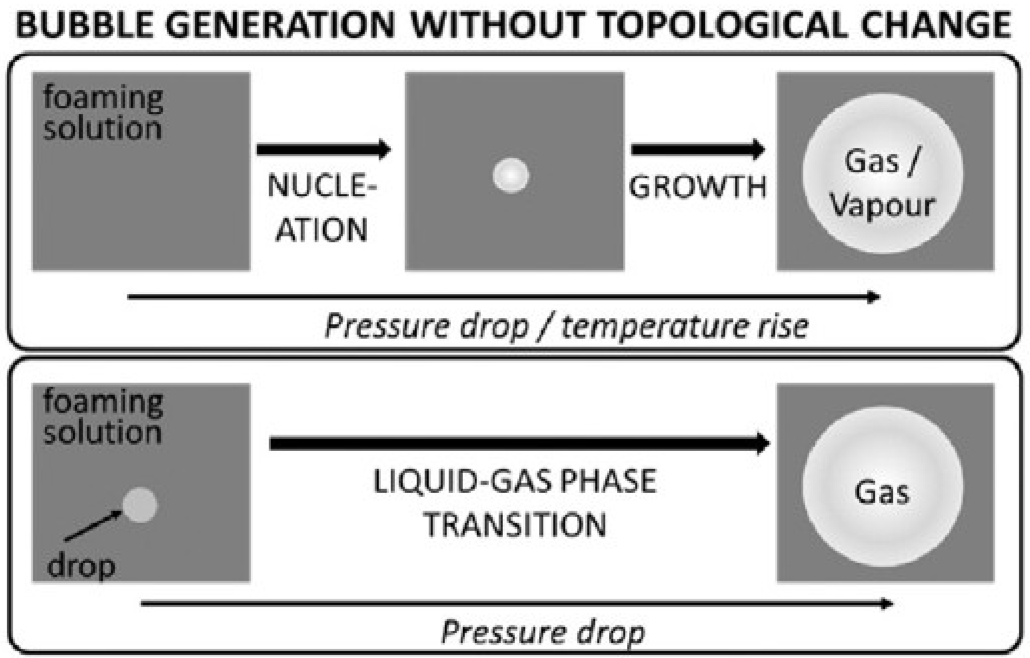
Types of bubble generation

- Physical, chemical, biological

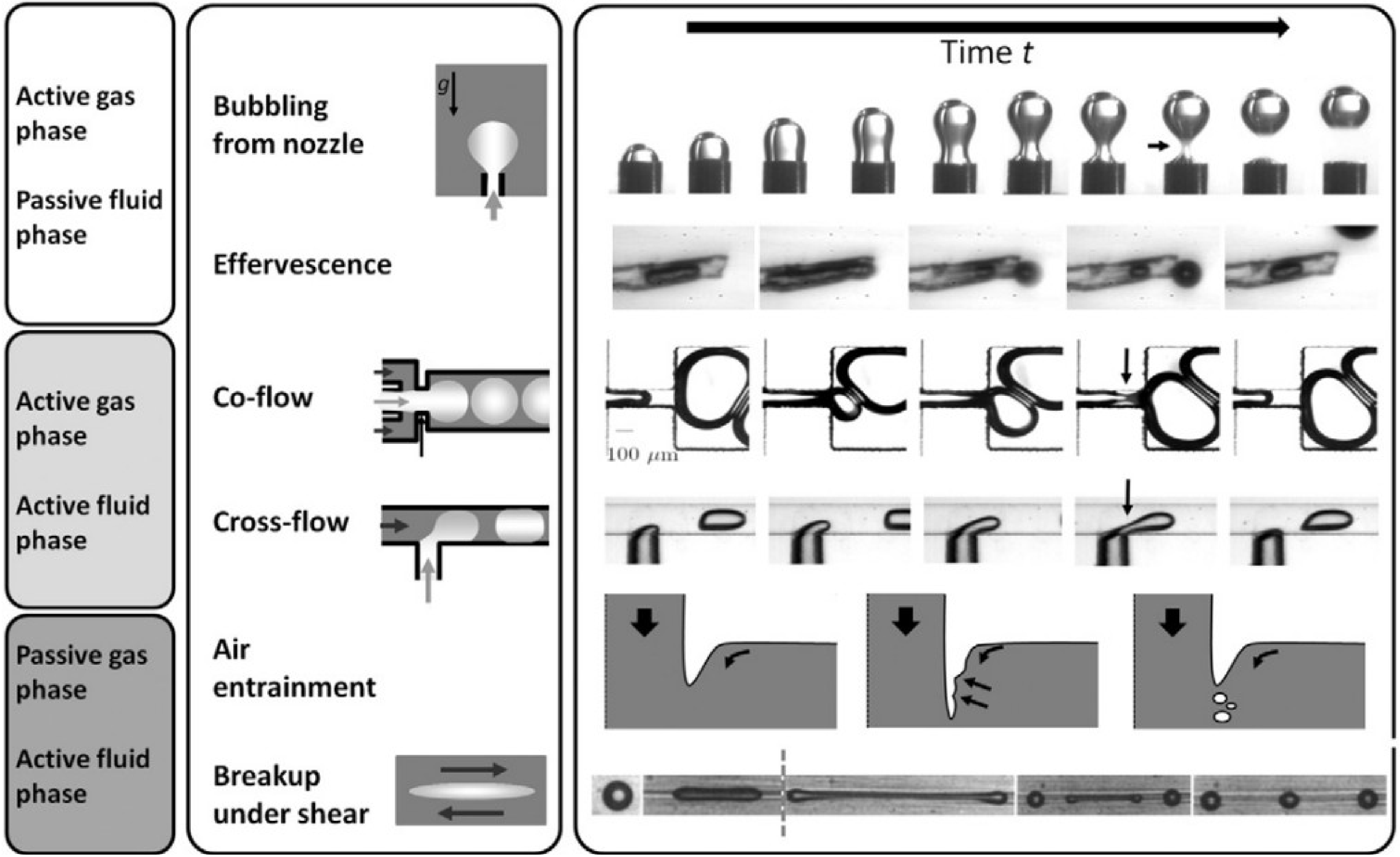
Global mechanism	Sub-mechanism	Examples
Physical foaming	Mechanical foaming	Bubbling, sparging, foam generation in porous media, wave breaking, shaking, rotor–stator mixers, kitchen blender, double syringe technique
	Phase transition	Champagne, beer, extrusion, cream dispenser, shaving foam
Chemical foaming	Chemical reaction	Fizzy drink tablets, baking powder, polyurethane foaming
	Electro-chemical reaction	Microflotation
Biological foaming	Yeast	Baking

Without topologigal change of interface

- Interface of a bubble is a closed sphere
- → remains a closed sphere during the bubble generation

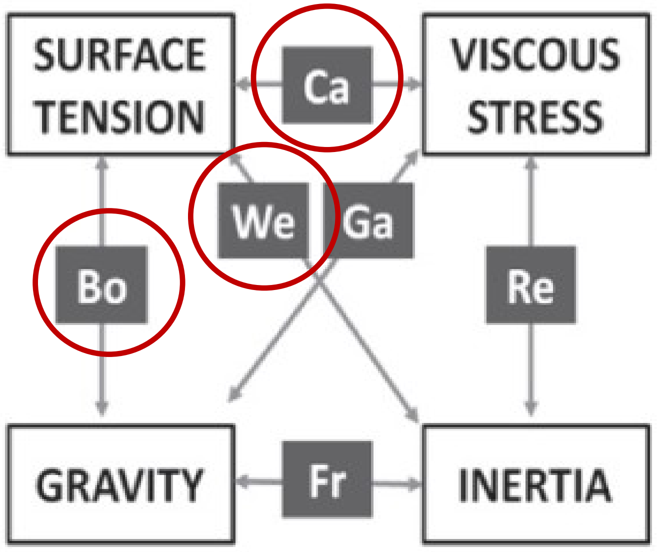


With topological change



Important dimensionless numbers

Name	Sym.	Definition	Ratio of stress
Bond number	Bo	$\frac{\Delta\rho\, g\, L^2}{\gamma}$	$\frac{Graviational\ stress}{Interfacial\ stress}$
Capillary number	Ca	$\frac{\eta U}{\gamma}$	$\frac{Viscous\ stress}{Interfacial\ stress}$
Reynolds number	Re	$\frac{\rho U L}{\eta}$	$\frac{Inertial\ stress}{Viscous\ stress}$
Froude number	Fr	$\frac{U}{\sqrt{gL}}$	$\frac{Inertial\ stress}{Graviational\ stress}$
Weber number	We	$\frac{\rho U^2 L}{\gamma}$	$\frac{Inertial\ stress}{Interfacial\ stress}$
Ohnesorg number	Oh	$\frac{\eta}{\sqrt{\rho\gamma L}}$	$\frac{Viscous\ stress}{\sqrt{Interfacial * inertial}}$
Galilei number	Ga	$\frac{g\rho^2 L^3}{\eta^2}$	Gravity vs viscosity



$$Ca = \frac{\eta U}{\gamma}$$

$$We = \frac{\rho U^2 L}{\gamma}$$

$$Bo = \frac{\Delta \rho g L^2}{\gamma}$$

Exercise: Energy input for bubble generation

- Surface energy has to be added
- How much (surface) energy is required to produce 1 liter of air bubbles with 0.5 mm diameter in pure water (γ=0.072N/m)

Exercise: Energy input for bubble generation

- Surface energy has to be added
- How much (surface) energy is required to produce 1 liter of air bubbles with 0.5 mm diameter in pure water (γ=0.072N/m)

$$n_b = \frac{V}{{}^4\!/_3\,\pi R^3} = 15.3 \ \times 10^6$$

$$E_b = \gamma A_b = \gamma\ 4\pi R^2 = 5.5 \times 10^{-8} Nm$$

$$E = n_b\, E_b = 0{,}84\, J$$

- Mechanical work for lifting 0.84 kg to 10 cm height
- No spontaneous bubble formation

Structure

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- Nozzle
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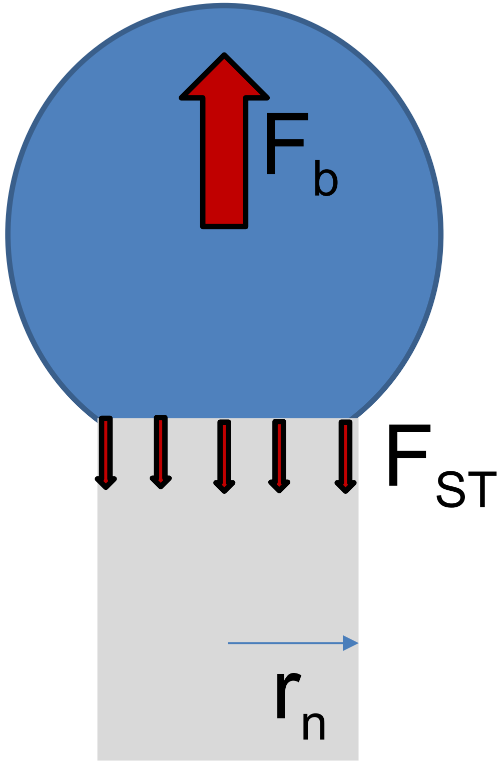
Slow blowing from a nozzle

- Quasi-static bubble shape → viscous and inertia forces can be neglected

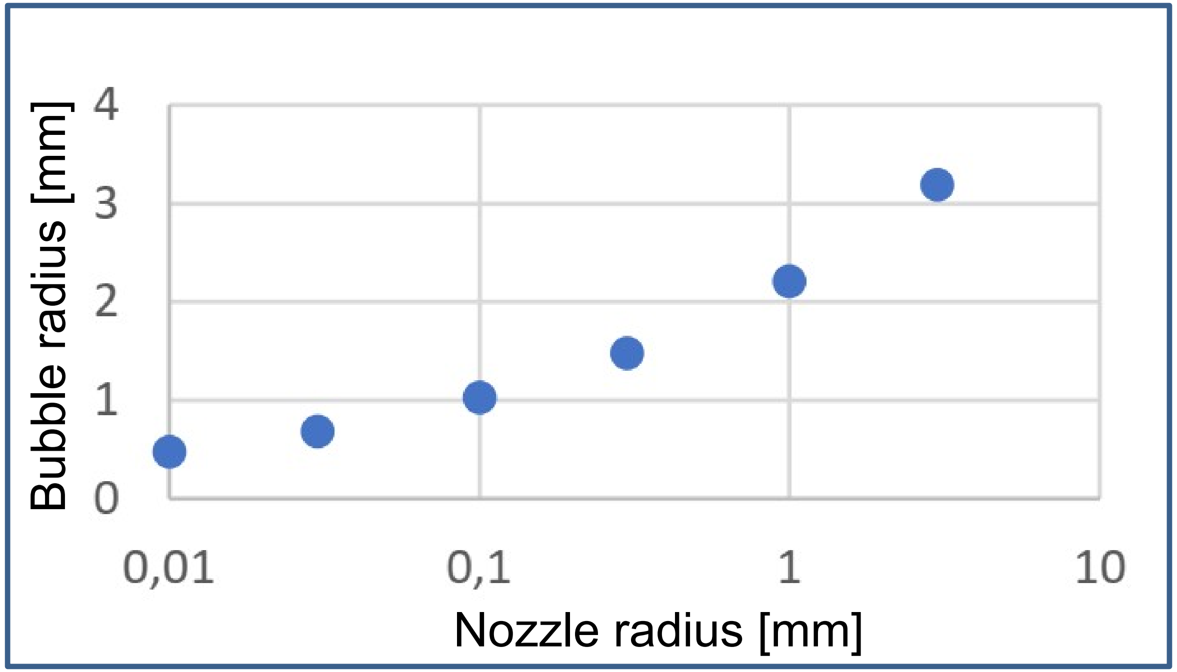


$$F_b = F_{ST}$$

$$\frac{4}{3}\pi R_b^{\,3}\,\Delta\rho\,g = 2\pi r_n \gamma$$

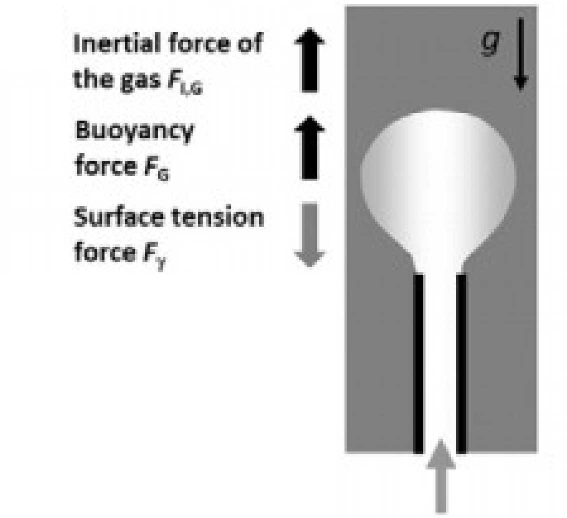
$$R_b = \sqrt[3]{\frac{2\pi r_n \gamma}{\frac{4}{3}\pi\,\Delta\rho\,g}}$$

$$\left(\frac{R_b}{r_n}\right)^3 = \frac{3}{2}\left(\frac{1}{r_n}\right)^2 \frac{\gamma}{\Delta\rho\,g} = \frac{3}{2}\frac{1}{Bo}$$

