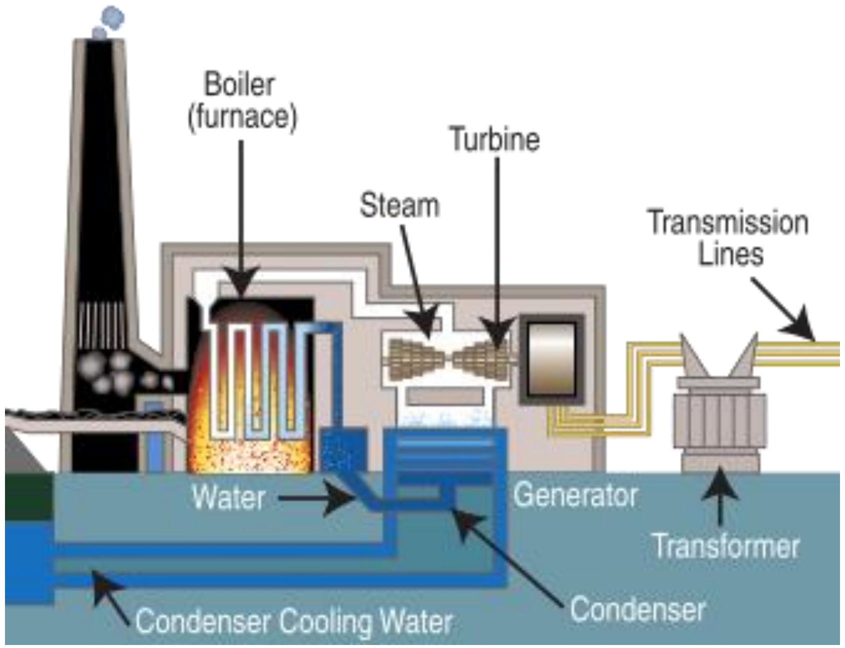
Capillary-driven Condensation for Heat Transfer Enhancement in Steam Power Plants

Project ID: DE-FE0031677
Yajing Zhao, Samuel Cruz, and Evelyn N. Wang
Department of Mechanical Engineering, MIT
Thomas G. Lestina
Heat Transfer Research Inc

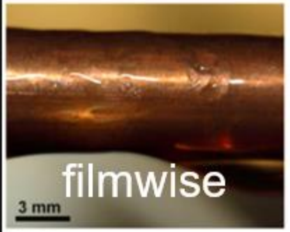
Project Description and Objectives

Motivation

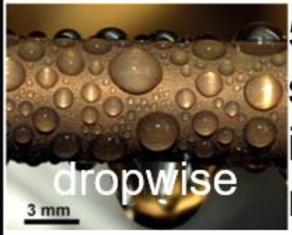
- Steam power plants are responsible for the largest amount of water[1] withdrawn from U.S. water bodies:
  - $HTC_{condenser}$ ↑, power ↑, $Q_{consum,\ water}$ ↓



- Industrial condensers rely on conventional filmwise condensation:



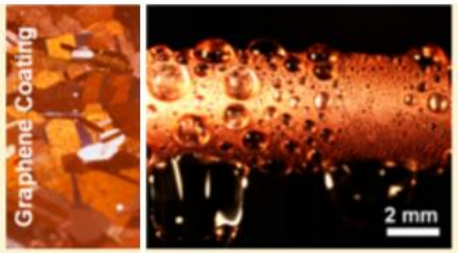
prevalent in industry; barriers to heat transfer



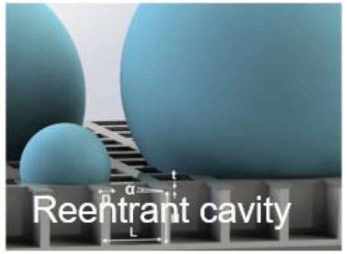
5-7x HTC shown in lab; insufficient robustness

- Scalability and robustness remain challenging for dropwise condensers:

lubricant infused surface[2]



graphene coating[3]



