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KOREAN NUCLEAR SOCIETY

The dropwise condensation heat transfer characteristics of CNT/OTS layered surface associated with non-condensable gas effect

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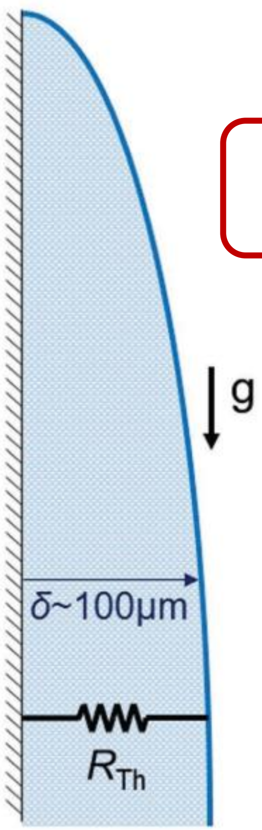
2020. 12. 16 ~ 18

Introduction

Dropwise condensation

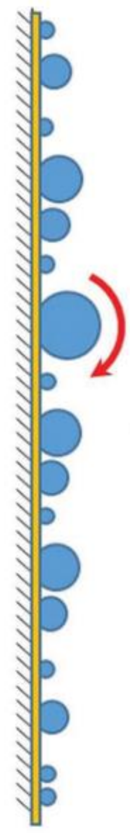
Filmwise



Hard to contact
Steam on surface

Large thermal
resistance

Dropwise



Easy to contact
Steam on surface

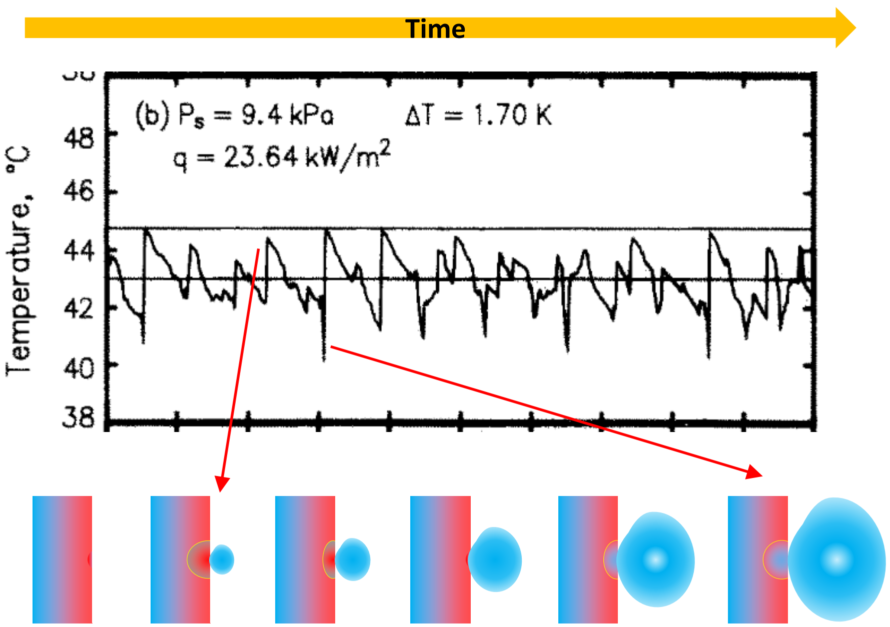
Droplet sweeping
and re-nucleation

Introduction

Dropwise condensation (Constriction resistance)

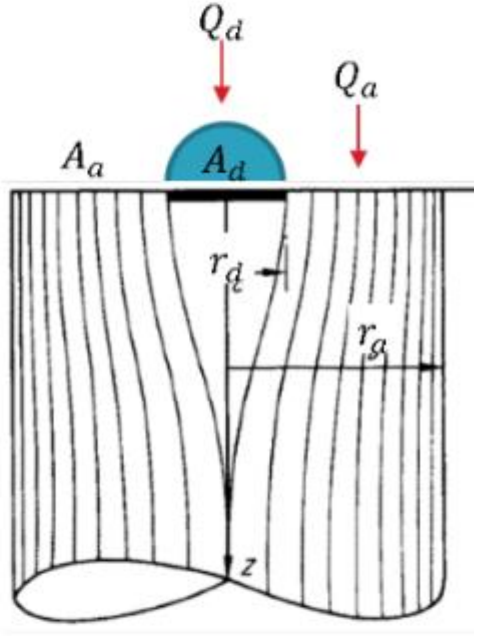
- **Constriction resistance** is caused by the bending of the heat flux lines in substrate
- It causes non-uniform heat flux and surface temperature on dropwise condensation

Temperature fluctuation



Droplet distribution

Heat flux line



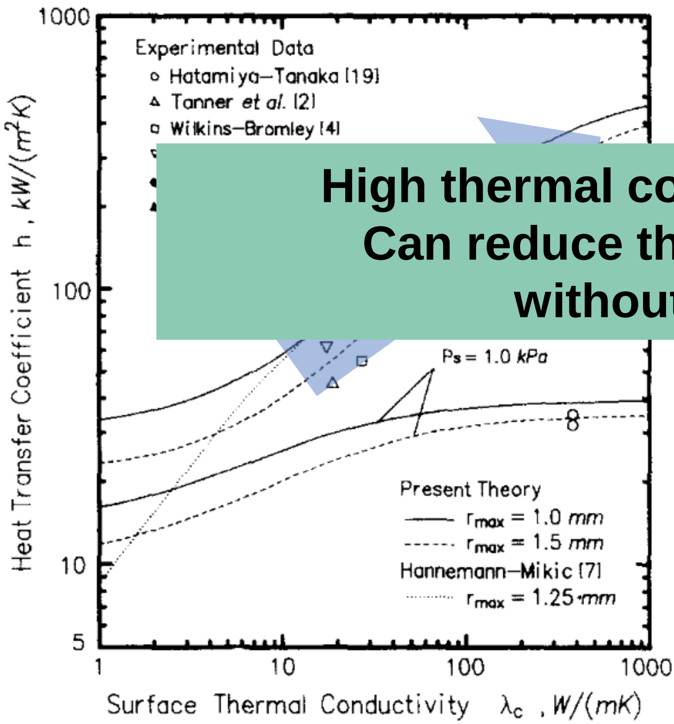
$$A = A_a + A_d$$

B. B. MIKIC, "On mechanism of dropwise condensation," International Journal of Heat and Mass Transfer 12 10, 1311 (1969); https://doi.org/10.1016/0017-9310(69)90174-4.

Introduction

Dropwise condensation (Constriction resistance)

- **High thermal conductive material** can reduce the constriction resistance
- The substrate material is often limited by its mechanical strength and integrity
- <u>**Changing the substrate material is impractical**</u> in many industrial applications



High thermal conductive material coatings
Can reduce the constriction resistance
without substrate change

surface

High heat transfer coefficient

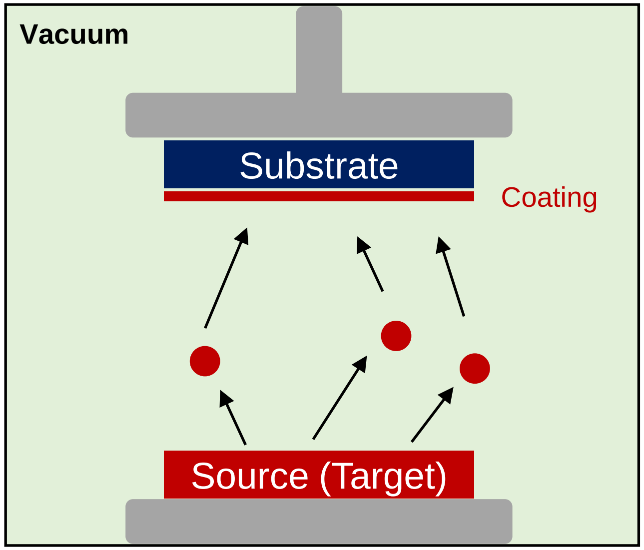
T. TAKAHARU and H. TANAKA, "A theoretical study on the constriction resistance in dropwise condensation," International Journal of Heat and Mass Transfer (1991); https://doi.org/10.1016/0017-9310(91)90237-9.

Introduction

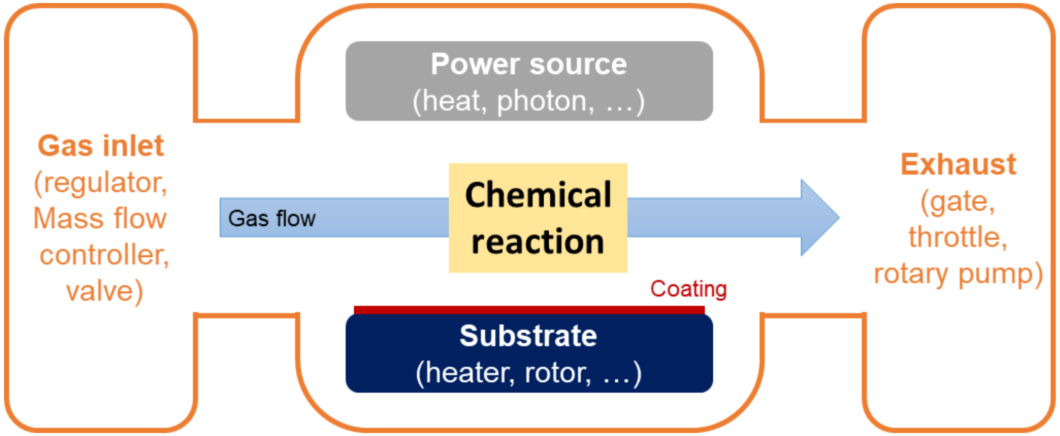
Surface modification technique

- Surface modification can change the surface material without altering substrate
- **CVD and PVD are well known surface modification techniques**
- However, it needs high temperature or vacuum condition
- It is difficult to apply the commercial heat transfer tubes such as heat exchanger

PVD



CVD



Introduction

The objective of this study

- Useful surface modification technique(**Layer-by-layer**) was selected.
- High thermal conductive material(Multi-walled carbon nanotube) was deposited
- **Condensation heat transfer experiment** was conducted on modified surface

