Novel Patterned Surfaces for Improved Condenser Performance in Power Plants

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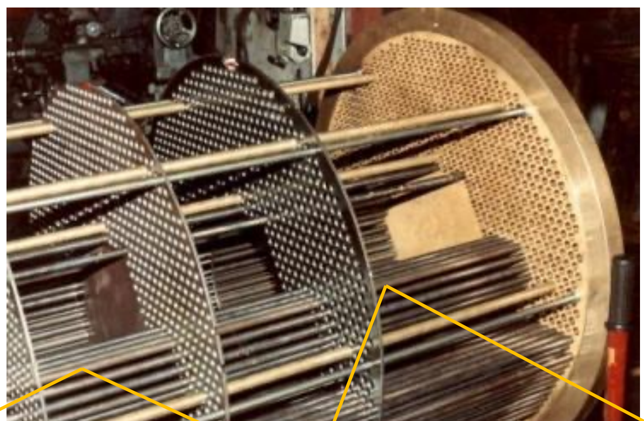
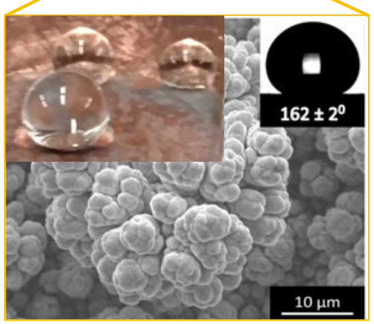
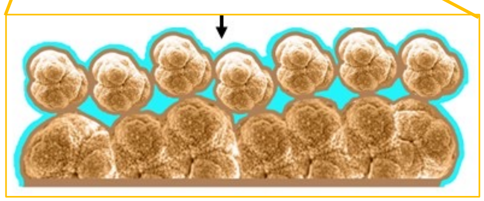
National Energy Technology Laboratory

Motivation and Inspiration

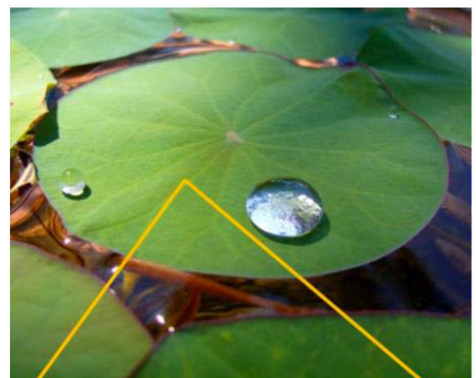
The overall motivation is to increase the performance of condensers in thermal power plants using patterned non-wetting superhydrophobic and liquid-infused surfaces on condenser materials.

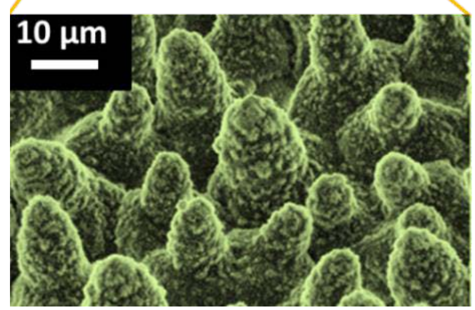




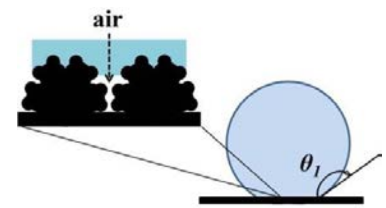


SLIPS on Condenser Tubes

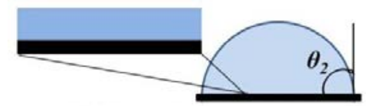




Beilstein J Nanotechnol. 2011; 2: 152–161



(a) Superhydrophobic Surface



(b) Smooth Surface

$\theta > 120^{o}$ (hydrophobic)
$\theta > 150^{o}$ (superhydrophobic)

Ants aquaplaning in a pitcher plant– SLIPS in nature

Source: The Internet

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Underlying Idea

If condenser tube surfaces can be engineered to be non-wetting (superhydrophobic or liquid infused), we can potentially enhance heat transfer performance by:

(1) promoting dropwise condensation of the steam on the shell side and eliminating flooding of the surface structure by maintaining low droplet adhesion, thus increasing condensation heat transfer coefficient;

(2) reducing the number of tubes, coolant water usage, and levelized cost of condenser; and

(3) deterring fouling and corrosion, thereby reducing fouling resistance and improving heat transfer

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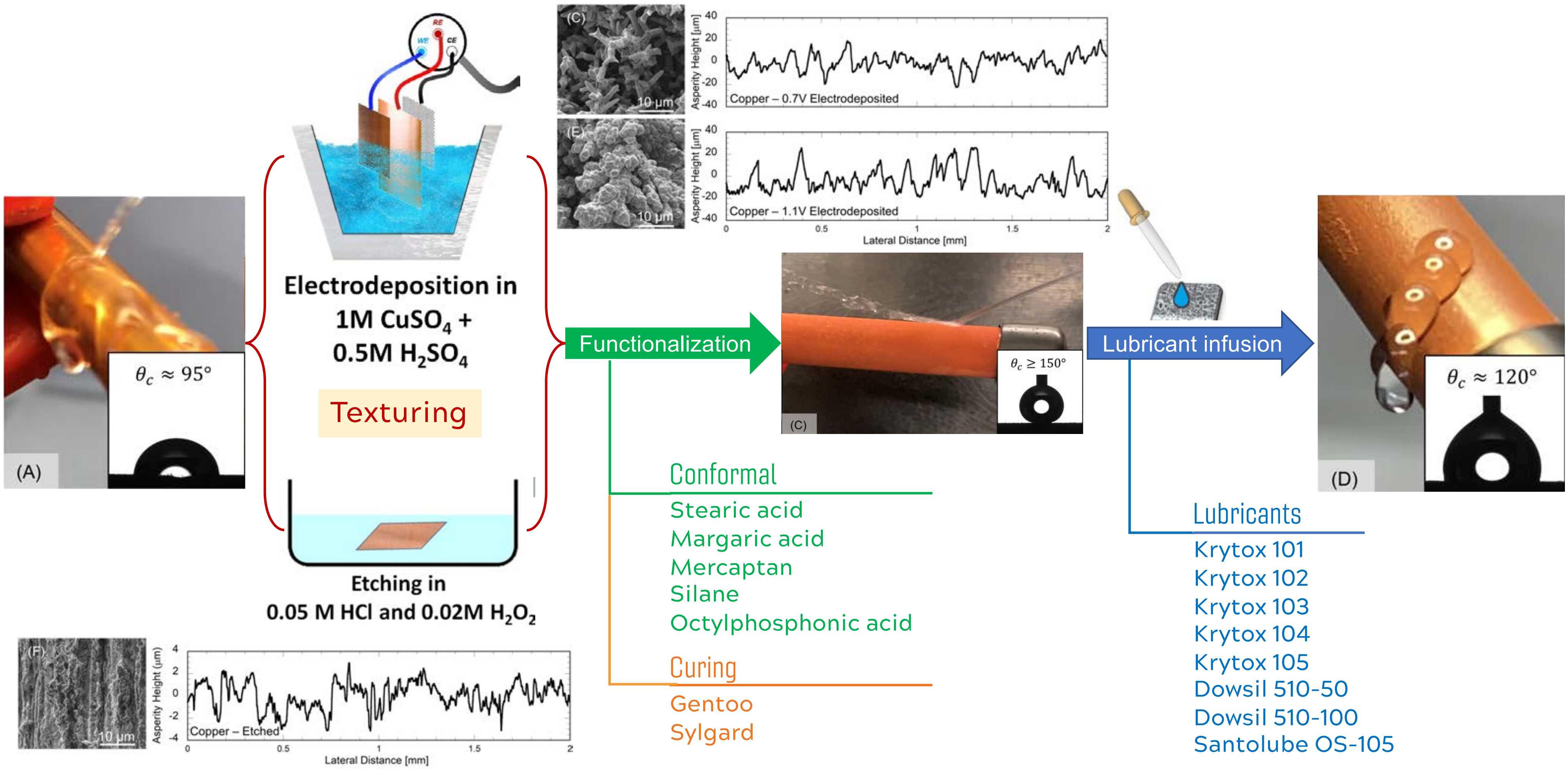
Fabrication Steps