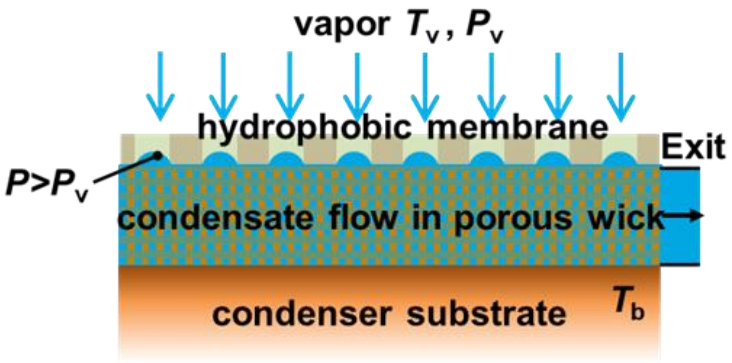
reentrant surface[4]

[1] Dieter, C.A. *et al*.(2018)
[2] Wong, T. *et al*.(2013)
[3] Preston, D. *et al*.(2015)
[4] Wilke, K. *et al*.(2018)

Project Description and Objectives

Proposed Concept—Capillary-Driven Thin-Film Condensation

Filmwise condensation with enhanced thermal conductivity & controlled condensate film thickness

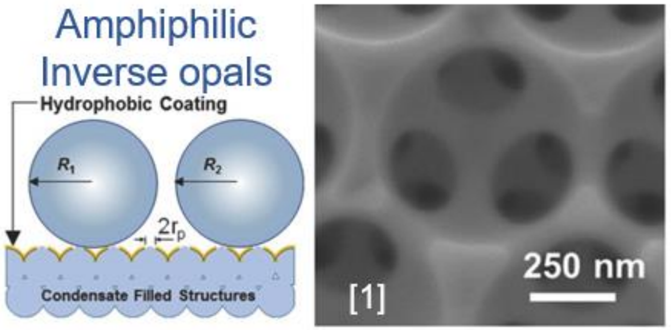


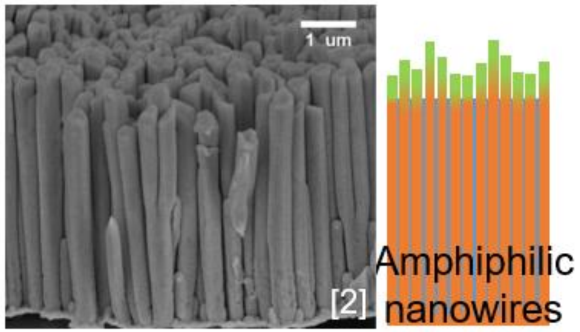
- Hierarchical surface consisting of a robust hydrophobic membrane and high thermal conductivity wick
- Vapor transports through membrane pores and condenses at the wick-membrane interface
- Capillary pressure at the membrane-wick interface provides additional driving-force to push condensate from the wick to an exit port for condensate removal

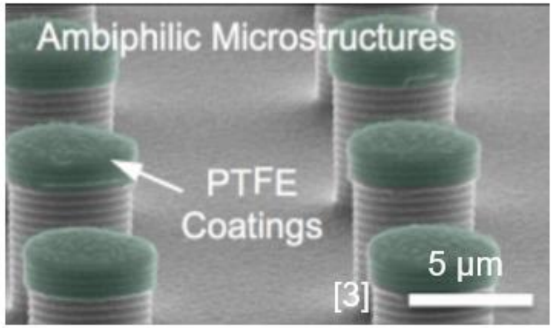
Project Description and Objectives

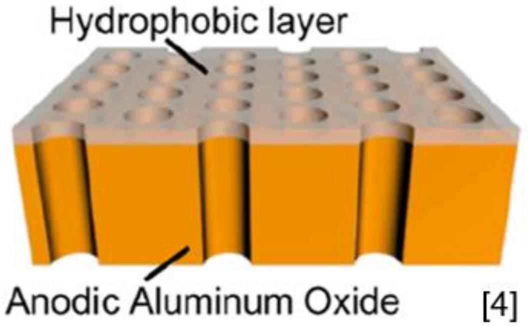
Technology Benchmarking

- Several wicking structures with hydrophobic coatings have been investigated to enhance condensation heat transfer









