EPFL

ETA-Lab
Energy Transport Advances

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

Condensation Enhancement

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2025 Fall Semester

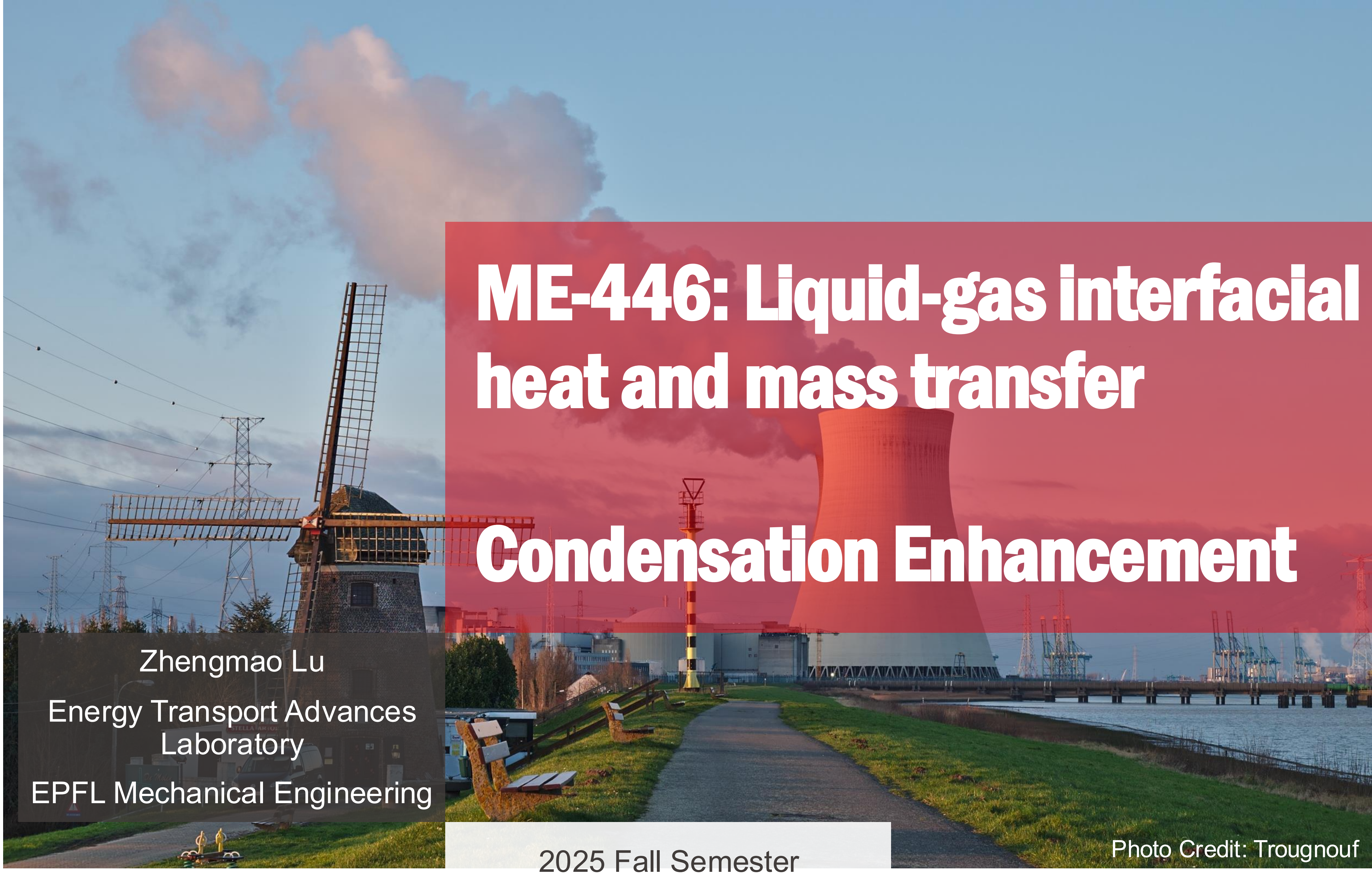


Photo Credit: Trougnouf

Last Time

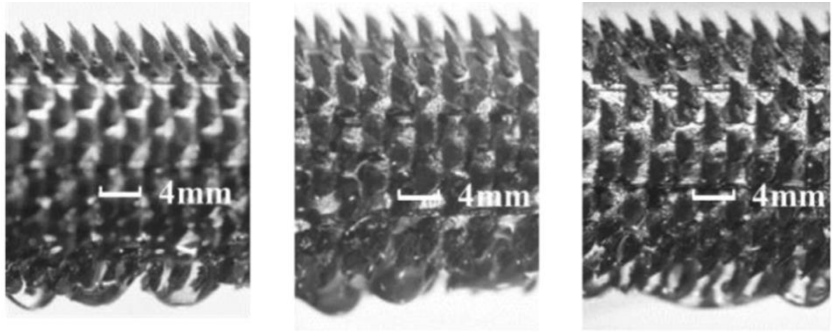
- Nucleation in condensation
- Rose's analysis of dropwise condensation
- Nusselt's analysis of filmwise condensation

Intended Learning Objective Today

- Typical condensation enhancement strategies
- Jumping-droplet condensation
- Design principles for lubricant infused surface
- Wicking condensation

