

ME-446: Liquid-gas interfacial heat and mass transfer

Bubbles from Electrochemical Reactions

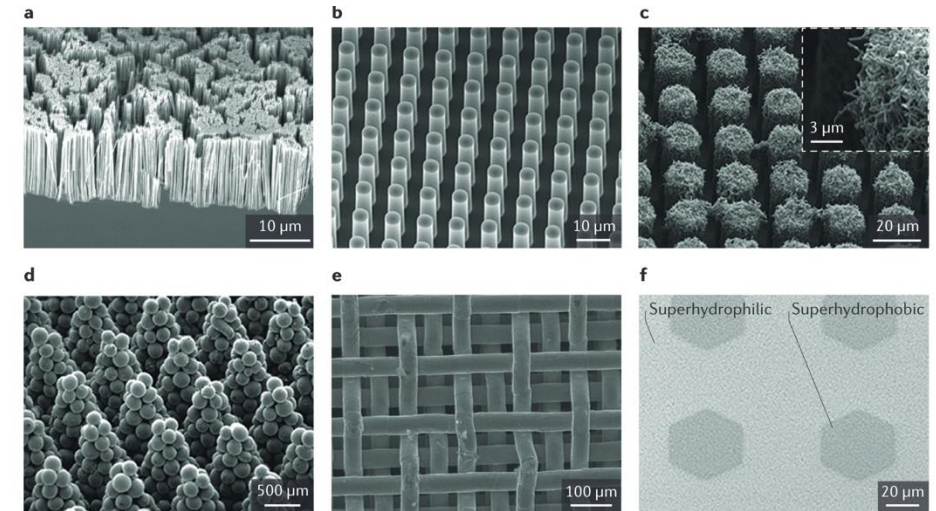
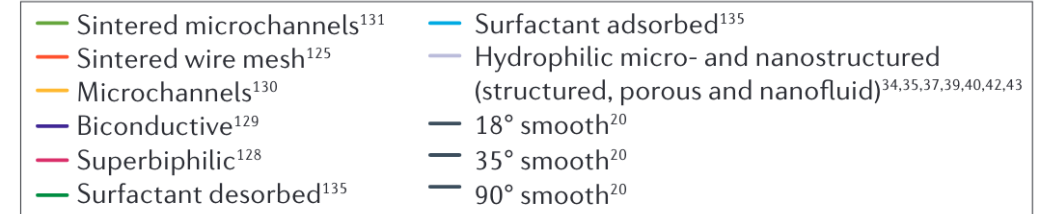
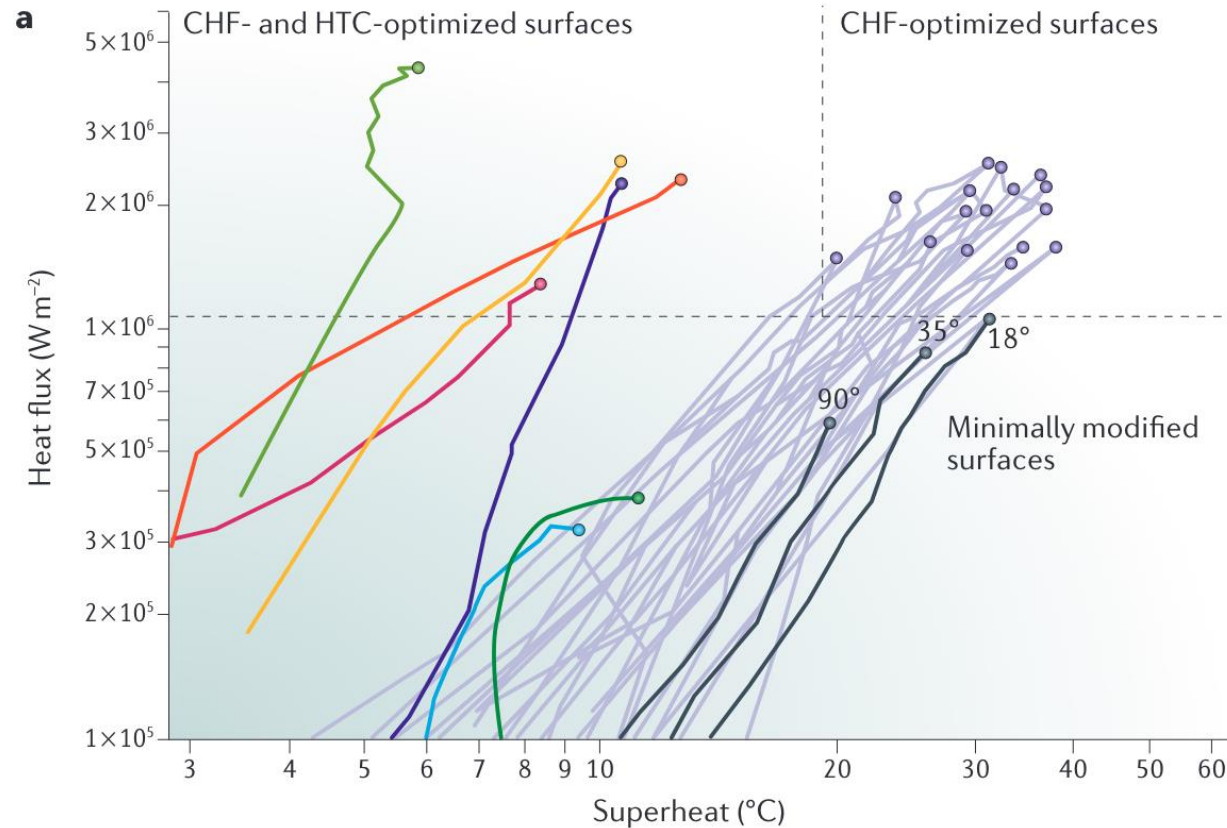
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Energy Transport Advances
Laboratory
EPFL Mechanical Engineering