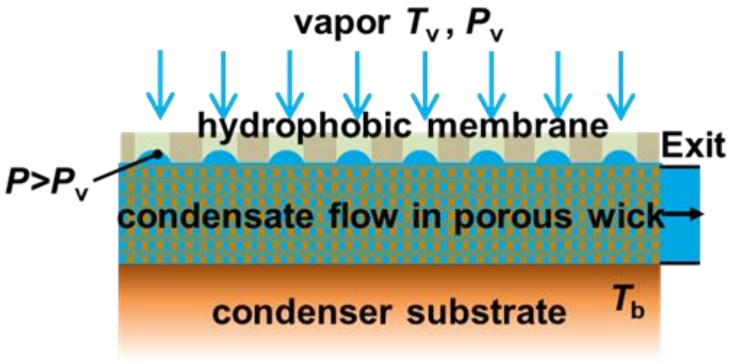
Challenges

- Coupling between driving force (capillary pressure) and viscous resistance
- Non-robust hydrophobic coating
- Non-scalable approach
- Limited to no experimental characterization

[1] Oh, J. *et al*. (2018) [2] Anderson, D. *et al*. (2012) [3] Winter, R. *et al*. (2021) [4] Liu, K. *et al*.(2018)

Project Description and Objectives

Proposed Concept—Capillary-Driven Thin-Film Condensation



Key Advantages

- Decouples driving force (P_{cap}~$2\sigma/r_p$) and viscous resistance (κ)
- Reduces thermal resistance by constraining condensate film thickness in a high thermal conductivity wick
- Improves robustness with robust hydrophobic membrane materials
- Enables potential for scalability

Project Update

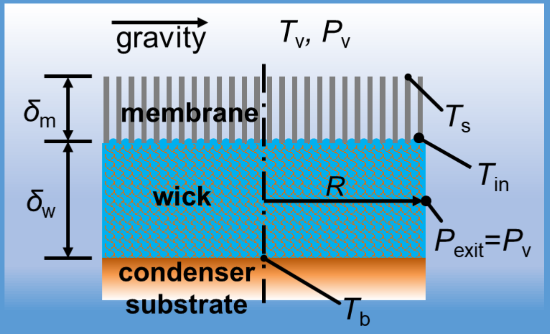
Approach

Model Development

Design parameters:

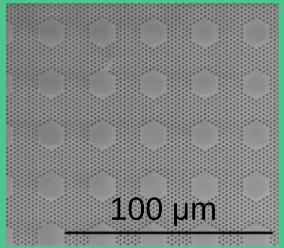
Wick: permeability, thickness, porosity, thermal conductivity

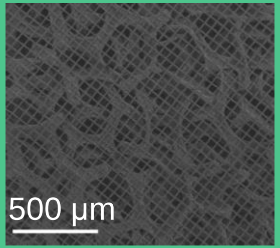
Membrane: pore size, porosity, thickness, thermal conductivity



Surface Fabrication

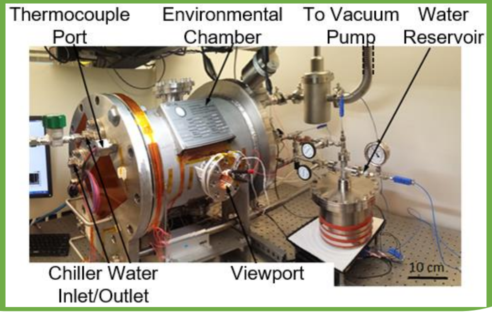
- Fabrication of highly defined geometries w/ MEMS
- Fabrication of scalable and robust surfaces w/ commercially available materials





Experiment

- Experimentally characterize highly defined geometries to validate model
- Experimentally demonstrate HTC enhancement w/ scalable surface designs