High thermal conductive coatings

↓

Condensation heat transfer experiment

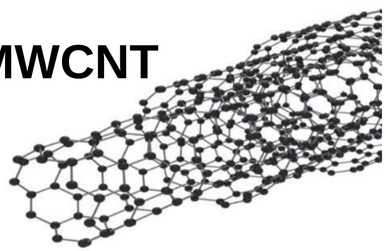
↓

Discussion of the constriction resistance

Surface modification

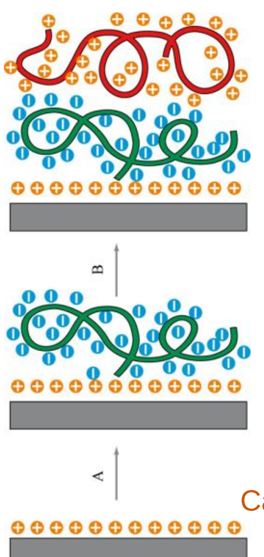
LbL assembled MWCNT coating

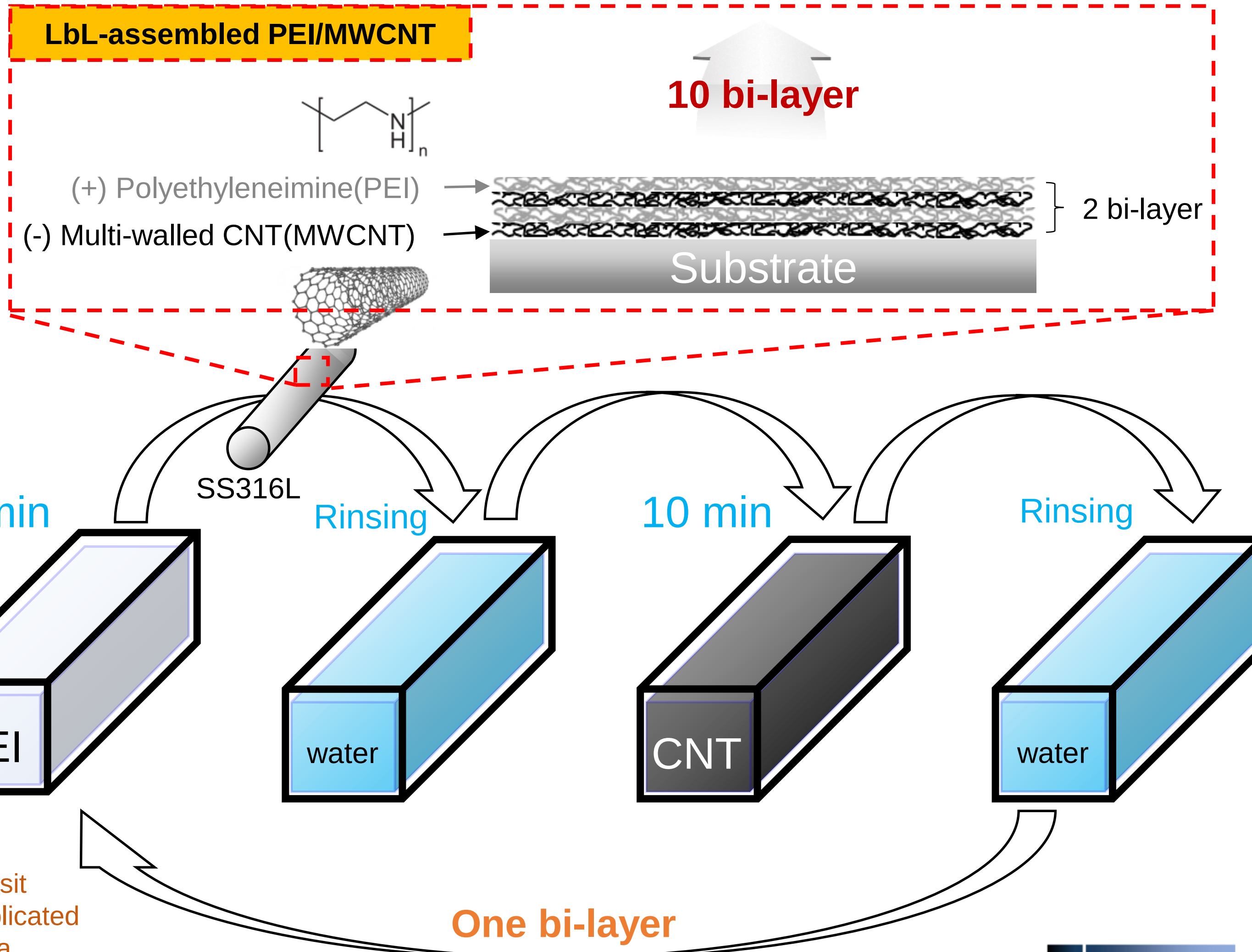
MWCNT



Tensile strength ↑
Thermal conductivity ↑

Layer-by-Layer(LbL)