Condensation Enhancement

Finned Tube Condenser



Gu *et al.*, *International Journal of Heat and Mass Transfer* 2020

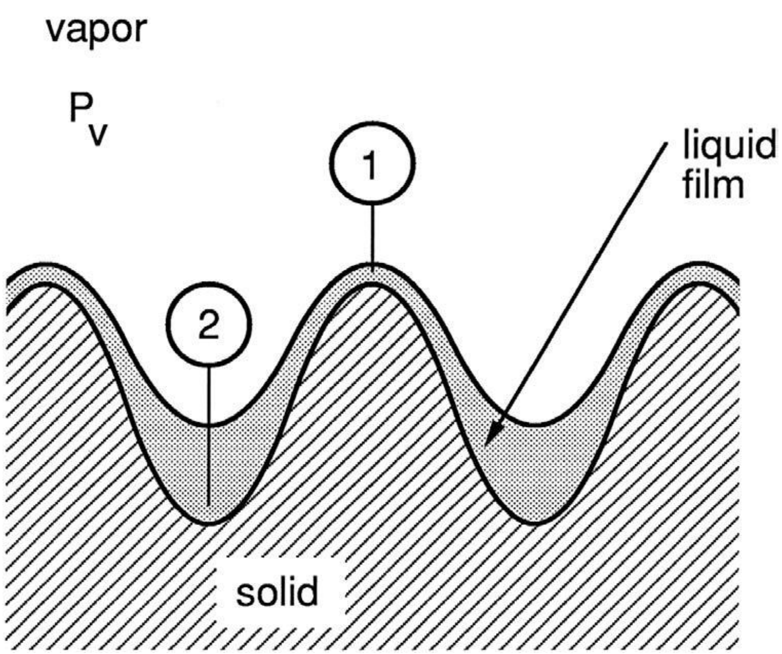
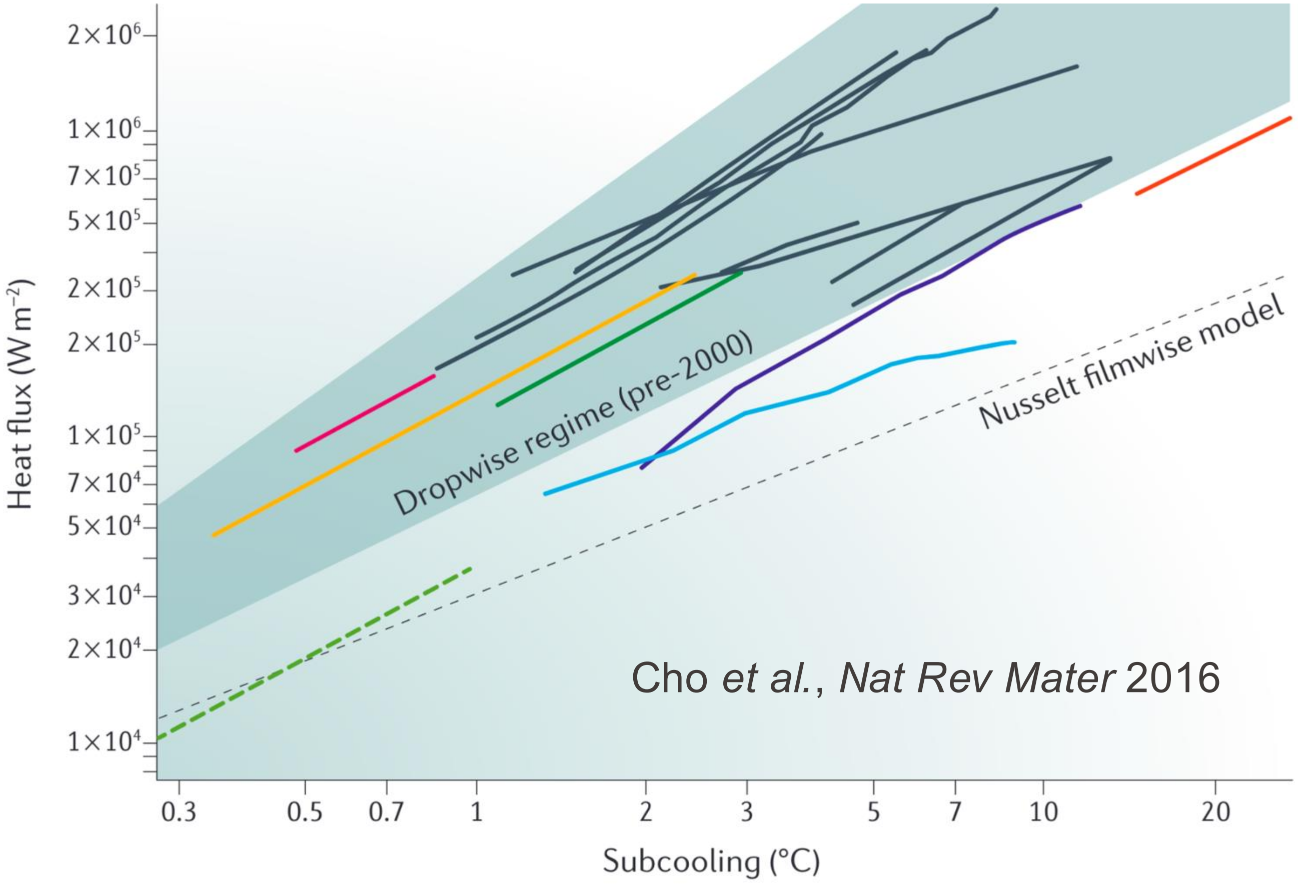


FIGURE 9.26 in Carey

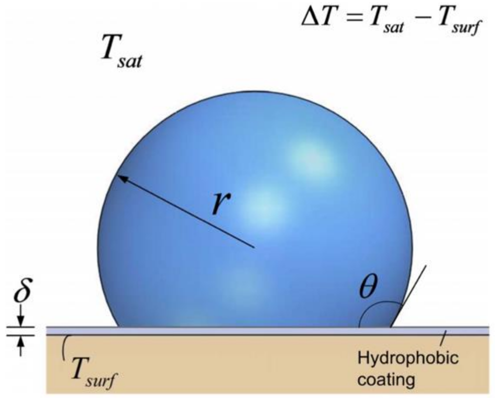
Increase condensation heat transfer area

