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Dynamics of bubble cutting by interaction with a solid cylinder

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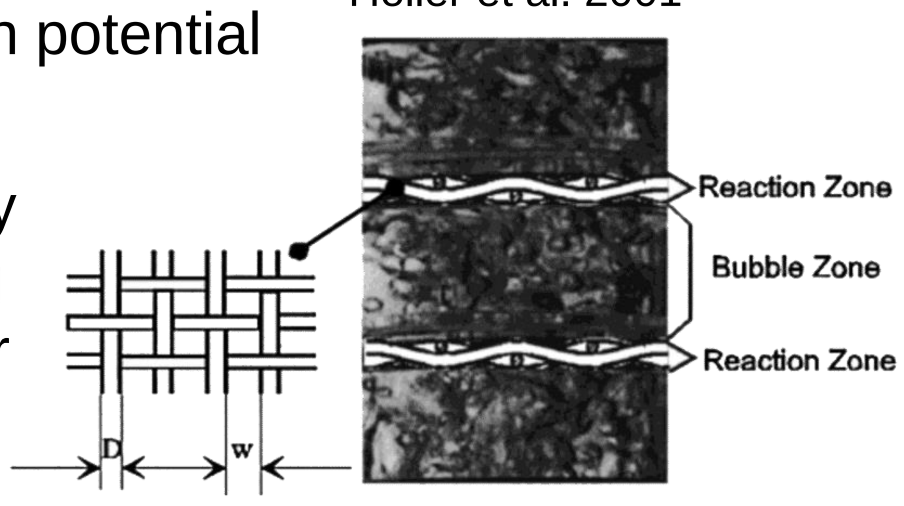
Motivation

- Widespread use of bubble columns in industry with high optimization potential
- Purpose of reactor internals
  - Increase interfacial area by bubble breakup enhancing thereby heat/mass transfer
  - Act as catalyst support[1]

Höller et al. 2001[1]



Objective

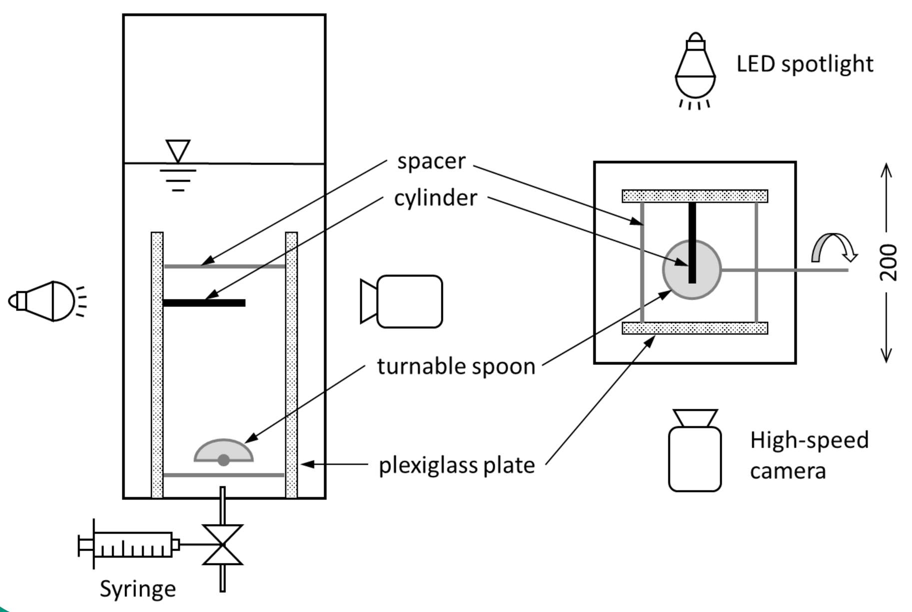
- Outcomes of bubble interaction with a cylinder[2,3]
  - Small bubbles bypass the cylinder
  - Large bubbles are cut by the cylinder with or without generation of satellite bubbles

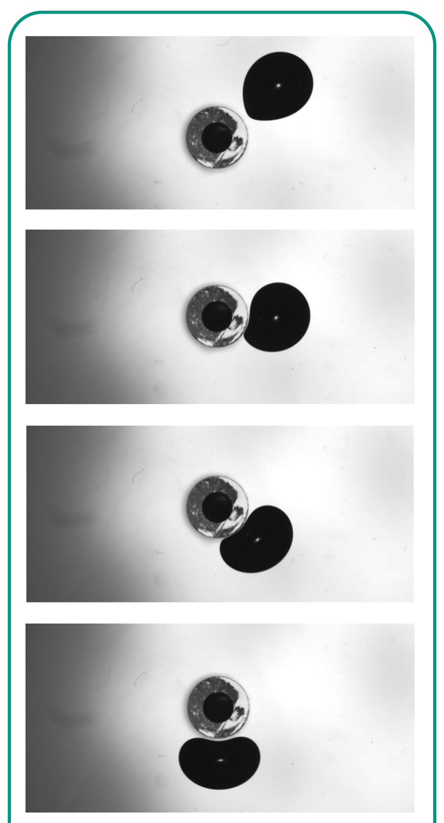
→ Study interaction dynamics experimentally