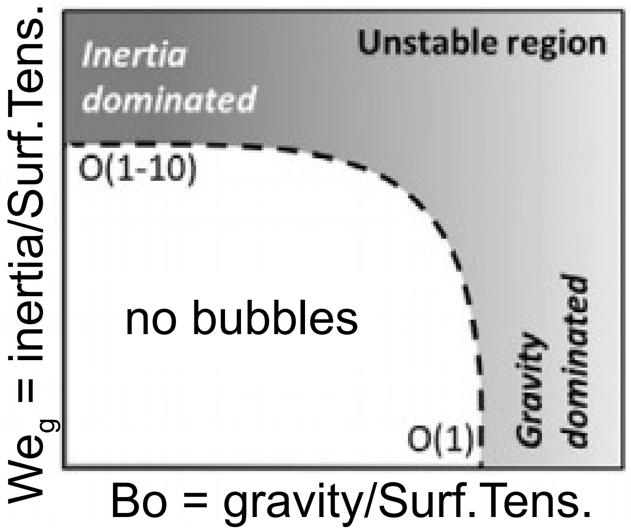


Blowing from a nozzle

- Buoyancy or inertia force to overcome surface tension



$$We = \frac{\rho\, U^2\, L}{\gamma}$$



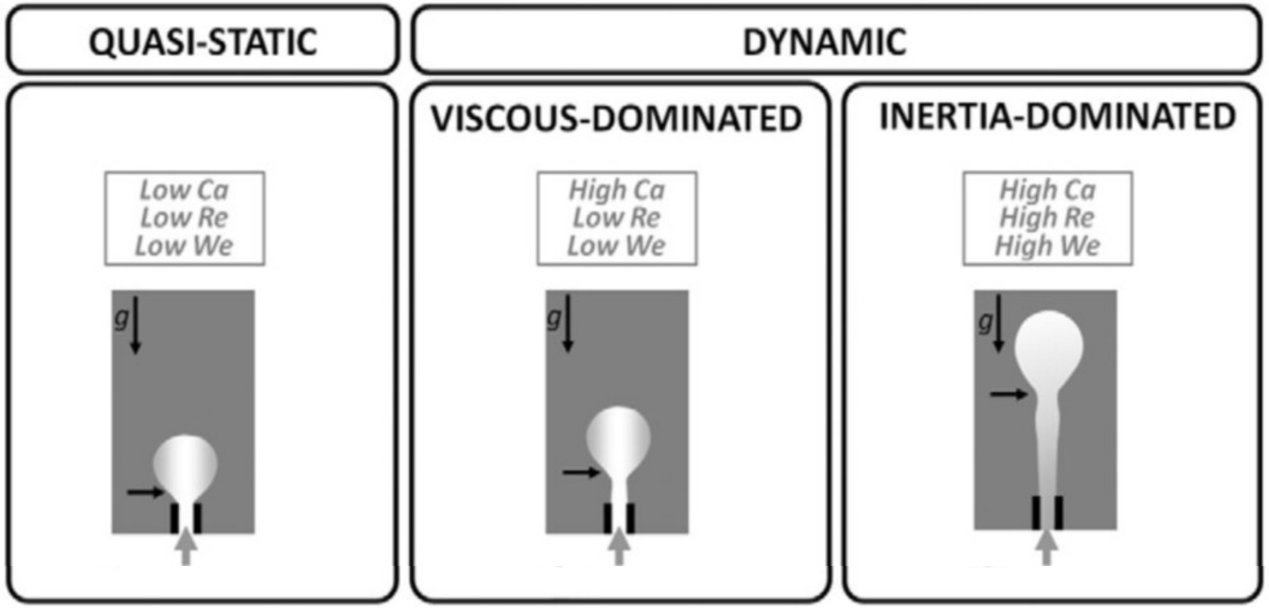
$$Bo = \frac{\Delta\rho\, g\, L^2}{\gamma}$$

Blowing from a nozzle

- Quasi-static: Buoyancy = surface tension
- Slow: Buoyancy = surface tension + viscous drag
- Fast: Buoyancy = surface tension + viscous drag +/- inertia

→ Bubbles become larger

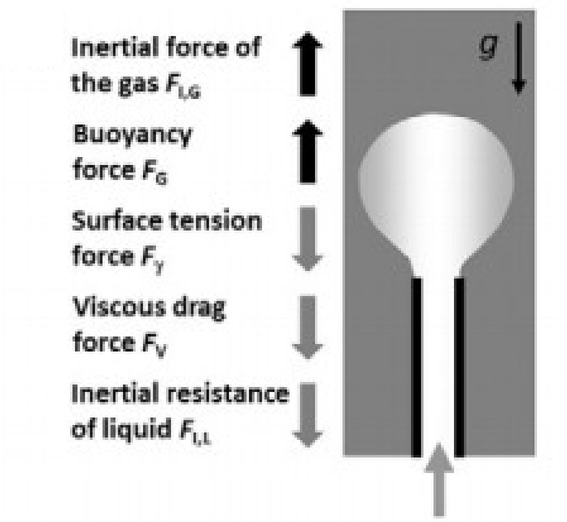
Bubbling from nozzle

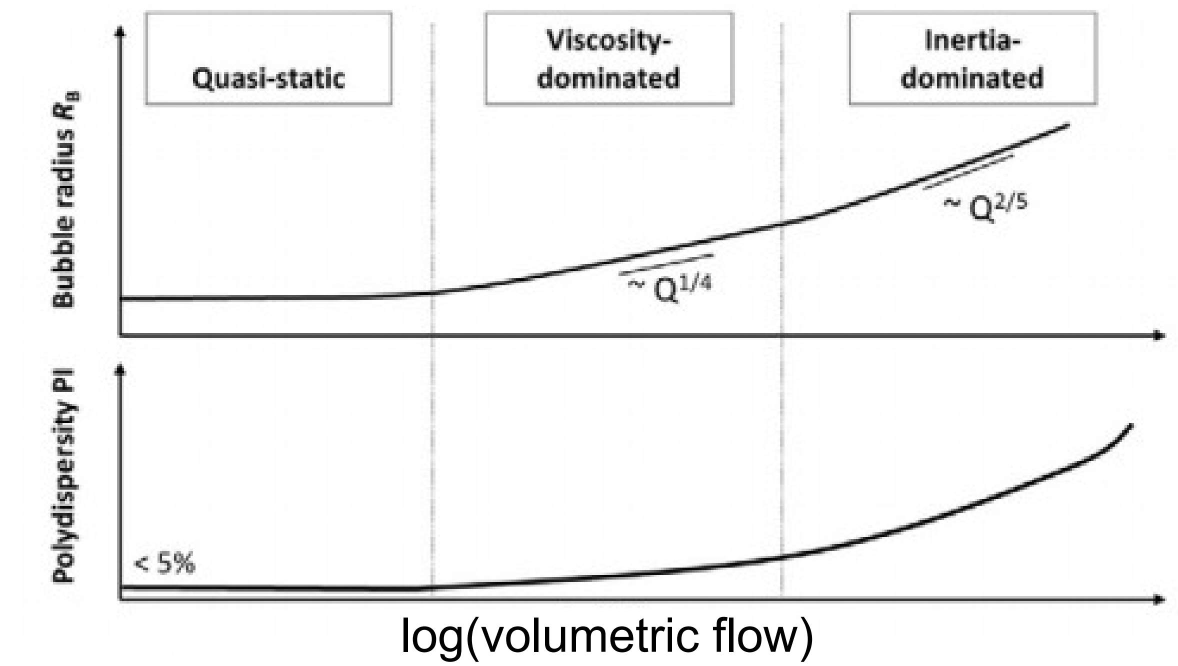


Blowing from a nozzle

- Very complex interaction of different effects, vast amount of literature
- Often used [Jamialahmadi et al. 2001]:

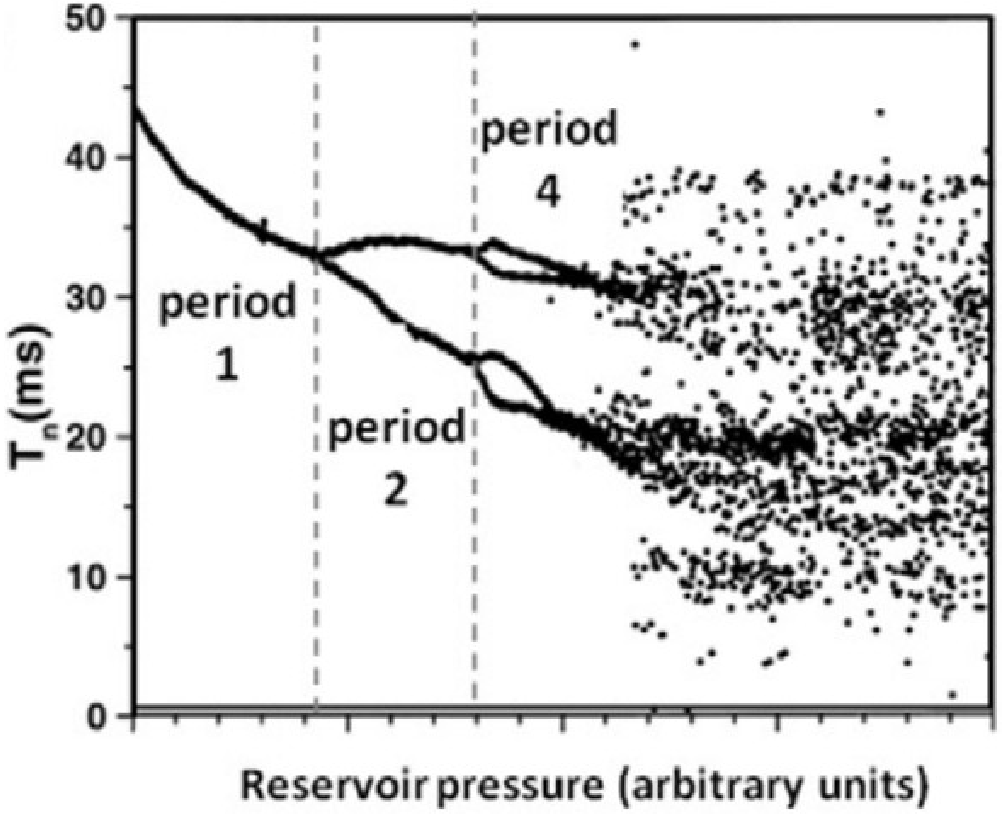
$$R_B = R_O \left[\frac{5.0}{Bo^{1.08}} + \frac{9.261\,Fr_G^{\;0.36}}{Ga_G^{\;0.39}} + 2.14 Fr_G^{\;0.51} \right]^{1/3}$$

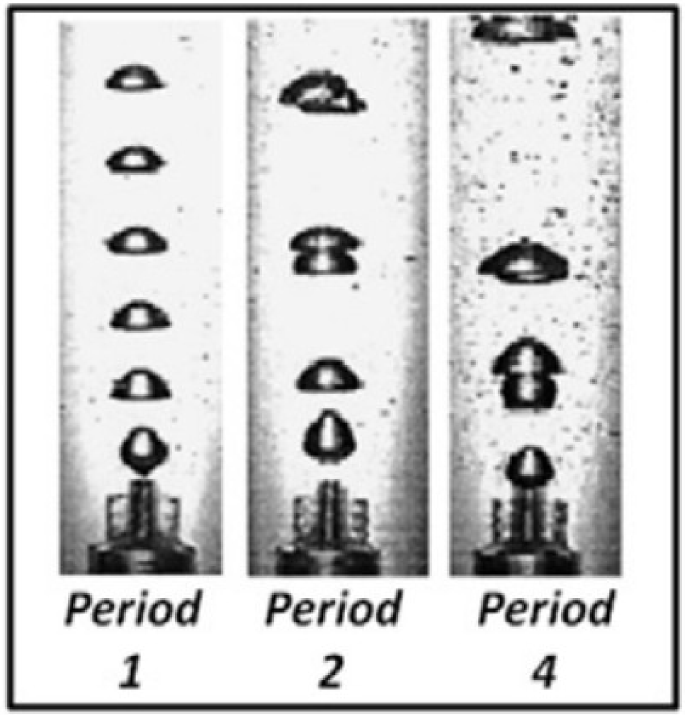




Non-periodic bubble generation

- Interaction of consecutive bubbles
- Interaction through the liquid
- Can lead to bi-disperse or polydisperse size distributions





[Tufaile, Physica A, 2000]

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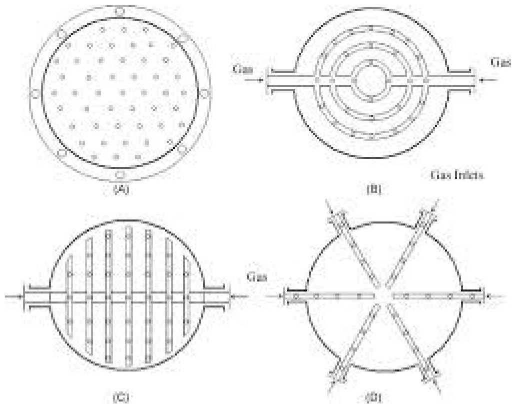
Sparger designs

- Orificed tubes/plates

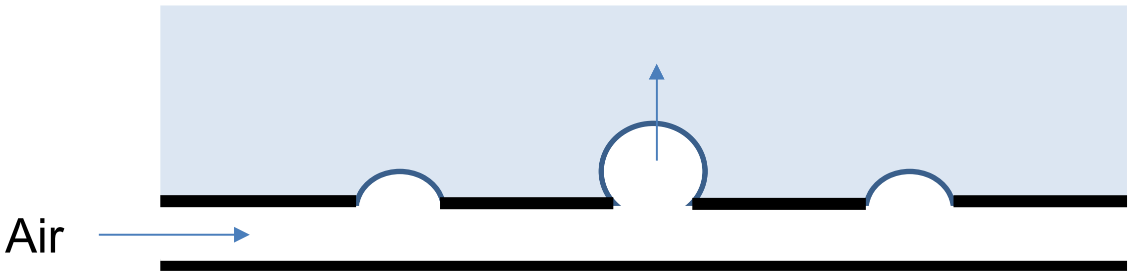


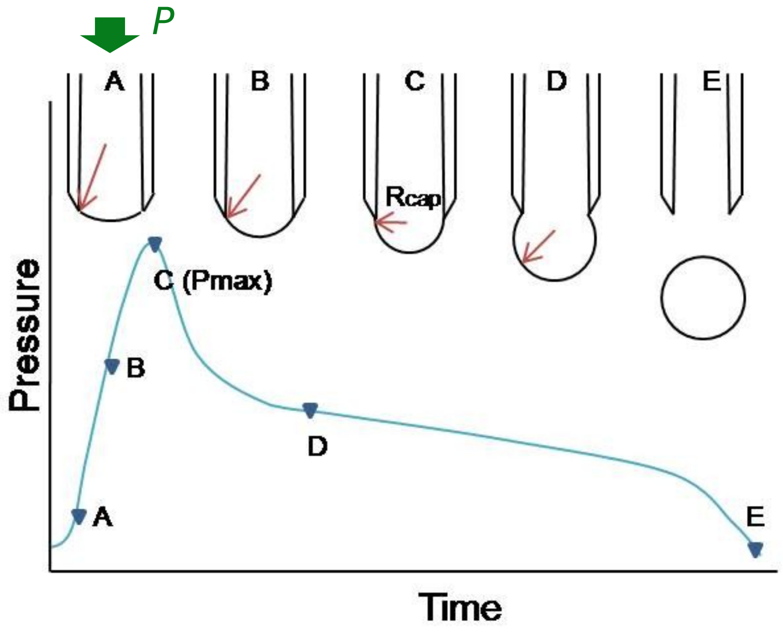
(a) Spider sparger (view from top)