2024 Fall Semester

Photo Credit: Trougnouf

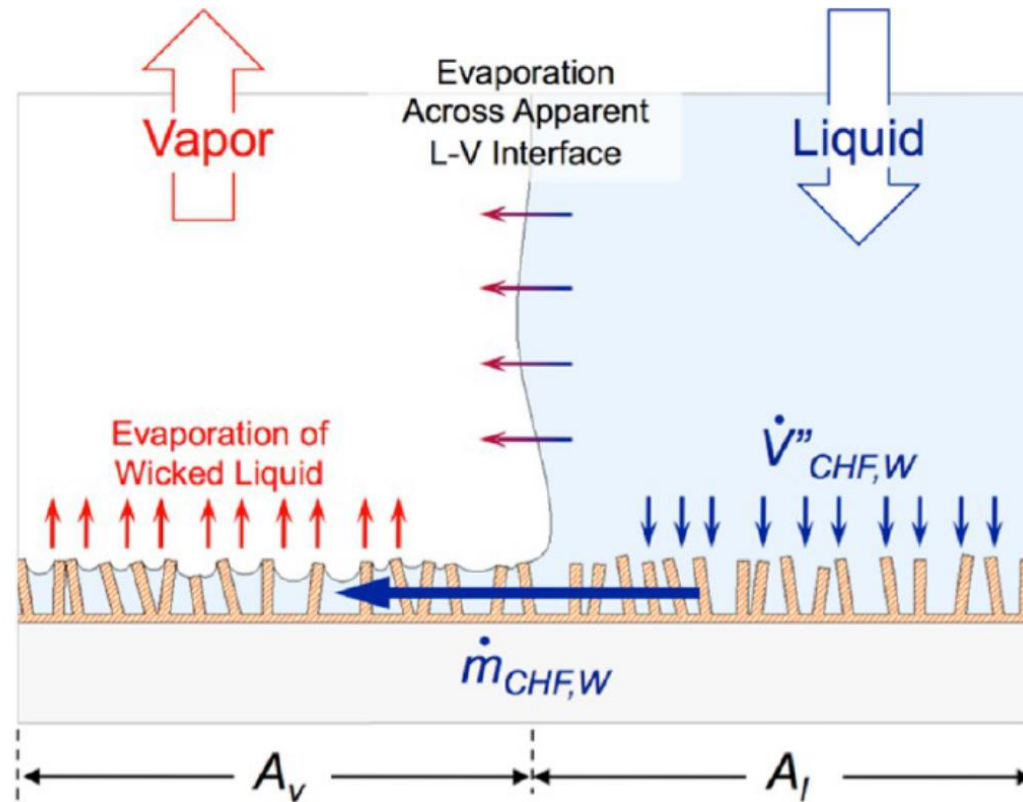
- Force balance model for CHF
- Statistical approach for CHF

- Isolated bubbles dissipate heat better than merged bubbles
- With elevated temperature, more nucleation sites become activated while more bubbles are likely to merge into each other.
- We consider the probability of having N bubbles on the surface and the probability distribution of nearest neighbor distance
- **CHF is reached when you have the maximum number of isolated bubbles**