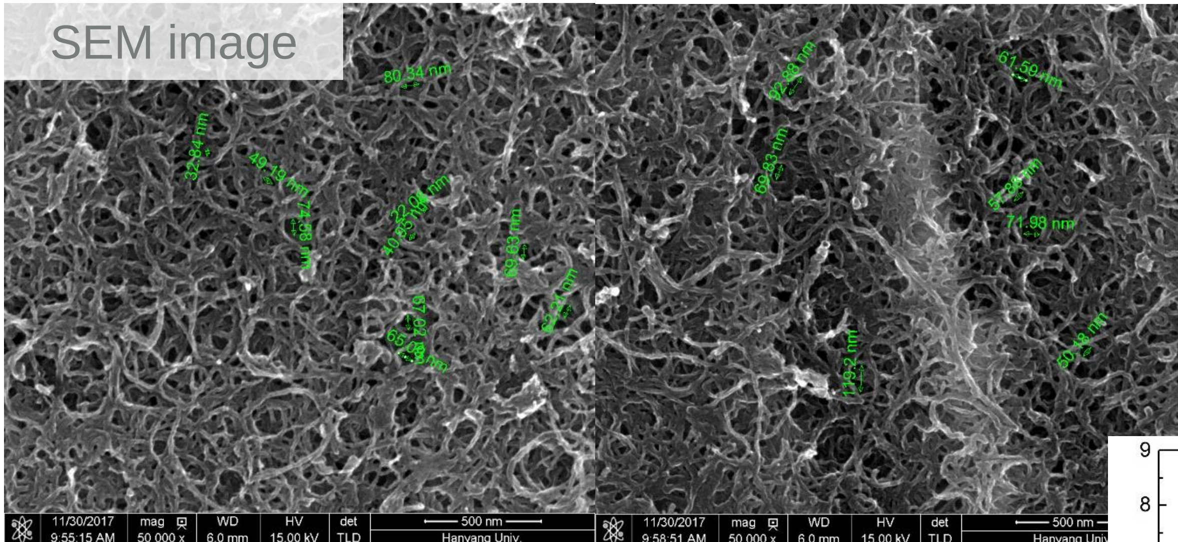


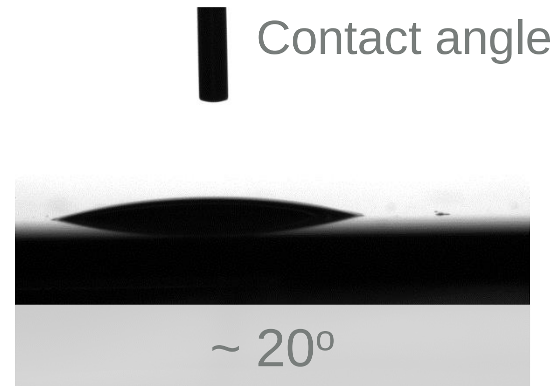


Easy to deposit
Capable on complicated
or large area

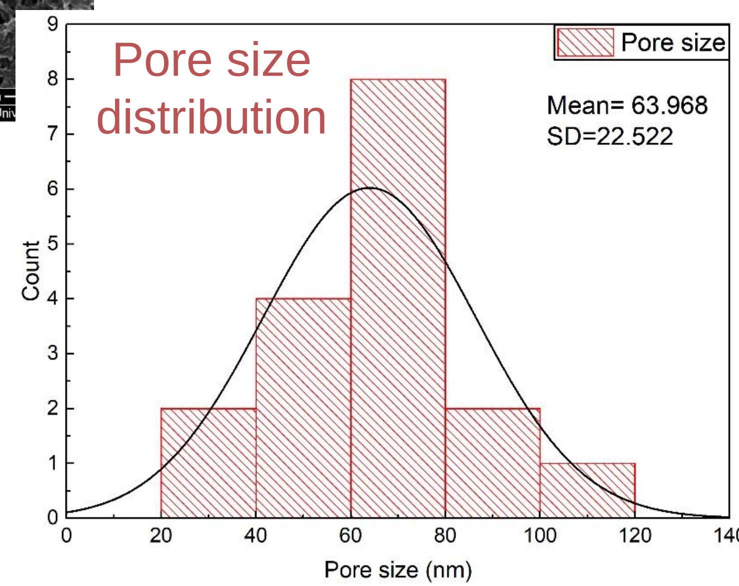
Surface modification

LbL assembled MWCNT coating



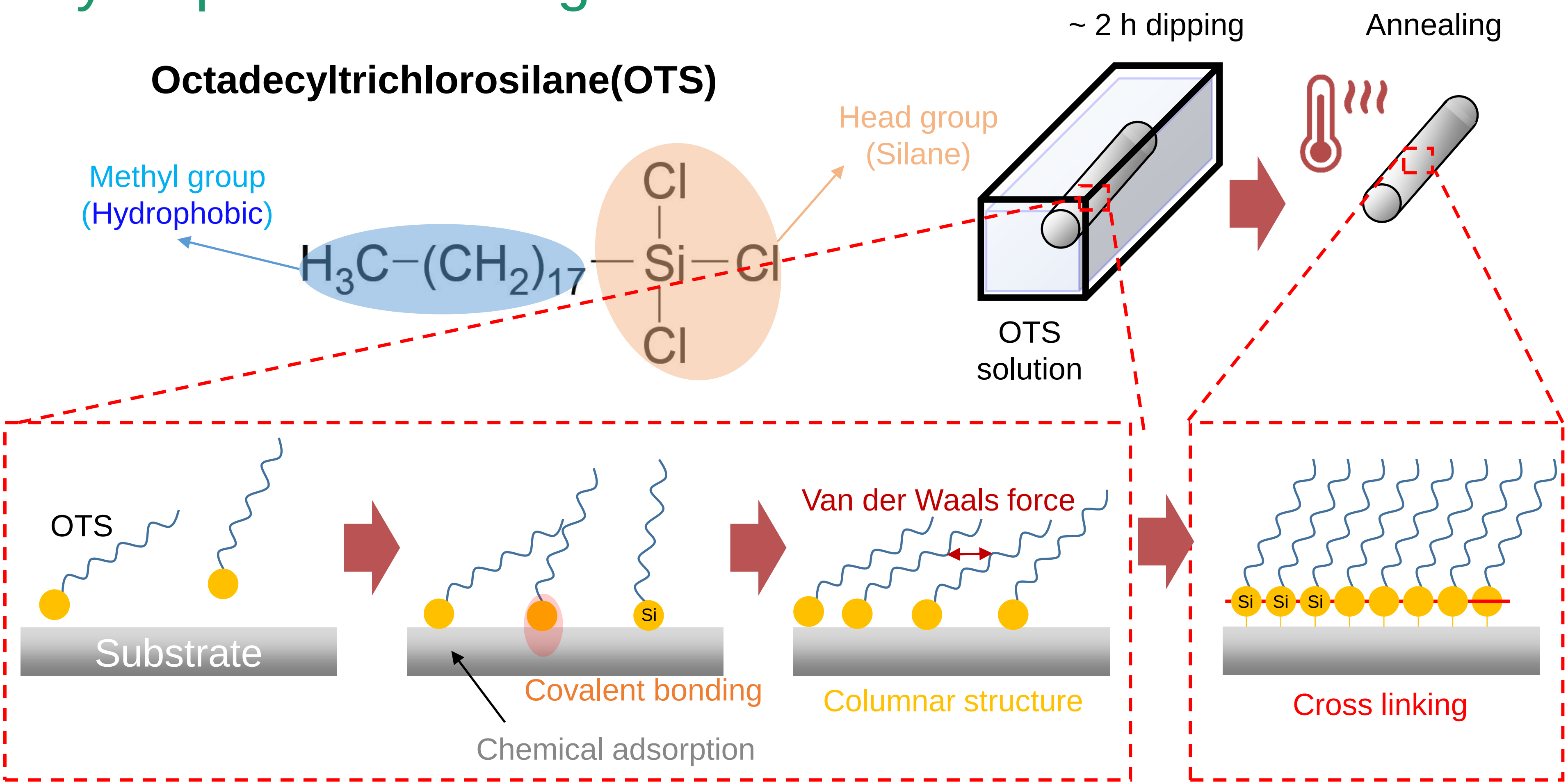


Coating material	CNT
Bi-layer	10
Pore size	~ 64 nm
Thickness	~ 760 nm (ref)
Contact angle	~ 20º



Surface modification

Hydrophobic coating

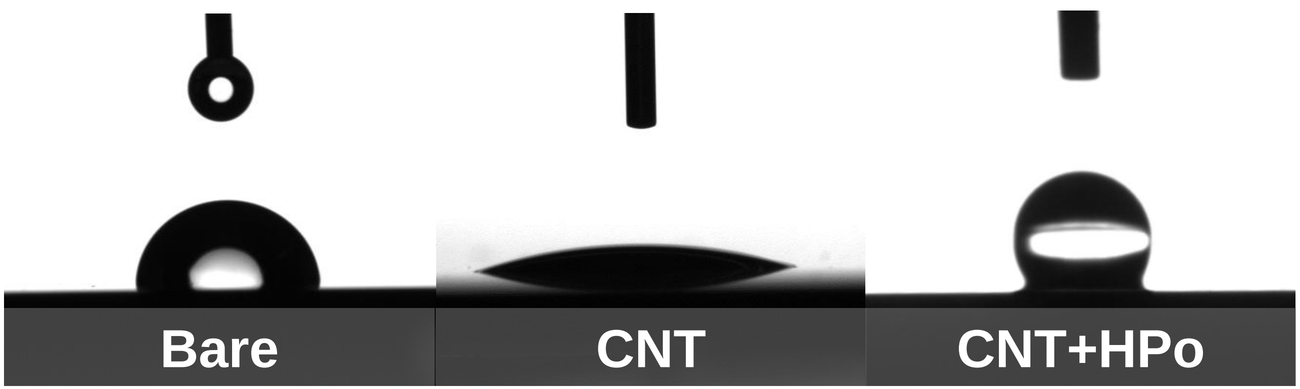


Surface modification

Surface preparation

- Three surface were prepared for the condensation heat transfer experiment
- The substrate was selected to commercial stainless-steel (Bare)
- LbL-assembled MWCNT surface(CNT) cannot promote the dropwise condensation
- Hydrophobic coatings on the CNT surface was deposited (CNT+HPo)

CA ~ 85º **CA ~ 20º** **CA ~ 105º**



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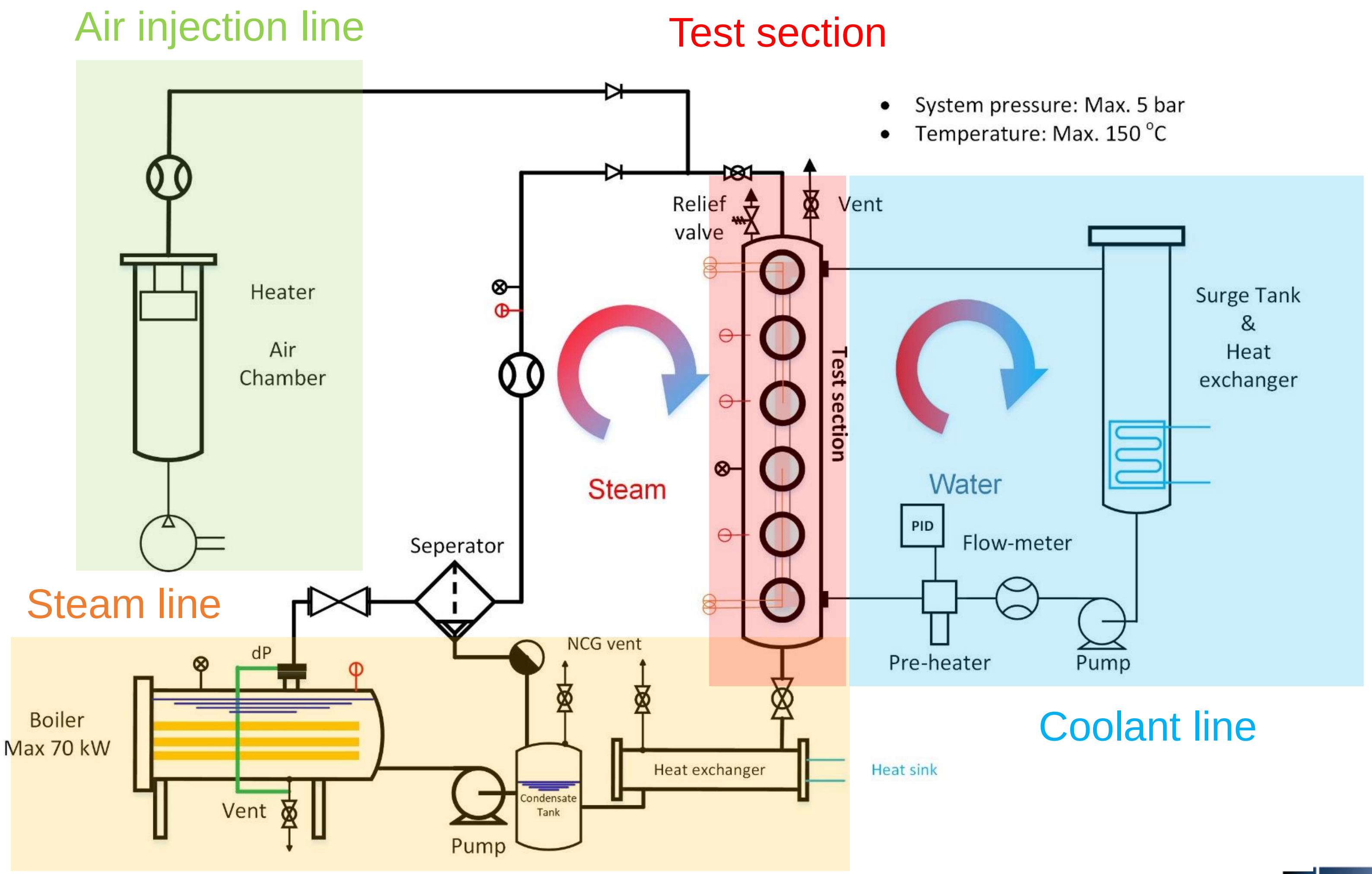
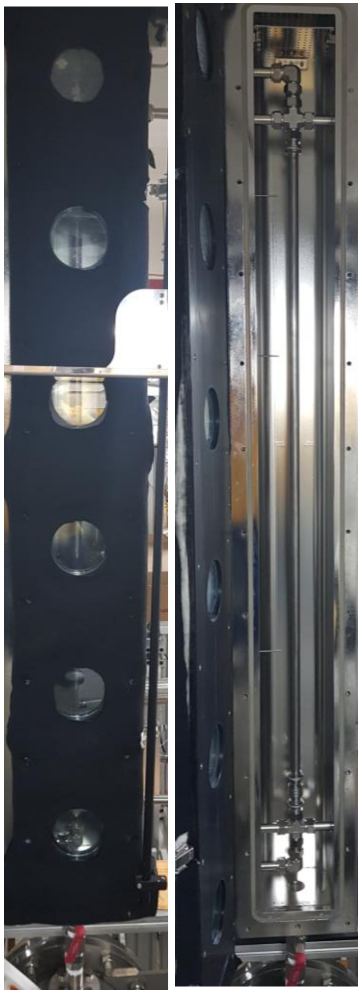
Method

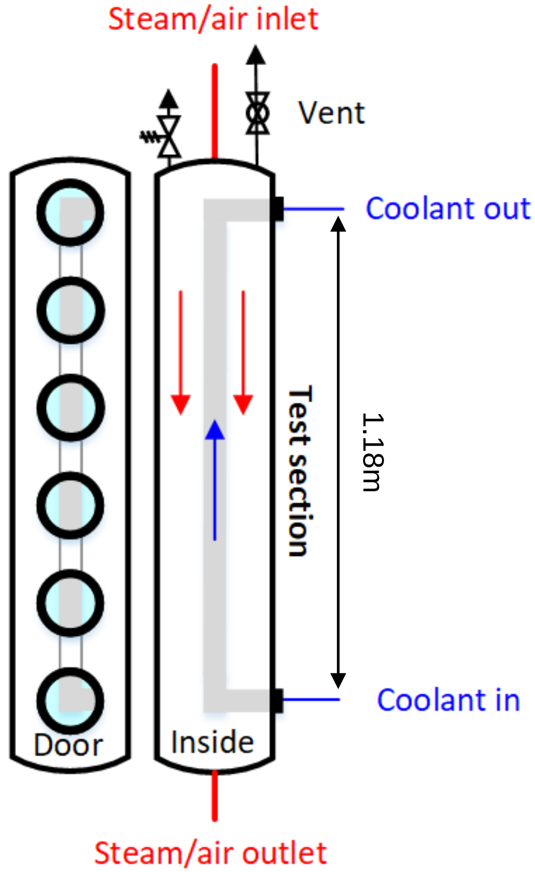
Experimental set up (Test Loop)



Method

Experimental set up (Test section)