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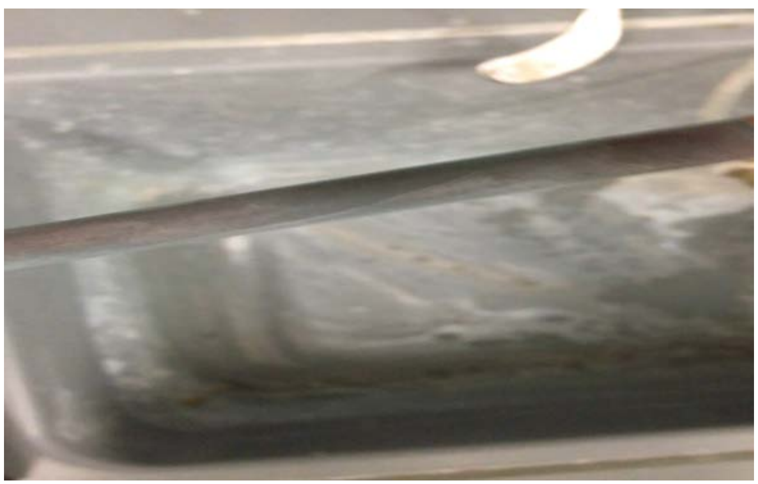
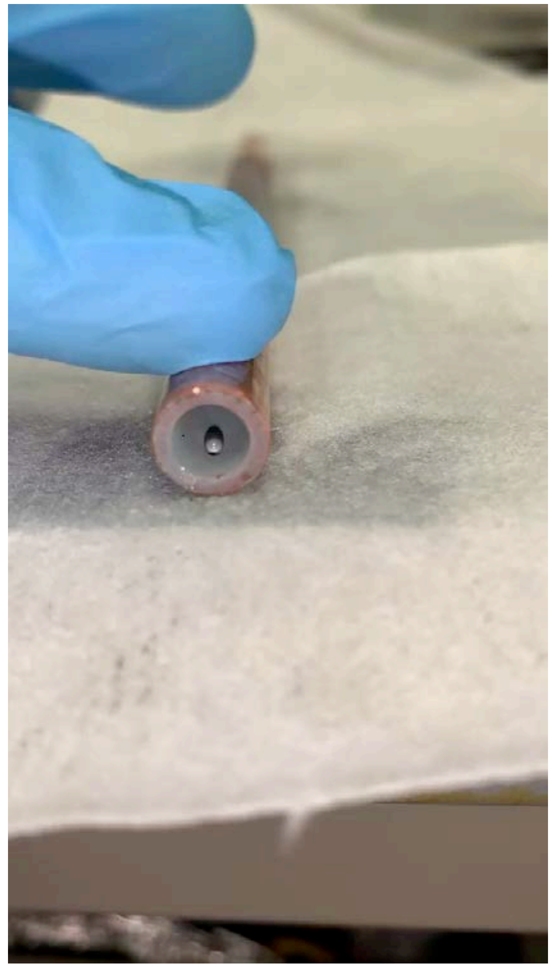
Fabrication Method Versatility





Wide range of materials

- Copper
- Brass
- Monel
- Inconel
- Stainless steel
- Aluminum

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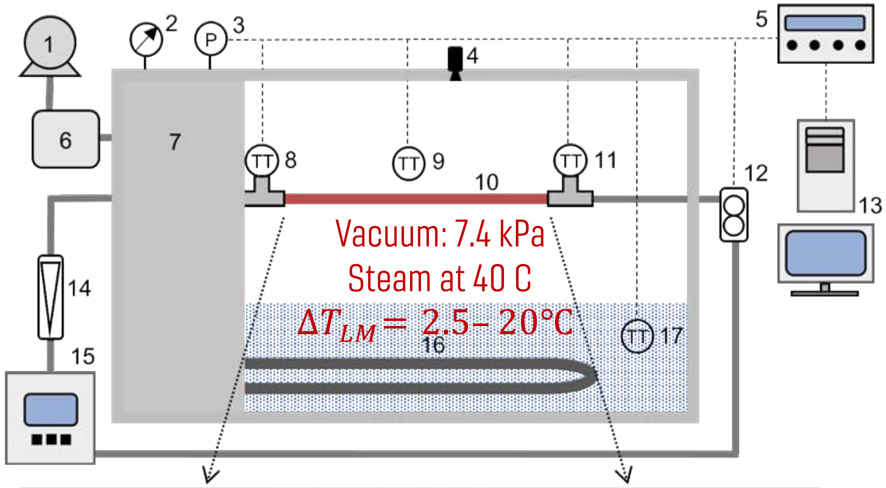
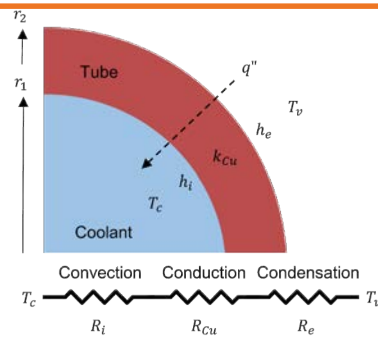
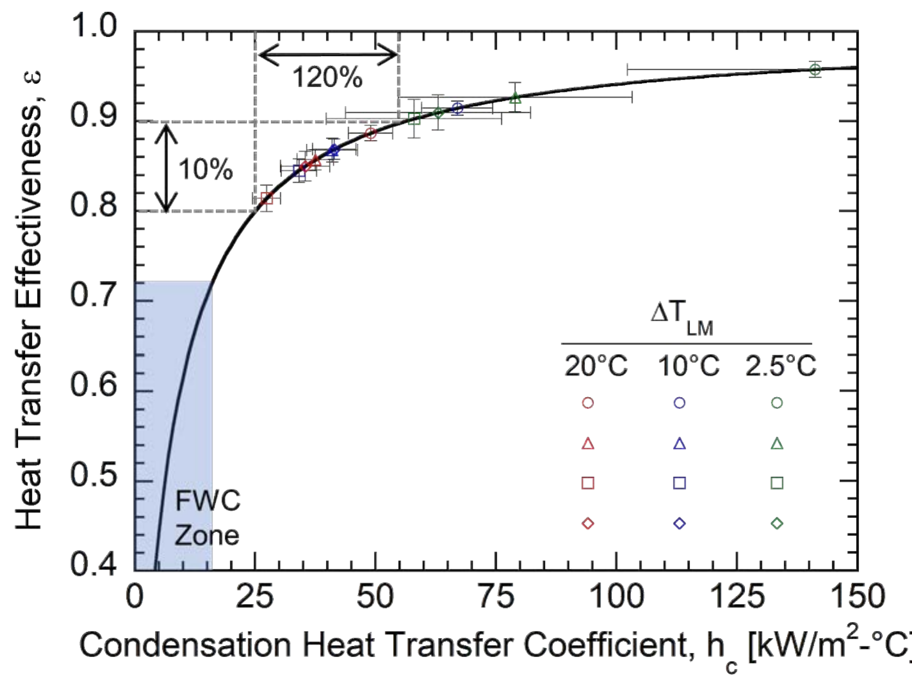
Condensation Heat Transfer