doi:10.1038/natrevmats.2016.92

Wicking Helps Boiling

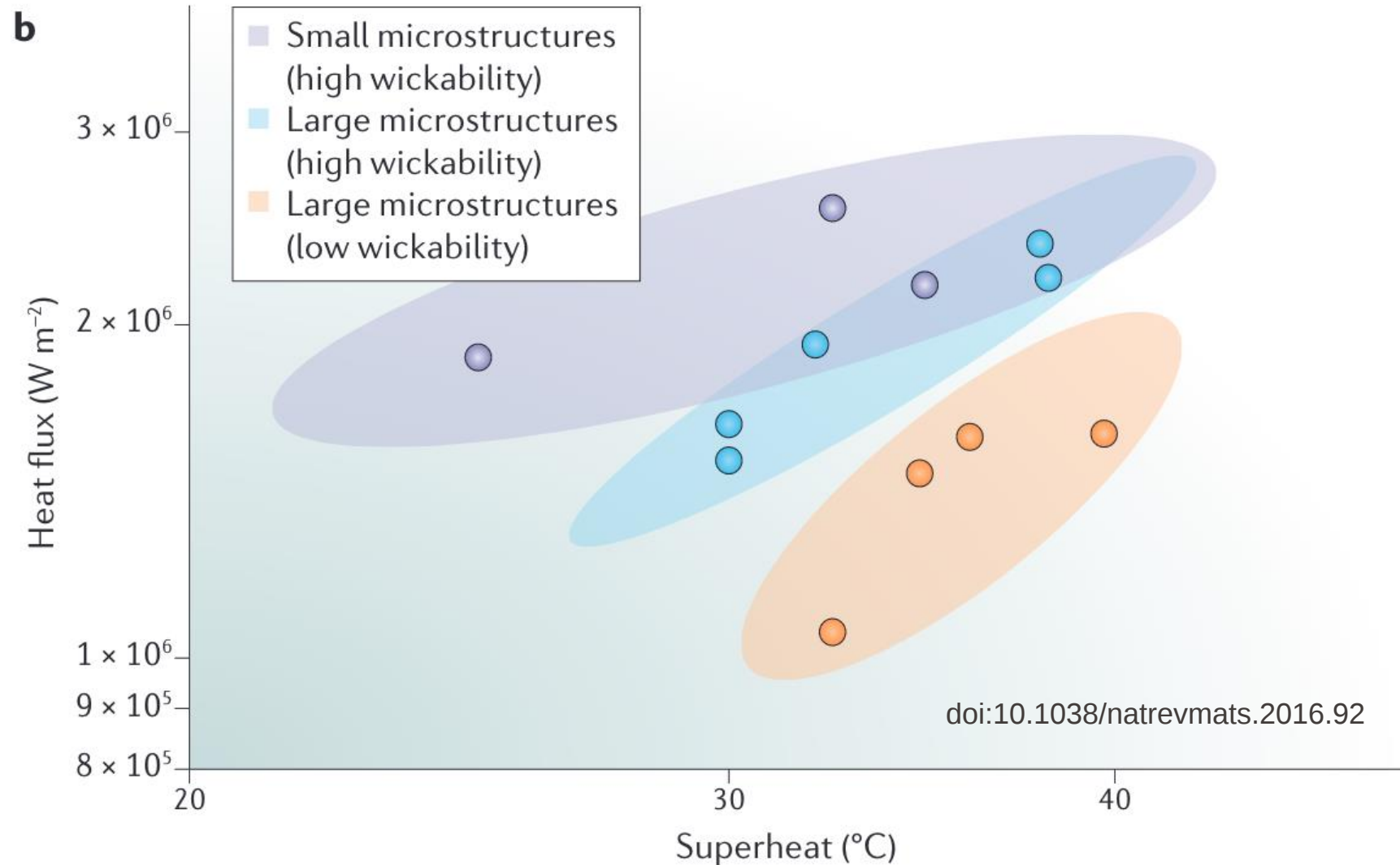


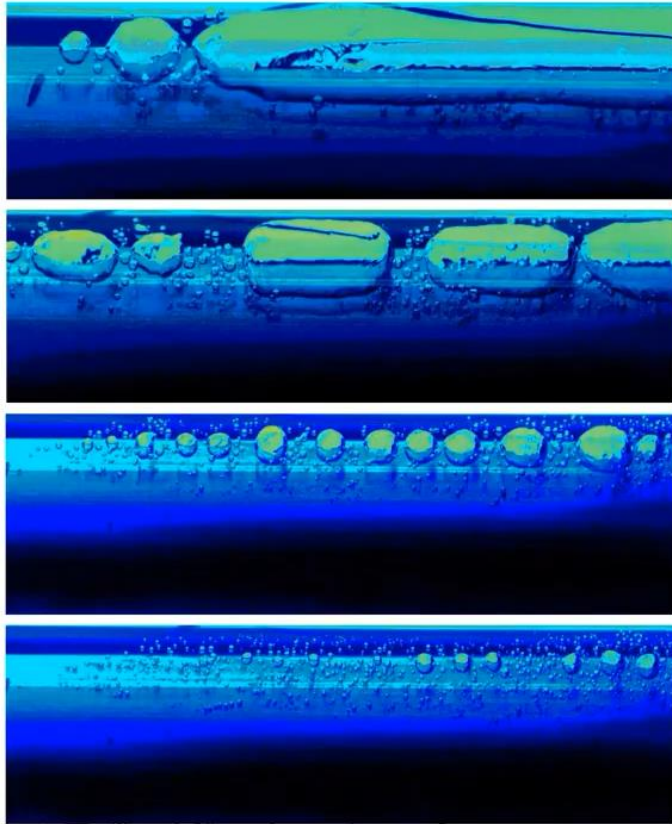
<https://doi.org/10.1021/la5030923>



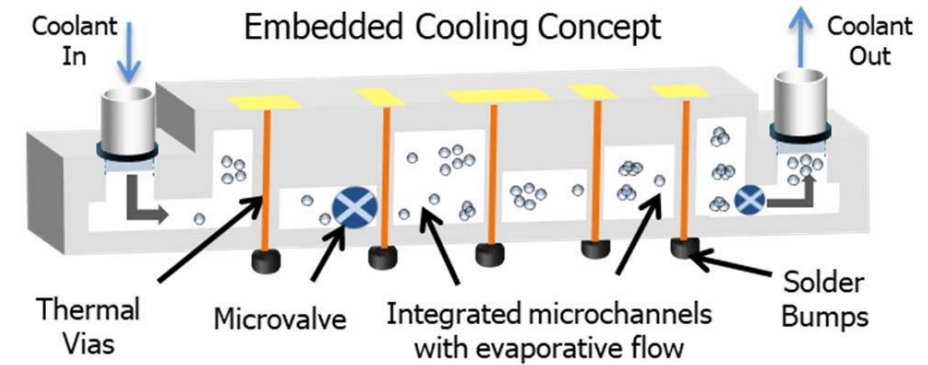
<https://doi.org/10.1021/acs.langmuir.7b01522>

Wickability Helps Boiling

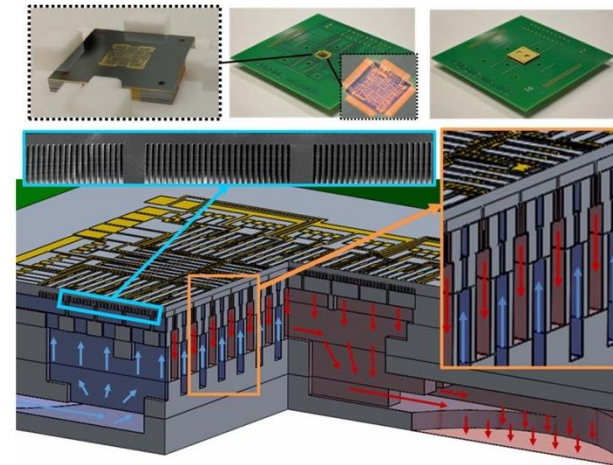




Primarily explored for high flux electronics cooling



DOI: 10.1109/TCPMT.2021.3111114

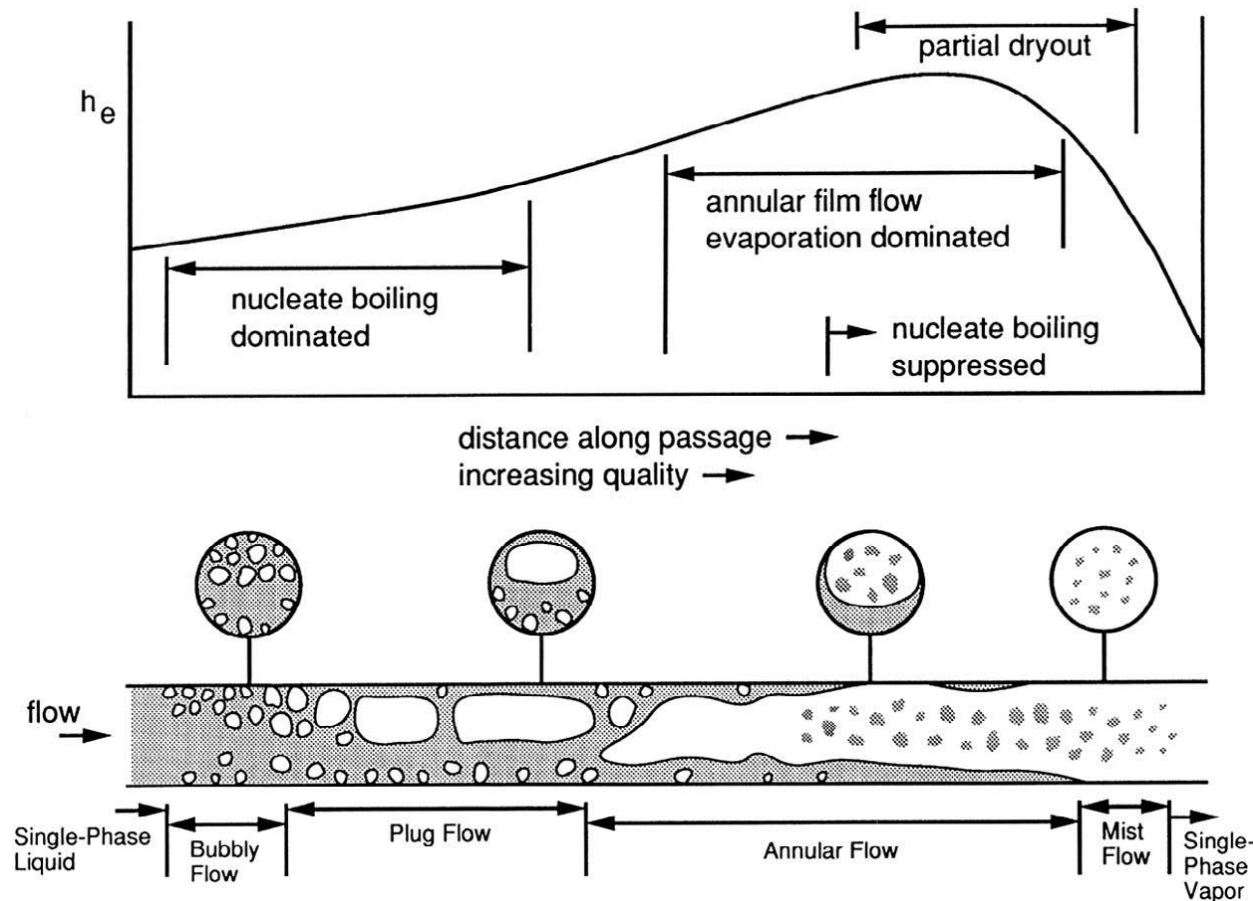


Different regimes in flow boiling
(slowed down 50 times)