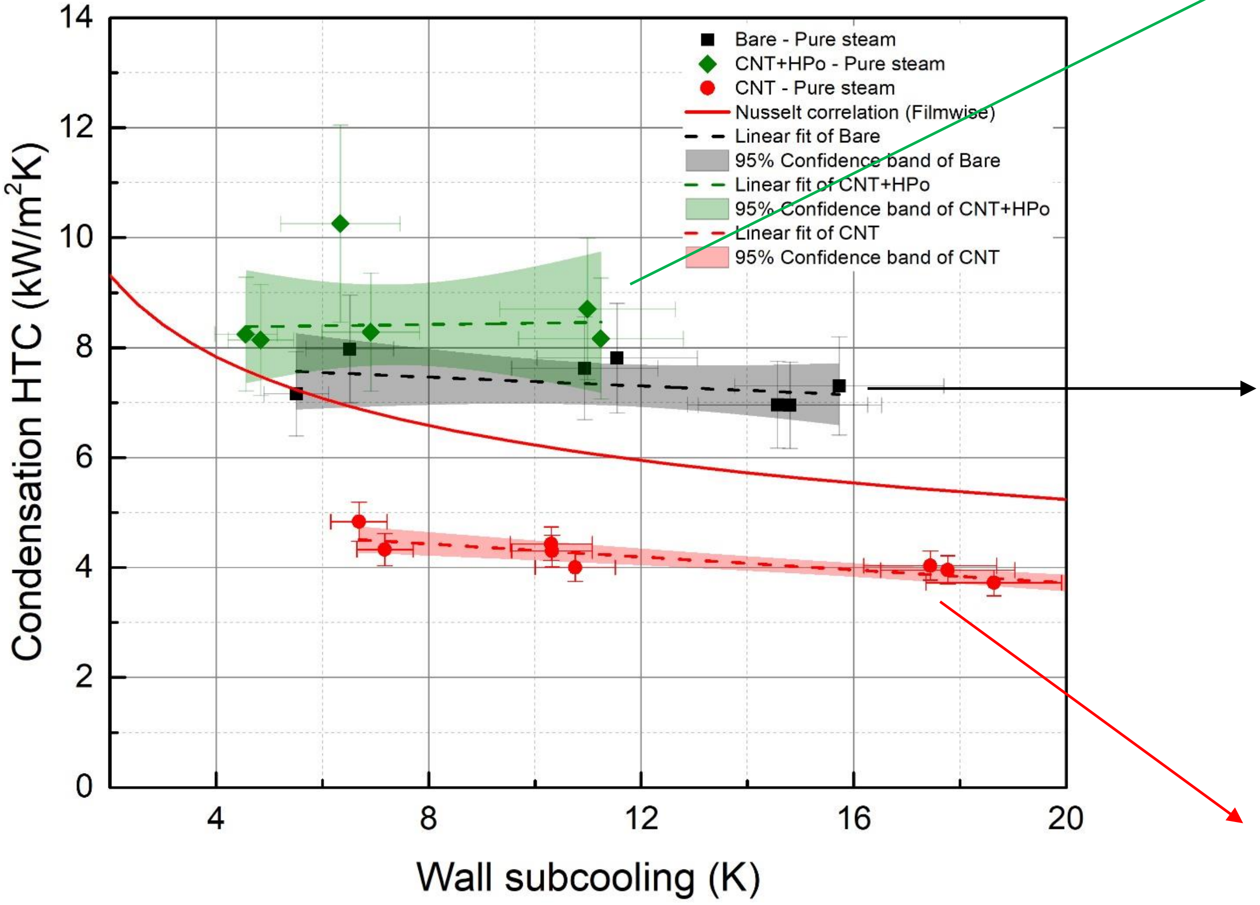


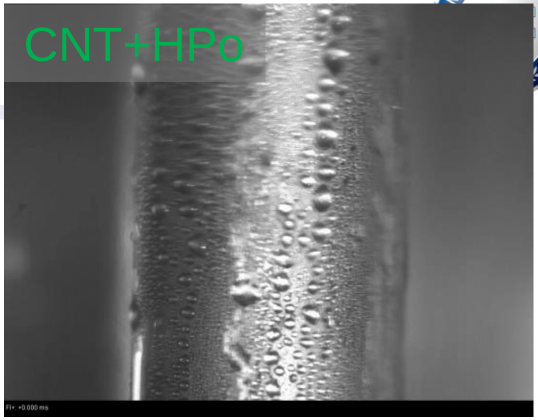


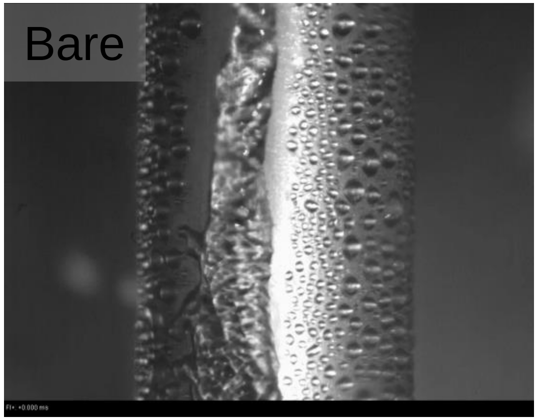
Steam flow area	0.02 m^2
Test specimen Length	1.18 m
Test specimen diameter	19.05 mm
Steam pressure	1 bar
Steam mass flux	0.1 kg/m^{2}s (~ 0.16 m/s)
Coolant mass flux	1600 kg/m^{2}s (~ 1.6 m/s)

Result

Condensation heat transfer coefficient

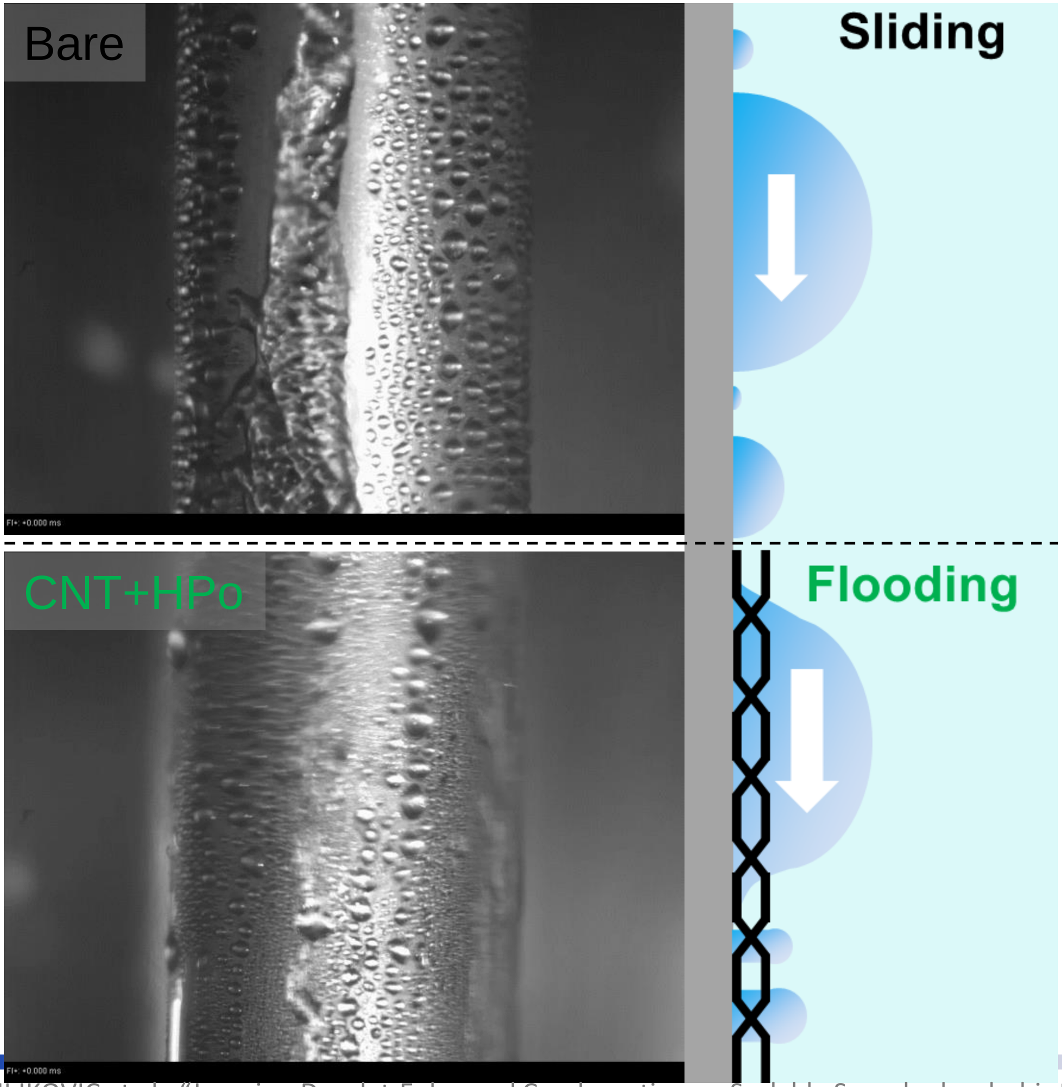




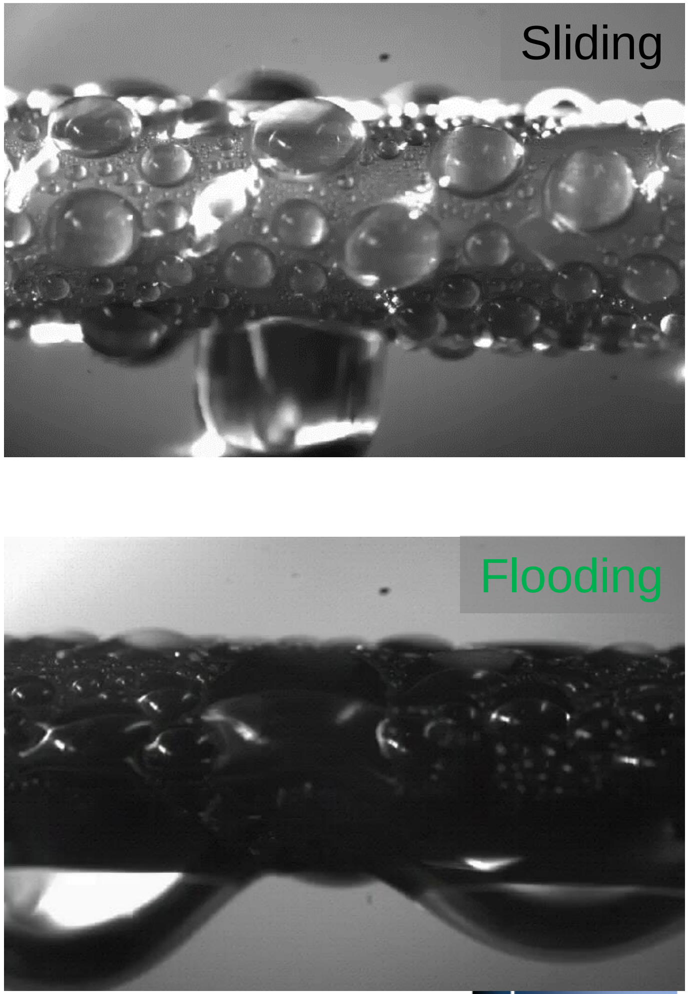


Result

Droplet morphology



Miljkovic et al. (2013)