Promoting Dropwise Condensation



Cho *et al.*, *Nat Rev Mater* 2016

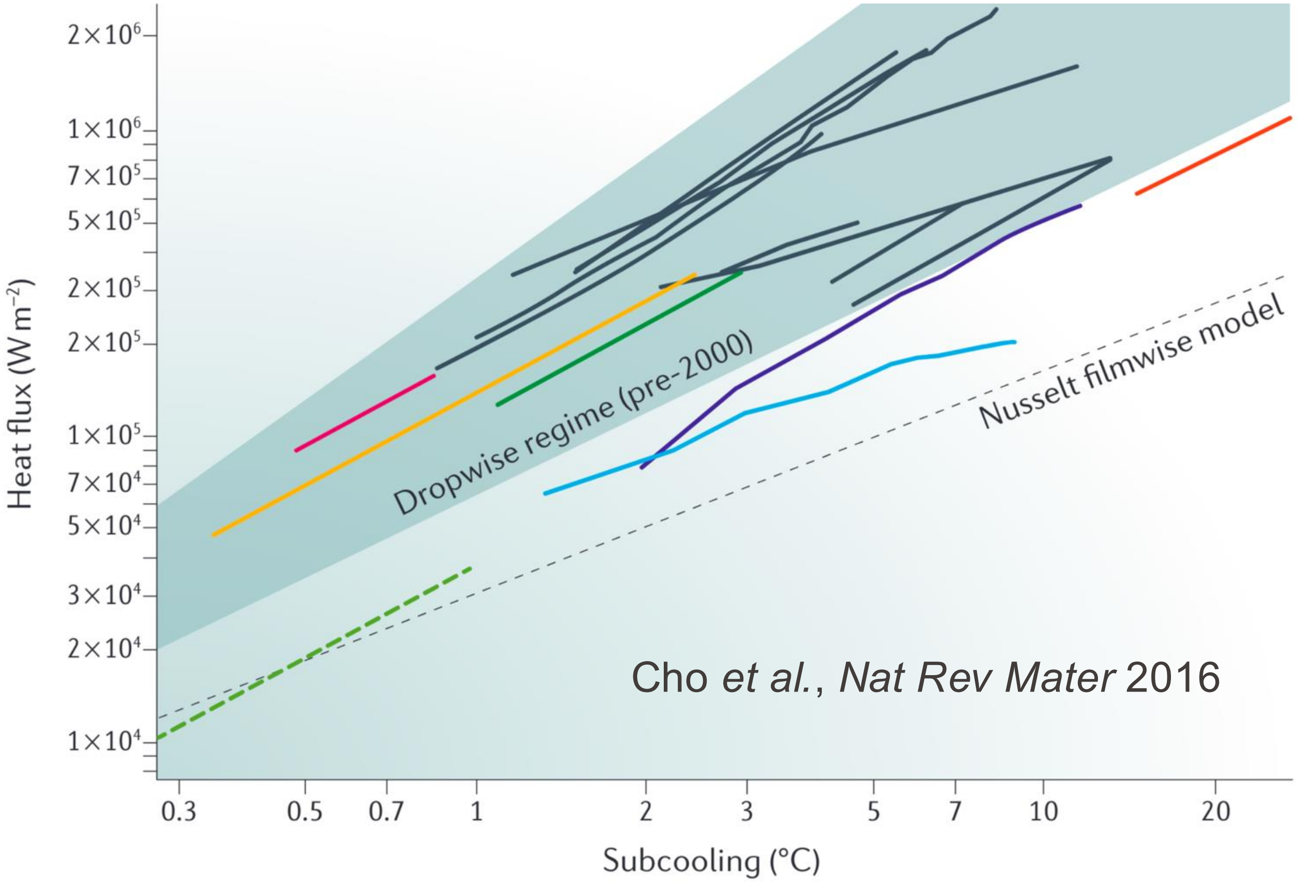
Flat Hydrophobic Coating



- Increase contact angle and decrease contact angle hysteresis

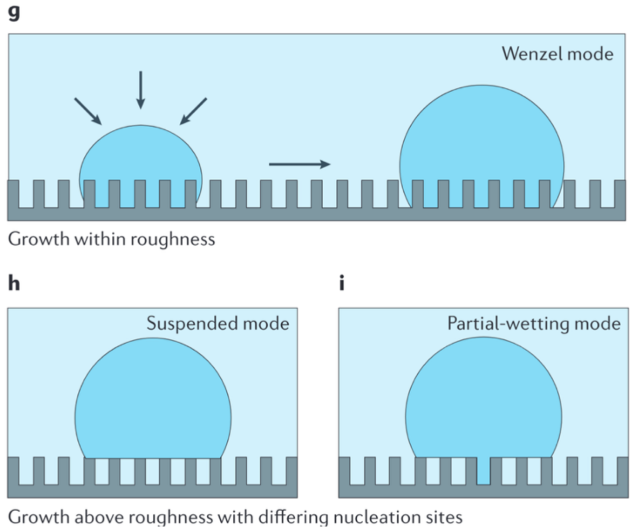
- When contact angle is be too large, there’s not enough contact area for heat transfer

Condensation Enhancement



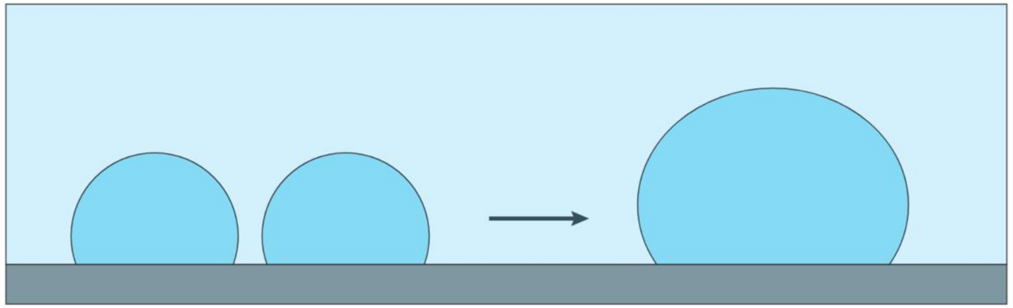
Cho *et al.*, *Nat Rev Mater* 2016

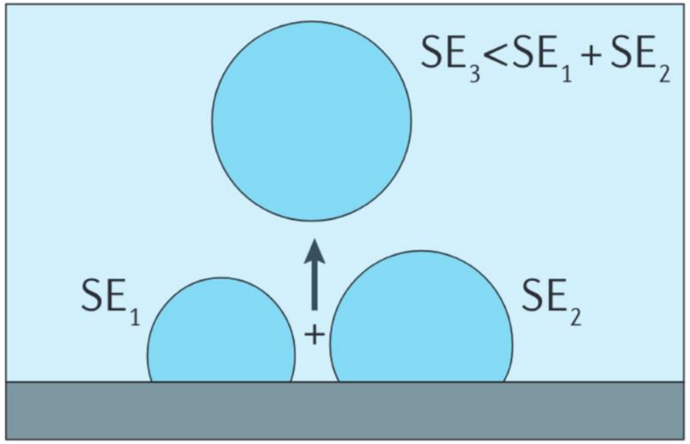
Surface Structure + Hydrophobic Coating



- When nucleation density becomes higher, surface structure may be flooded

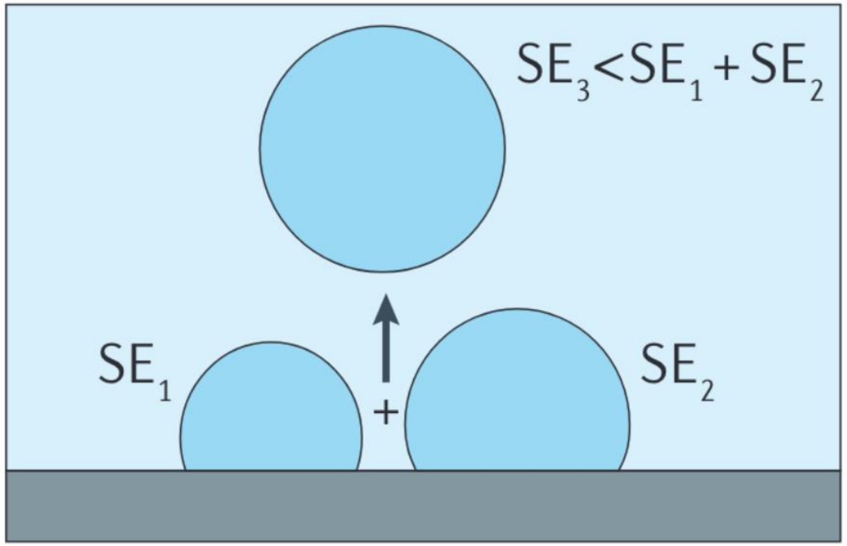
Jumping Droplet Condensation





https://doi.org/10.1103/PhysRevLett.103.184501

Jumping Droplet Condensation



Coalescence departure

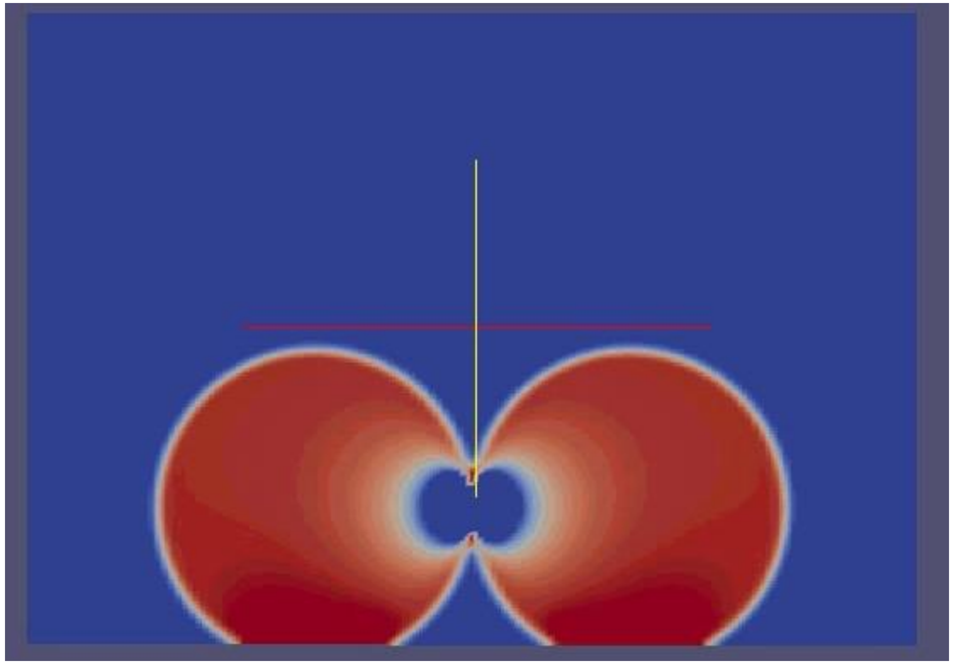
$$\Delta E_s \sim \sigma \Delta A \sim \sigma R^2$$