- Sintered blocks

Multiple holes

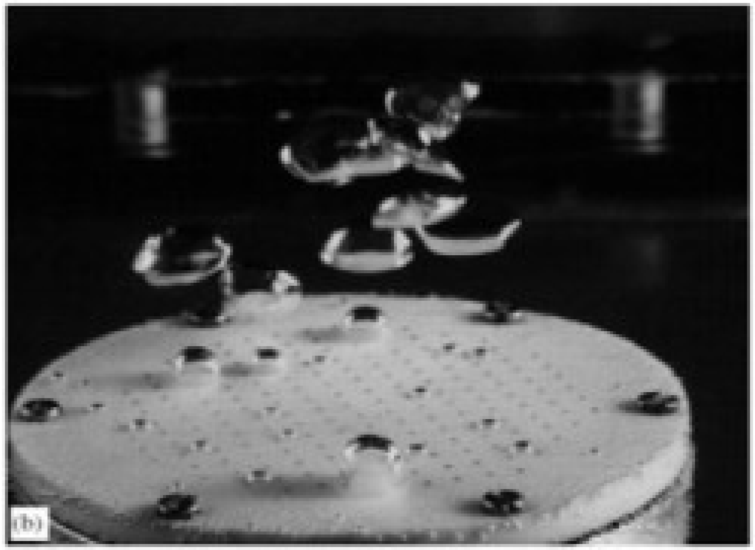
- Interaction through the reservoire – only some holes are active



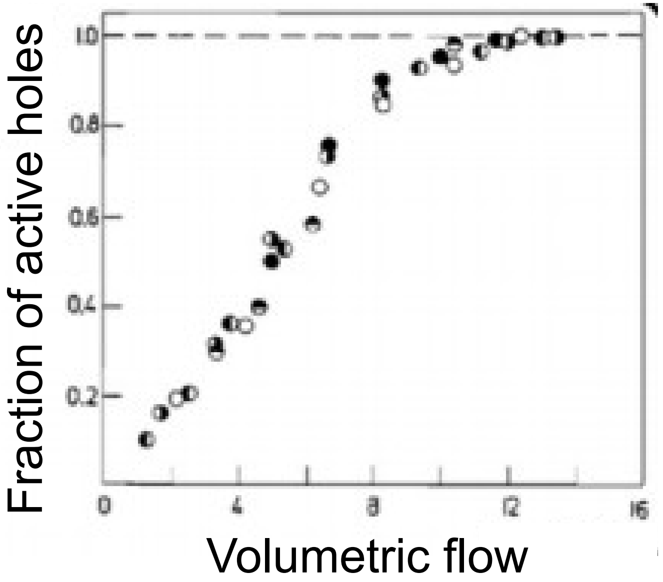


Orificed plate

- Interaction through the reservoire – only some holes are active
- Increasing flow rate → increasing pressure loss
- Increasing flow rate → more holes are active → reduced pressure loss
- $\Delta p > {}^{2\gamma}/_{r_{hole}}$ → all holes are active



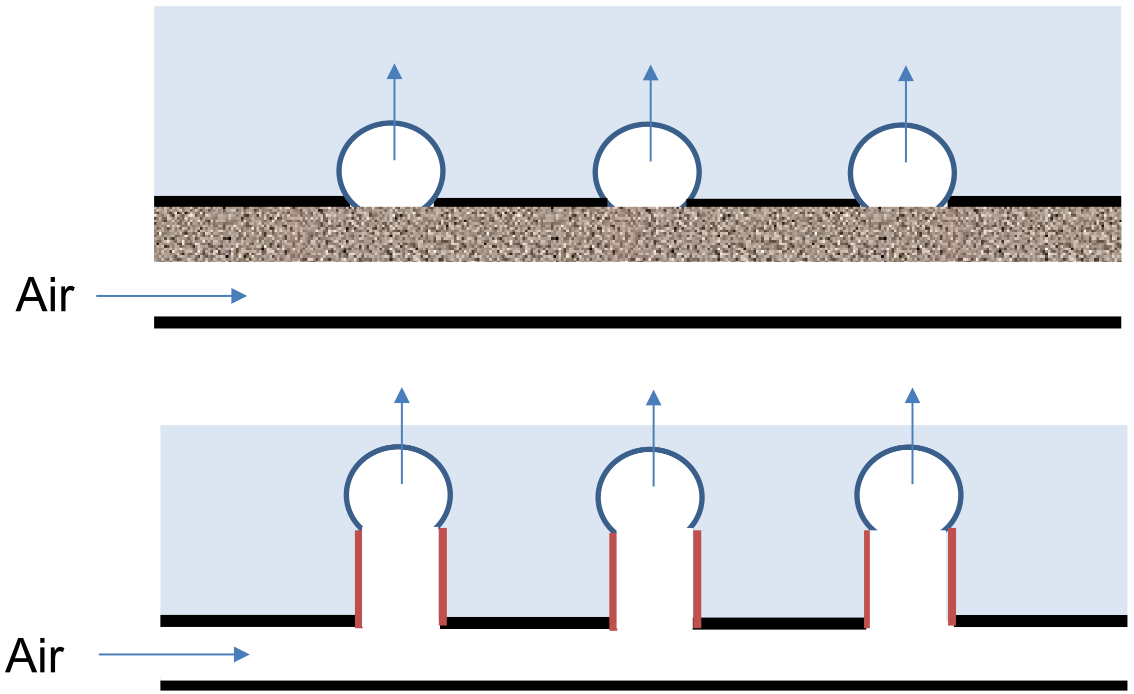
[Zahradnik et al. 1979]



[Loimer et al. 2004]

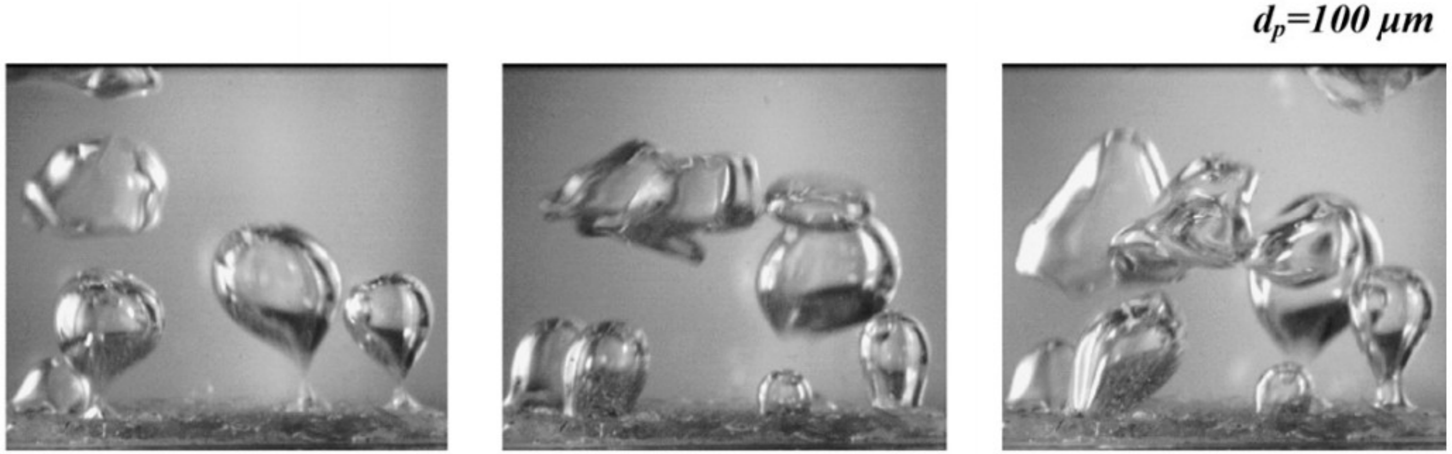
Orificed plate

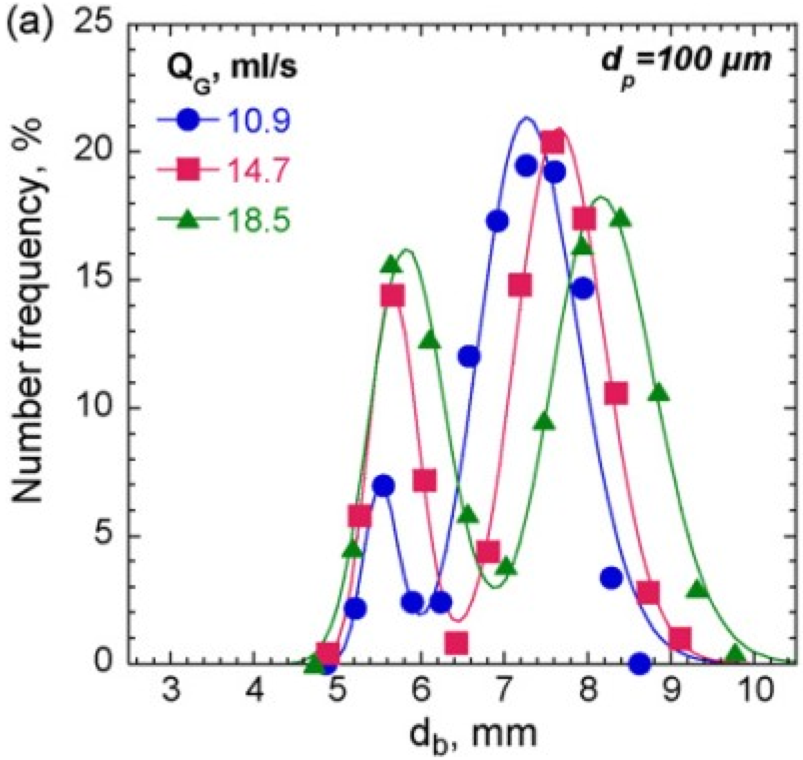
- Orificed plate at low volumetric flow produces equal bubble size → preferred
- → Additional flow resistance in reservoir/hole
- $\Delta p > {}^{2\gamma}/_{r_{hole}}$ → all holes are active



Sintered spargers

- Commercially available (filters), cheap
- Higher polydispersity than orificed plates
- Polydispersity grows with flow rate (smaller holes become active)





[Kazakis et al. 2007]

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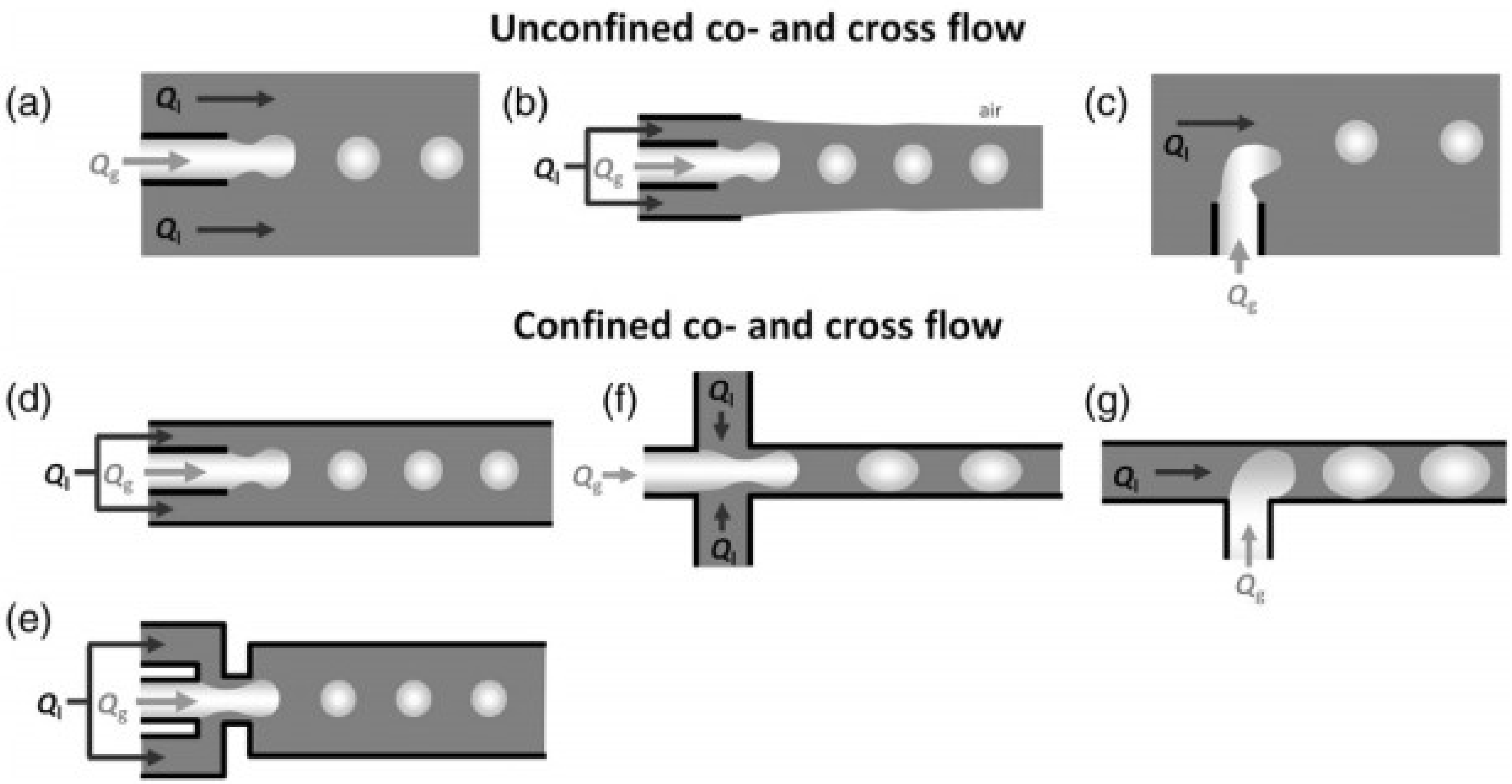
Milli/microfluidic bubble generation

- Co-flow of air and fluid, stable flow rate required
- Periodic behaviour, very monodisperse bubble size



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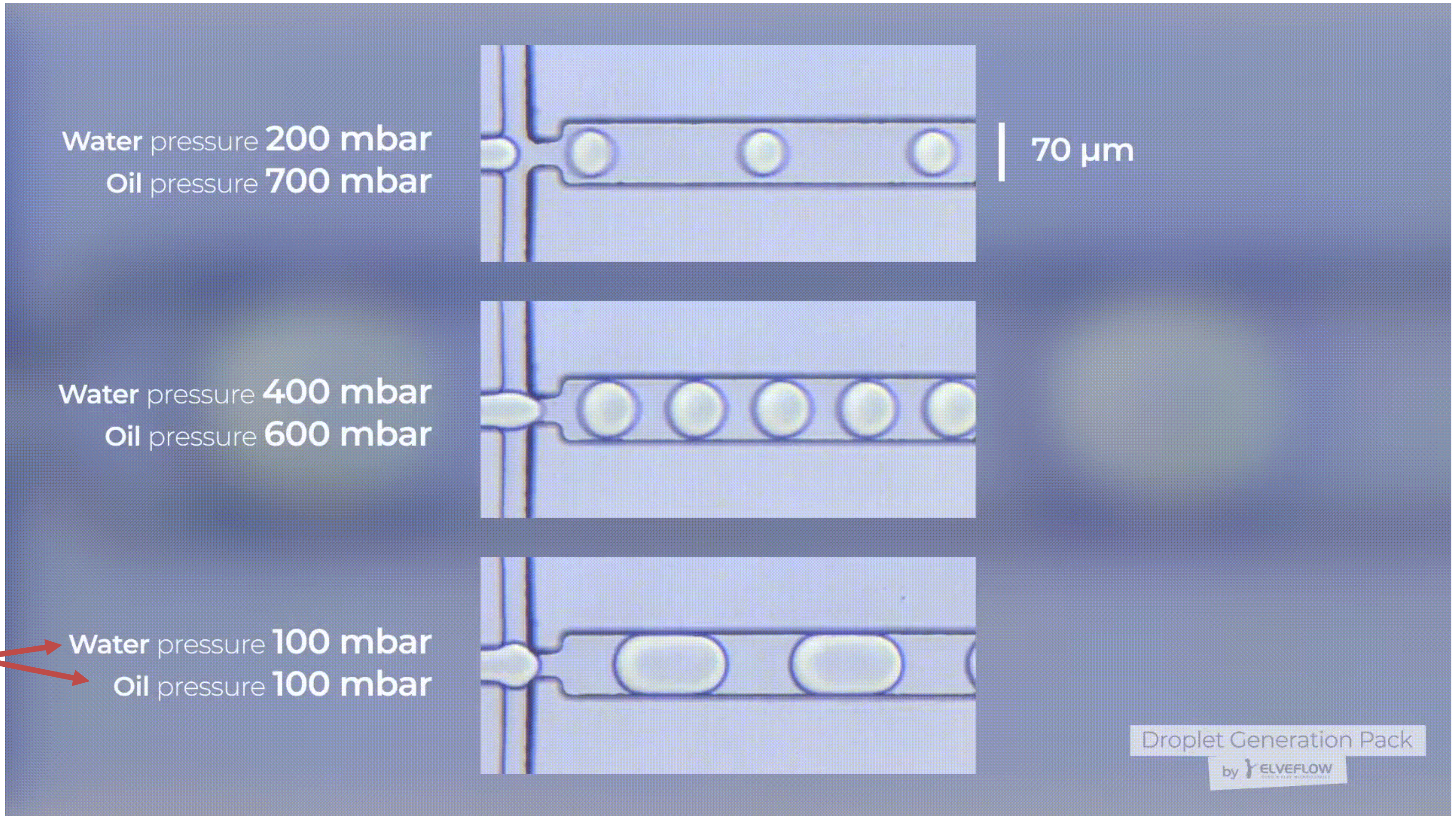


1000 mbar!