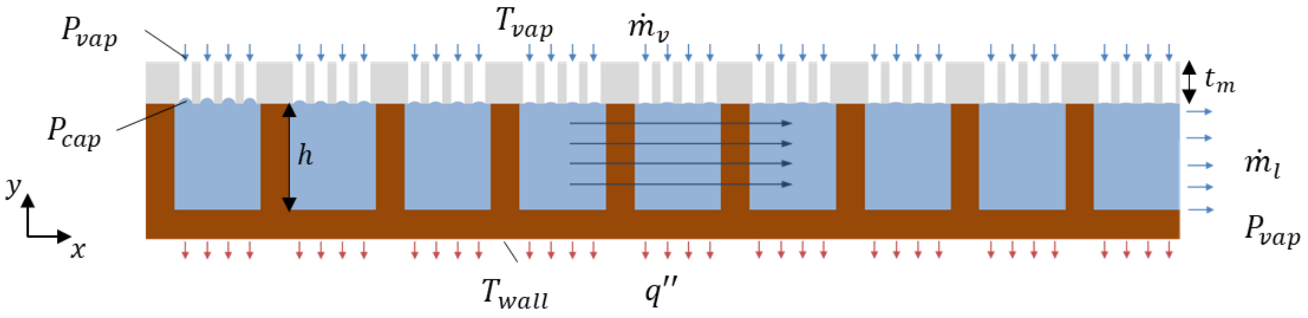


Modeling capillary-driven condensation

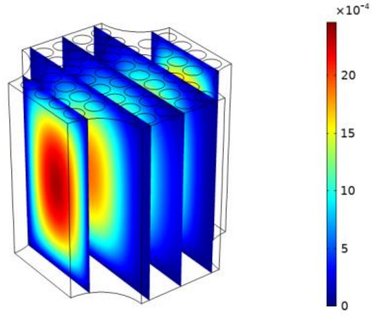
High-Performance Design Utilizing Highly Defined Geometry

- Developed a finite element heat transfer model using COMSOL
  - Utilized well-defined geometry for systematic understanding of physics
  - Performed **parametric studies** to better understand factors that drive performance
  - Performed **global optimizations** to select high performance rational designs