<https://www.youtube.com/shorts/HNcp7zDtwx8?feature=share>

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117 (2018) 319–330

Figure 12.1 in Carey



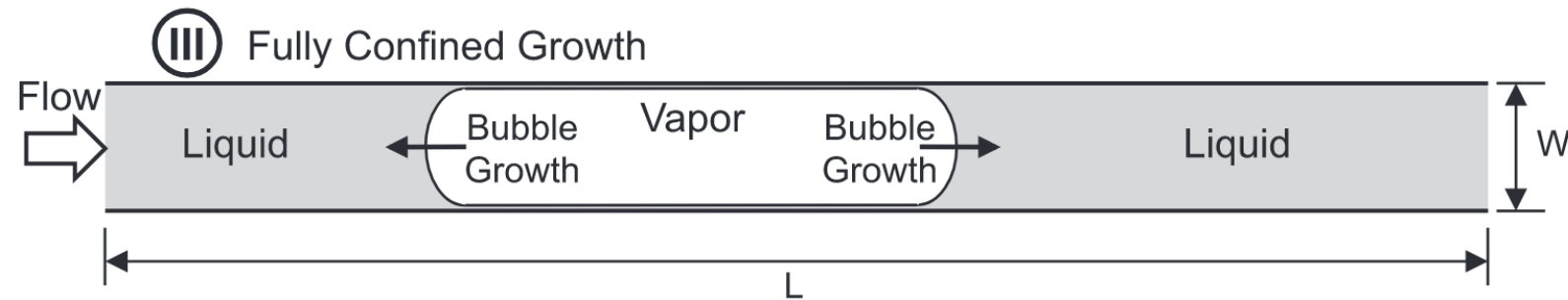
Bubbly flow: discrete bubbles dispersed in continuous liquid phase

Plug flow: coalescence of small bubbles produces large bubbles flowing in the upper portion

Annular flow: most liquid flowing along the wall and gas flowing in the central core

Mist flow: discrete droplets dispersed in continuous vapor phase

Oscillations in Microchannel Flow Boiling



Bubble expansion toward the inlet causing density wave oscillation in microchannels

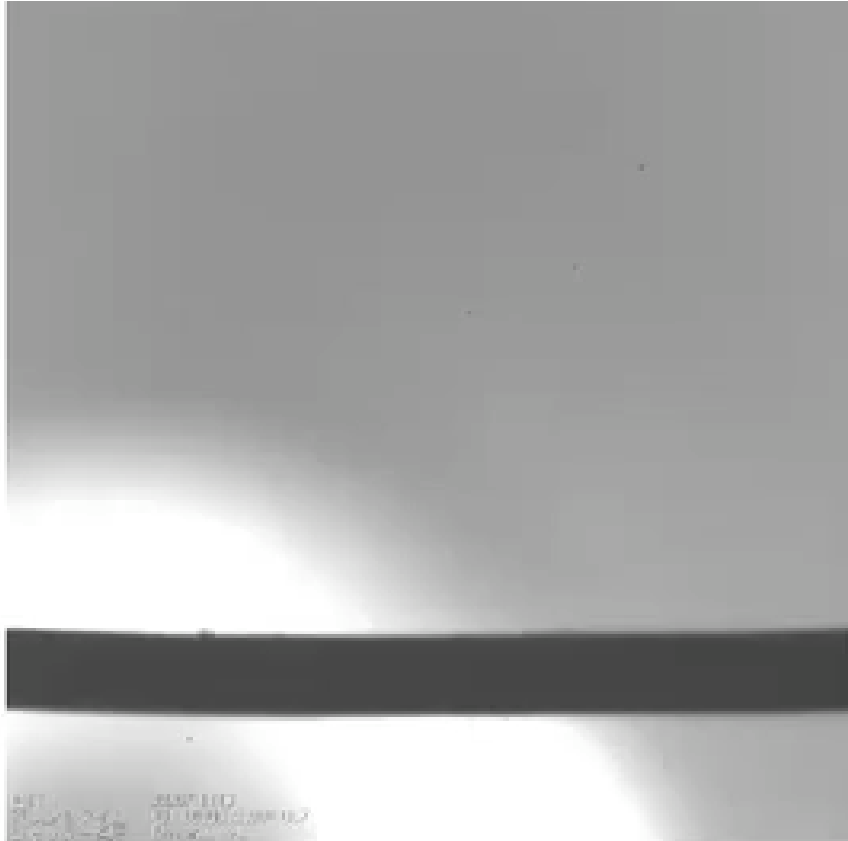
Flow rate reduced (potentially leading to backflow), which gives rise to further vapor expansion toward the inlet

Eventually, liquid rushes back into the channel when sufficient pressure is built up

Vapor Backflow Instability

60 fps; real time duration: 210 ms

Credit: Mark
Schepperle



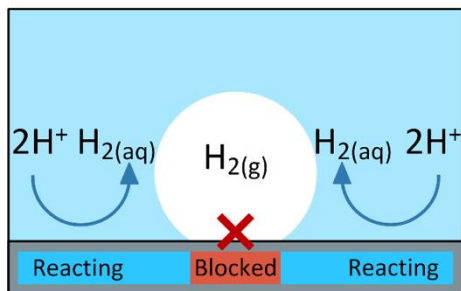
Industrial electrochemical processes that involves bubbles

Water splitting

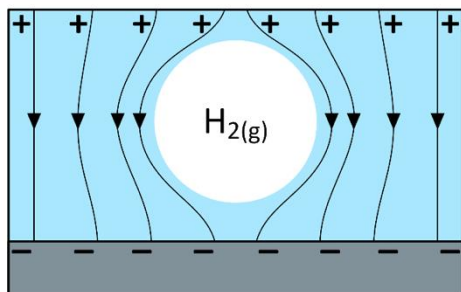
Aluminum production

Sodium chlorate production

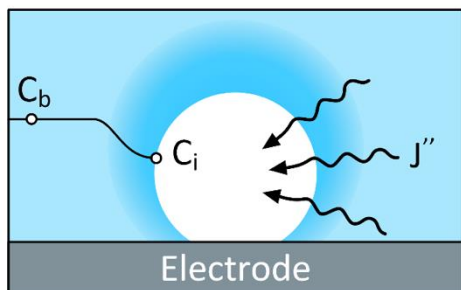
Chlorine and sodium hydroxide production