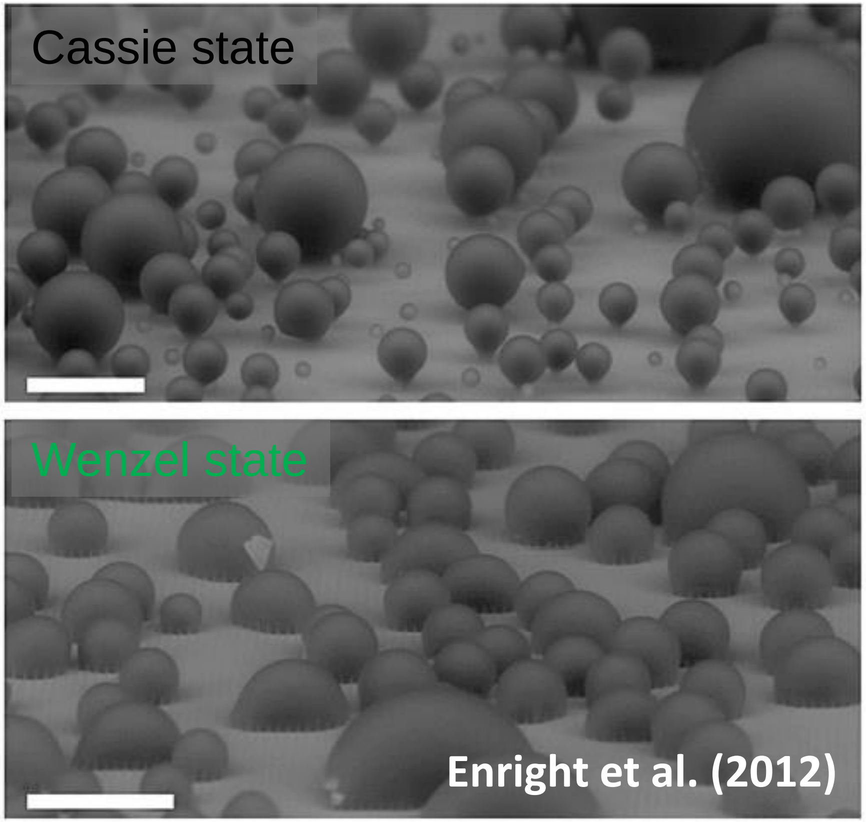


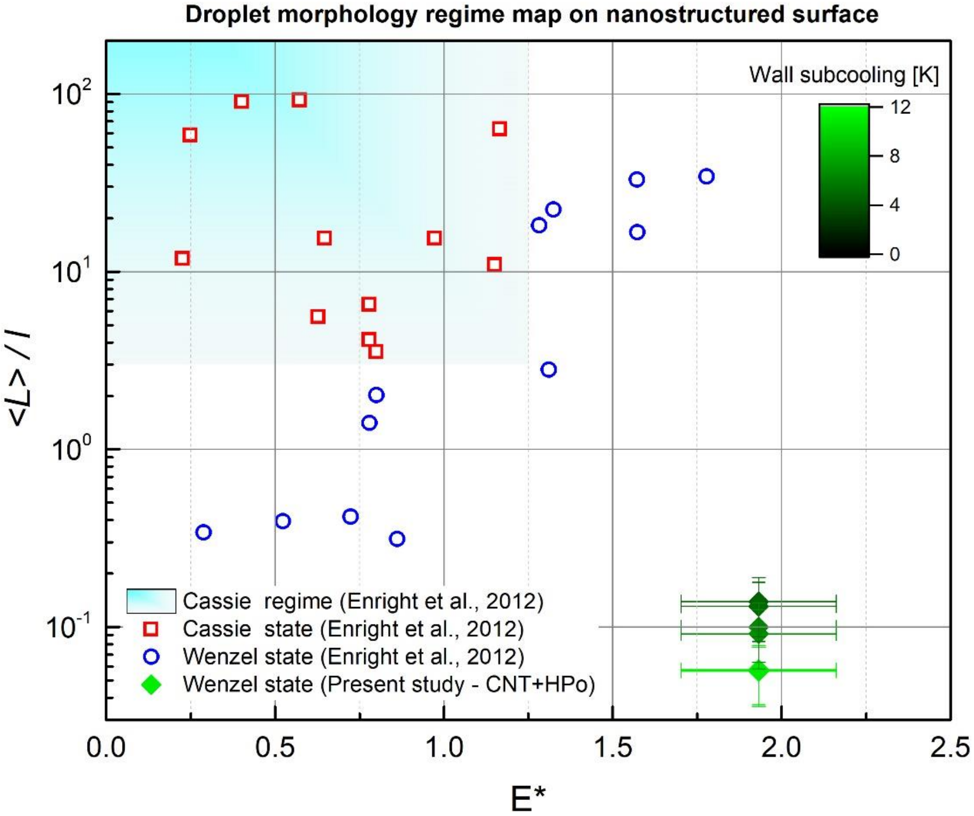
N. MILJKOVIC et al., "Jumping-Droplet-Enhanced Condensation on Scalable Superhydrophobic Nanostructured Surfaces," Nano Letters 13 1, 179 (2013); https://doi.org/10.1021/nl303835d.

Result

Droplet morphology (Regime map)

- Droplet morphology regime map was developed by Enright et al.
- CNT+HPo surface was in Wenzel state region, and it caused flooding condensation





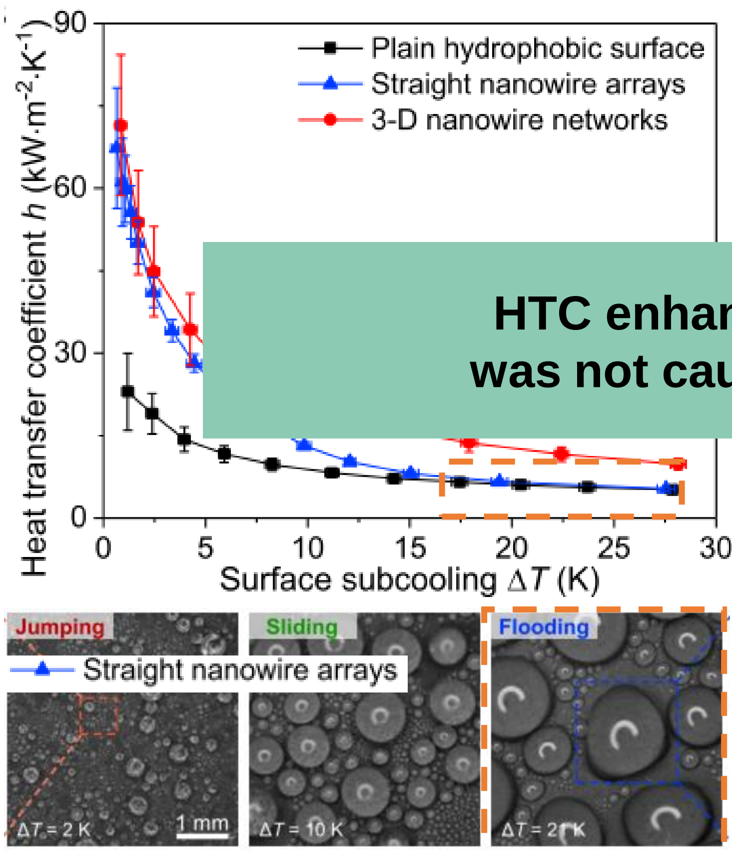
R. ENRIGHT et al., "Condensation on Superhydrophobic Surfaces: The Role of Local Energy Barriers and Structure Length Scale," Lang muir 28 40, 14424 (2012); https://doi.org/10.1021/la302599n.

Result

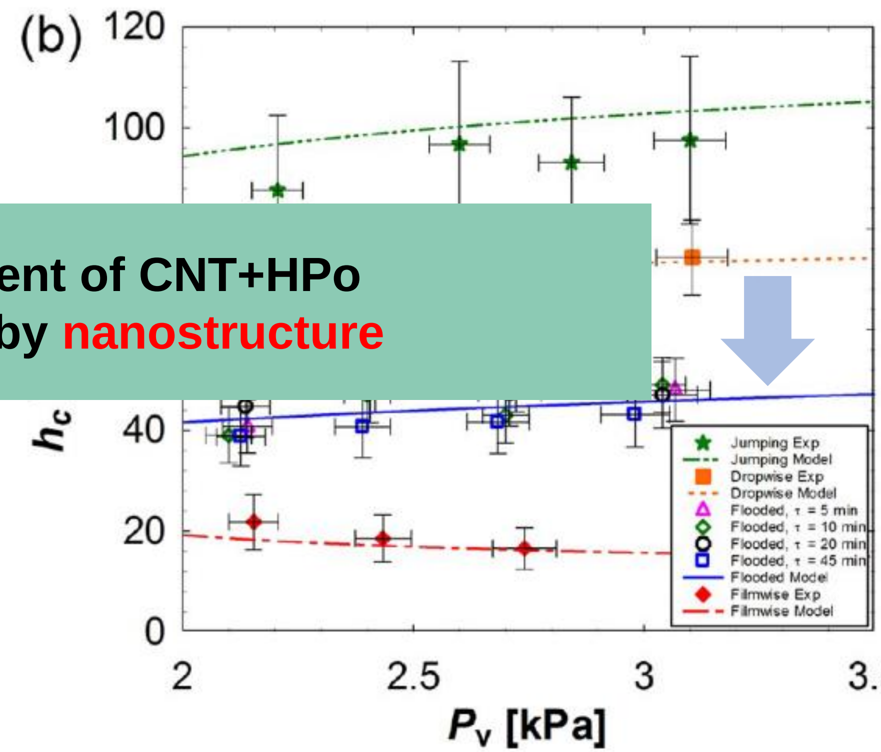
Droplet morphology (Condensation heat transfer)

- **Flooding has no enhancement** of condensation heat transfer than the sliding

Wen et al. (2018)



Miljkovic et al. (2013)