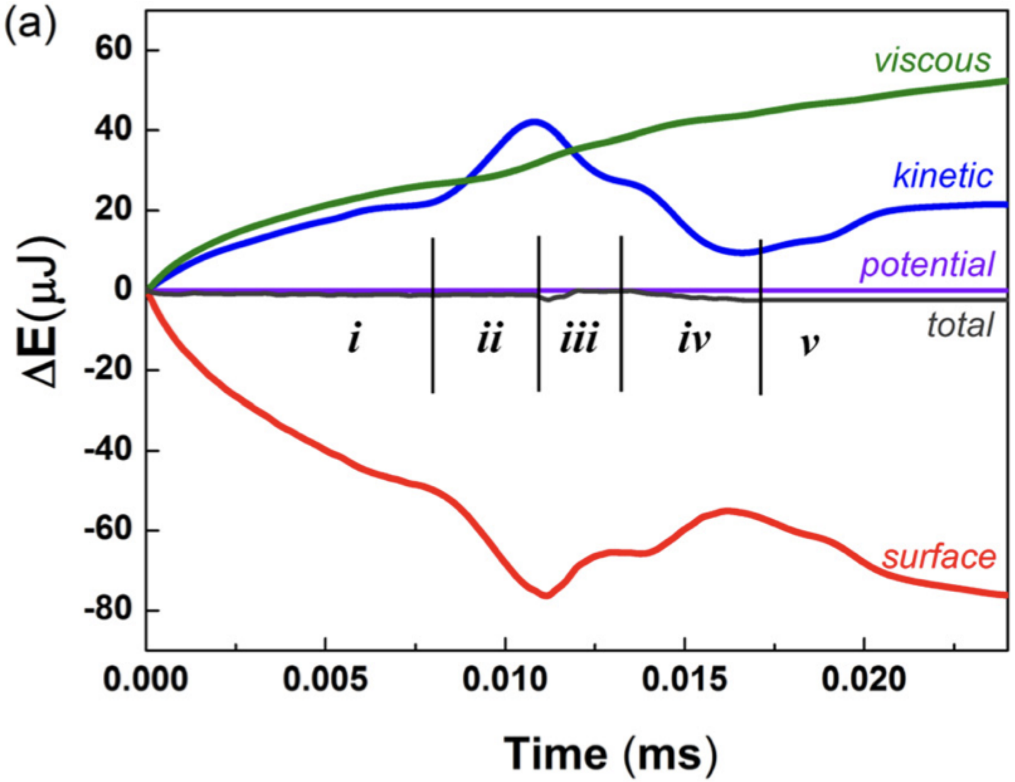
$$KE \sim \frac{1}{2}\rho R^3 U^2$$

$$U \sim \sqrt{\frac{\sigma}{\rho R}}$$

Viscous dissipation ignored

Jumping Droplet Condensation





Appl. Phys. Lett. 103, 161601 (2013)

Only possible when the surface is superhydrophobic

Distribution of Droplet Radii in Dropwise Condensation

- Probability density function

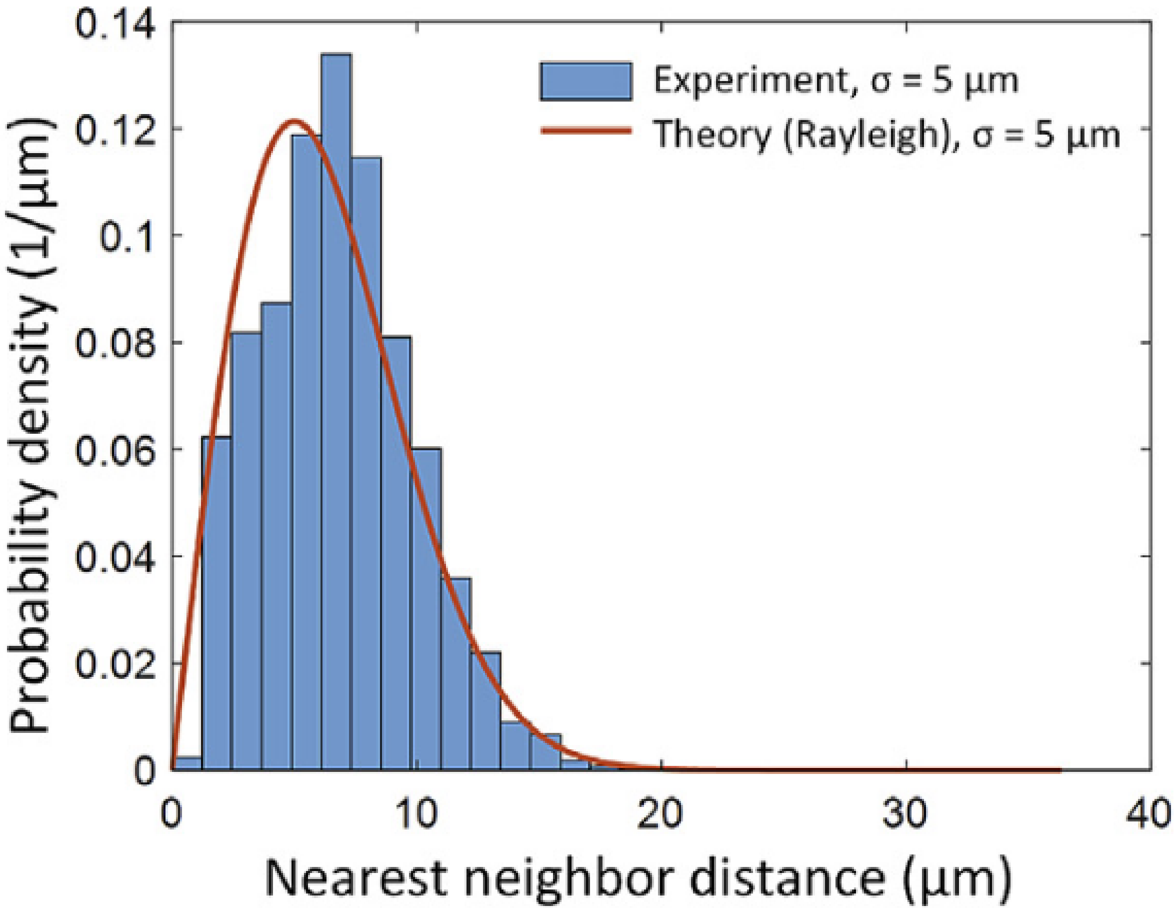
$$A(r) = \frac{r^{-2/3}}{3r_{max}^{1/3}} \qquad r_{max} = K_3\sqrt{\frac{\sigma}{\rho g}} \qquad \text{for } r_e < r \leq r_{max}$$

$$h_{dc} = \frac{1}{\Delta T_t}\int_{r_e}^{r_{max}} \frac{q_d}{2\pi r^2} A(r)dr$$

Average droplet radius

$$\bar{r} = \int_{r_e}^{r_{max}} rA(r)dr \approx \frac{1}{4} r_{max} \sim 300\ \mu m$$

Distribution for Jumping Droplet Condensation

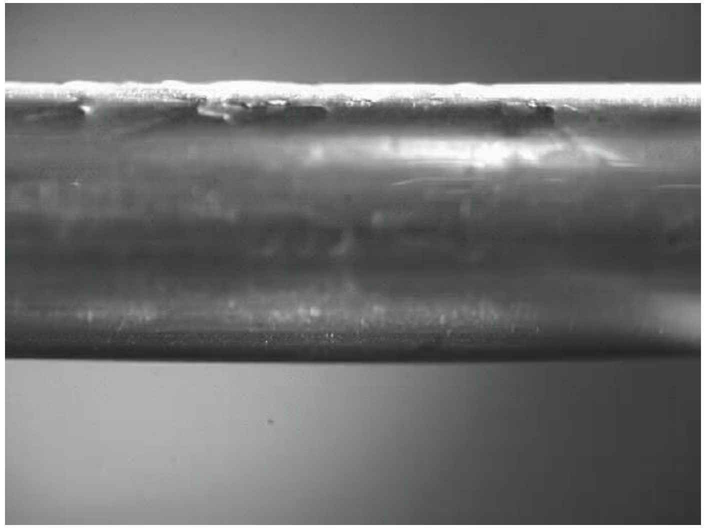


- Since contacting neighboring droplet will cause jumping removal, droplet radius should be around half the nearest neighbor distance