$$q''_{max} = \frac{\Delta T_{LM}}{A_S(R_i + R_m)}$$

$$\varepsilon = \frac{q''}{q''_{max}} = \frac{R_i + R_m}{R_i + R_m + R_e}$$



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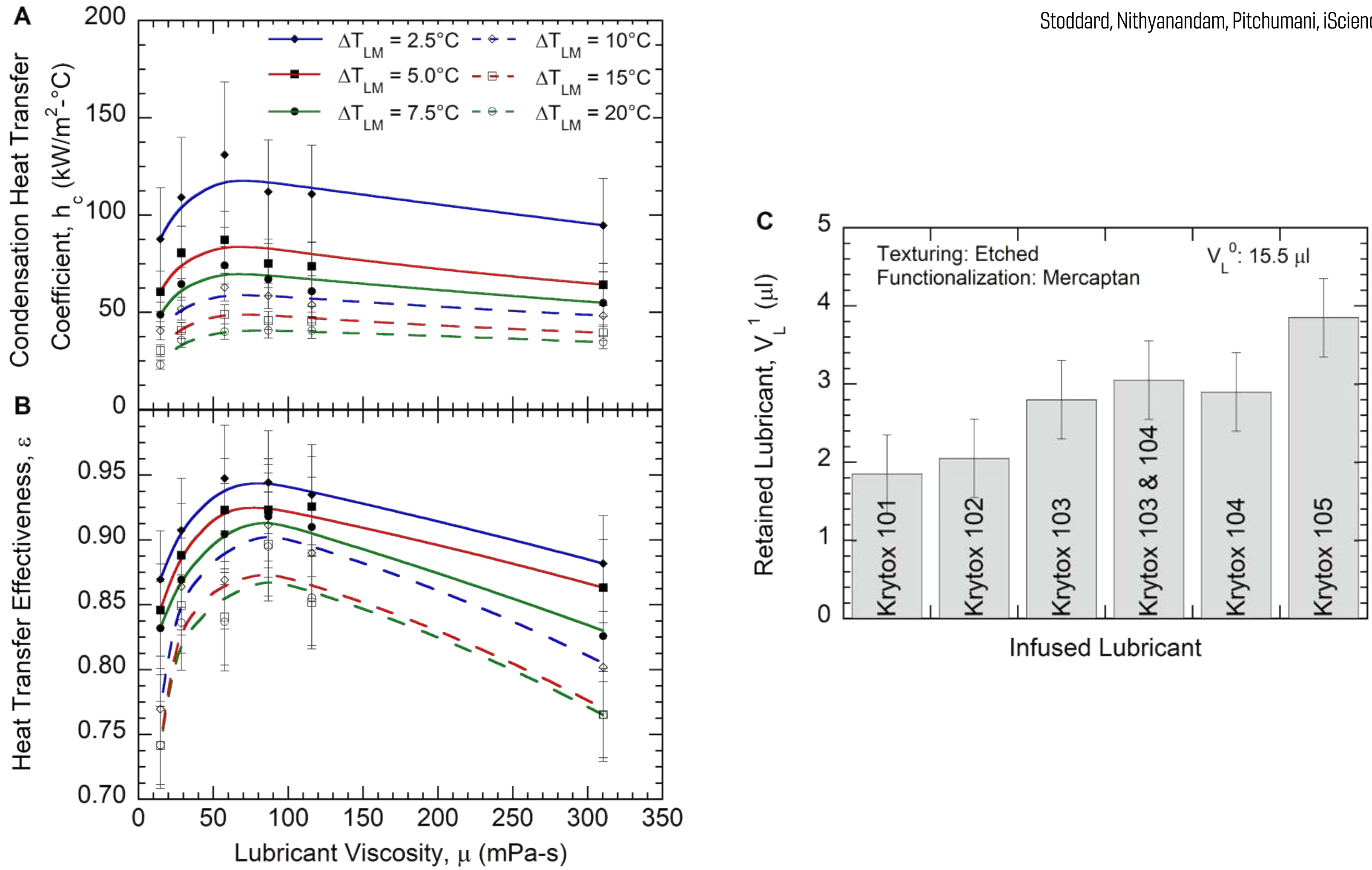
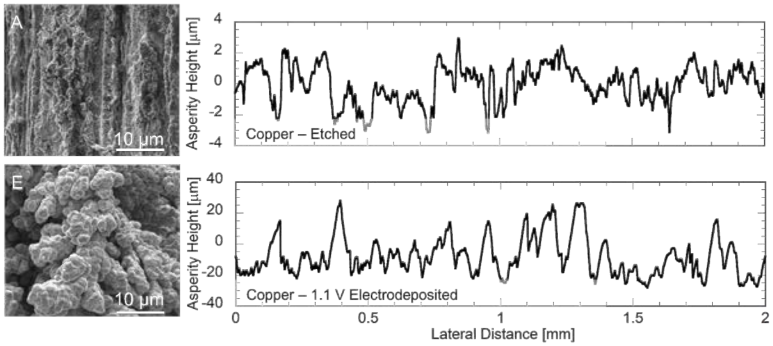
LIS: Viscosity Dependence