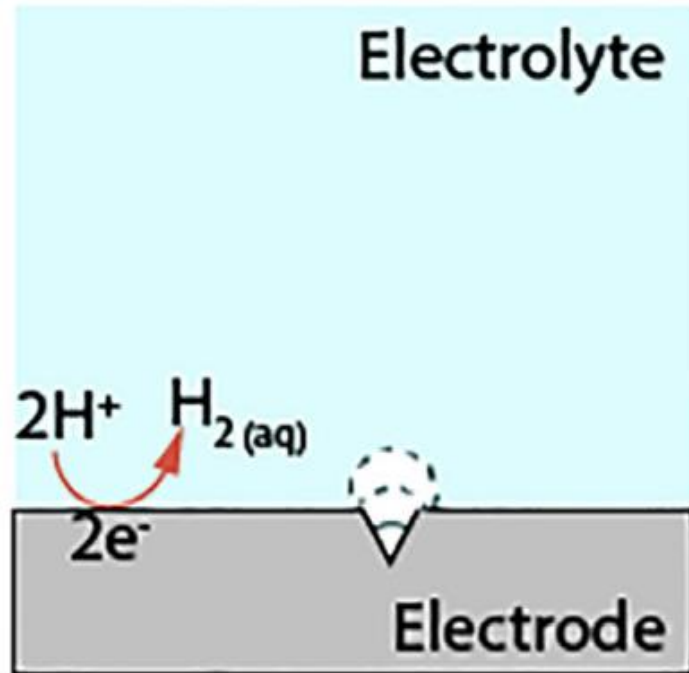
Blocking reaction area



Additional resistance for ion transport



Additional diffusion resistance
Bubble-induced convection



<https://doi.org/10.1016/j.joule.2020.01.005>

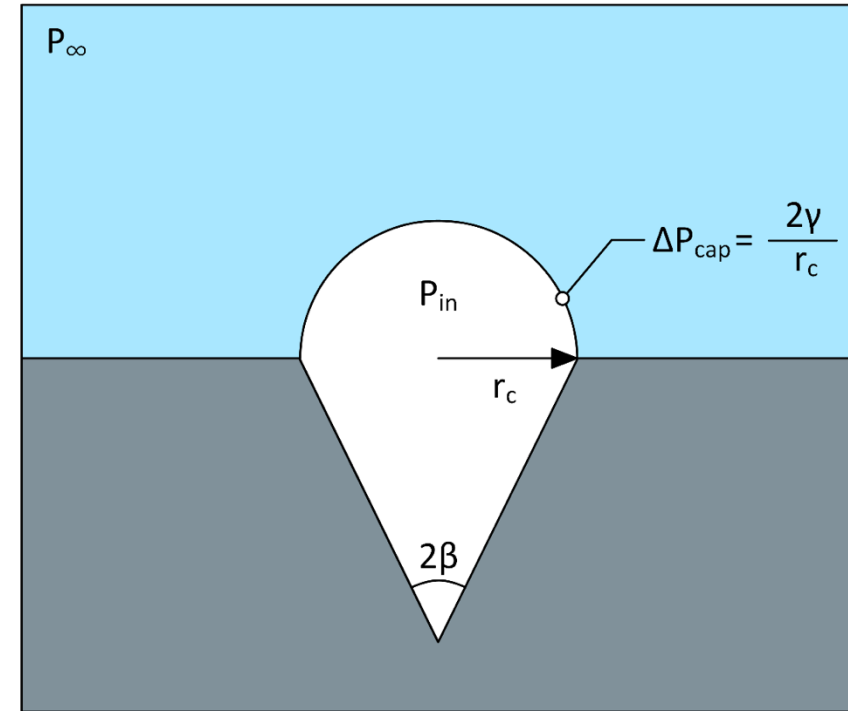
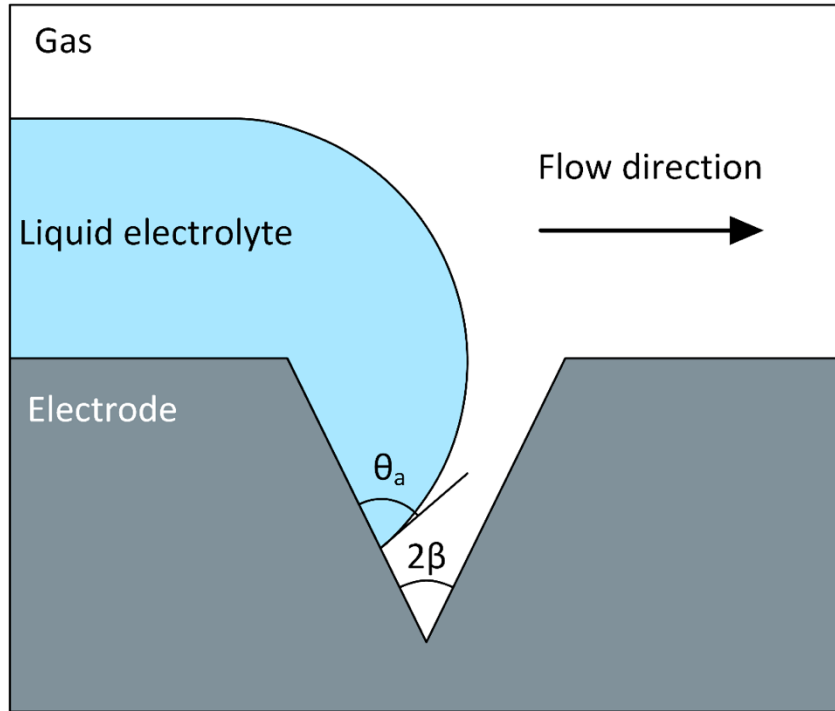
Equilibrium saturation concentration of dissolved gas in liquid is governed by Henry's law

$$C_{sat} = PK_H(T)$$

P : partial pressure of the gas acting on a liquid

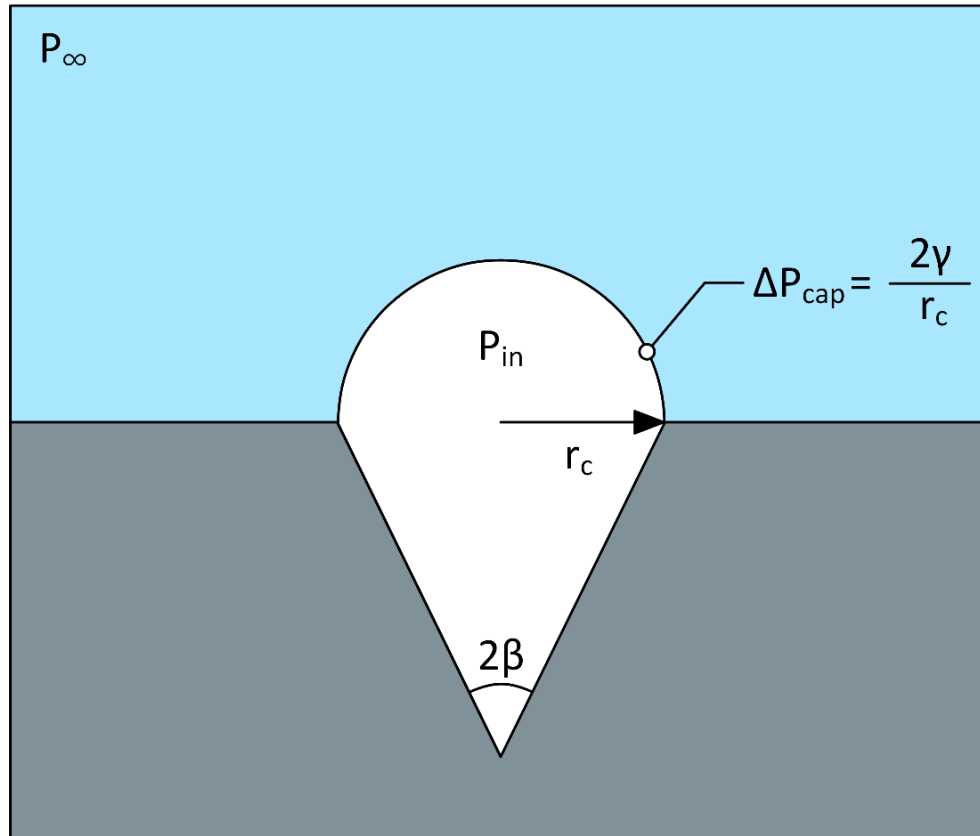
K_H : Henry's solubility constant (decreasing with T)