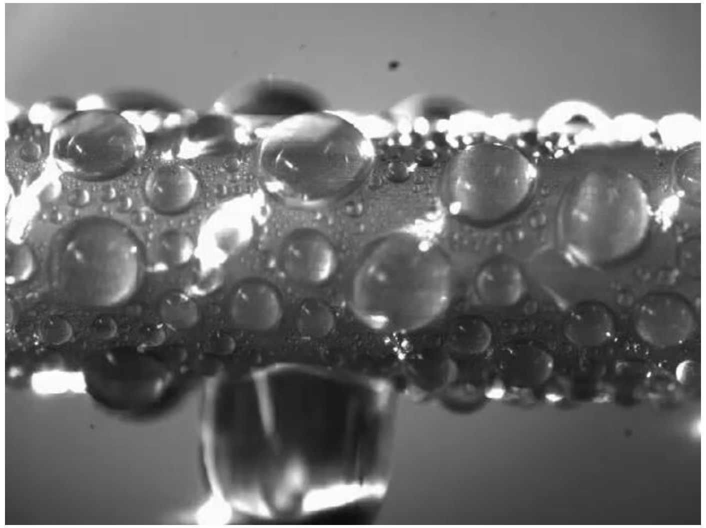
- Jumping-droplet mode will result in smaller average droplet sizes on the surface and better heat transfer

Different Condensation Mode

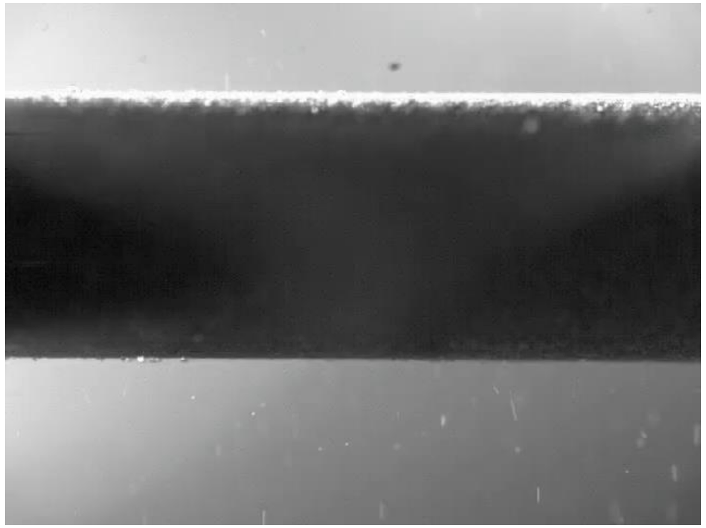
Superhydrophobic surface



Filmwise condensation



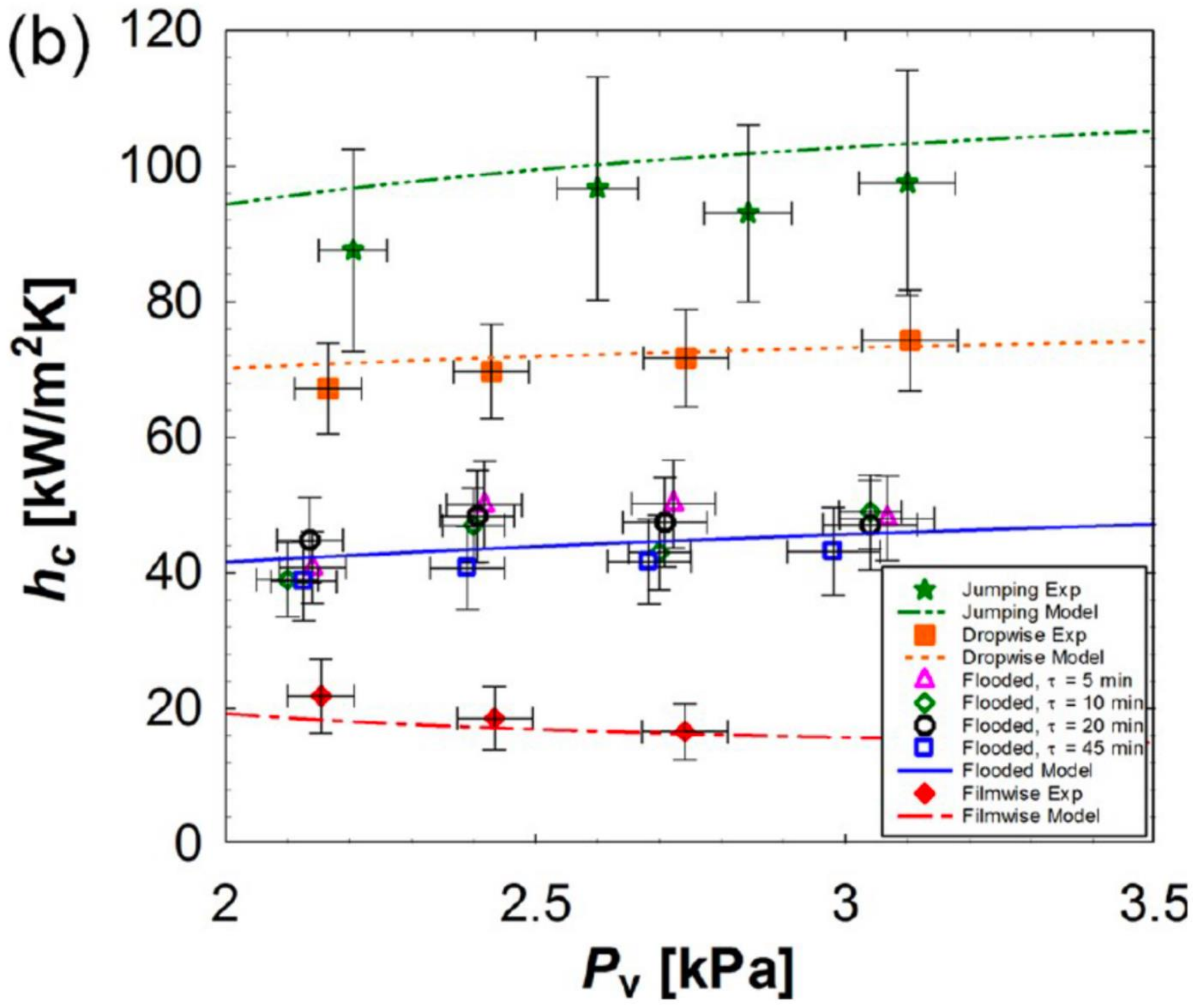
Dropwise condensation



Jumping-droplet condensation

Miljkovic *et al.*, *Nano Lett.* (2013)