Stoddard, Nithyanandam, Pitchumani, iScience, 2021

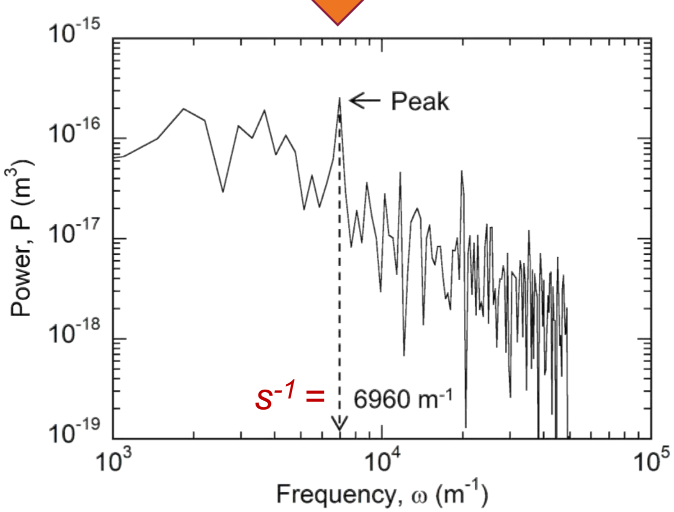


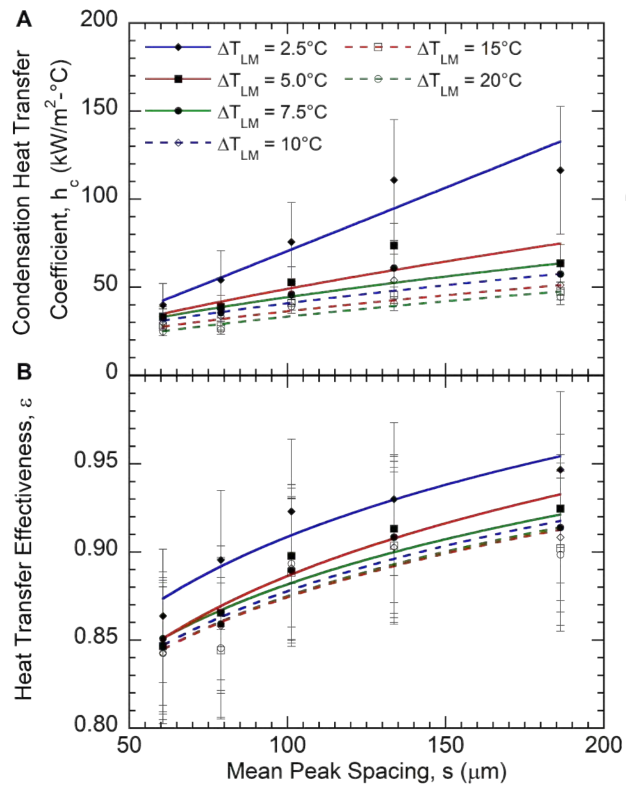
LIS: Texture Dependence

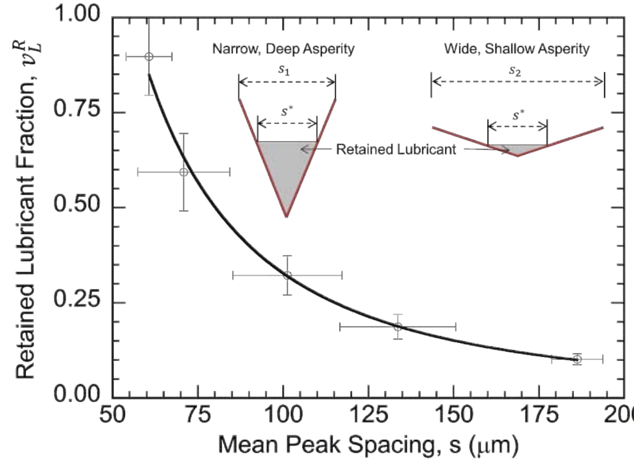
Stoddard, Nithyanandam, Pitchumani, iScience, 2021



Fast Fourier Transform







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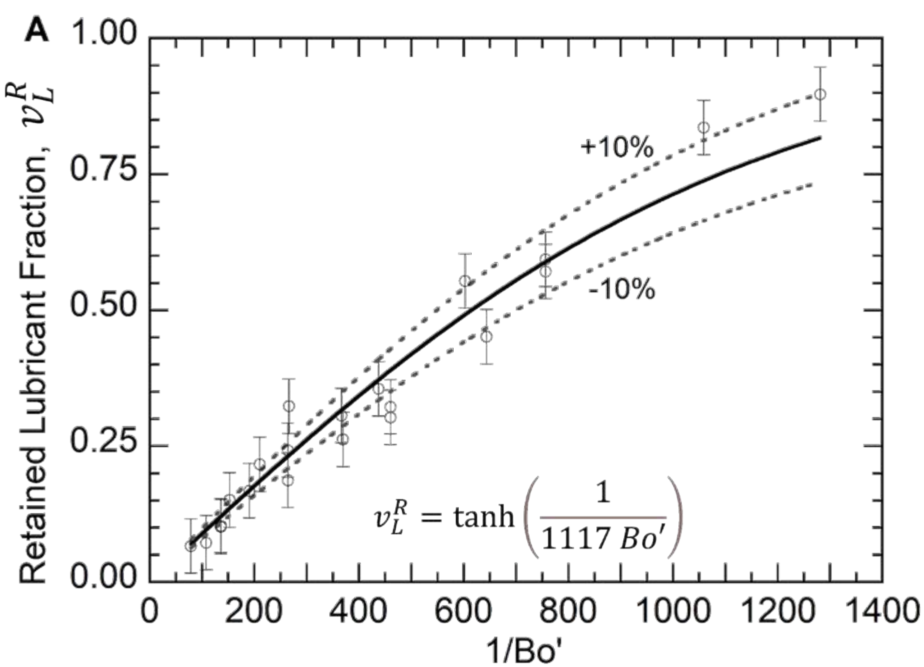
Bringing it all together

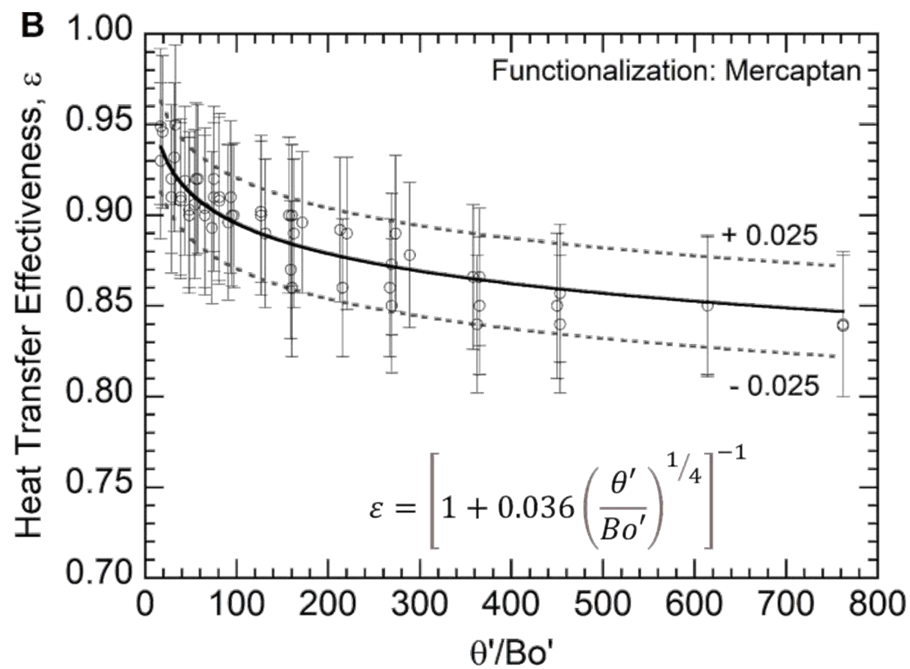
Stoddard, Nithyanandam, Pitchumani, iScience, 2021