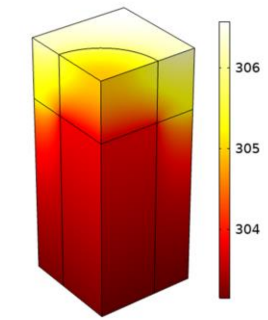
- Device geometry



present case: micropillar wick, through-pore porous membrane



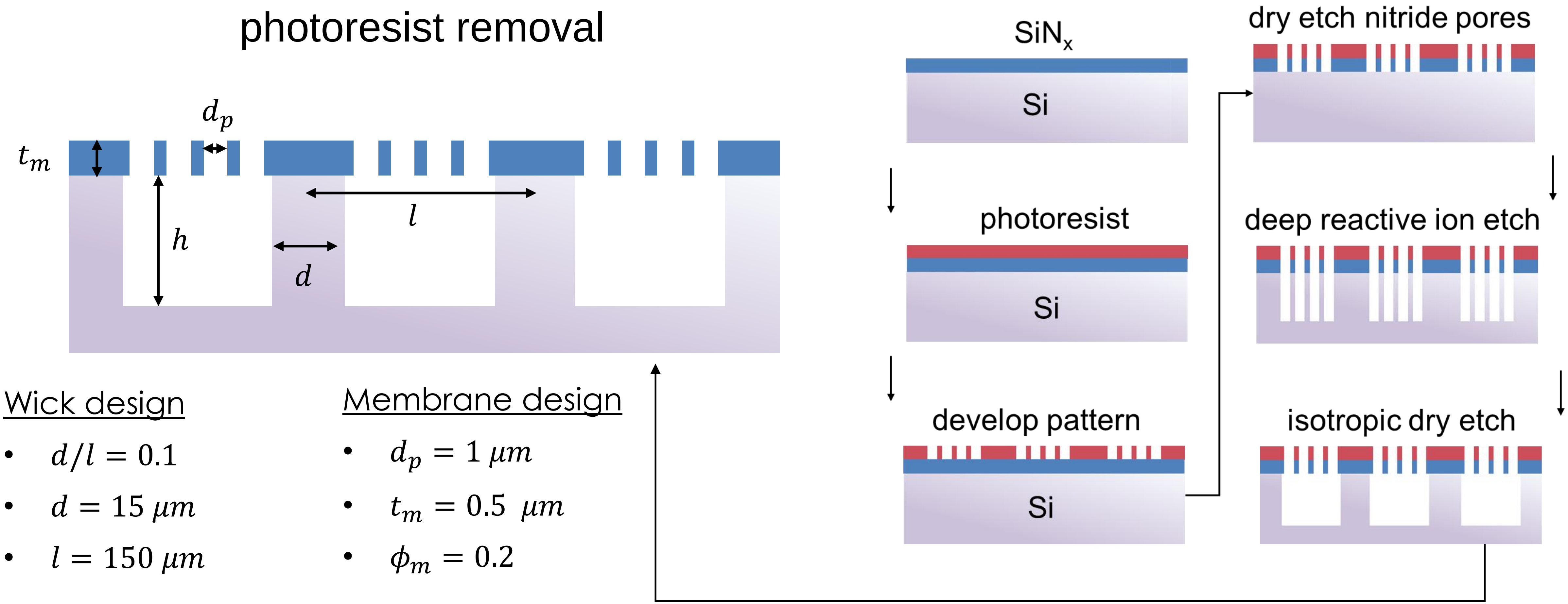
permeability of COMSOL unit cell



HTC of COMSOL unit cell

Geometry and Fabrication

micropillar wick with a silicon nitride membrane bonded on top



Wick design

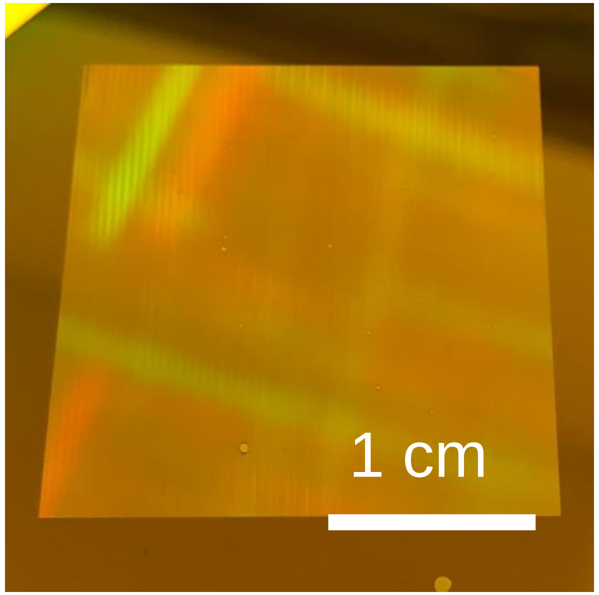
- $d/l = 0.1$
- $d = 15\ \mu m$
- $l = 150\ \mu m$

Membrane design

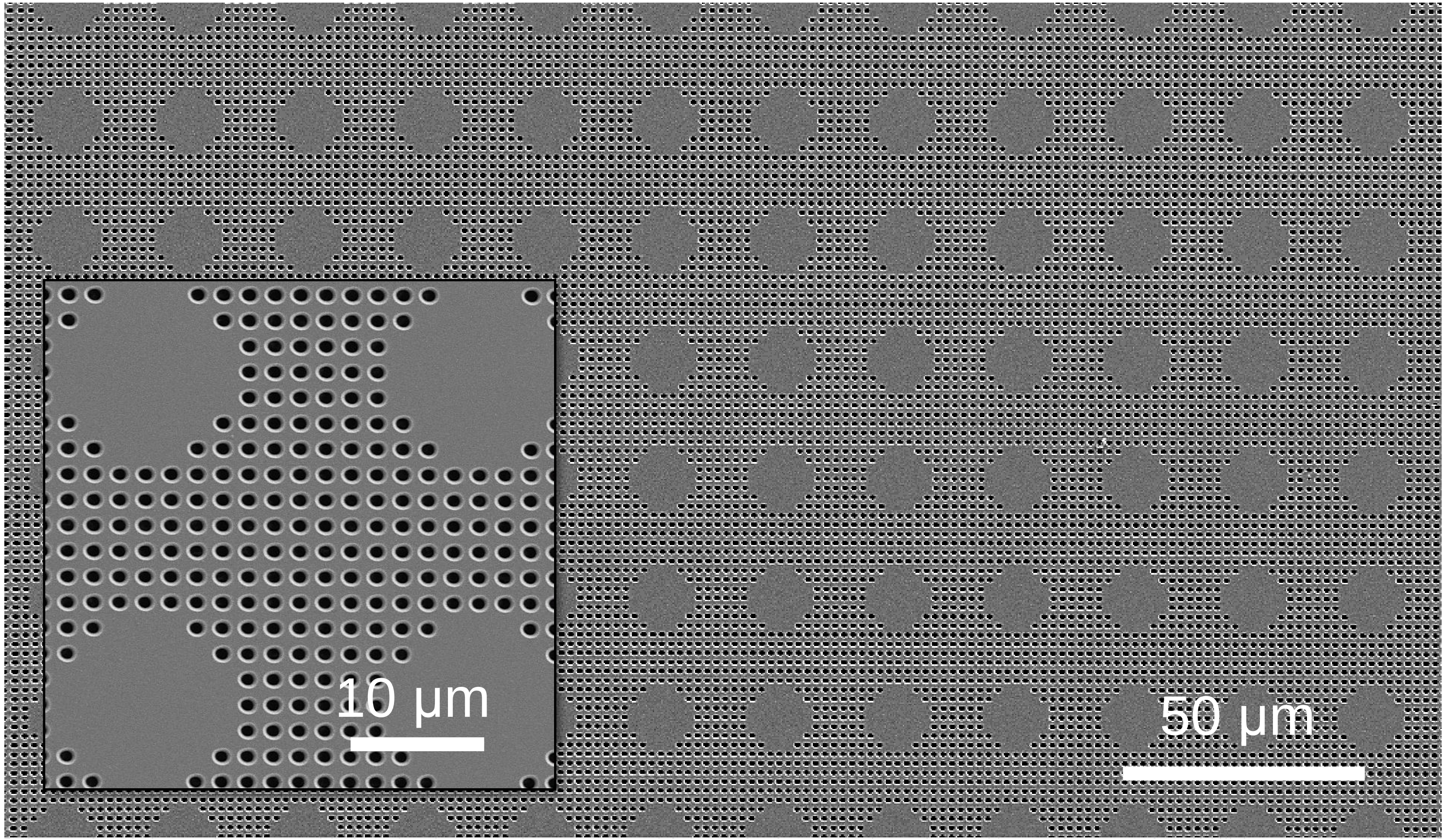
- $d_p = 1\ \mu m$
- $t_m = 0.5\ \mu m$
- $\phi_m = 0.2$