→ Determine a theoretical criterion for the critical bubble size which separates both regimes

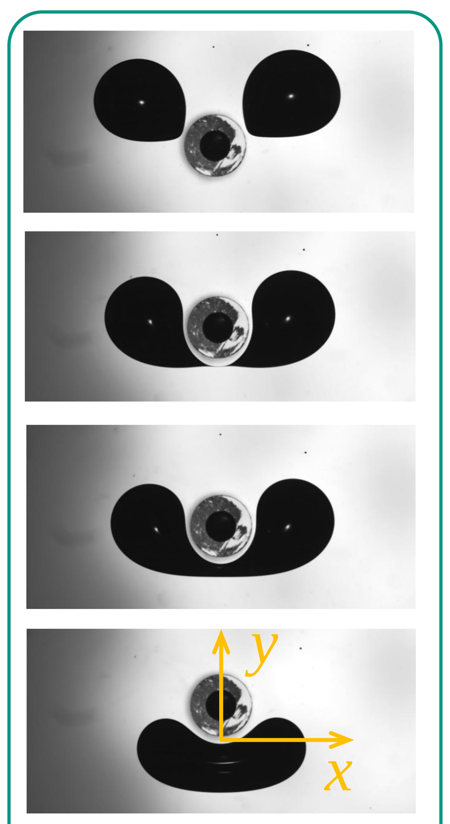
Experiment

- Set-up adapted from Segers[2]
- Glycerol-water solution $M = 0.068$
- Bubble volume $V_B = 25 - 1000\ \mu L$
- Cylinder diameter $d_{cyl} = 4$ mm
- Recording by HS camera and image analysis with Matlab