Heat Transfer Enhancement



Jumping-droplet

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Dropwise

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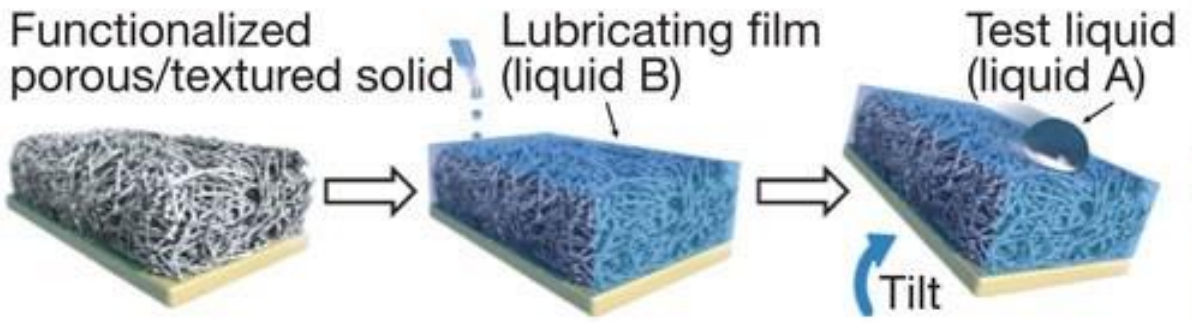
Filmwise

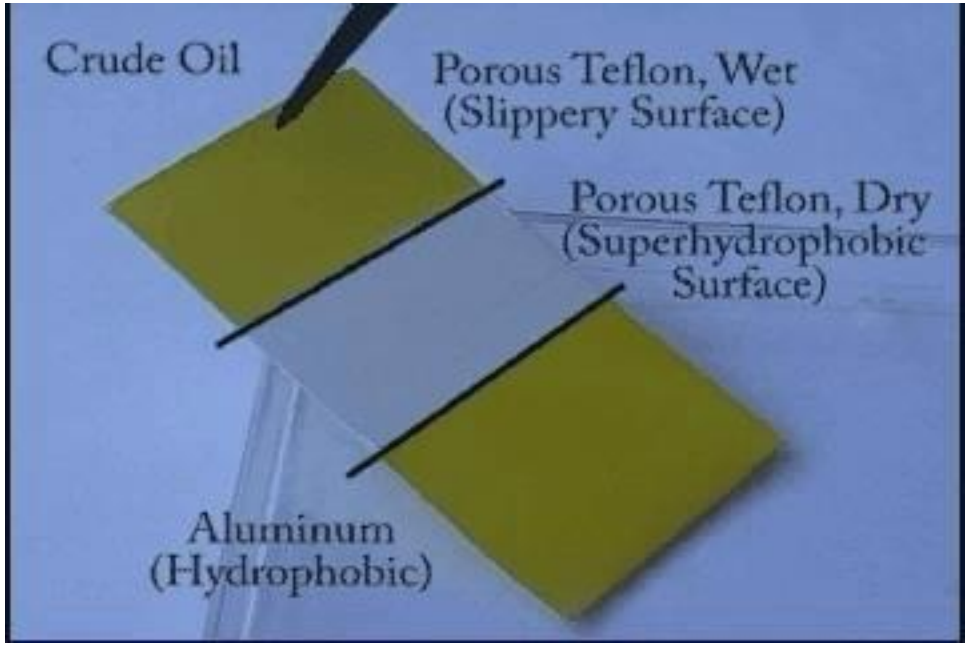
Nano Lett. 2013, 13, 179−187

How About Low Surface Tension Fluids

Lubricant Infused Surface (LIS)



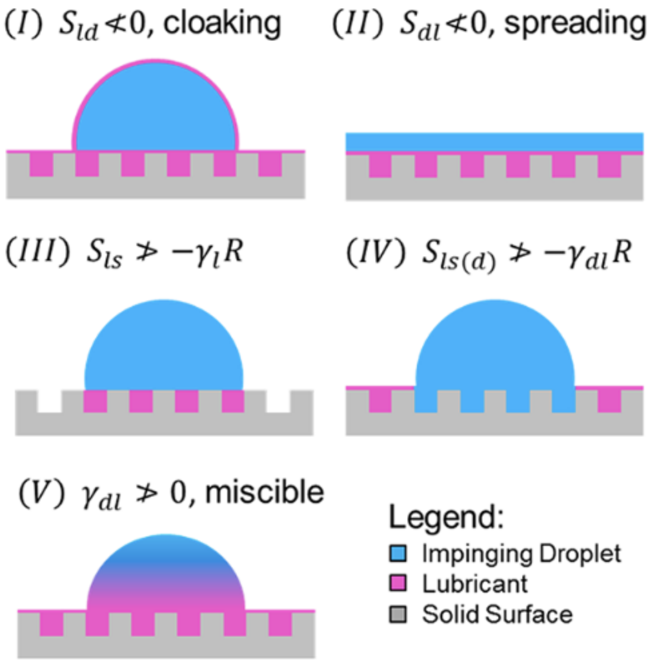
Nature volume 477, pages 443–447 (2011)