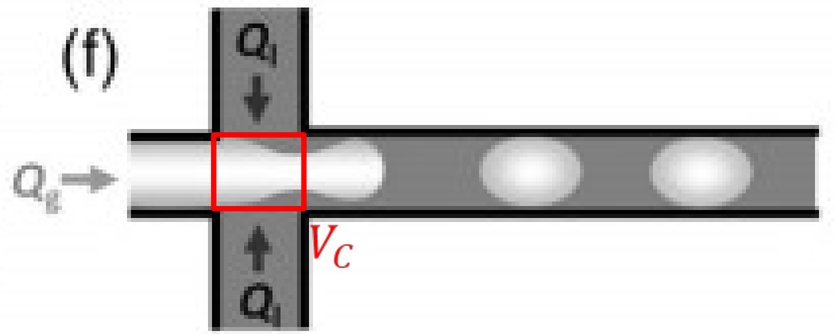
Milli/microfluidic bubble generation

- Quasistatic regime (in confined flow): bubbles blocks channel, squeezed by liquid

  → Bubble size controlled by ratio of flow rates: $V_b \sim V_C \frac{Q_g}{Q_l}$

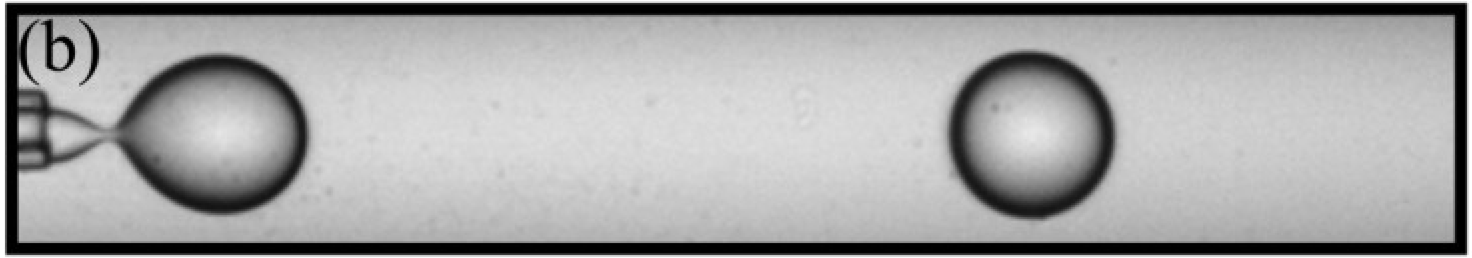
  → Bubble diameter ~ 10...1000 μm, Polydispersity < 2%

$$\dot{n}_b = \frac{Q_g}{V_b} \sim \frac{Q_l}{V_C}$$



- Dynamic regime: viscous forces balance surface tension forces $R_b \sim \frac{\gamma}{\eta_l U} R_0$

  → Bubble sizes controlled by capillary diameter R_0



[Utada et al. 2007]

Milli/microfluidic bubble generation

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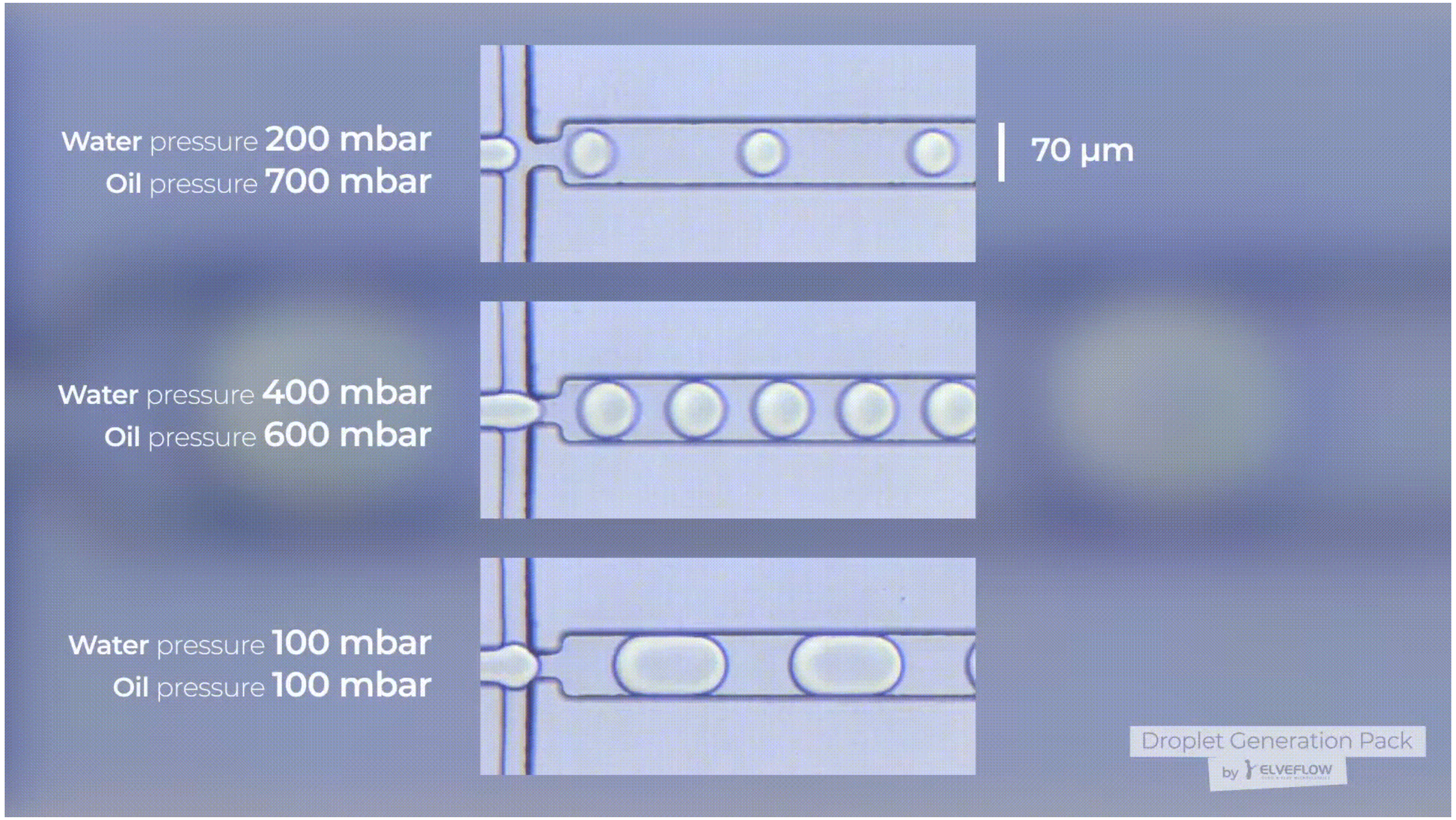
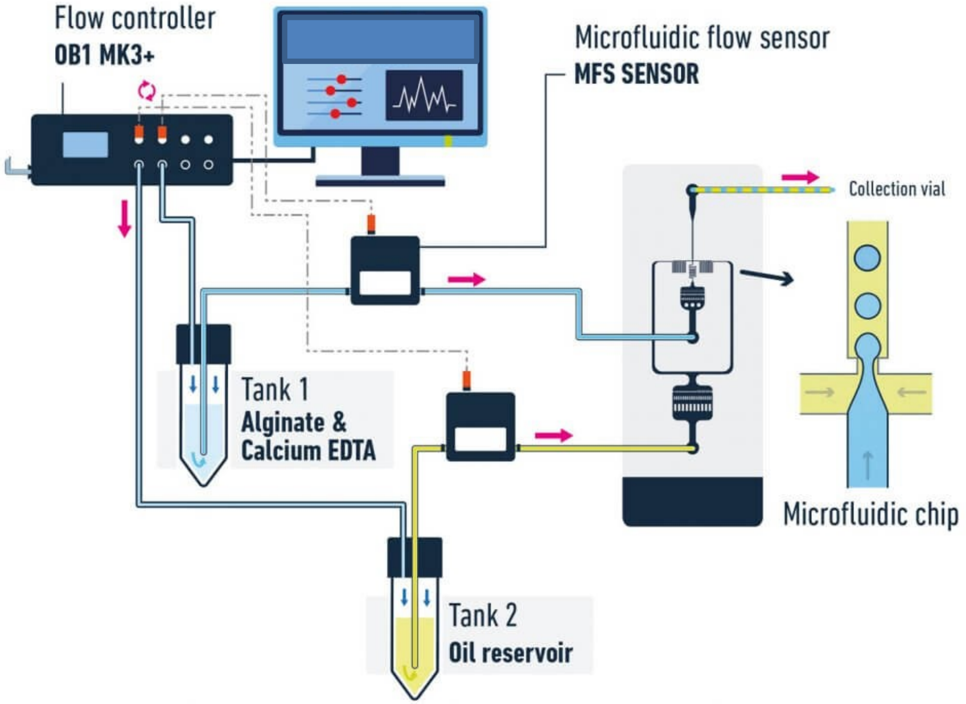
- Periodic behaviour, very monodisperse bubble size

1000 mbar!



Milli/microfluidic bubble generation

- Stable flow generated by syringe pumps or pressure controller



- Cheap, ~2.000 € (vs. 10.000 €)
- No pressurized air required

- More precise to control
- Easy refill
- No offset time

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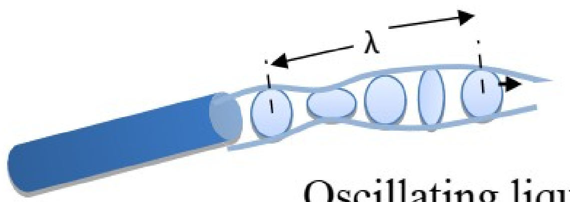
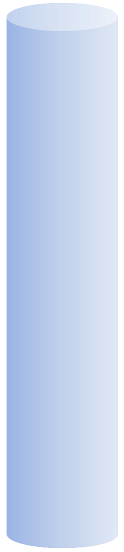
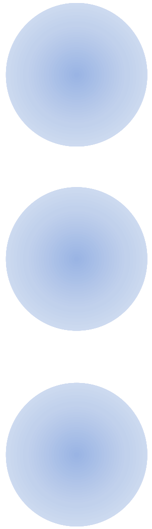
- Bubble size measurement

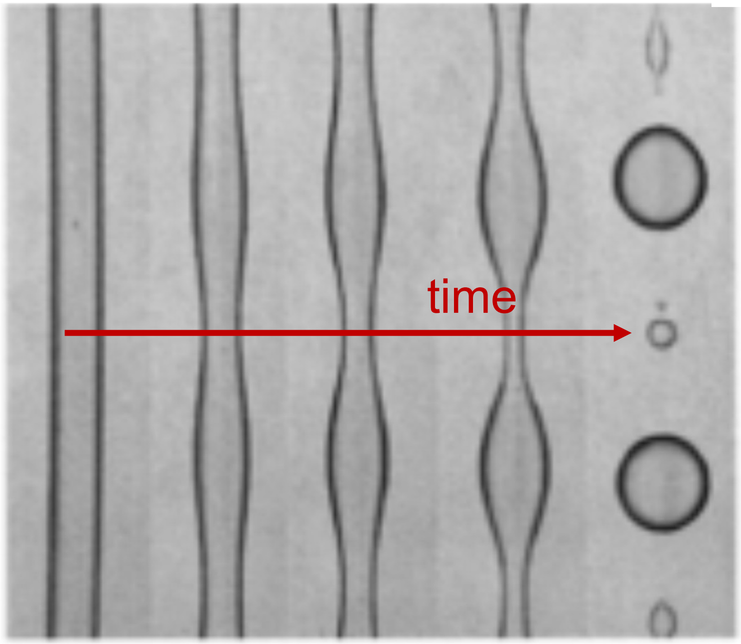
Rayleigh-Plateau instability

- Describes breaking of gas ligaments, relevant for jetting regimes









$$E_{Cylinder} > E_{Spheres}$$

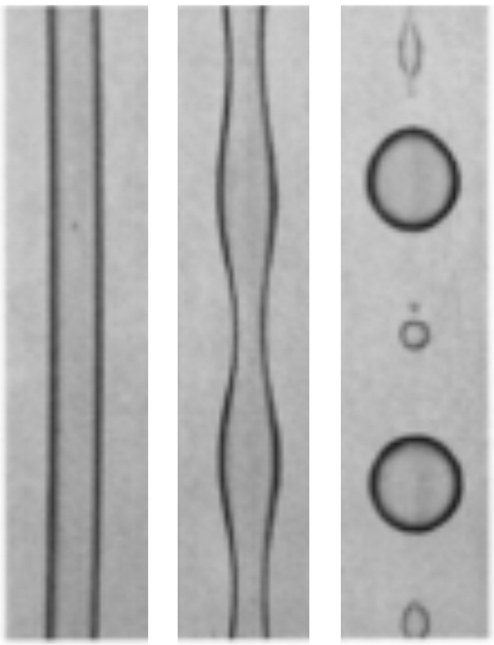
Rayleigh-Plateau instability

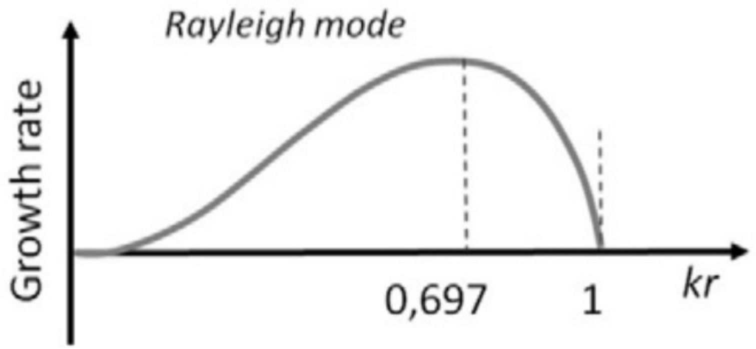
- Short waves (λ<2πr) are not unstable (Mean curvature < 0)
- Long waves (k→0) grow very slowly
- Fastest growing mode:

$$k\,r = \frac{2\pi}{\lambda_{max}}\,r = 0.697$$

$$\rightarrow \lambda_{max} = 9.02\,r$$

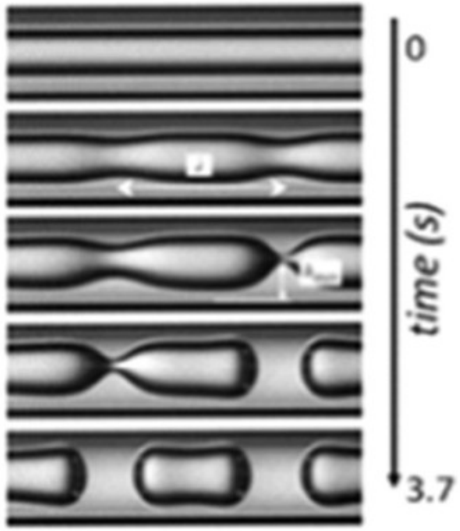
$$\rightarrow R_b \approx 2\,r$$

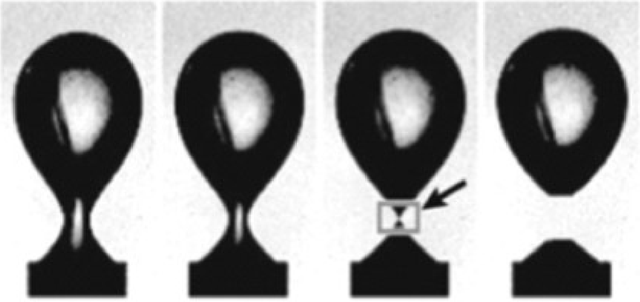




Rayleigh-Plateau instability

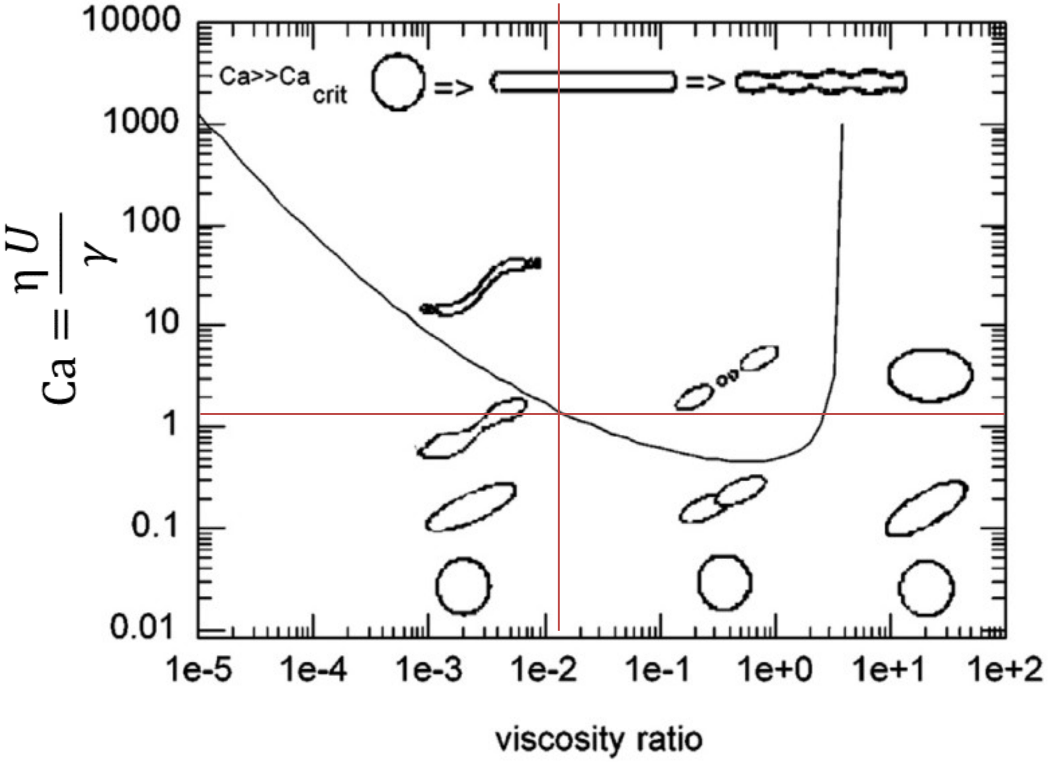
- Gas-filled capillary
- Bubble pinch-off
- Bubble in shear flow





N_2 in glycerine/water mixture

Air in water

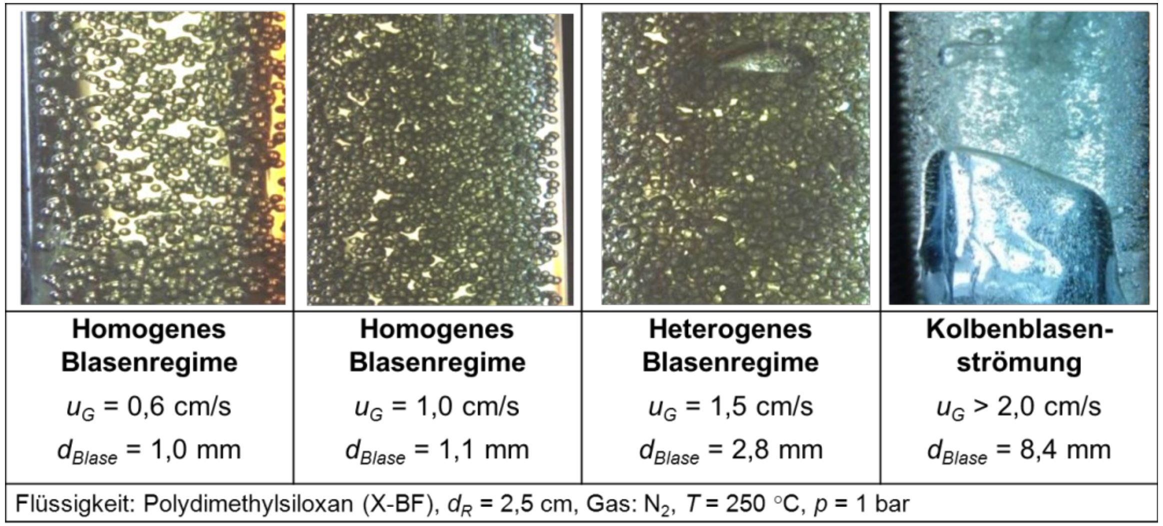


Structure

- Review lecture 2
- Bubble generation
- Nozzle
- Sparger
- Microfluidic
- Rayleigh-Plateau instability
- Bubble size measurement

Why do we measure bubble size?

- Chemical reactors
  - Available surface area per volume
  - Gas hold-up
- Froth flotation
  - Large bubbles to carry large particles
  - Small bubbles to collide with small particles
- Foam and Froth
  - Influence on drainage, permeability
  - Influence on rheological properties
  - Influence on foam stability



- Bubble size is key ingredient for many experiments / industrial applications

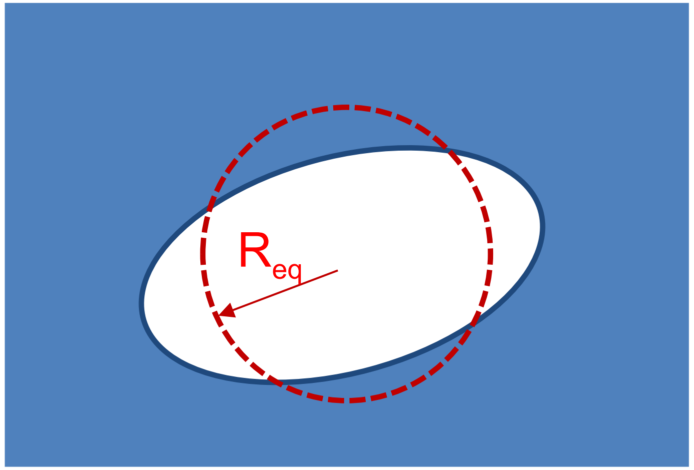
Equivalent diameter

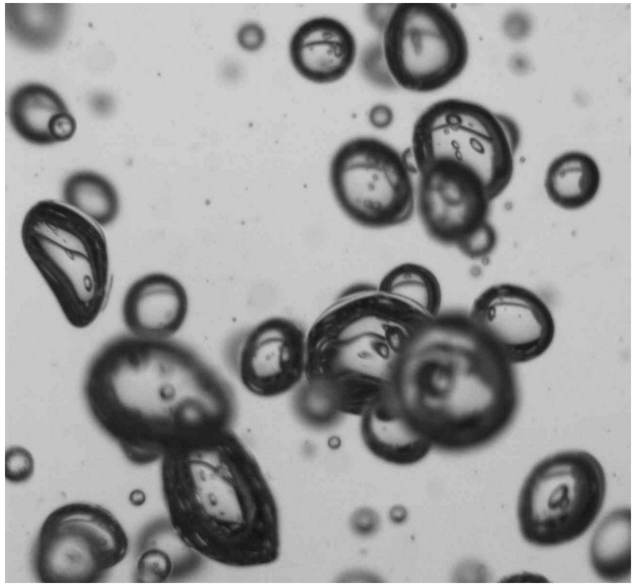
- Bubbles often have no constant shape
- ⇒ steady description by bubble volume

$$\frac{4}{3}\pi R_{eq}^{3} = V_{eq} = const$$

- For spherical bubbles:

$$R_{eq} = R$$



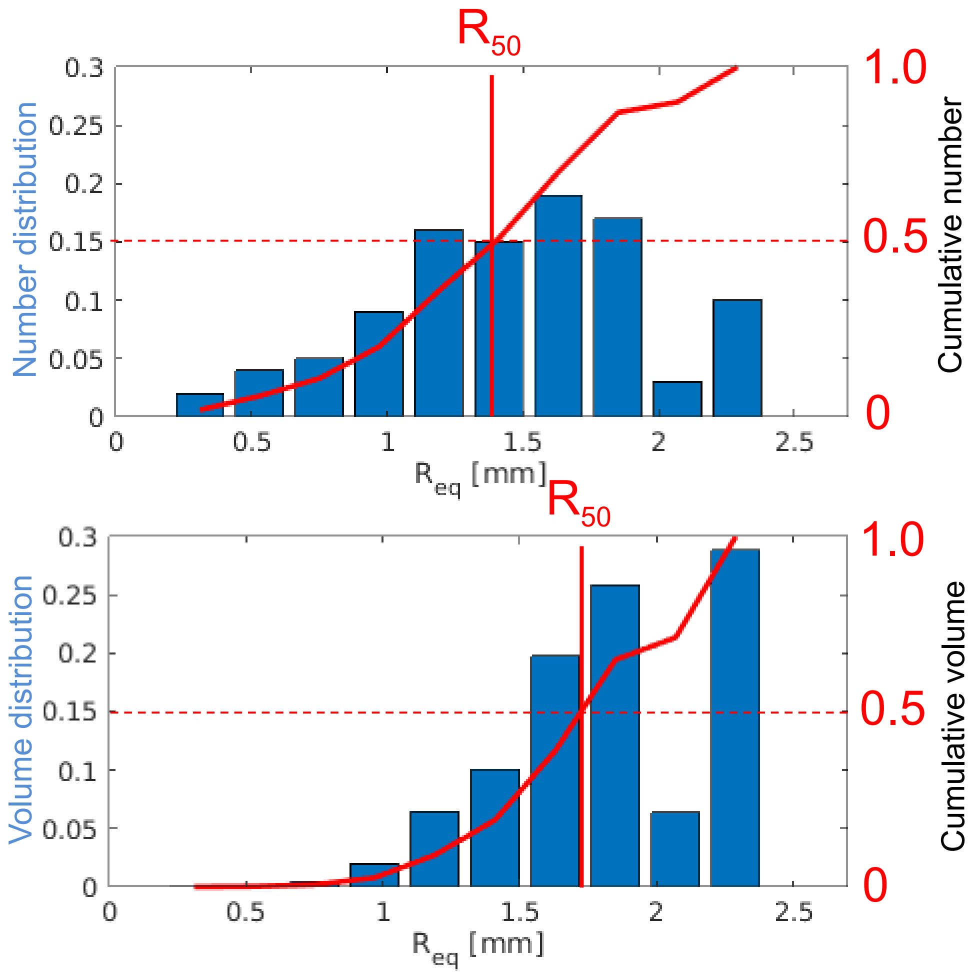


Bubble size distribution

- Probability density function (PDF):
- „Amount" H of bubbles vs. bubble size R_{eq}
- „Amount" can refer to number or volume

- Cummulative distribution function

$$H_{int}(R_{eq}) = \frac{\int_0^{R_{eq}} H(r)dr}{\int_0^{\infty} H(r)dr}$$



Exercise: Area per gas Volume

- Mono-disperse bubble distribution:
  - 10 bubbles with R_{eq}=5.5mm
- Bi-disperse bubble distribution:
  - 10 bubbles with R_{eq}=1mm
  - 10 bubbles with R_{eq}=10mm

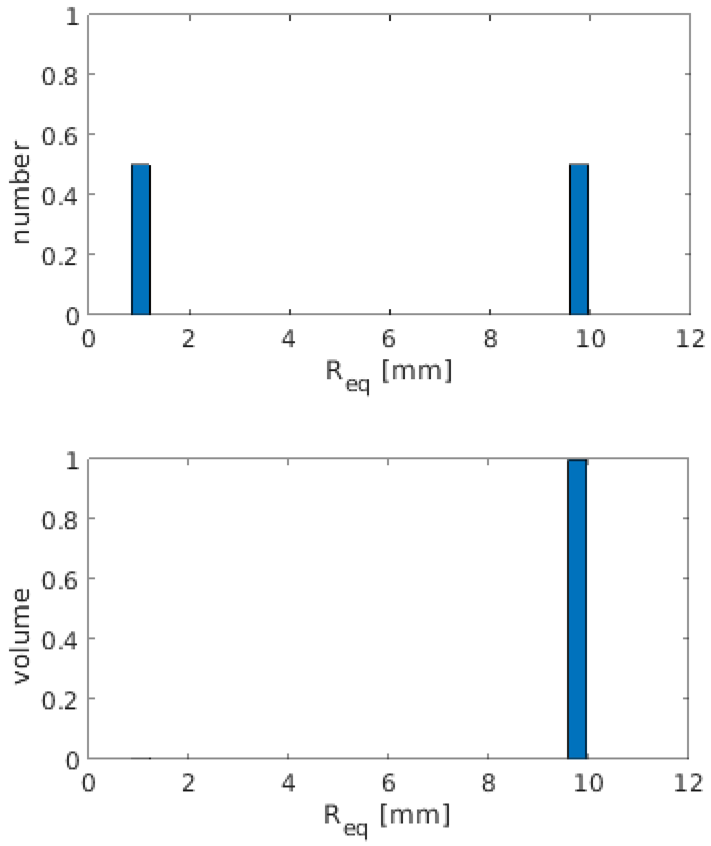
→ What is the average bubble radius? (arithmetic mean)

→ What is the average bubble volume? (arithmetic mean)

→ What is the volume per area ratio for the mono- and bidisperse distribution, respectively?