Large-scale fabrication

Imaging of fabricated structure



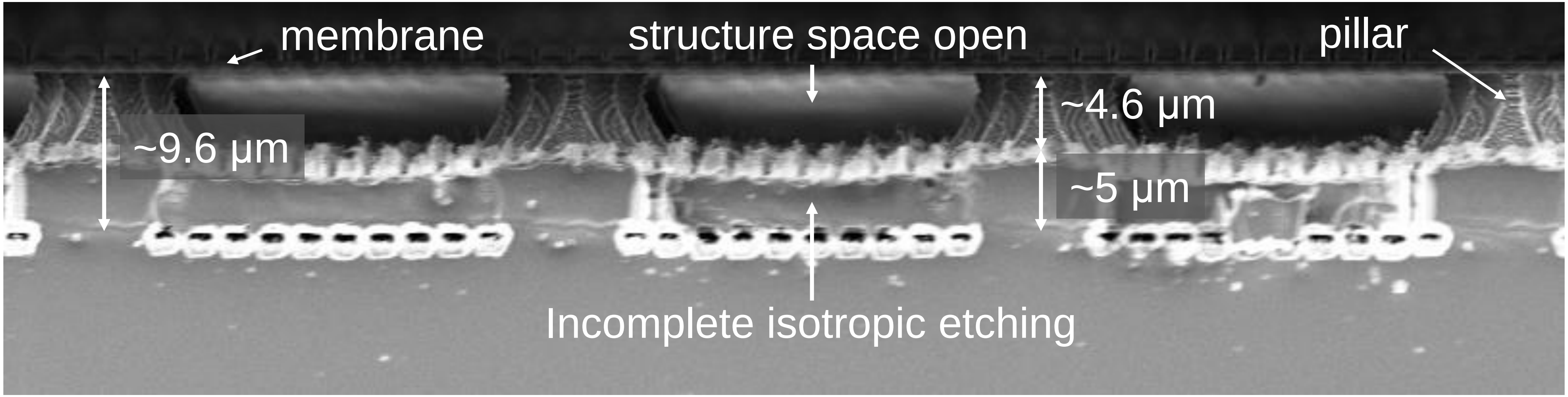
- Achieved large area
- Qualitatively uniform