Bond number: $Bo = \frac{\Delta \rho g l^2}{\sigma}$

Modified Bond number: $Bo' = \frac{(\rho_L - \rho_v) g s^2}{\sigma_L} \left(\frac{\mu_w}{\mu_L}\right)^{1/3}$

Dimensionless LMTD: $\theta' = (\Delta T_{LM} / T_v)^{3/4}$





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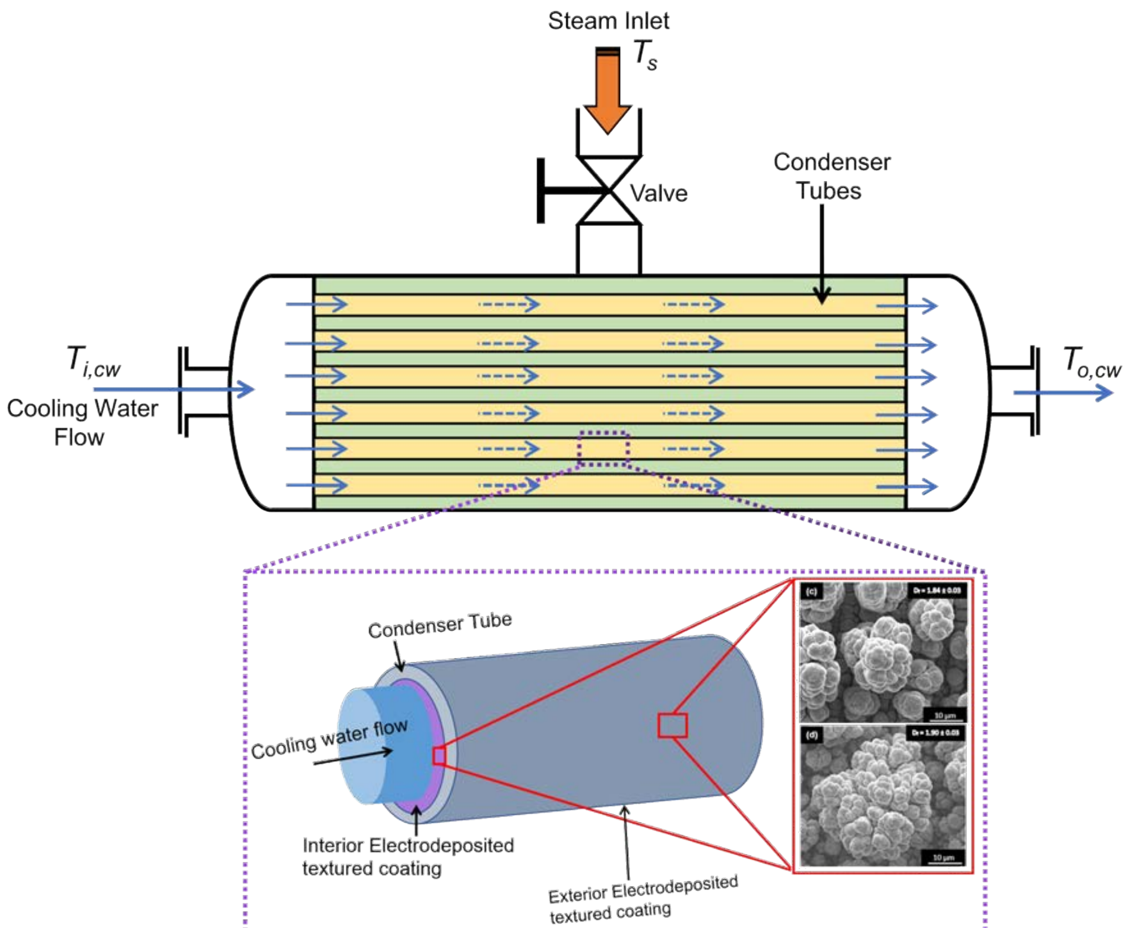
Condenser Technoeconomic Analysis

Nithyanandam, Shoaei, Pitchumani, Energy, Invited Article, 2021



Thermoeconomic Model

Nithyanandam, Shoaei, Pitchumani, Energy, Invited Article, 2021

Condenser and Power Plant Performance

$$P_e = \frac{\dot{Q}_c}{HR'(1+HR_c)} - \frac{\Delta\mathcal{P}_{cw}\dot{m}_{cw}N_t}{\rho_{cw}\eta_p}$$

$$\Delta\mathcal{P}_{cw} = f\,\frac{L_t}{2d_i}\rho_{cw}V_{cw}^2$$

$$\dot{m}_{cw} = \rho_{cw}V_{cw}N_t\pi d_i^2/4$$

$$\dot{Q}_c = (UA_o)N_t\Delta T_{LM}$$

Condenser heat rejection rate

$$R_T = R_{cw} + R_f + R_m + R_c$$

$$\eta = \frac{P_e}{\dot{Q}_c}\times\left\{1 - \frac{1}{HR'(1+HR_c)}\right\}$$

$$HR' = 2.942\ kW_t/kW_e$$

is the heat rate at turbine back pressure of 3 in Hg abs

HR_c: Heat rate correction factor (Webb)

Cost Model

Total condenser cost: $C_T = C_{HX} + C_E$

$$C_{HX} = 3.291\cdot F_p\cdot F_m\cdot F_l \cdot \exp\{11.667 - 0.8709\,[\ln(A_oN_t)] + 0.0986[\ln(A_oN_t)]^2\}$$

F_p: Pressure factor $= f(\text{max. steam pressure})$ (Walker, et al., 2012)
F_m: Material factor = $f(\mathrm{A_o}, \mathrm{N_t})$ (Sieder, et al., 2004)
F_l: Tube length factor

$$C_E = C_{E,cm} + C_{E,l} + C_{E,eq}$$

$$C_{E,cm} = \rho_{cm}\times(A_o + A_i)\times N_t\times b_{cm}\times\bar{C}_{cm}$$

$$C_{E,l} = N_t\left[\dot{C}_d\times\frac{(A_o+A_i)}{A_b}\times t_d + \dot{C}_s\times t_s\right]$$

$$C_{E,eq} = \dot{C}_eN_t\left[\frac{(A_o+A_i)}{A_b}\times t_d + t_s\right]$$

Levelized Cost of Condenser (20 year lifetime)

$$\mathrm{LCOC} = \frac{\left[C_T + (C_M\times N_o\times N_y) + (C_E\times\gamma\times N_y)\right]}{Q_e\times N_y}$$