In electrochemical processes, nucleation takes place when concentration of dissolved gas becomes much larger than saturation values



Surface cavity can cause gas-entrapping to facilitate nucleation

On hydrophilic surfaces: critical pressure $P_{in} = P_\infty + \frac{2\gamma}{r_c}$



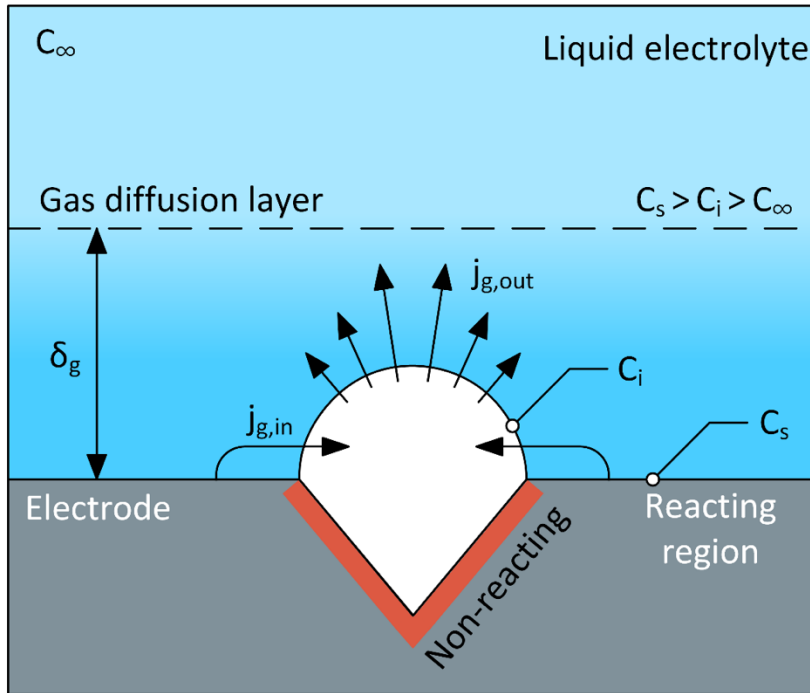
Far field saturation concentration

$$C_{\infty} = K_H P_{\infty}$$

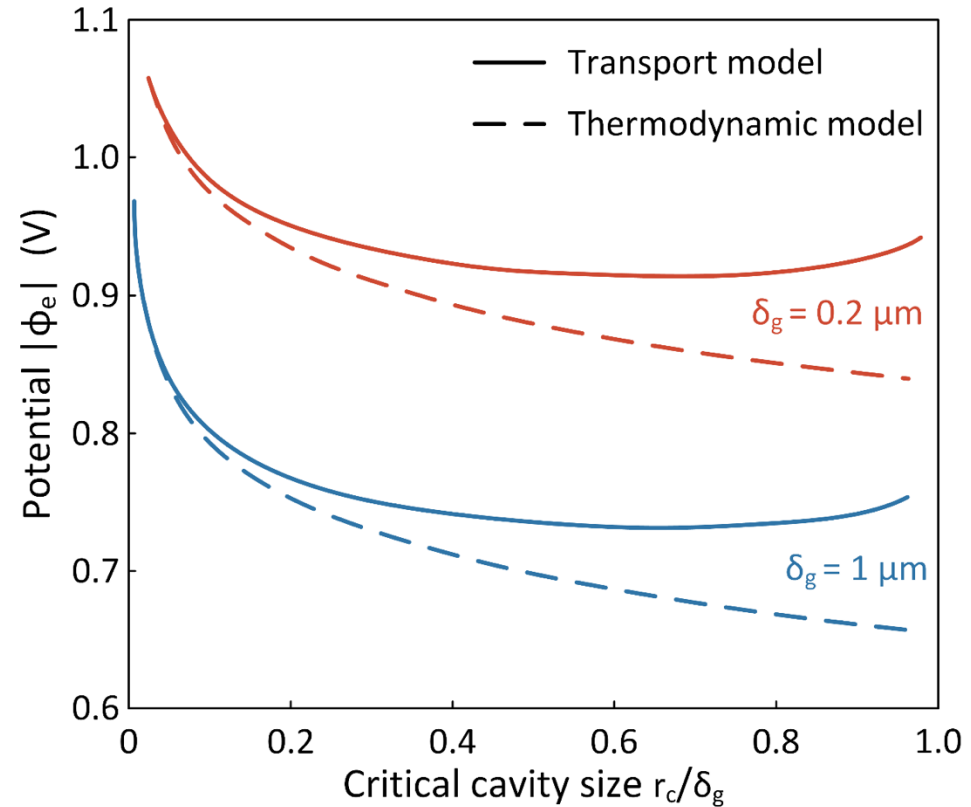
Interface saturation concentration

$$C_S = K_H \left(P_{\infty} + \frac{2\gamma}{r_c} \right) = C_{\infty} \left(1 + \frac{2\gamma}{r_c P_{\infty}} \right)$$

For $r_c = 10 \text{ nm}$, $C_S/C_{\infty} \sim 100$



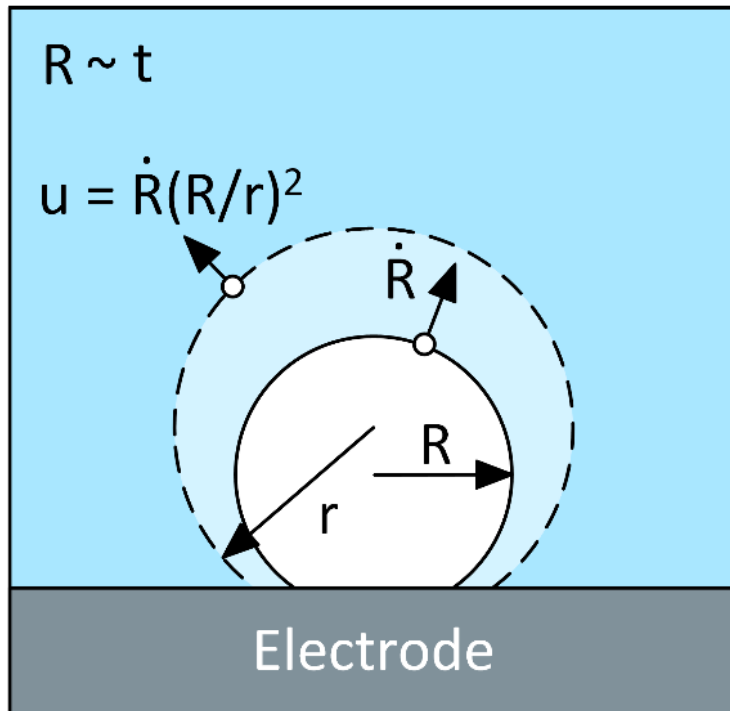
<https://doi.org/10.1021/acs.langmuir.0c02690>



The presence of bubble will impact how the gas is supplied to the bubble

When cavity is too large, the outgassing to the far field can collapse the bubble even when the gas is supersaturated at the electrode