- total Volume / total Area !!

$$A = 4\pi R^2 \qquad V = \frac{4}{3}\pi R^3$$



Exercise: Area per gas volume

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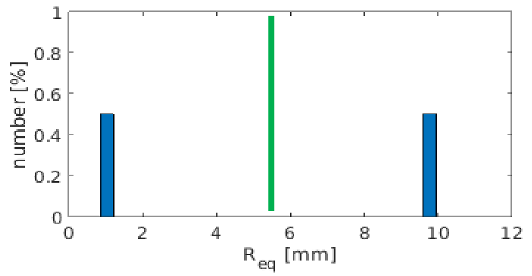
  - 10 bubbles with R_{eq}=5.5mm

- Bi-disperse bubble distribution:
  - 10 bubbles with R_{eq}=1mm
  - 10 bubbles with R_{eq}=10mm



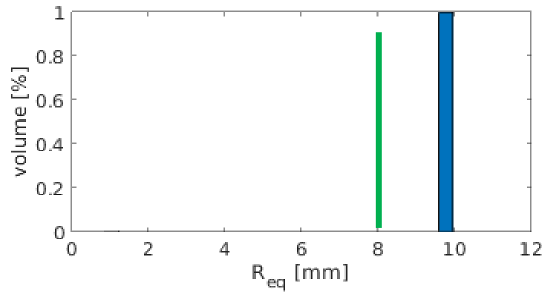
$$\langle R \rangle = 5.5\,mm$$

$$\langle R \rangle = \frac{(10mm + 1mm)}{2} = 5.5\,mm$$

$$\langle V \rangle = \frac{4}{3}\pi\,\langle R^3 \rangle = 697\,mm^3$$

$$\langle V \rangle = \frac{4}{3}\pi\,\langle R^3 \rangle = \frac{4}{3}\pi\frac{(1000mm^3 + 1mm^3)}{2}$$

$$\langle V \rangle = 2096\,mm^3 = \frac{4}{3}\pi\,(7.94mm)^3 \neq \frac{4}{3}\pi\,\langle R \rangle^3$$



$$\frac{\langle A \rangle}{\langle V \rangle} = \frac{\langle 4\pi\,R^2 \rangle}{\left\langle \frac{4}{3}\pi\,R^3 \right\rangle} = 0.545\frac{1}{mm} = \frac{3}{\langle R \rangle}$$

$$\frac{\langle A \rangle}{\langle V \rangle} = \frac{\langle 4\pi\,R^2 \rangle}{\left\langle \frac{4}{3}\pi\,R^3 \right\rangle} = \frac{4\pi(100mm^2+1mm^2)}{\frac{4}{3}\pi(1000mm^3+1mm^3)} = 0.303\frac{1}{mm} = \frac{3}{9.91\,mm} \neq \frac{3}{\langle R \rangle}$$

Exercise: Area per gas Volume

- Mono-disperse bubble distribution:
    - 10 bubbles with R_{eq}=5.5mm
- Bi-disperse bubble distribution:
    - 10 bubbles with R_{eq}=1mm
    - 10 bubbles with R_{eq}=10mm

→ What is the average bubble radius? (arithmetic mean)

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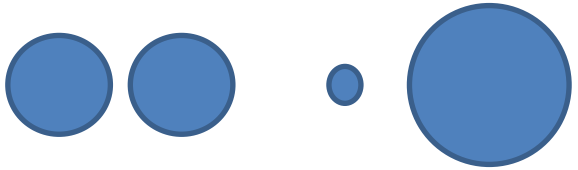
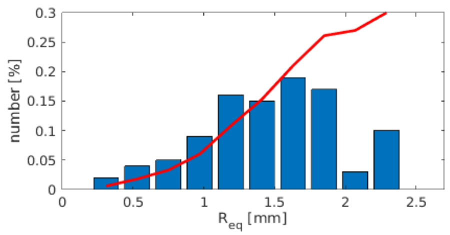
$$A = 4\pi R^2 \qquad V = \frac{4}{3}\pi R^3$$



	5.5 mm	1mm + 10mm
Mean R	5.5 mm	5.5 mm
Mean V	697 mm^3	2097 mm^3
V/A	1.83 mm =R/3	3.304 mm ≈10mm/3

Measures of average bubble size



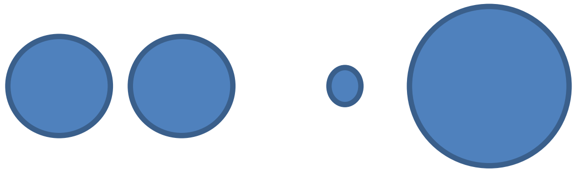
- Arithmetic mean diameter ($R_{1,0}$):

$$R_{1,0} = \frac{\int_0^\infty r^1 H(r)dr}{\int_0^\infty r^0 H(r)dr} = \frac{\sum_{i=1}^N {r_i}^1}{\sum_{i=1}^N {r_i}^0} = \frac{\sum_{i=1}^N {r_i}^1}{N}$$

- Sauter mean diameter ($R_{3,2}$):

$$R_{3,2} = \frac{\int_0^\infty r^3 H(r)dr}{\int_0^\infty r^2 H(r)dr} = \frac{\sum_{i=1}^N {r_i}^3}{\sum_{i=1}^N {r_i}^2} = \frac{\sum_{i=1}^N V_i}{\sum_{i=1}^N A_i \frac{1}{3}}$$

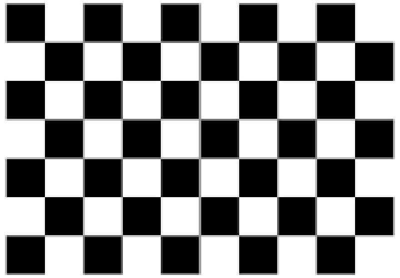
- Sauter mean diameter is a measure for the amount of surface area for a given gas volume
- Sauter mean diameter overweights larger bubbles



	5.5 mm	1mm + 10mm
Mean R	5.5 mm	5.5 mm
Mean V	697 mm³	2097 mm³
V/A	1.83 mm	3.304 mm
3*V/A = R_{32}	5.5 mm	9,91 mm

Optical bubble size measurement

- Camera and (back)light
- Spatial calibration with target at measurement position
- Low frame rate, but small exposure time → much light
- Image analysis with ImageJ, MATLAB, ...



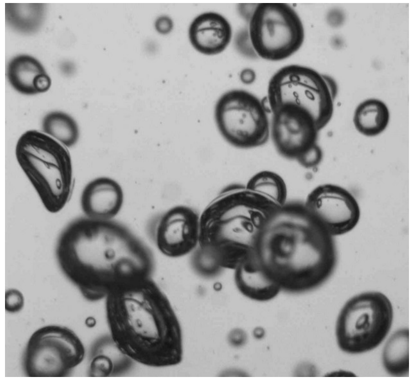
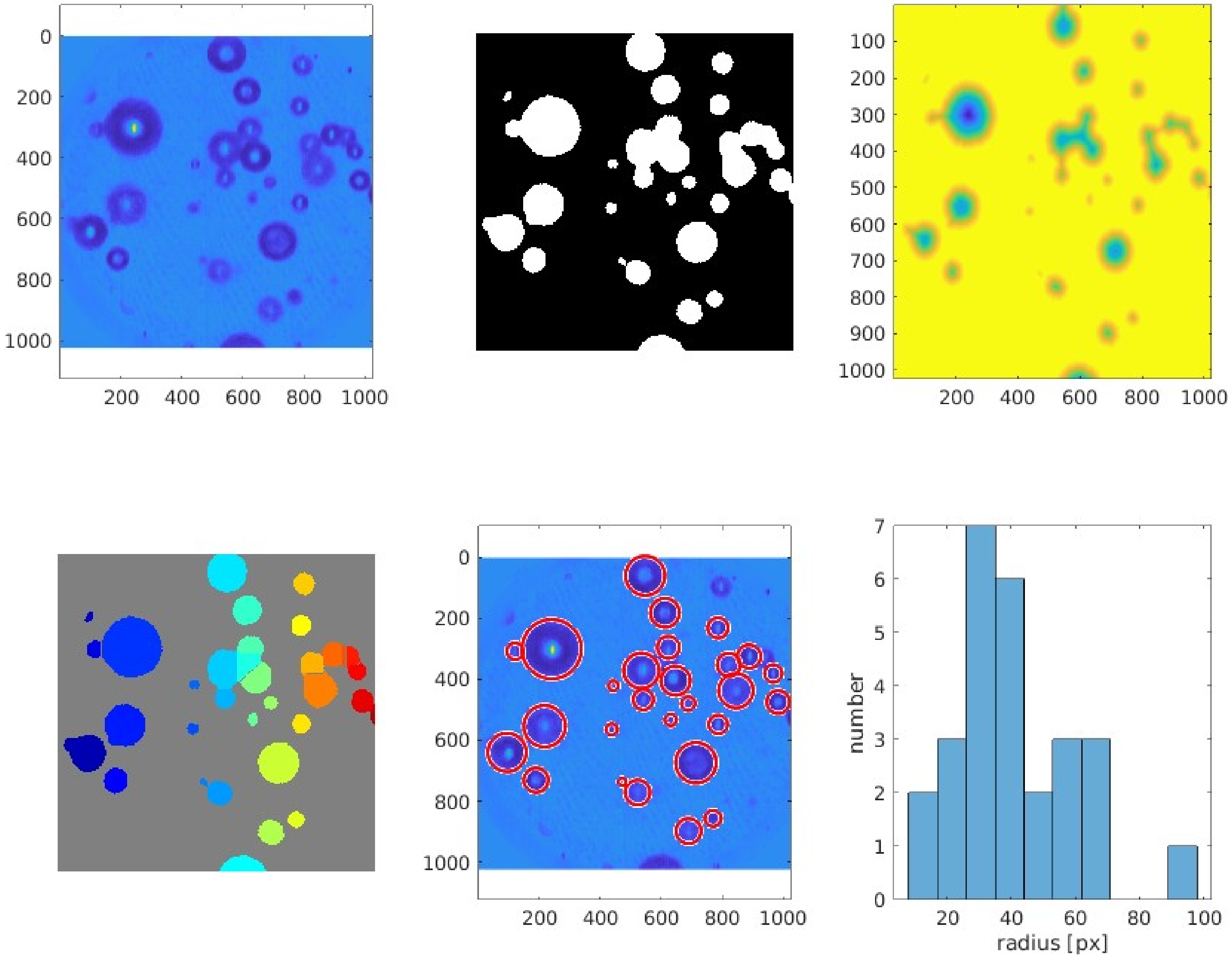


Image analysis

- Segmentation (with watershed)
- 1. Binarize Image
- 2. Compute distance to rim
- 3. Gauss-filter
- 4. Perform watershed
- 5. Remove Artefacts
- 6. Perform statistics



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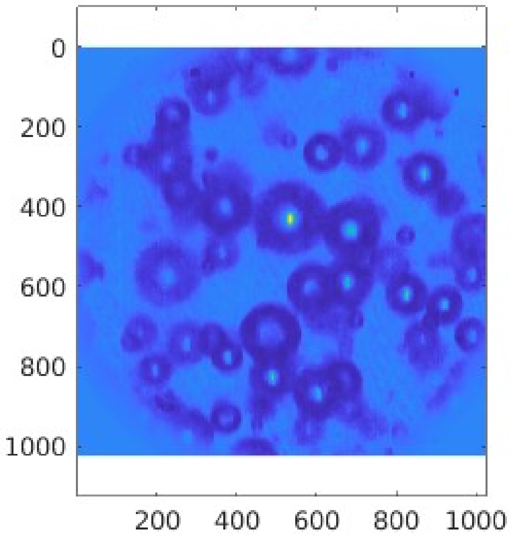
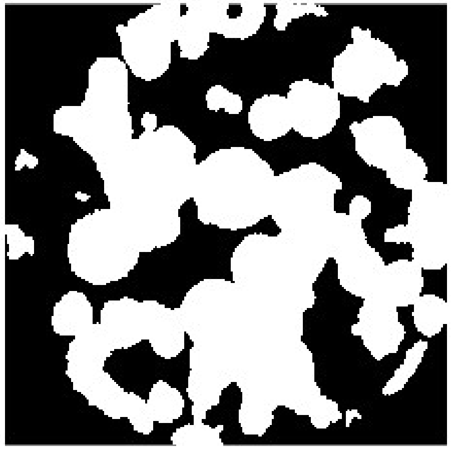
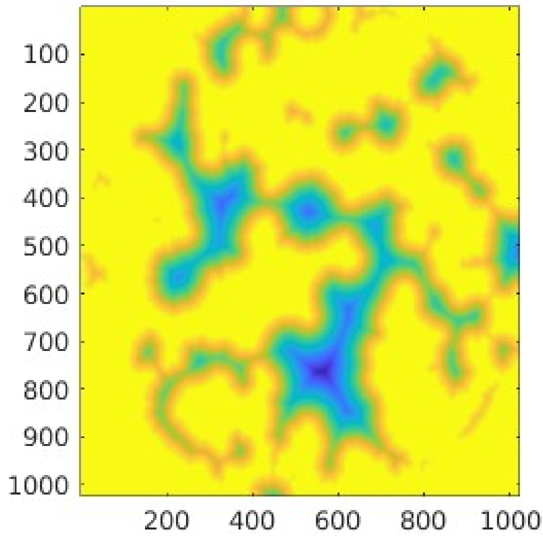
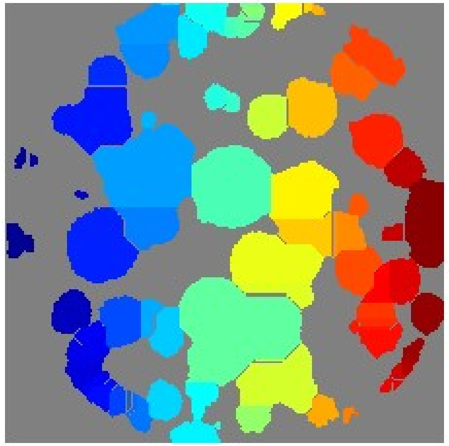
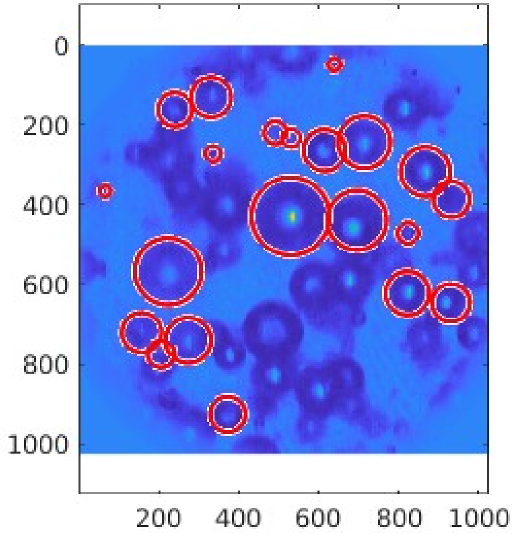