Net annual electric energy

$$Q_e = \sum_{n_d=1}^{365} P_e\times 24$$

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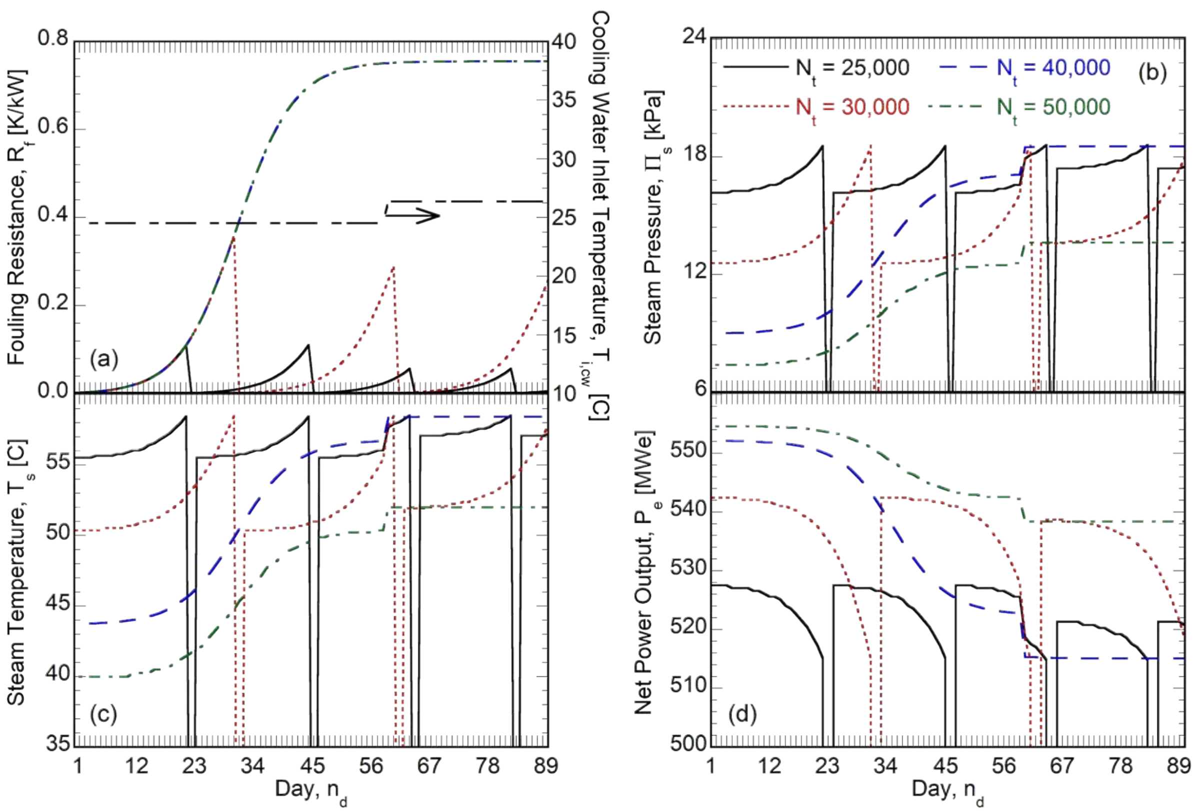
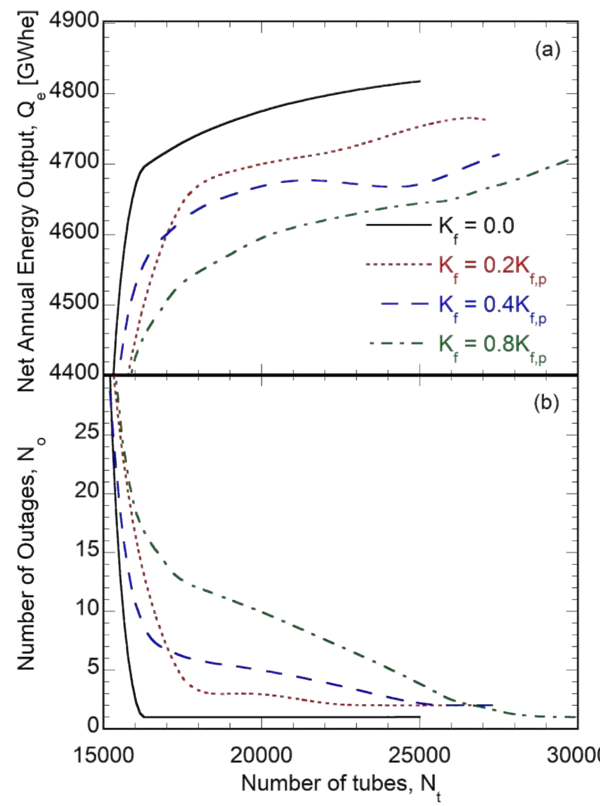
Plant Simulation

Nithyanandam, Shoaei, Pitchumani, Energy, Invited Article, 2021





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Levelized Cost of Condenser

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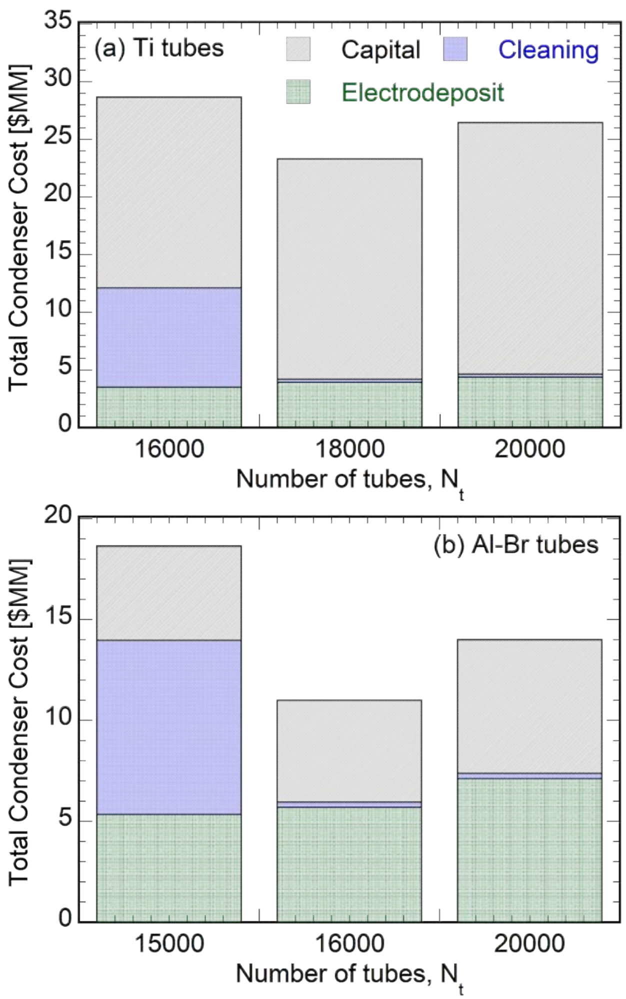