- First stage: inertial-controlled growth

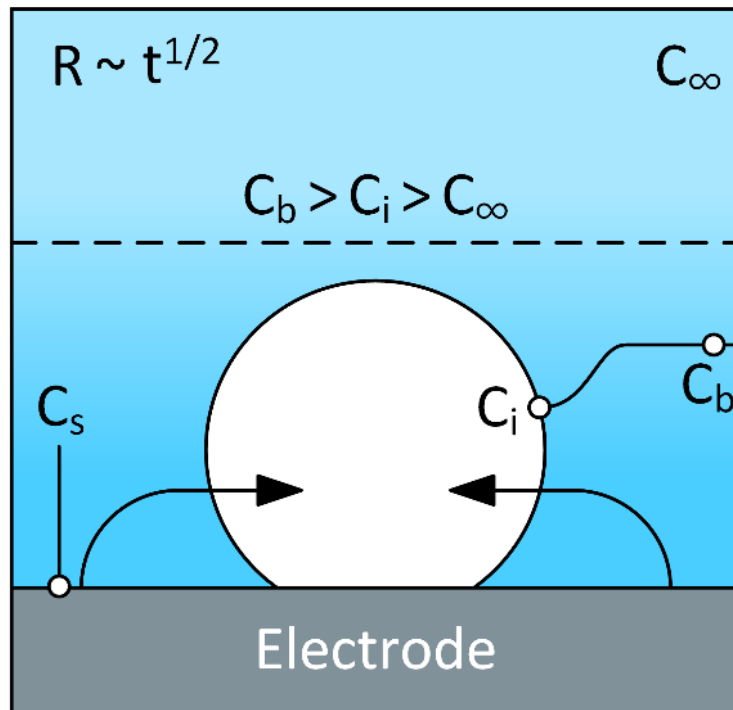


Balancing the kinetic energy of the flow field and the total work exerted from the pressure driven bubble expansion

$$R \sim t$$

Rayleigh–Plesset equation
(similar to the boiling case)

- Second stage: diffusion-controlled growth

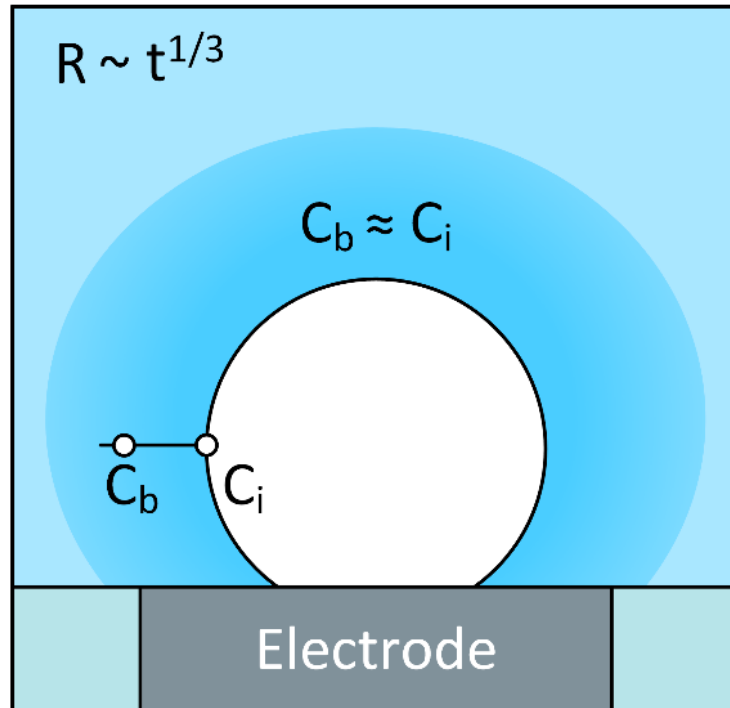


Bubble growth dictated by gas diffusion from the electrode to liquid-gas interface

$$R \sim \sqrt{t}$$

In boiling, this corresponds to thermal conduction from heated surface to liquid-vapor interface

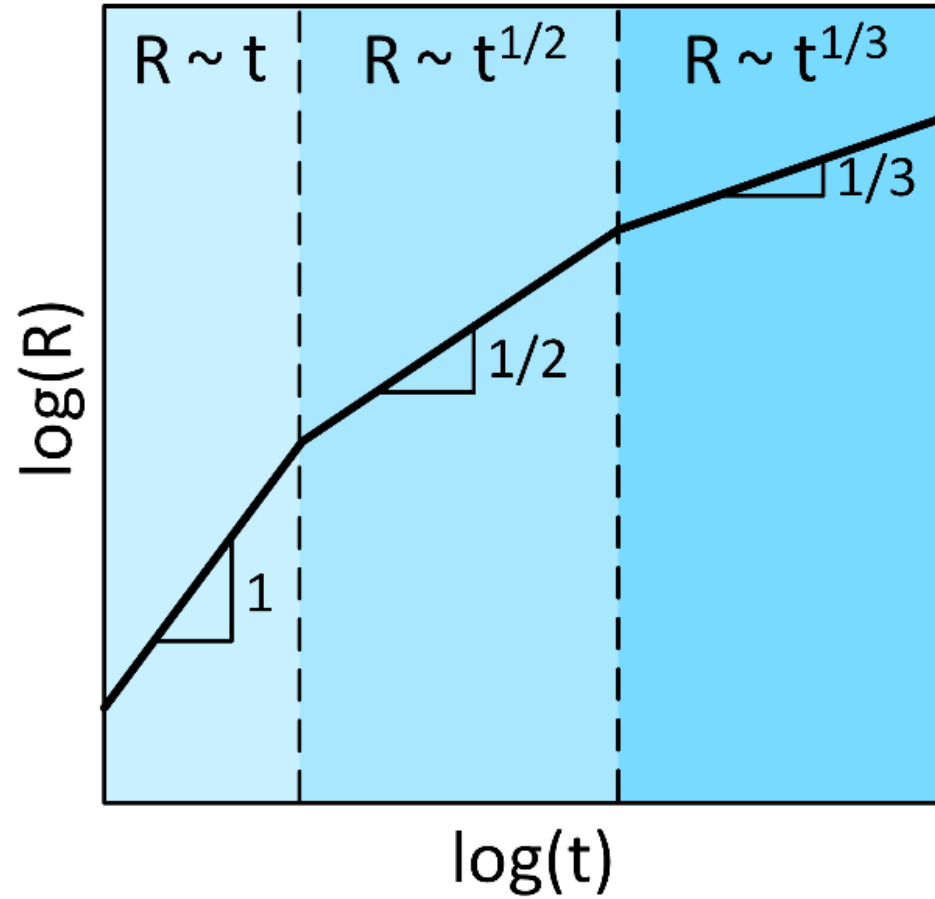
- Third stage: reaction-controlled growth