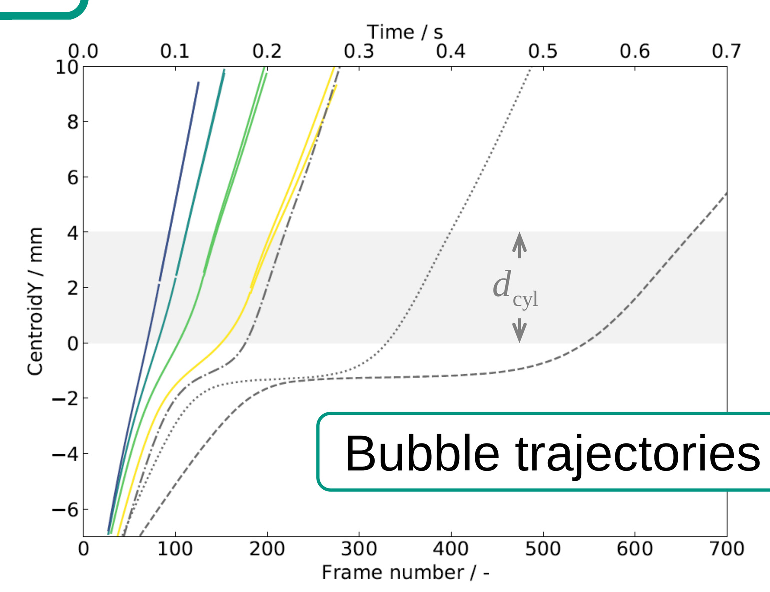


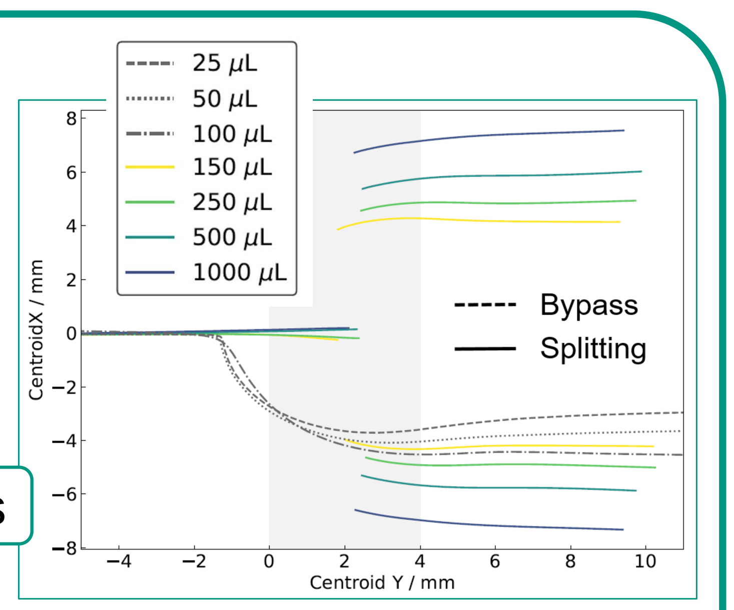


$V_B = 50\ \mu L$
$d_B = 4.6$ mm
$We_B = 0.8$

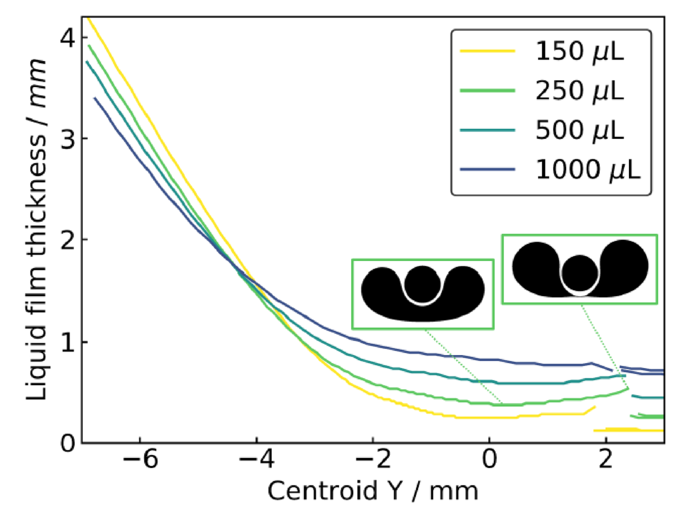


$V_B = 250\ \mu L$
$d_B = 7.8$ mm
$We_B = 3.7$





- $V_{B,crit} = 100 - 150\ \mu L$ $\rightarrow 1.73 < We_{crit} < 2.66$
- Exp. Segers[2] $We_{crit} \approx 2$
- Liquid film thickness increases with V_B → (minimum before split)



Analytical model

- Energy balance for free rise of mother (*B*) and two equal-size daughter (*b*) bubbles

$$E_{kin}^B + E_\sigma^B + E_g^B = 2E_{kin}^b + 2E_\sigma^b + 2E_g^b + E_{diss}$$

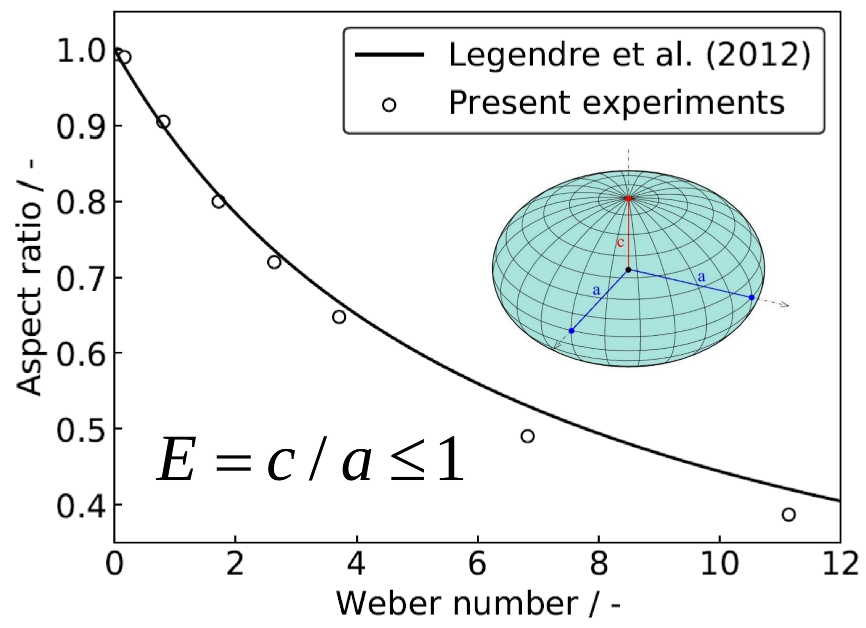
$$We_B = \frac{\rho_l d_B u_B^2}{\sigma},\ u_b = \alpha u_B \rightarrow We_b = \frac{\alpha^2}{\sqrt[3]{2}} We_B$$