How to Design LIS

Spreading Coefficient $S_{xy} = \gamma_y - (\gamma_{xy} + \gamma_x)$

$S_{xy} \geq 0$ implies *x* can spread on *y*



ACS Appl. Mater. Interfaces2017, 9, 42383−42392

Possible ways to fail

(I) Lubricant cloaking $S_{ld} \geq 0$

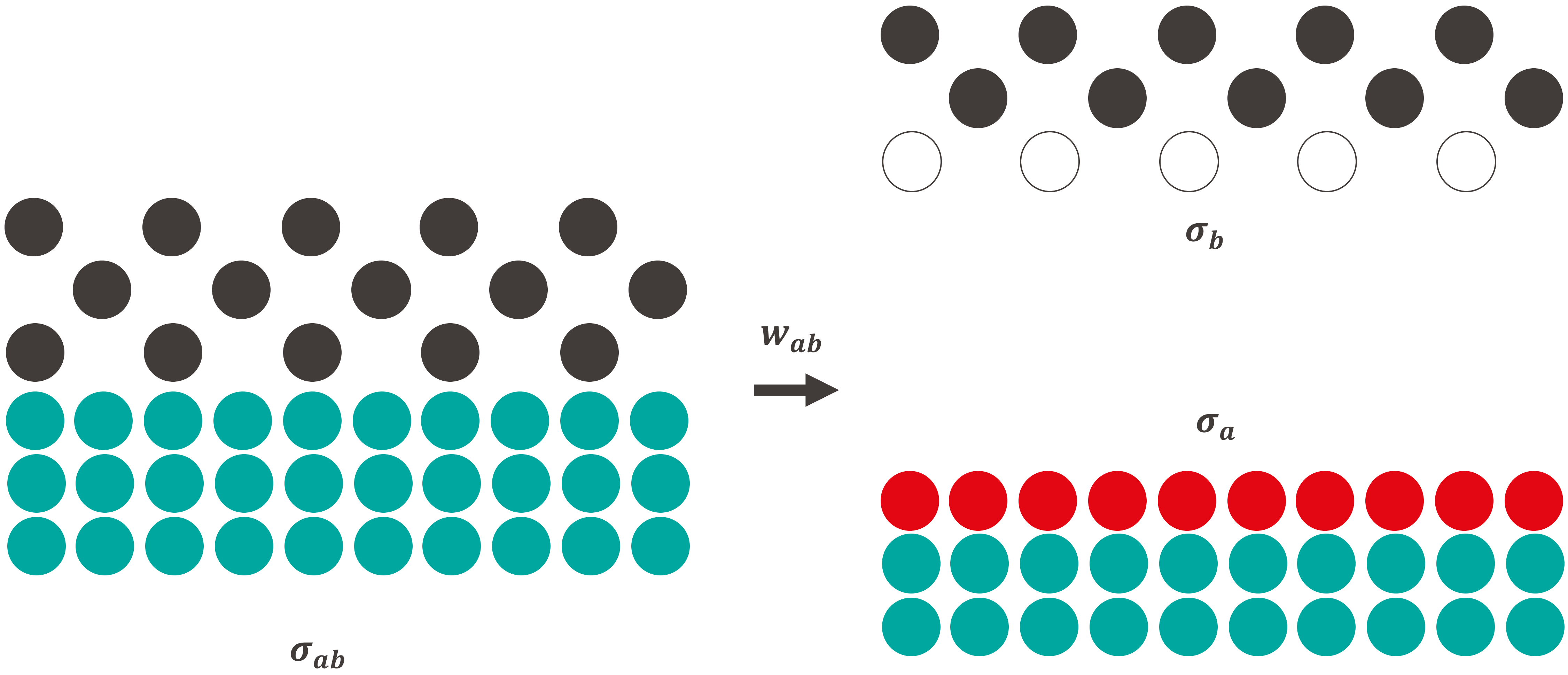
(II) Droplet spreading $S_{dl} \geq 0$

(III) No infusing $S_{ls} \leq \frac{r-1}{r-\phi}\gamma_l$

(IV) No infusing $S_{ls(d)} \leq \frac{r-1}{r-\phi}\gamma_{dl}$

(V) Miscible

From Week 2



$$\sigma_{ab} = \sigma_a + \sigma_b - w_{ab}$$

w_{ab} depends on intermolecular interactions

van Oss, Chaudhury, and Good (vOCG Model)

Langmuir 1992,8, 2877-2879

$$\gamma_A^{tot} = \gamma_A^{LW} + 2\sqrt{\gamma_A^+ \gamma_A^-}$$

$$\gamma_{AB}^{tot} = \gamma_A^{LW} + \gamma_B^{LW} - 2\sqrt{\gamma_A^{LW}\gamma_B^{LW}} + 2\sqrt{\gamma_A^+ \gamma_A^-} + 2\sqrt{\gamma_B^+ \gamma_B^-} - 2\sqrt{\gamma_A^+ \gamma_B^-} - 2\sqrt{\gamma_B^+ \gamma_A^-}$$