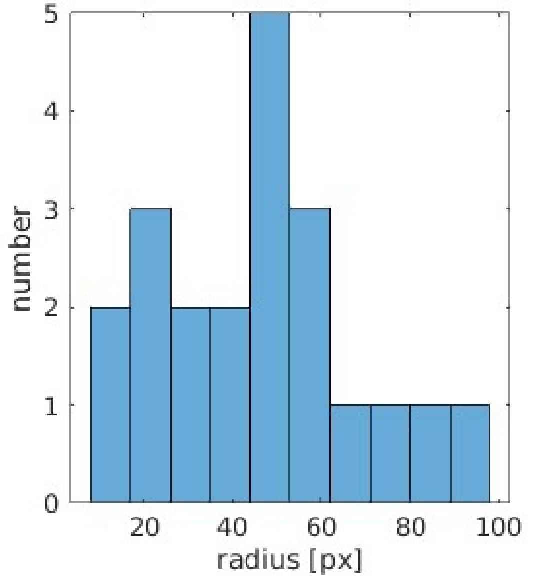
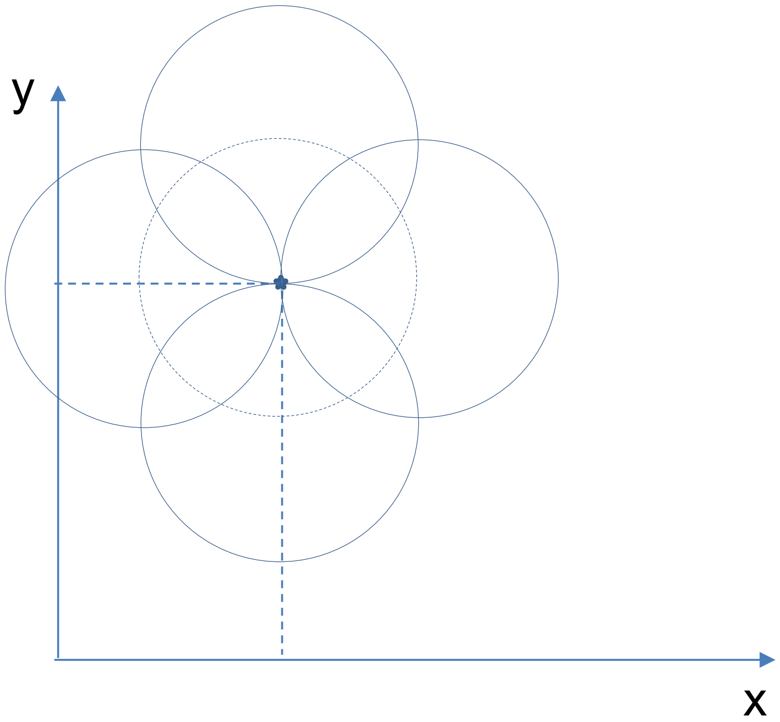
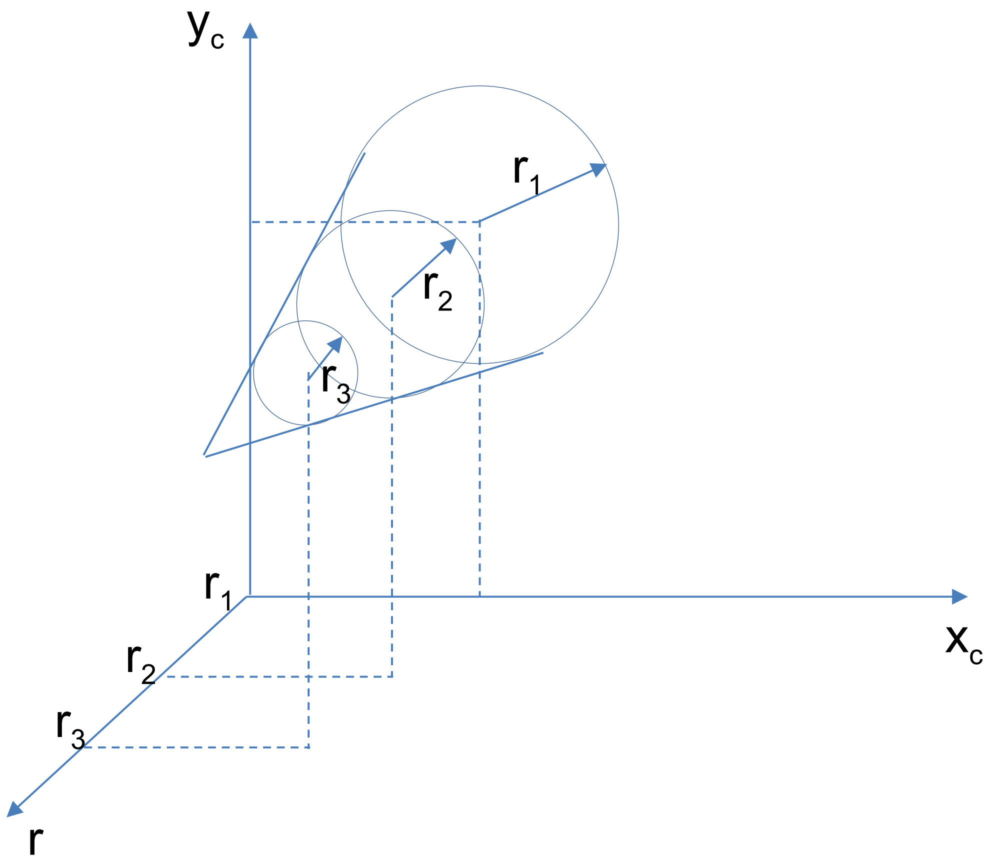


Image analysis

- Hough transformation / radon transform (for circles)
- E.g.: imfindcircle (matlab)





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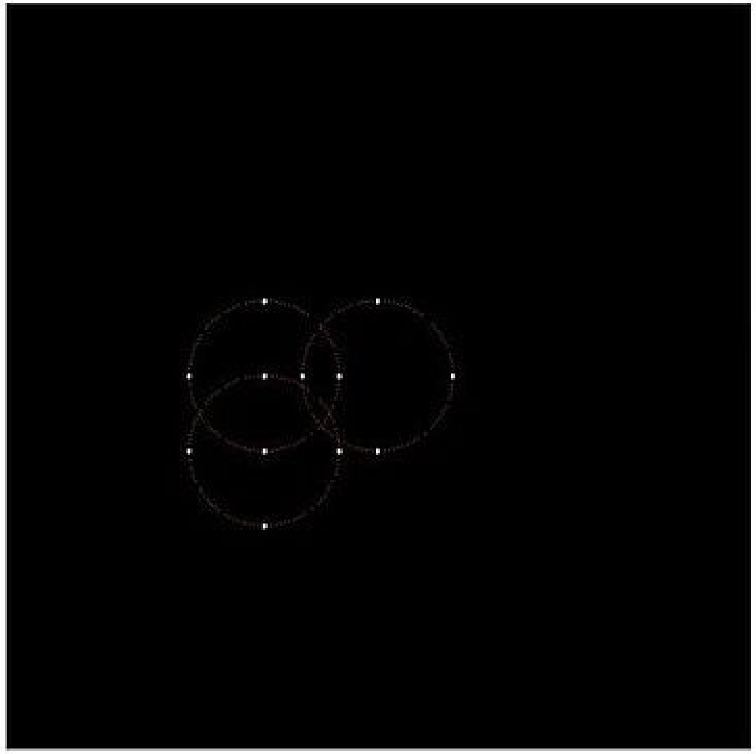


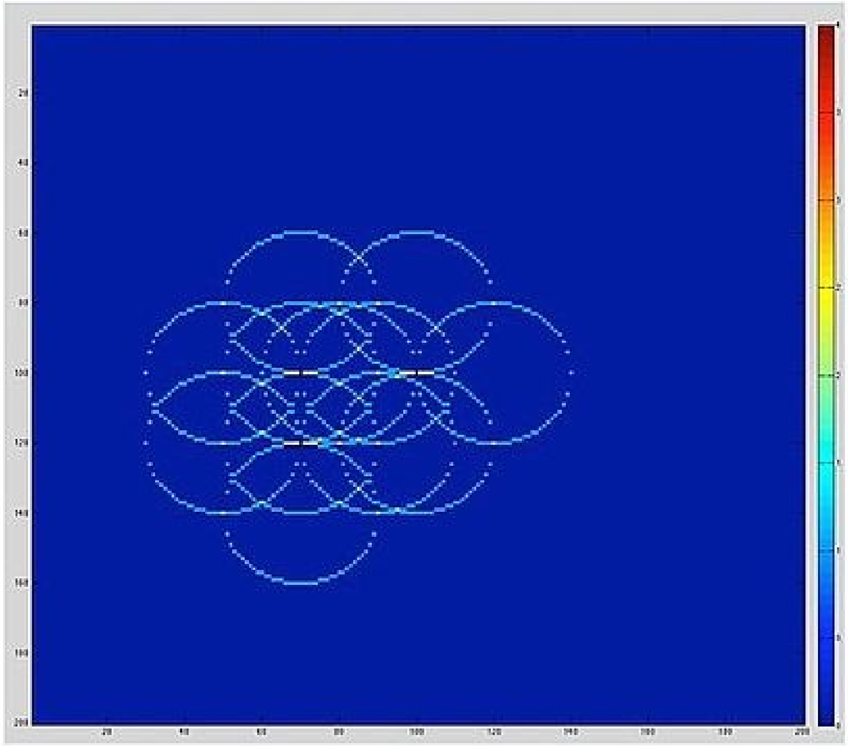


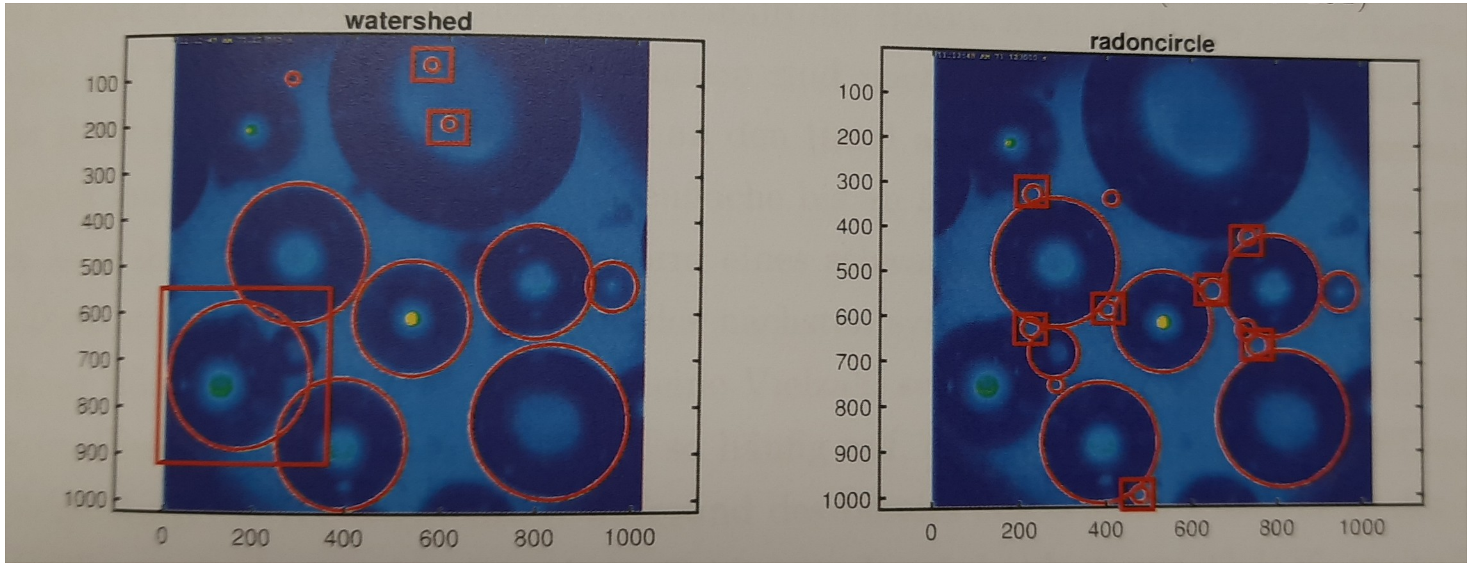
Image analysis

Segmentation (with watershed)

- Lower computational effort
- Detection of deformed bubbles
- Additional information (circularity, orientation,...)

Hough-Transformation

- Detection of overlapping bubbles
- Low-quality images possible
- False-positive detections



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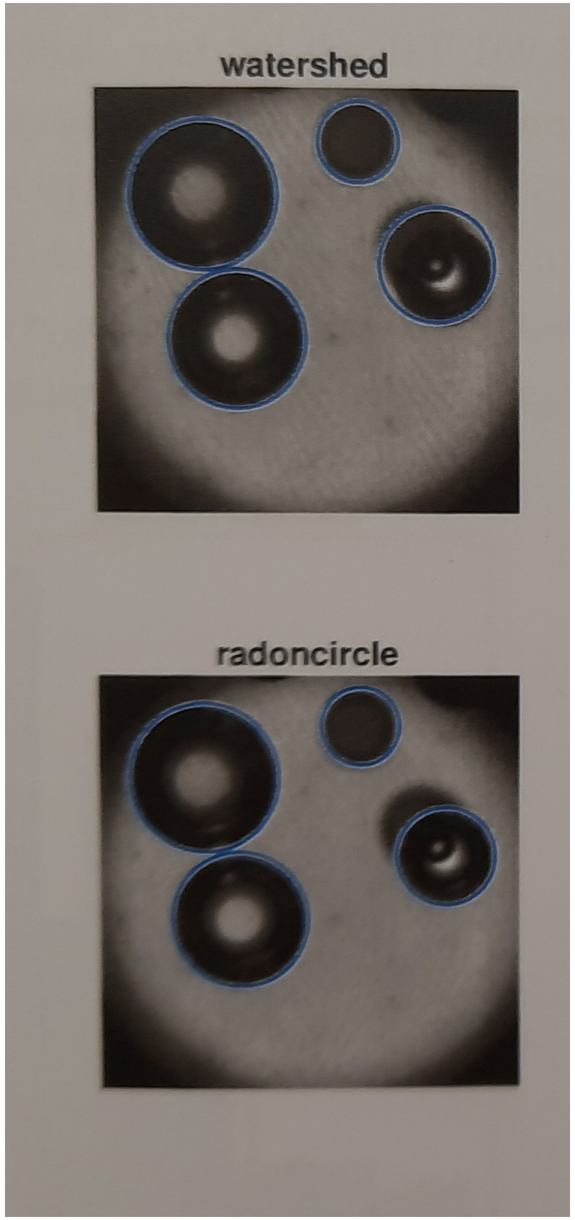
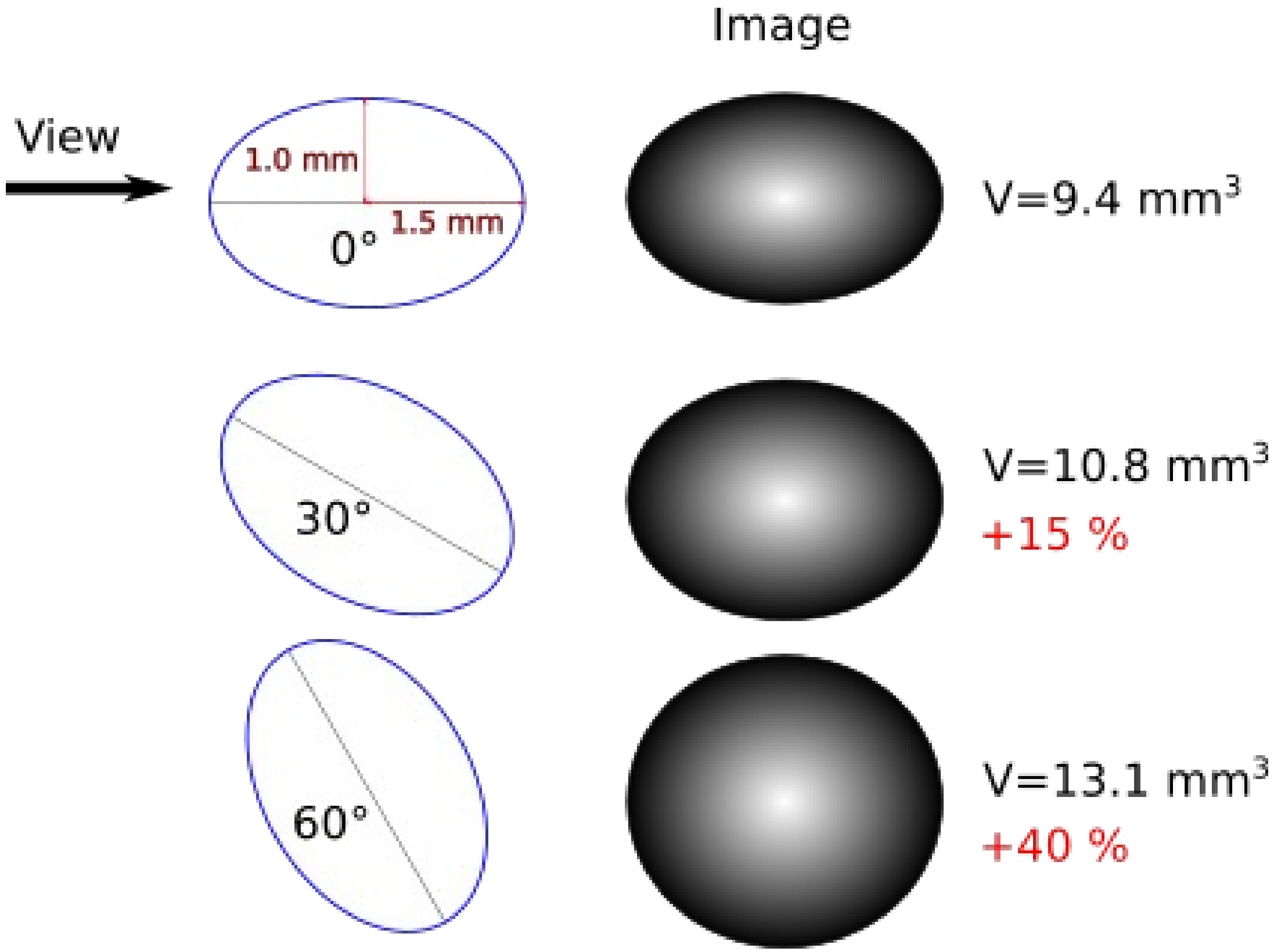