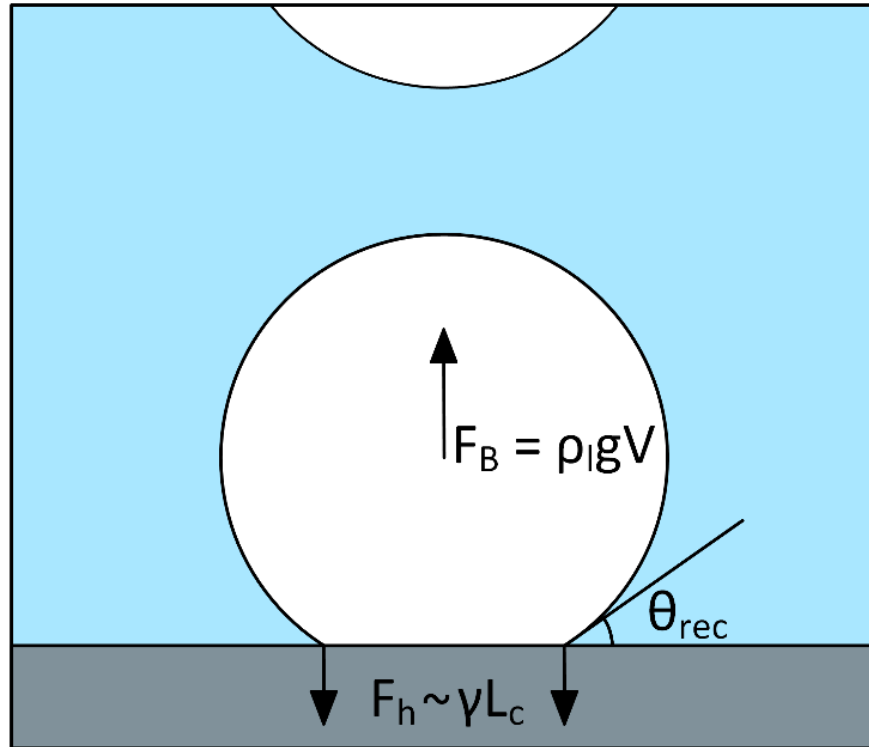


Rate of bubble volumetric increase is ultimately proportional to the total electrochemical reaction rate over the entire electrode surface

When bubble size is comparable to the electrode size,

$$R \sim t^{1/3}$$

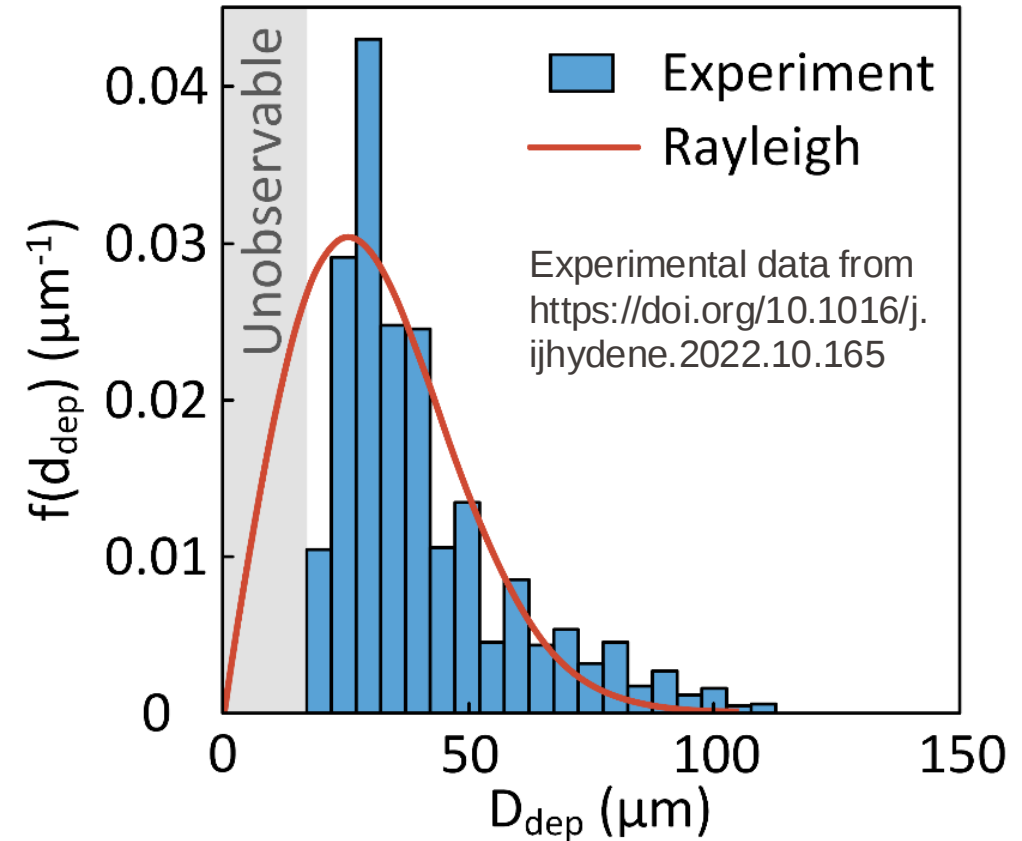
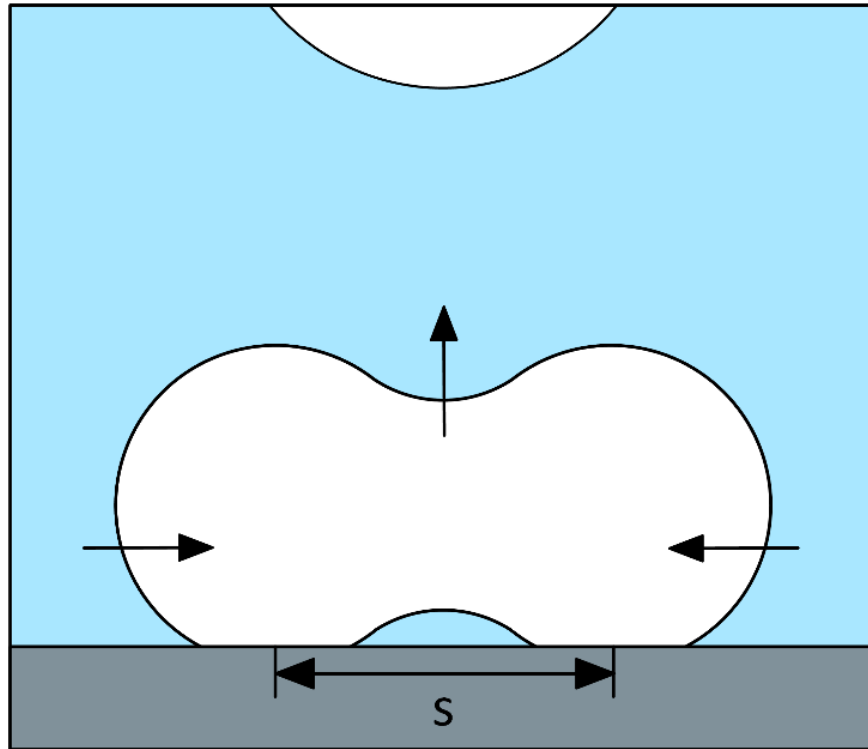




Fritz expression for
bubble departure

$$\text{Bo}_d^{1/2} = 0.0208\theta$$

$$\text{Bo}_d = \frac{(\rho_l - \rho_v)d^2g}{\sigma_{lv}}$$



When two bubbles coalesce into one, volume is roughly conserved, but surface area becomes smaller. Excess surface energy needs to be released.