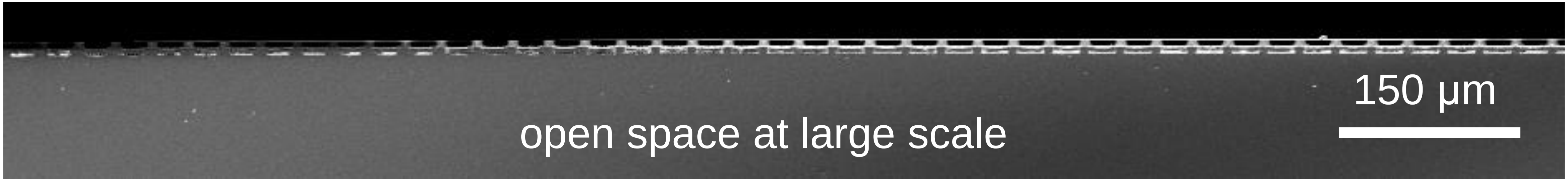


- Plane view SEM: qualitatively uniform; open pores

Large-scale fabrication

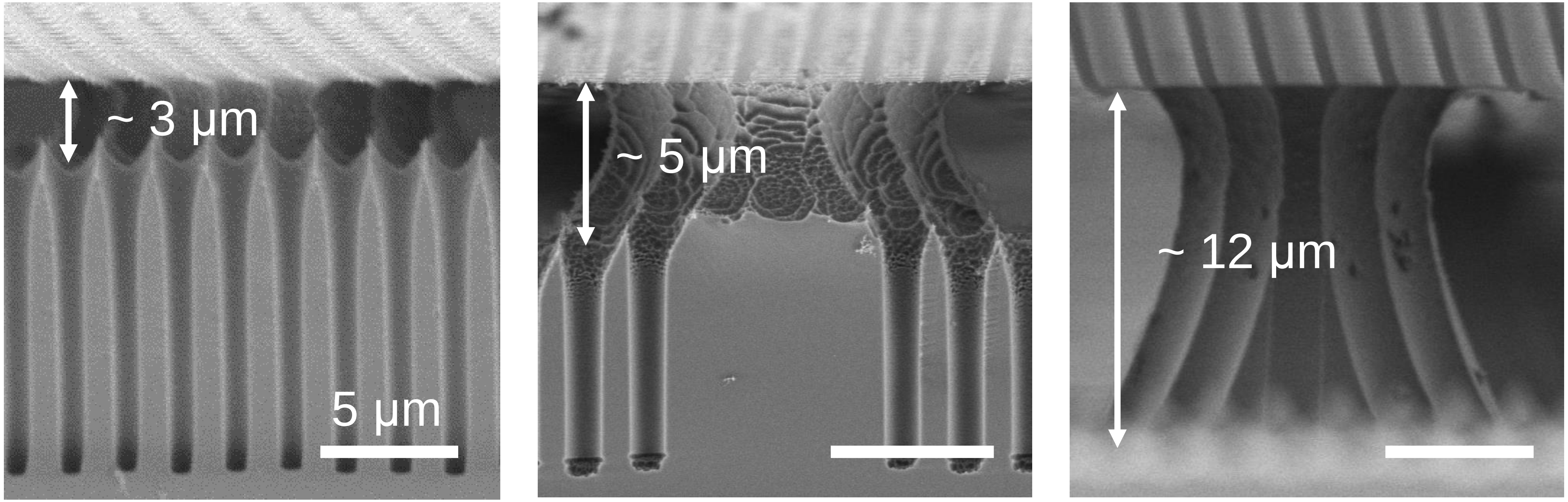
Cross section SEM





Developing isotropic etching recipe

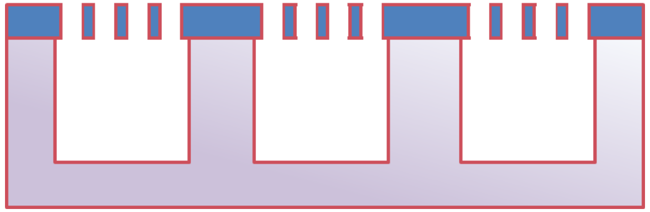
Successfully opened wicking space to delay flooding



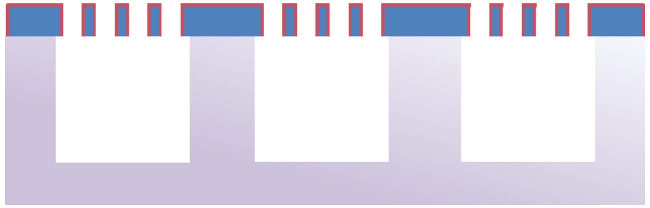
- Challenges removing material between trenches
- Developed a multi-step recipe to open wicking structure