Size measurement bias: 2D-projection

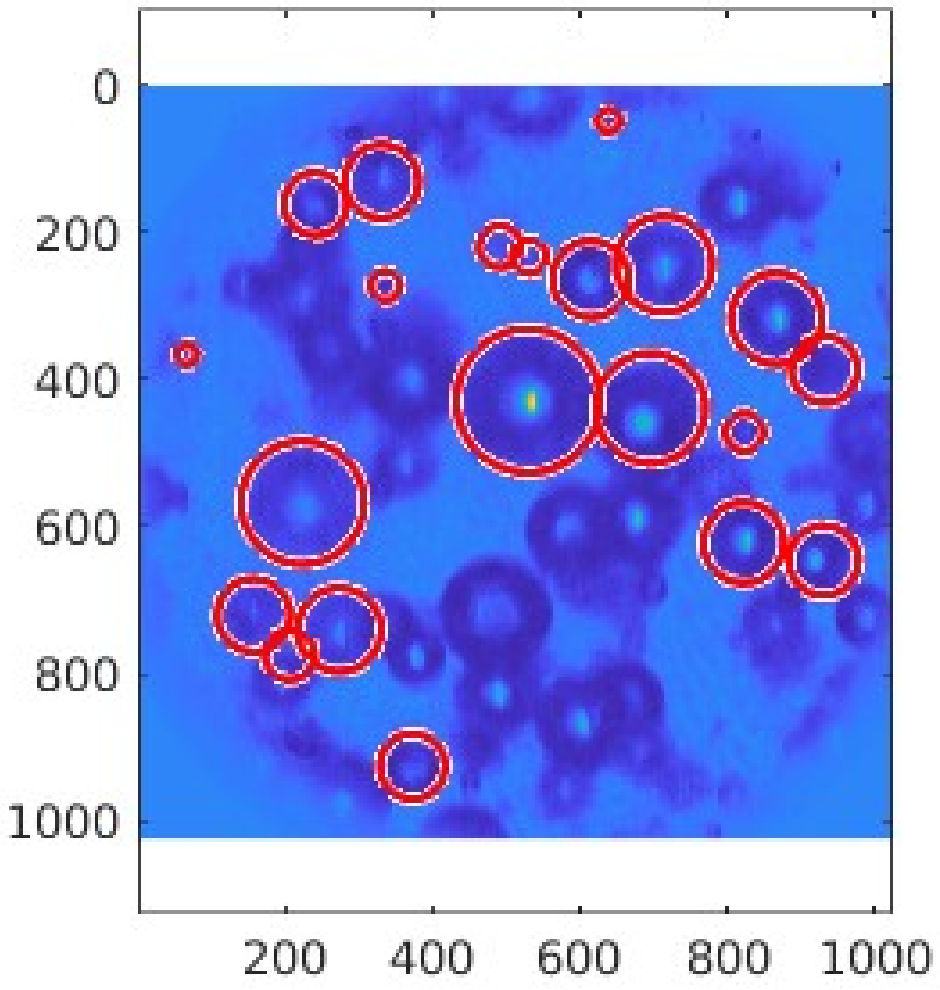
- After detection: Volume estimation
- Fitting of circle/ellipse
- BUT:
- Third dimension contributes to volume
- Non-spherical bubble shape
- ▭ third dimension has to be guessed



Size measurement bias: overlapping

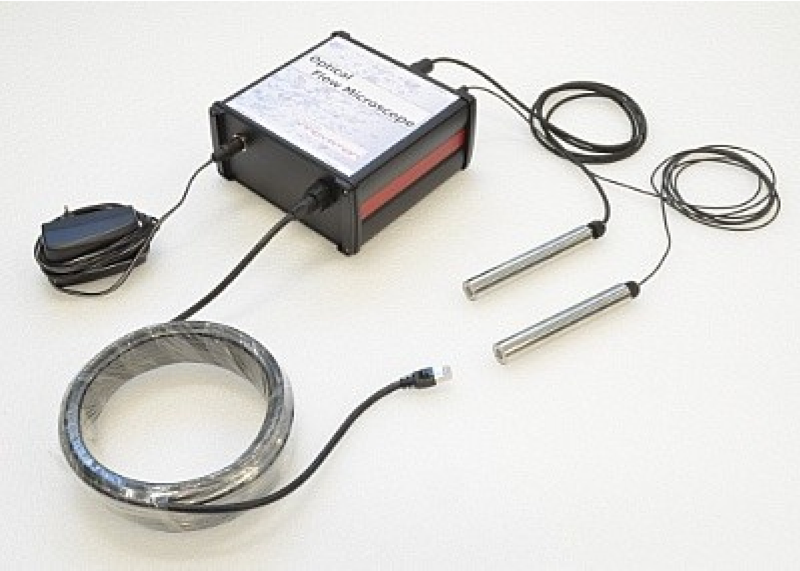
- Segmentation: reduced bubble size / no detection
- Hough-Transformation: no detection

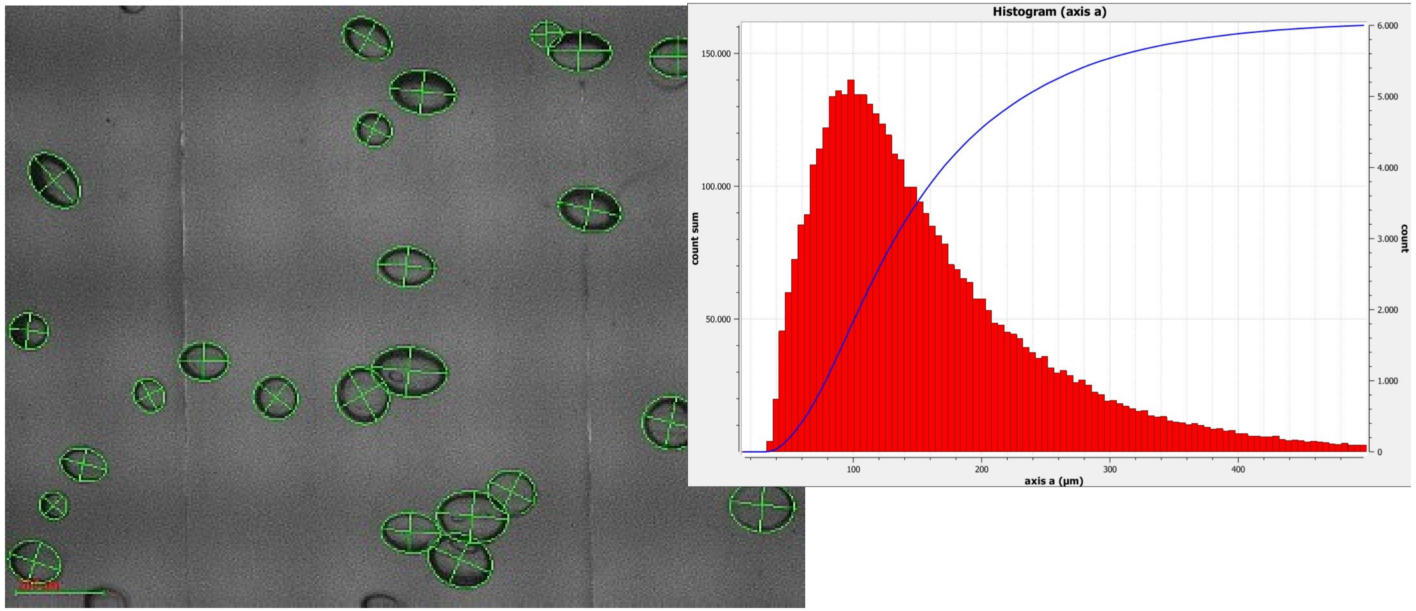
- Large bubbles are more likely to be overlapped
- ⇨ shifts distribution to smaller bubbles



Process microscope

- Observation directly inside the process
- Commercially available (different companies)
- Camera and (back)light + analysis tool
- Easy and conveniant usage

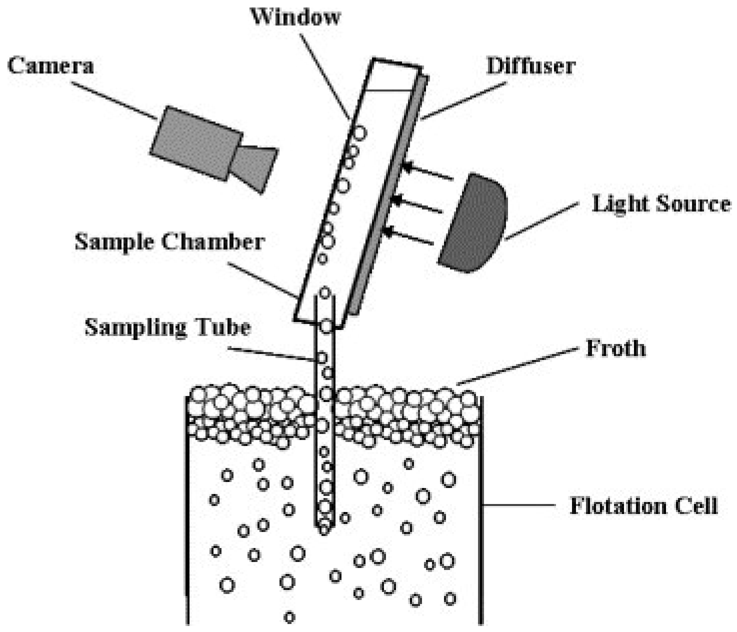




(C) HZDRi: Process microscope

Bubble viewer

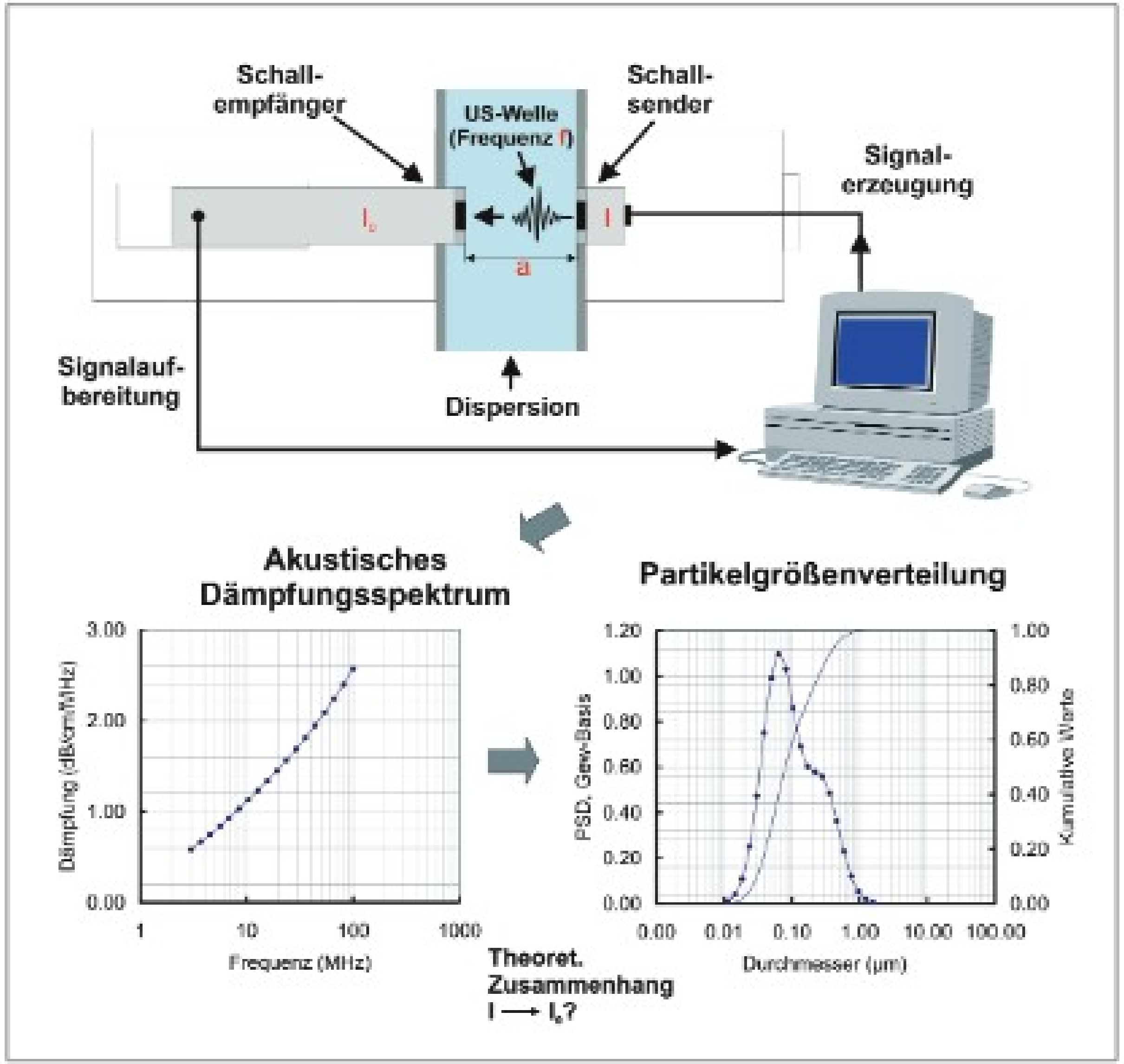
- Extraction of bubbly liquid
- Small tilt to concentrate bubbles
- More easy observation
- Potential coalescence, selection bias



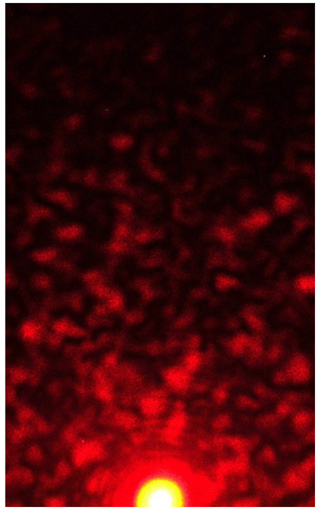
[Girgin et al. MinEng 19, 2006]

Particle sizer

- Acoustic attenuation spectroscopy
- Applicable only for small bubbles (<<1mm)
- Commercially available (for particles)



Particle sizer



- Laser diffraction on spherical objects
- Applicable only for small bubbles (0.1 µm ... 1mm)
- Commercially available (for particles)