HTC enhancement of CNT+HPo was not caused by nanostructure

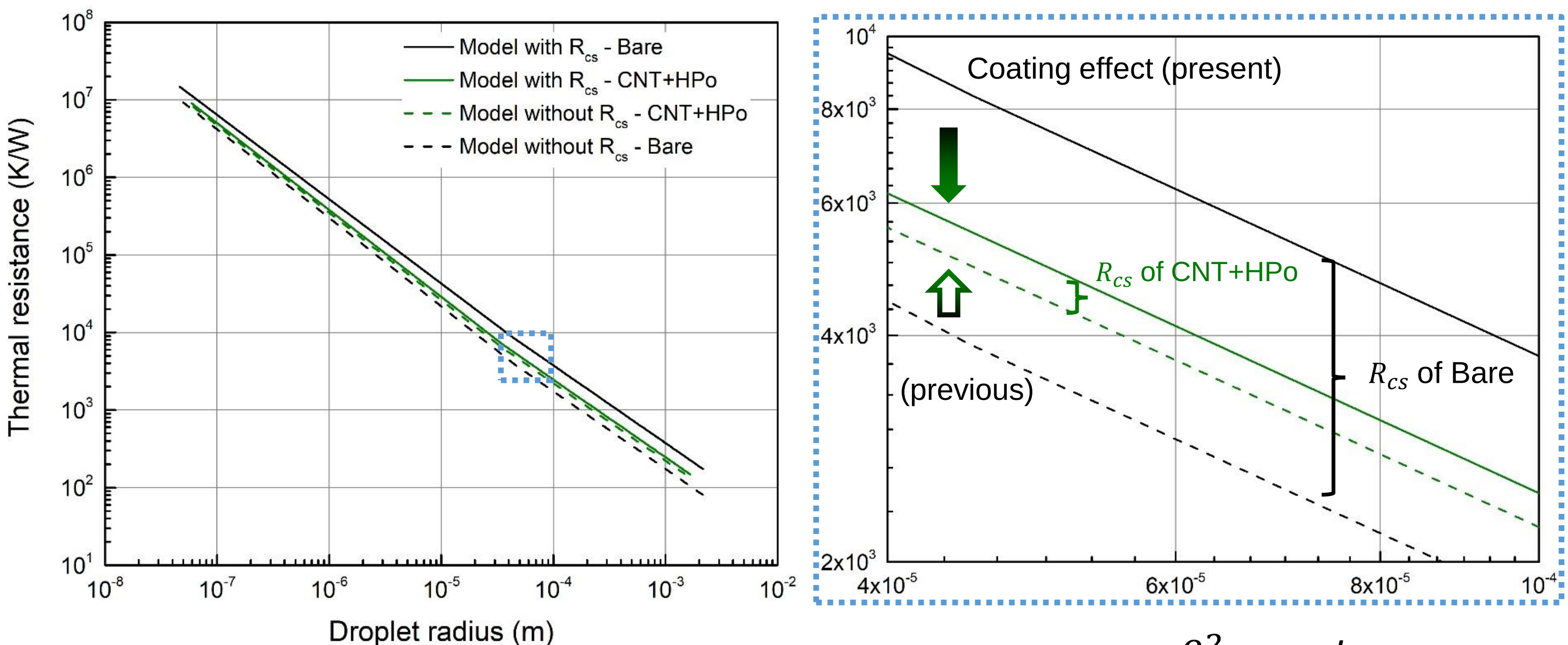
R. WEN et al., “Three-Dimensional Superhydrophobic Nanowire Networks for Enhancing Condensation Heat Transfer,” Joule 2 2, 269, Elsevier Inc. (2018); https://doi.org/10.1016/j.joule.2017.11.010.

Result

Effect of the constriction resistance

- The CNT layers of the CNT+HPo surface can reduce the constriction resistance
- Constriction resistance was inserted to the condensation HTC model

Thermal resistance of the single droplet



$$R = R_{lv} + R_{drop} + R_{coat} + R_{ls} + \color{red}{R_{cs}}$$

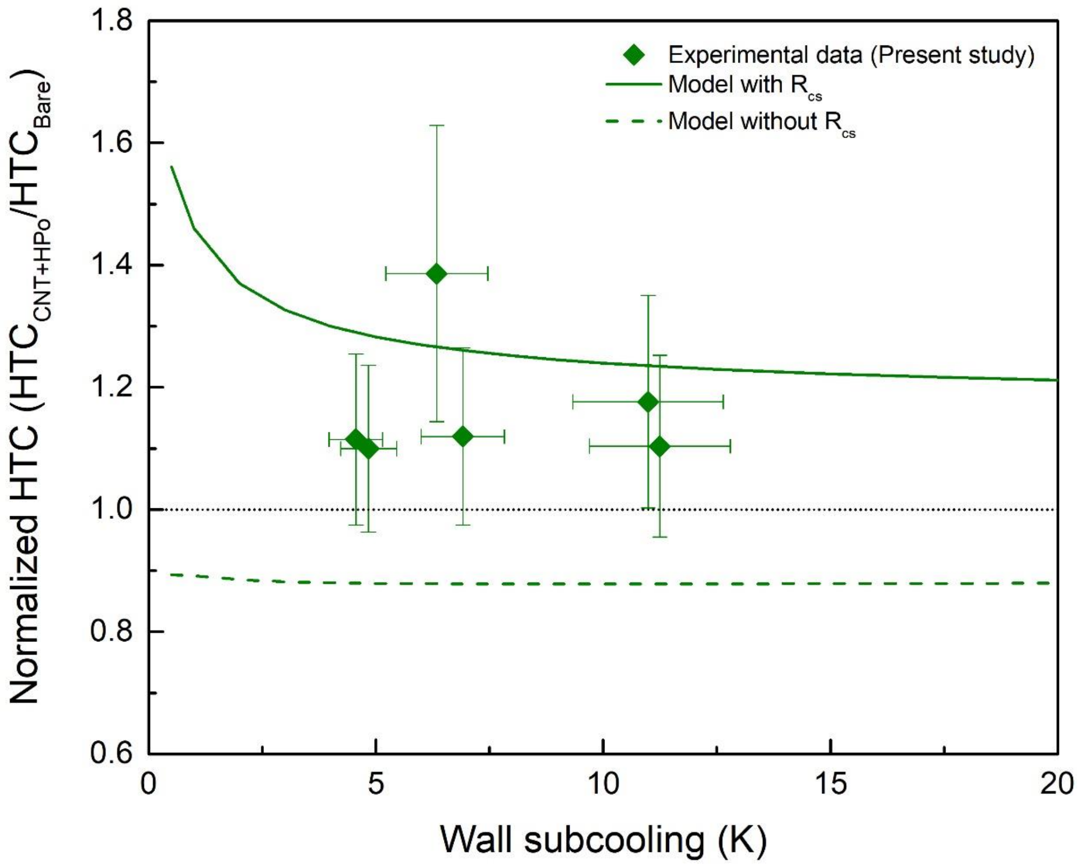
$$R_{cs} \approx \frac{\beta^2}{(1-\beta)^2} \frac{\psi}{4\color{red}{k_s}r}$$

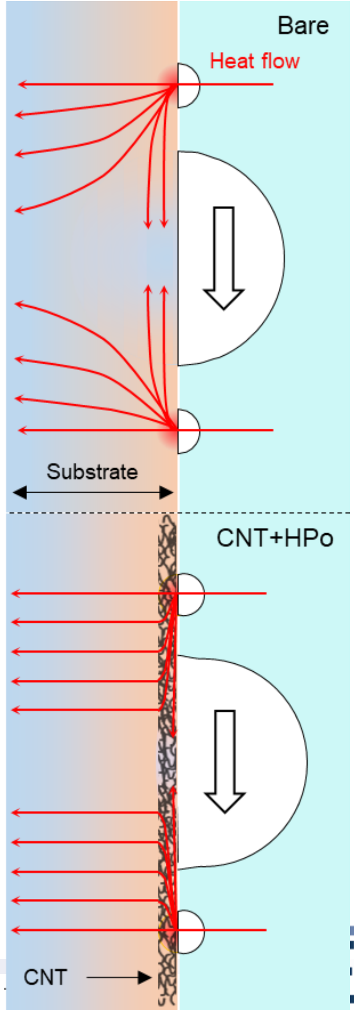
B. B. MIKIC, “On mechanism of dropwise condensation,” International Journal of Heat and Mass Transfer 12 10, 1311 (1969); https://doi.org/10.1016/0017-9310(69)90174-4.

Result

Effect of the constriction resistance

- The present model (with constriction) is in line with the experimental result



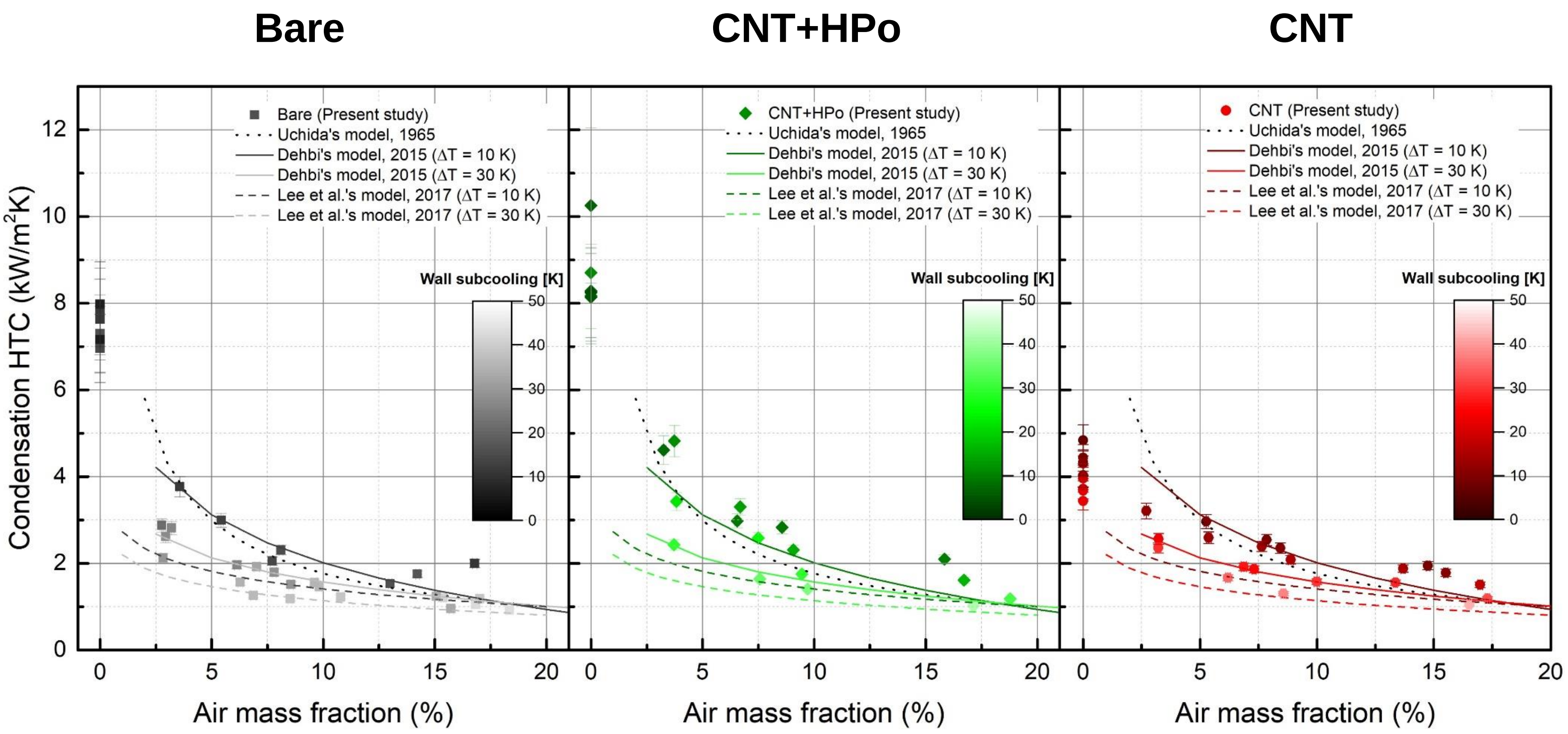


J. WANG et al., "Improved modeling of heat transfer in dropwise condensation," International Journal of Heat and Mass
Elsevier Ltd (2020); https://doi.org/10.1016/j.ijheatmasstransfer.2020.119719.