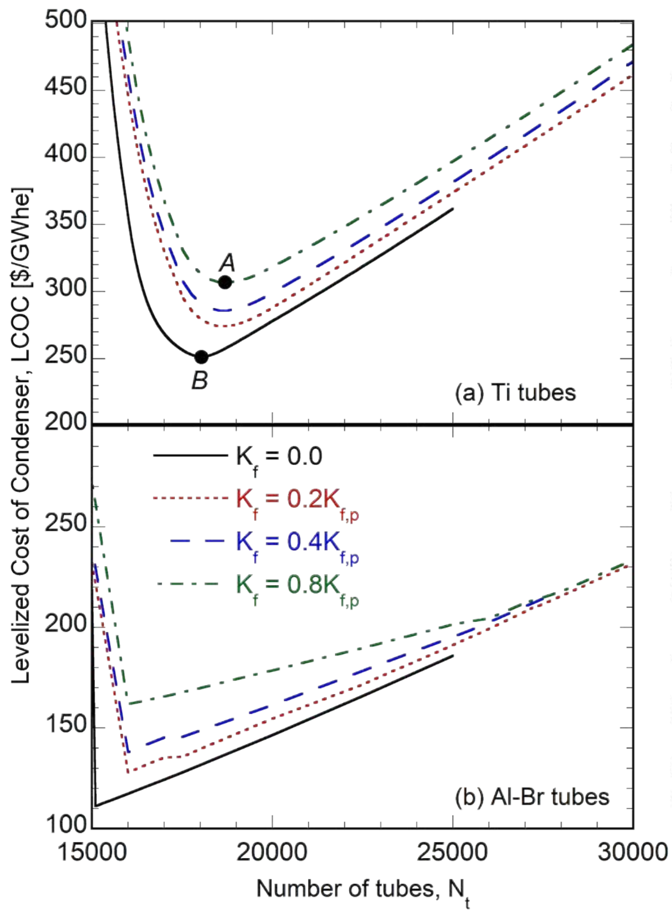

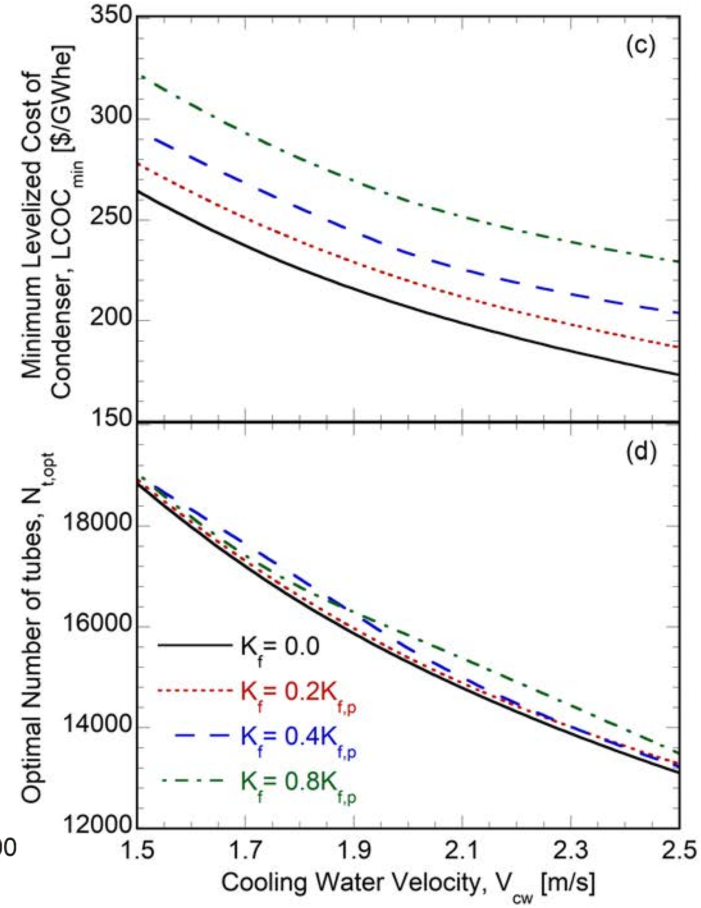

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Economic Advantage of Condensers with Nonwetting Surfaces

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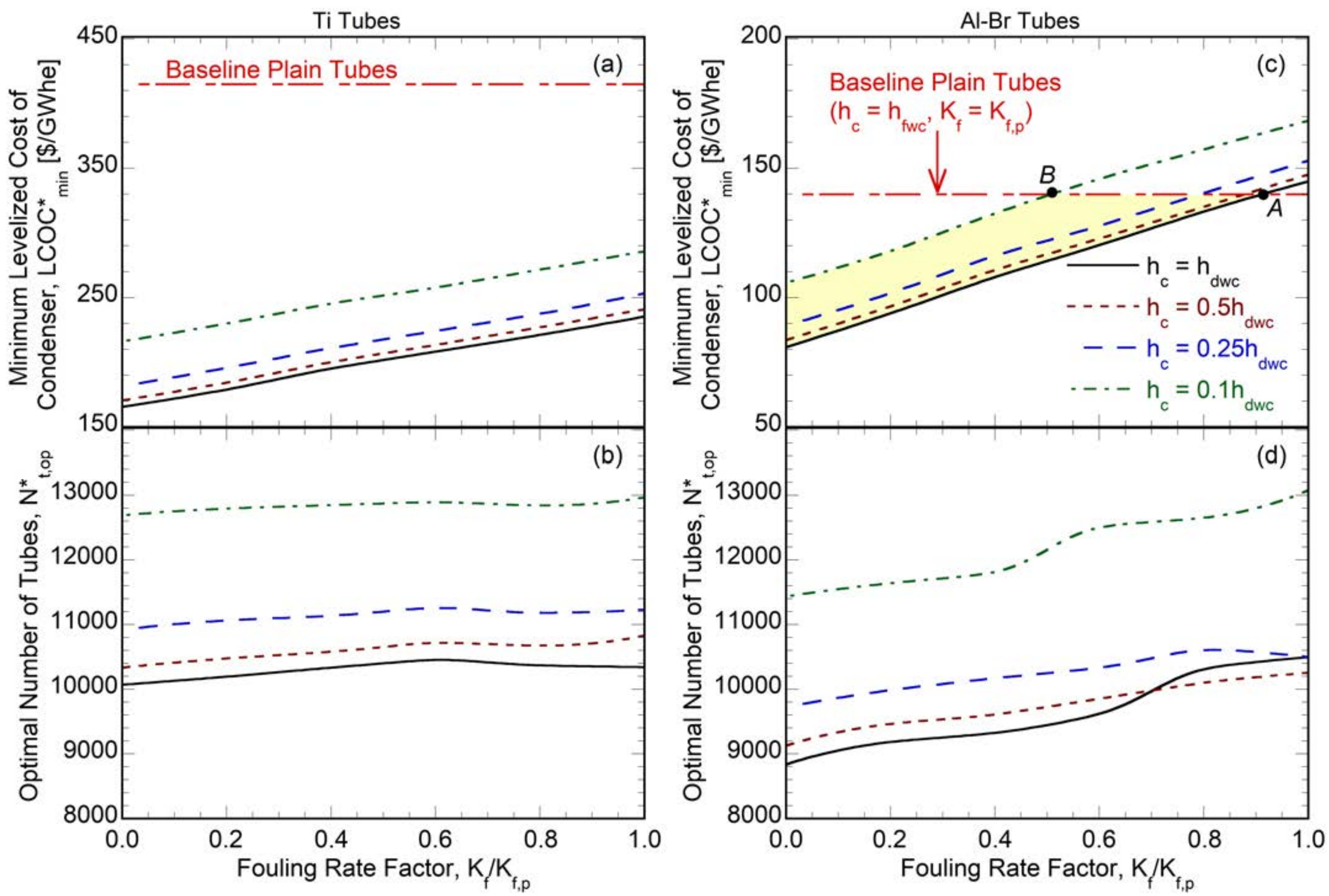