Phenomenological, Lifshitz-van der Waals component + polar component

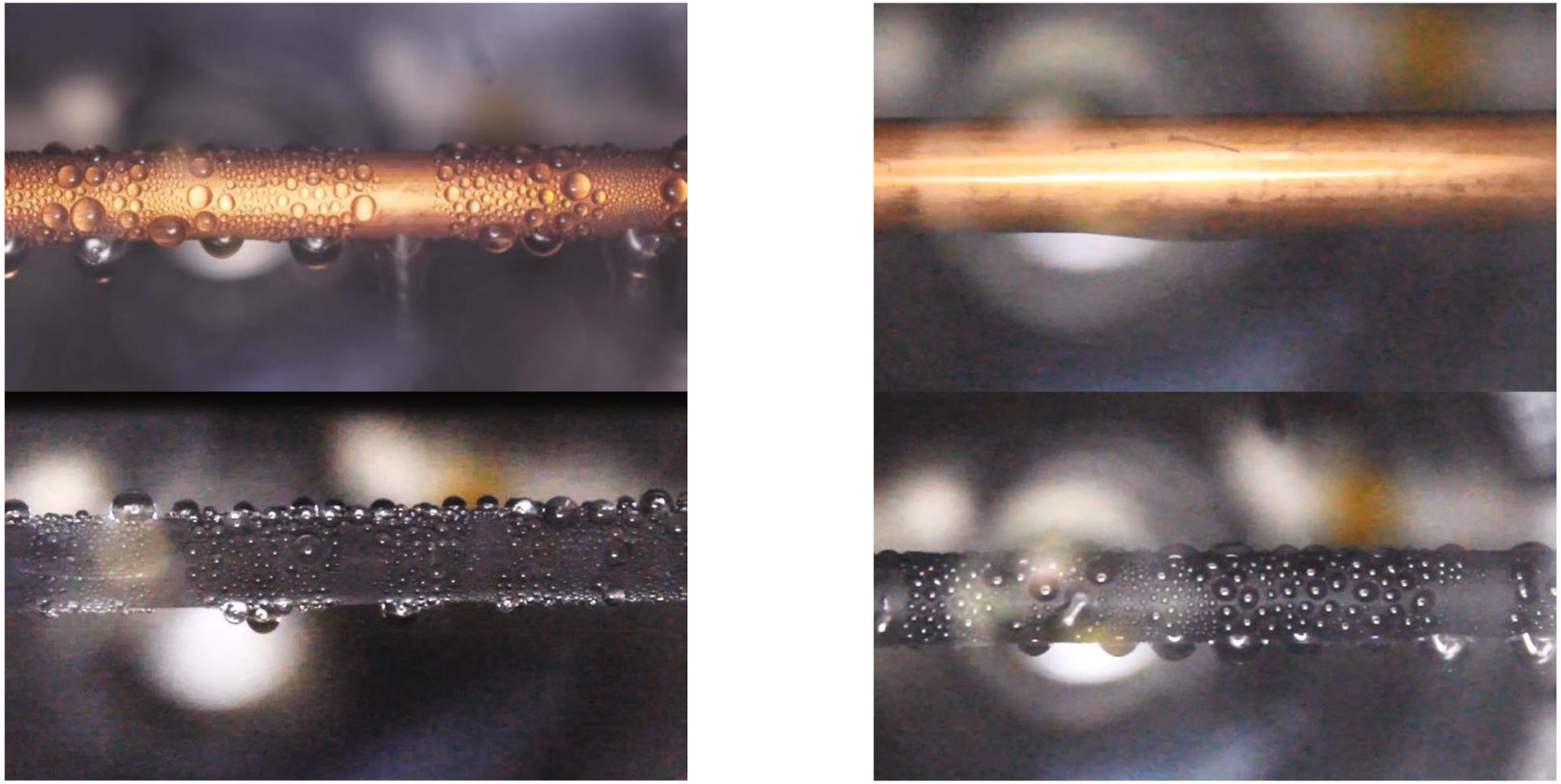
Metallic interactions not considered

Condensation Experiment

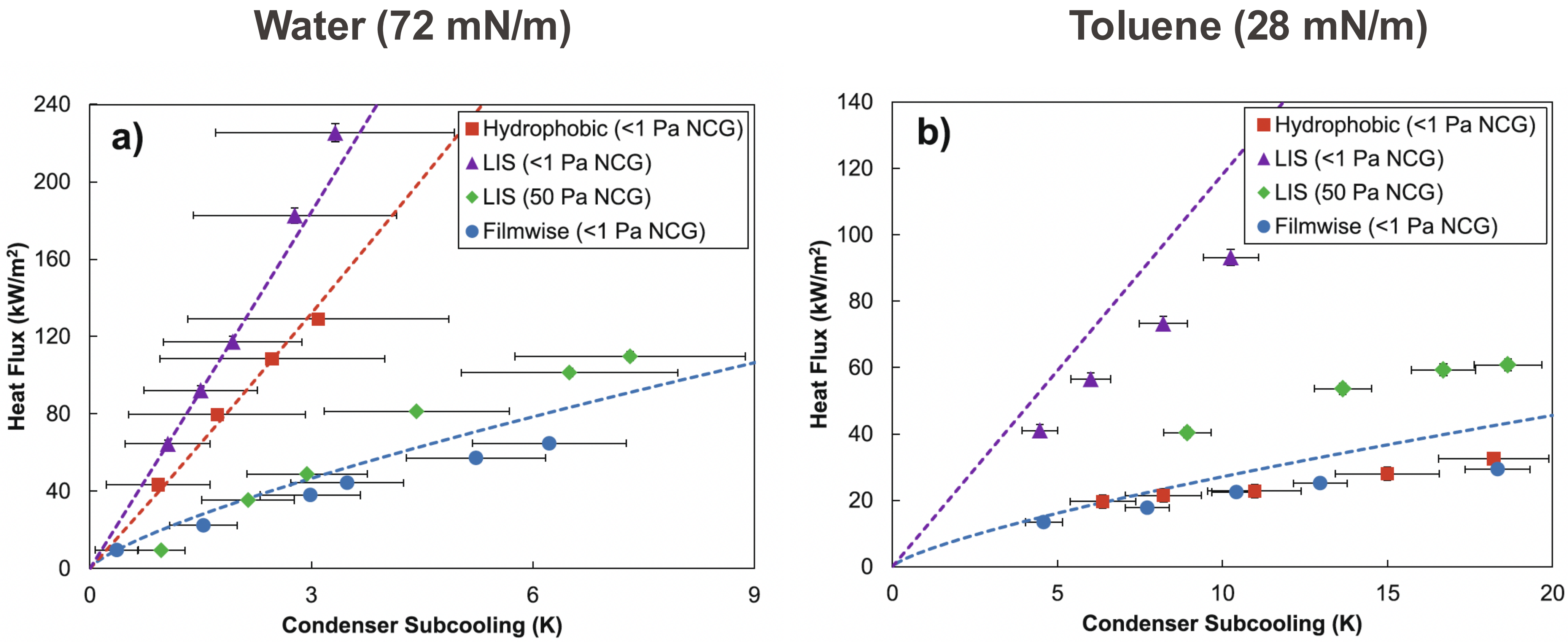
Water (72 mN/m) | Toluene (28 mN/m)

Regular hydrophobic

LIS



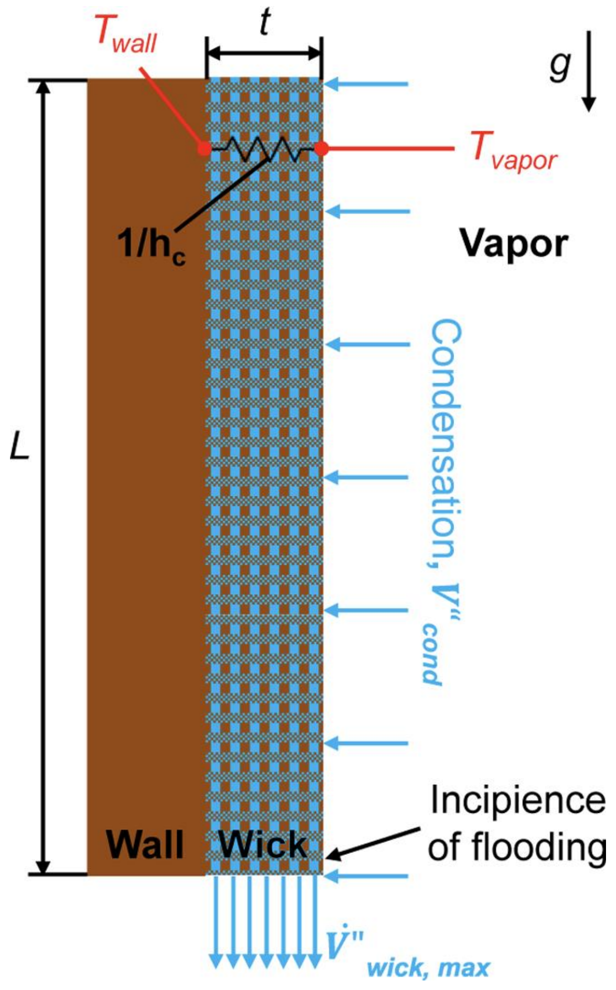
Heat Transfer Enhancement



Preston, D.J. et al. Sci Rep 8, 540 (2018)

Note the effect of NCG (non-condensable gases)

Wicking Condensation



Langmuir 2018, 34, 4658−4664

$$h_c = \frac{k_{wick}}{t}$$

$$\dot{m}''_{cond} h_{fg} = h_c \Delta T$$

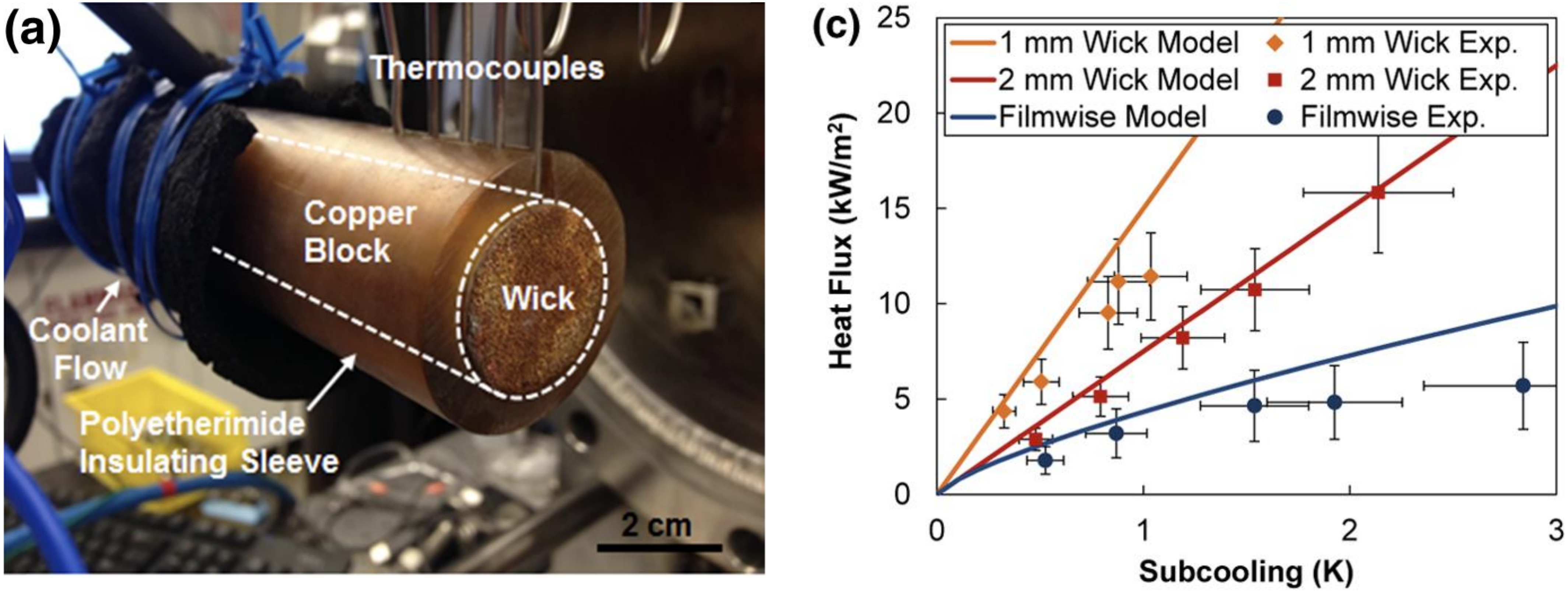
$$\dot{V}''_{wick,max} = \frac{\dot{m}''_{cond} L}{\rho t} = \frac{K}{\mu}\left|\frac{dP}{dx}\right|_{max}$$

K: permeability

$$\left|\frac{dP}{dx}\right|_{max} = \rho g$$

$$\Delta T < \frac{K \rho^2 g h_{fg} t^2}{L k_{wick} \mu}$$

Experimental Results



Langmuir 2018, 34, 4658−4664