Result

Effect of the non-condensable gas

- The condensation HTC of each surface decreased as air mass fraction increased

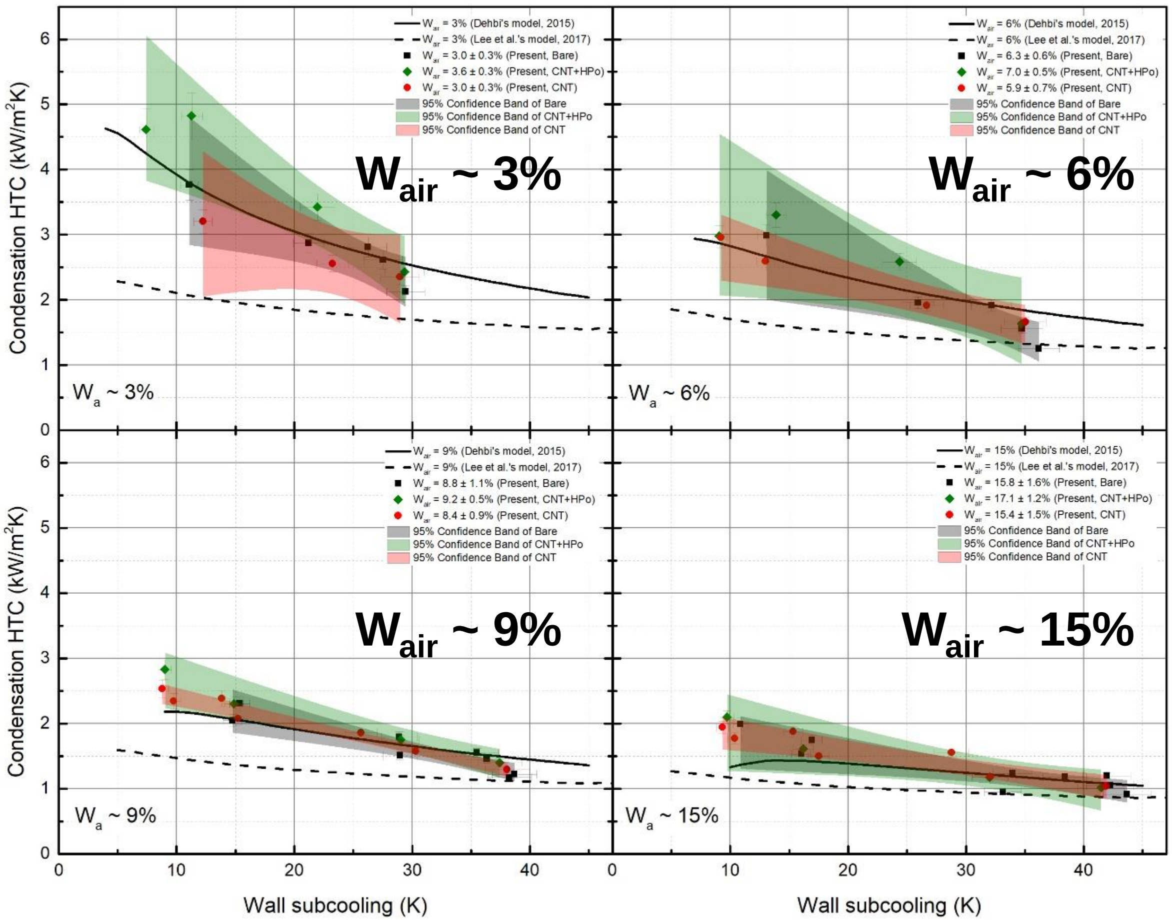


A. DEHBI, "A generalized correlation for steam condensation rates in the presence of air under turbulent free convection," International Journal of Heat and Mass Transfer 86, 1, Elsevier Ltd (2015); https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.034.

Result

Effect of the non-condensable gas

- Dropwise condensation HTC was similar with the filmwise as air fraction increased



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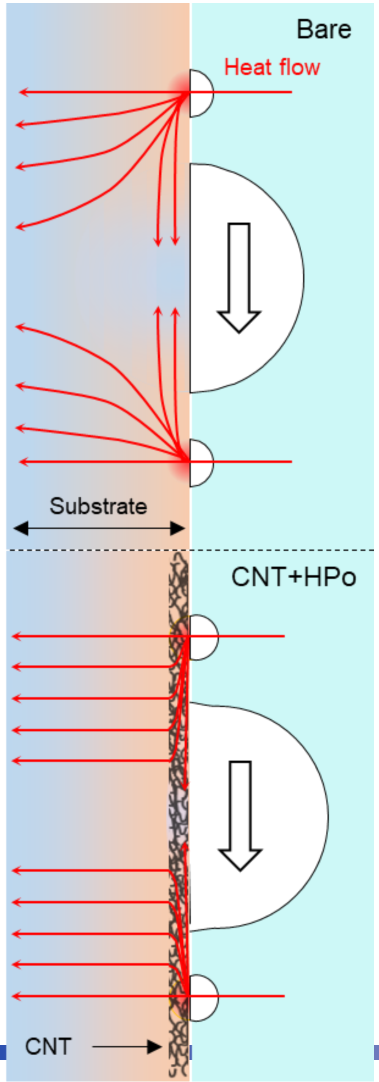
B.-J. CHUNG et al., "Experimental comparison of film-wise and drop-wise condensations of steam on vertical flat plates with the presence of air," International Communications in Heat and Mass Transfer 31 8, 1067 (2004); https://doi.org/10.1016/j.icheatmasstransfer.2004.08.004.

Conclusion

Effect of CNT layers on the dropwise condensation



LbL assembled CNT coatings

↓

Reduce the constriction resistance

↓

Condensation HTC enhancement

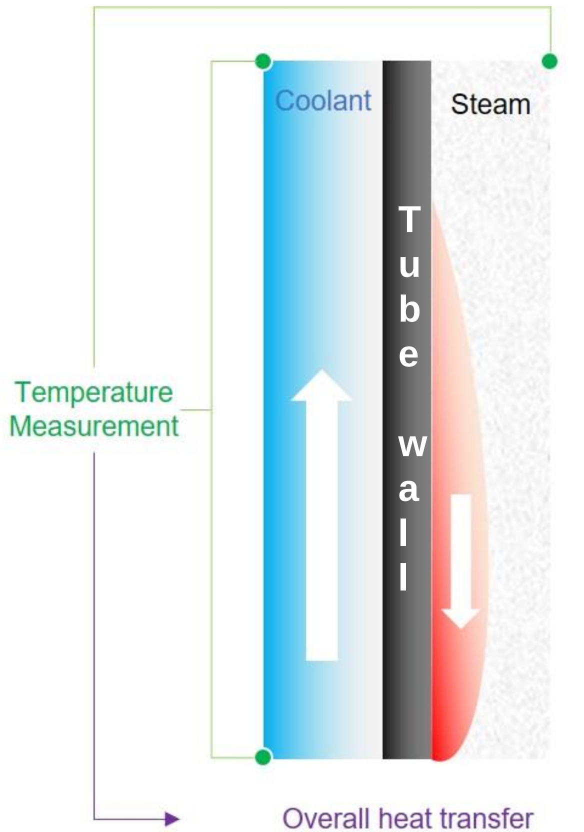
Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Science & ICT (MSIT, Korea) grant numbers [NRF-2016R1A5A101391921]

Thank you for your attention

Appendix

Data reduction (LMTD method)



Overall heat transfer

Convection (Correlation)

Conduction (1D equation)

Condensation (Result)

Overall

Convection

Conduction

Condensation

$$U = \frac{Q}{A_{surface}\Delta T_{LMTD}}$$

$$Q = \dot{m}C_p(T_{out} - T_{in})$$

$$\Delta T_{LMTD} = \frac{T_{out} - T_{in}}{ln\left(\frac{T_{steam} - T_{in}}{T_{steam} - T_{out}}\right)}$$

$$Nu = 0.023Re^{0.8}Pr^{0.4}$$

$$R_{cond} = \frac{ln(r_2/r_1)}{2\pi kL}$$

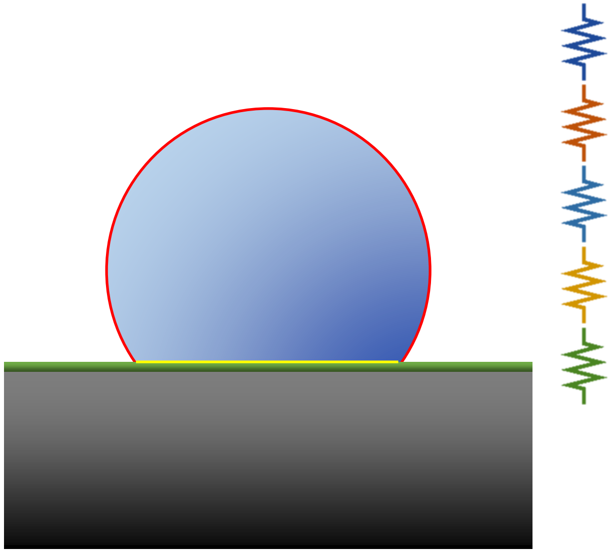
$$h = \frac{1}{\frac{1}{U} - \frac{d_o}{d_i}\frac{1}{h_{conv}} - \frac{d_o}{k}ln\frac{d_o}{d_i}}$$

$$T_{sub} = \frac{Q}{hA_{surface}}$$

Appendix

Dropwise condensation HTC model

$$\Delta T = \Delta T_{curv} + \Delta T_{lv} + \Delta T_{drop} + \Delta T_{ls} + \Delta T_{coat} + q_d \times R_{cs}$$



$$\Delta T_{curv} = \frac{2T_{sat}\sigma}{h_{fg}\rho_l r}$$

$$\Delta T_{lv} = \frac{q_d}{2\pi r^2(1-\cos\theta)h_{lv}}$$

$$\Delta T_{drop} = \frac{\theta q_d}{4\pi r k_l \sin\theta}$$

$$\Delta T_{ls} = \frac{q_d}{\pi r^2 \sin^2\theta\, h_{ls}}$$

$$\Delta T_{coat} = \frac{\delta q_d}{\pi r^2 \sin^2\theta\, k_{coat}}$$

$$\therefore q_d = \frac{\Delta T - \frac{2T_{sat}\sigma}{h_{fg}\rho_l r}}{\frac{\delta}{k_{coat}\sin^2\theta} + \frac{r\theta}{4k_l\sin\theta} + \frac{1}{2h_{lv}(1-\cos\theta)} + \frac{1}{h_{ls}\sin^2\theta}}$$

D. NIU et al., "Dropwise condensation heat transfer model considering the liquid-solid interfacial thermal resistance," International Journal of Heat a nd Mass Transfer 112, 333 (2017); https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.061.