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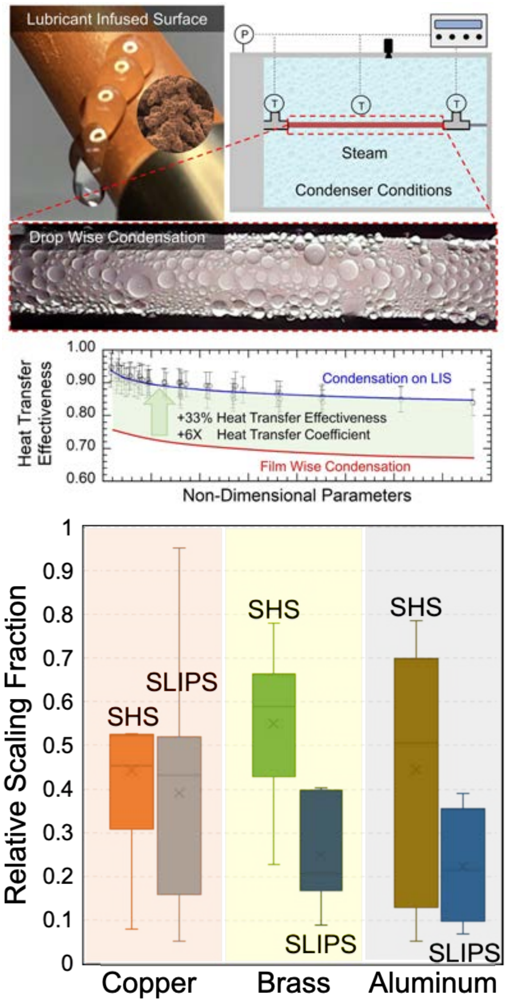
Technoeconomics of Our Surfaces



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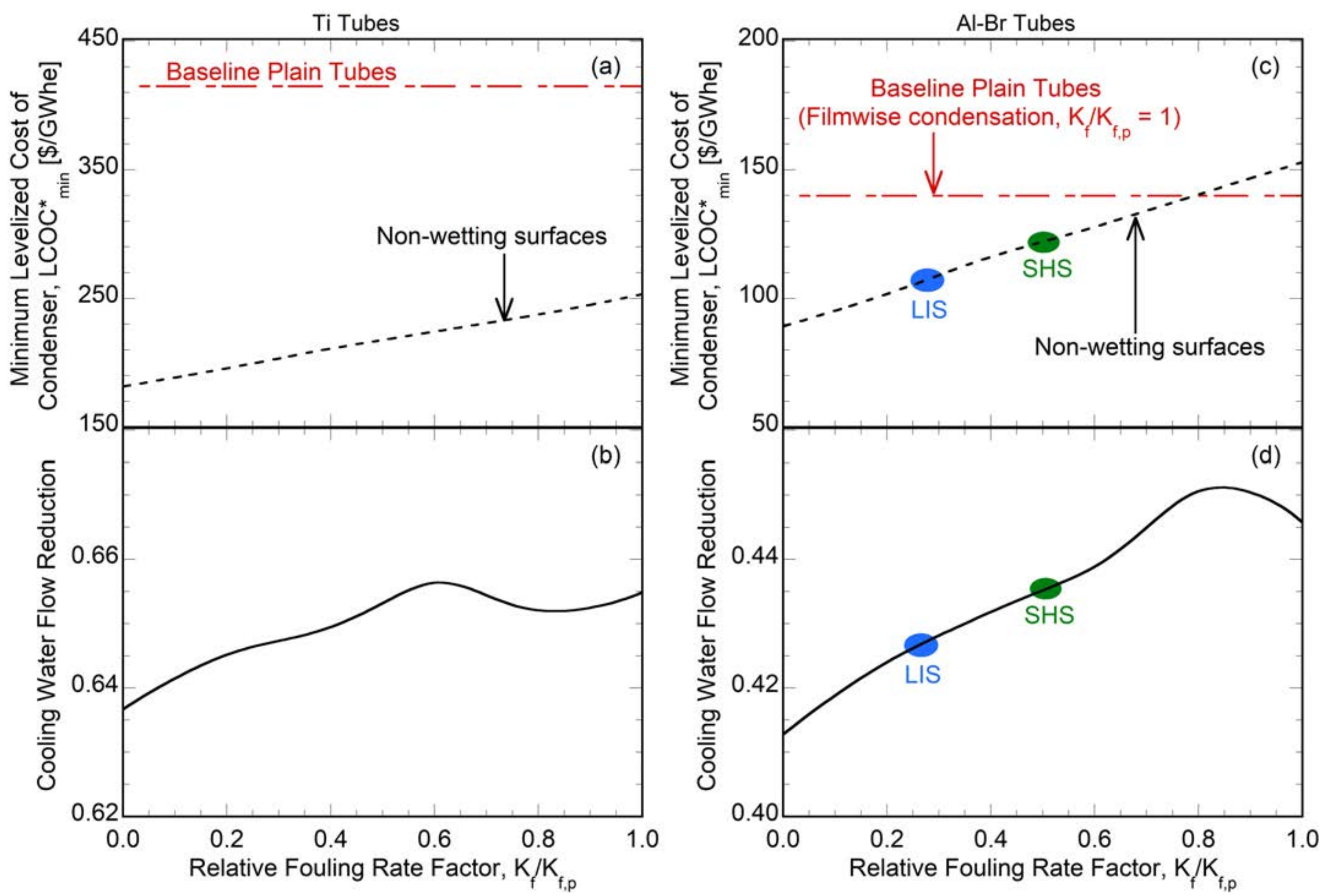

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