- Sphericity of an oblate spheroid (for E_σ)

$$\psi = f_\psi(E) = 4E^{2/3}\left[2 + \frac{E^2}{\sqrt{1-E^2}} \ln\left(\frac{1+\sqrt{1-E^2}}{1-\sqrt{1-E^2}}\right)\right]^{-1}$$

- Bubble aspect ratio[4] (M = Morton no.)

$$E = f_E(We, M) = 1 - \frac{9}{64}\frac{We}{1+0.2M^{0.1}We}$$



- Added mass of oblate spheroid[5] (E_{kin})

$$C_{am}^{-1} = 2\left(1 - \tfrac{6.6}{128}We\right)^3\left(1 + \tfrac{3}{64}We\right)^2\left(1 - \tfrac{3}{32}We\right)$$

- Gravitational energy and dissipation

$$E_g^B - 2E_g^b - E_{diss} = g(\rho_l - \rho_g) H V_B (1-\beta)$$

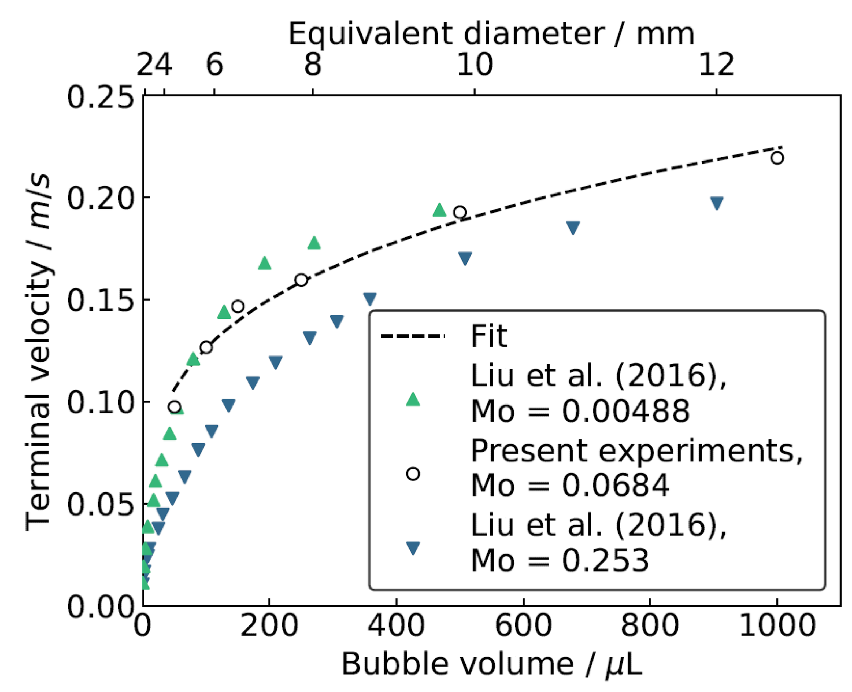
- Weber number criterion from energy balance

$$\frac{We_{crit}}{12} = \frac{2^{1/3}/f_\psi(f_E(We_B, M)) - 1/f_\psi(f_E(We_b, M))}{C_{am}(We_B) - \alpha^2 C_{am}(We_b) + 8n(1-\beta)/3C_D^B}$$

- Free bubble rise velocity (exp.)

$$u_B \sim V_B^{1/4} \rightarrow \alpha = u_b / u_B = 2^{-1/4} = 0.84$$

$$C_D^B \approx 5,\quad n = H/d_B \approx 10$$



- Iterative solution required
- Dissipation parameter β (=1 for free rise)

β	1.00	0.93	0.75
We_{crit}	3.09	2.66	1.73

$\beta < 1$ is reasonable
← range from exp.

[1] Höller et al., *Ind. Eng. Chem. Res.* **40** (2001) 1575–1579
[2] Segers, PhD thesis, TU Eindhoven, 2015
[3] Wang et al., *Chem. Ing.Techn.* **94** (2022) 385–392
[4] Legendre et al., *Phys. Fluids* **24** (2012) 043303
[5] Kendoush, Physics Letters A **366** (2007) 253-255
[6] Liu et al., *Exp. Therm. Fluid Sci.* **78** (2016) 254-265

Conclusions

- Outcomes of bubble-cylinder interaction: bypass or splitting
  - Duration of interaction increases with decrease of bubble volume
  - Development of analytical Weber number criterion for break-up
- Liquid film eliminates influence of solid material on interaction
  - Film thickness (i.e. diffusion path) increases with bubble volume
  - Reducing bubble size is essential to intensify 3-phase-reactions

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