Appendix

Dropwise condensation HTC model

$$n(r) = \frac{1}{3\pi r_e^3 r_{max}}\left(\frac{r_e}{r_{max}}\right)^{-\frac{2}{3}} \frac{r(r_e - r_{min})}{r - r_{min}} \frac{A_2 r + A_3}{A_2 r_e + A_3} \exp(B_1 + B_2)$$

$$A_1 = \frac{\Delta T}{2 h_{fg} \rho_l}$$

$$A_2 = \pi r (1 - \cos\theta)(R_{drop} + R_{cs})$$

$$R_{cs} \approx \frac{\beta^2}{(1-\beta)^2} \frac{\psi}{4 k_s r}$$

$$A_3 = \pi r^2 (1 - \cos\theta)(R_{vl} + R_{ls} + R_{coat})$$

$$\beta = \frac{r^2}{b^2}$$

$$B_1 = \frac{A_2}{\tau A_1}\left[\frac{r_e^2 - r^2}{2} + r_{min}(r_e - r) - r_{min}^2 \ln \frac{r - r_{min}}{r_e - r_{min}}\right]$$

$$\psi = \left[\frac{32}{3\pi^2}\left(1 - \frac{r}{b}\right)^{1.5}\right]$$

$$B_2 = \frac{A_3}{\tau A_1}\left[(r_e - r) - r_{min} \ln \frac{r - r_{min}}{r_e - r_{min}}\right]$$

$$\tau = \frac{3 r_e^2 (A_2 r_e + A_3)^2}{A_1 (11 A_2 r_e^2 - 14 A_2 r_e r_{min} + 8 A_3 r_e - 11 A_3 r_{min})}$$

S. KIM and K. J. KIM, "Dropwise Condensation Modeling Suitable for Superhydrophobic Surfaces," Journal of Heat Transfer 133 8, 081502 (2011): htt ps://doi.org/10.1115/1.4003742.

Appendix

Dropwise condensation HTC model

$$N(r) = \frac{1}{3\pi r^2 r_{max}} \left(\frac{r}{r_{max}}\right)^{-\frac{2}{3}}$$

$$r_{max} = \left(\frac{6(\cos\theta_r - \cos\theta_a)\sin\theta}{\pi(2 - 3\cos\theta + \cos^3\theta)} \frac{\sigma_{lv}}{\rho_l g}\right)^{0.5}$$

$$r_e = (4N_s)^{-1/2}$$

$$N_s = \frac{0.037}{r_{min}^2}$$

$$q''_{drop} = (\int_{r_{min}}^{r_e} q_{drop}(r) n(r) dr + \int_{r_e}^{r_{max}} q_{drop}(r) N(r) dr)$$

S. KIM and K. J. KIM, “Dropwise Condensation Modeling Suitable for Superhydrophobic Surfaces,” Journal of Heat Transfer 133 8, 081502 (2011); https://doi.org/10.1115/1.4003742.

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Appendix

Dropwise condensation HTC model

$$\Delta\Psi(r) = \int [\Delta g + (p_{sat}(T_{sat}) - p_l)v_l dm_l + \sigma_{lv}A_{lv} + \sigma_{sl}A_{sl} - \sigma_{sv}A_{sv}$$

$$\Delta g = \frac{h_{fg}(T_l - T_{sat})}{T_{sat}} + v_l\left(p_l - p_{sat}(T_{sat})\right)$$

$$dv = A_s d\bar{\varepsilon} = \pi r^3 \sin^3\theta \frac{(1-\cos\phi)^2}{\sin^4\phi} d\phi$$

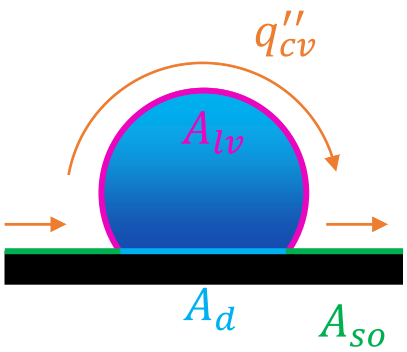
$$\therefore \Delta\Psi = \rho_l \pi r^3 \sin^3\theta \int_0^\theta \frac{h_{fg}}{T_{sat}} \frac{(1-\cos\phi)^2}{\sin^4\phi} \times \left(-\Delta T_{sub} + \frac{q_{drop}(r)\delta}{\pi r^2 \sin^2\theta\, k_{coat}} + \frac{q_{drop}(r)\phi}{4\pi r \sin\theta\, k_l} + \frac{q_{drop}(r)}{\pi r^2 \sin^2\theta\, h_{ls}}\right) d\phi + \sigma_{lv}(2 - 3\cos\theta + \cos^3\theta)\pi r^2$$

$$\left.\frac{\partial\Delta\Psi}{\partial r}\right|_{r=r_{min}} = 0$$

X. LIU and P. CHENG, "Dropwise condensation theory revisited: Part I. Droplet nucleation radius," International Journal of Heat and Mass Transfer 83, 833, Elsevier Ltd (2015); https://doi.org/10.1016/j.ijheatmasstransfer.2014.11.009.

Appendix

Dropwise condensation HTC model



$$Nu = \frac{h_F l}{k_v} = 0.664 Re^{1/2} Pr^{1/3} \quad Re < 5 \times 10^5$$

$$Nu = (0.037 Re^{0.8} - 871) Pr^{1/3}, Re > 5 \times 10^5$$

$$A_d = \left(\int_{r_{min}}^{r_e} \pi r^2 \sin^2\theta \, n(r) dr + \int_{r_e}^{r_{max}} \pi r^2 \sin^2\theta \, N(r) dr \right) A$$

$$A_{so} = A - A_d$$

$$A_{lv} = \left(\int_{r_{min}}^{r_e} 2\pi r^2 (1 - \cos\theta) n(r) dr + \int_{r_e}^{r_{max}} 2\pi r^2 (1 - \cos\theta) N(r) dr \right) \mathrm{A}$$

$$q''_{cv} = (A_{so} + A_{lv}) h_F \Delta T / A$$

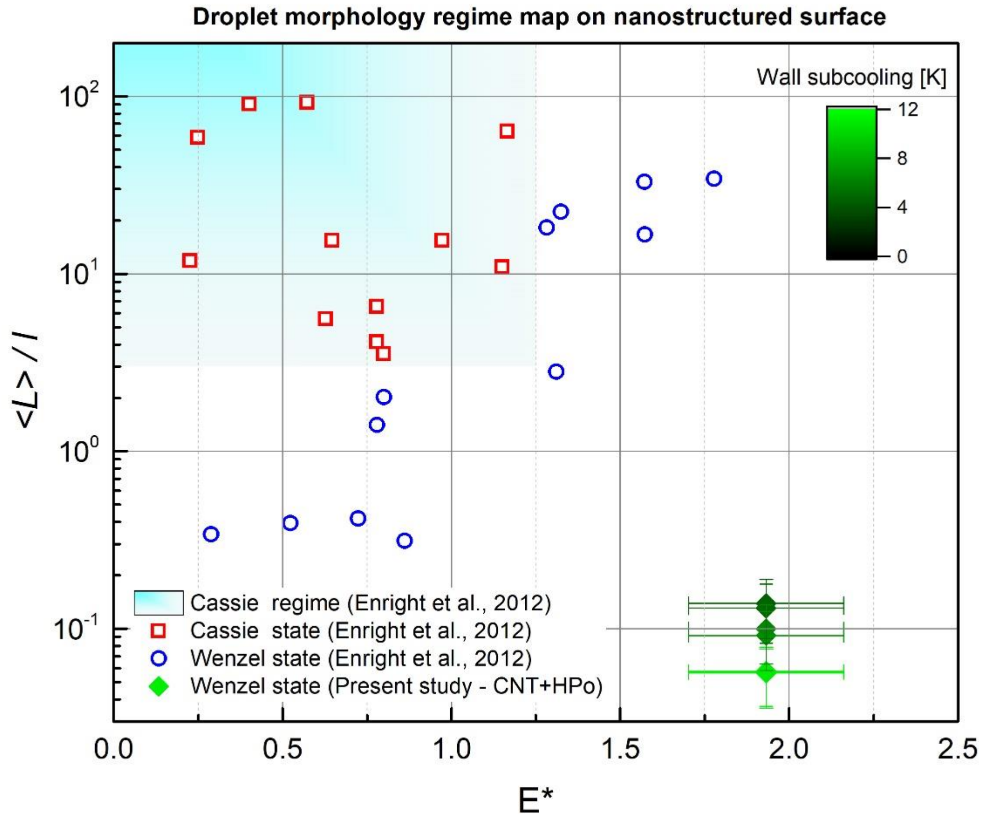
$$\therefore q'' = q''_{cv} + q''_{drop}$$

J. WANG et al., "Improved modeling of heat transfer in dropwise condensation," International Journal of Heat and Mass Transfer 155, Elsevier Ltd (2020); https://doi.org/10.1016/j.ijheatmasstransfer.2020.119719.

Appendix

Droplet morphology regime map

$$< L > = 2 \times r_e$$



$$E^* = -1/r\cos\theta_a$$

R. ENRIGHT et al., "Condensation on Superhydrophobic Surfaces: The Role of Local Energy Barriers and Structure Length Scale," Langmuir 28 40, 14424 (2012); https://doi.org/10.1021/la302599n.