Coating the structure

Multiple coating strategies can change operation

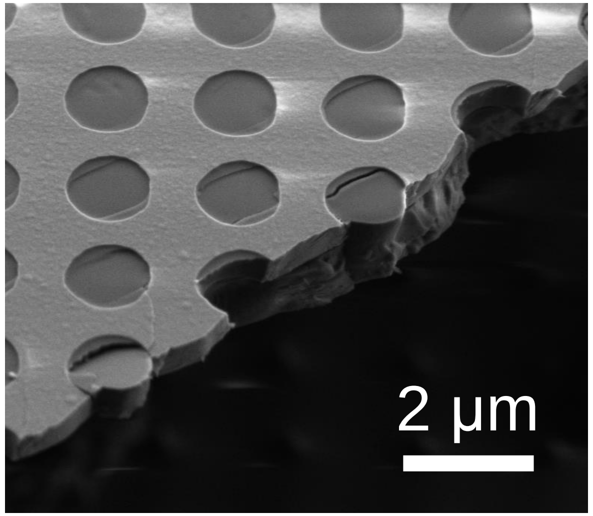


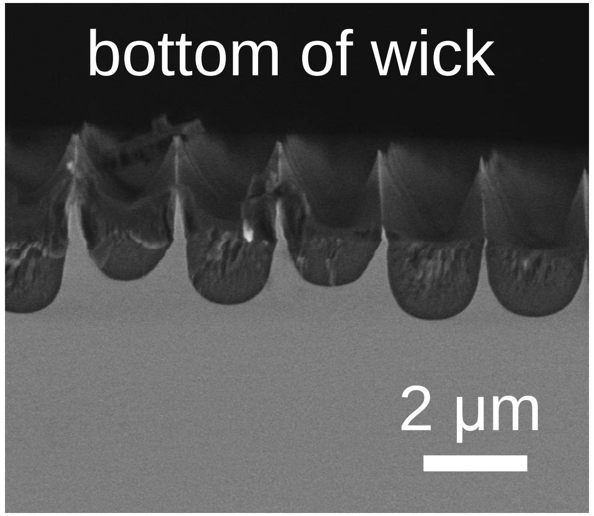
1) Coat the wick and membrane hydrophobic: Easy

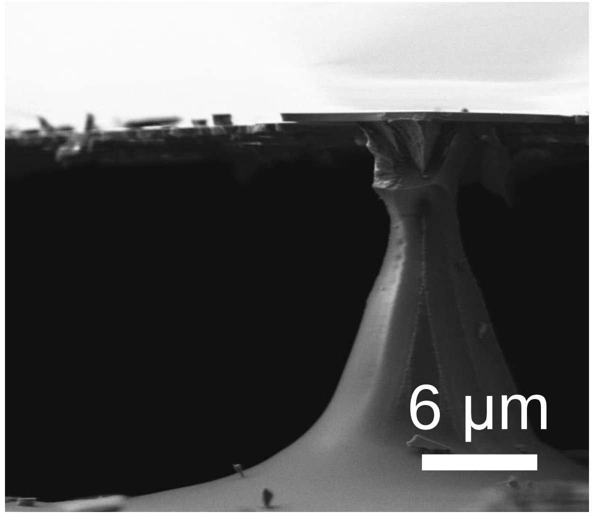


2) Coat only the membrane hydrophobic: Difficult

2)

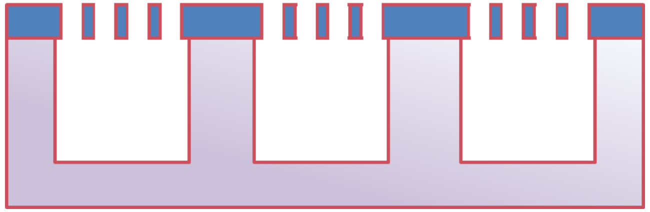




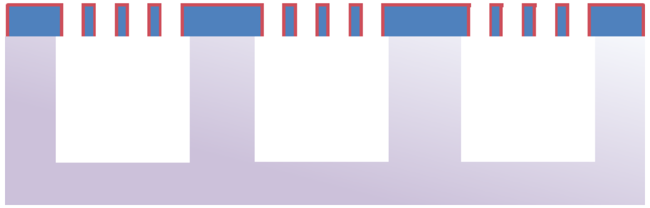


Ambient air condensation

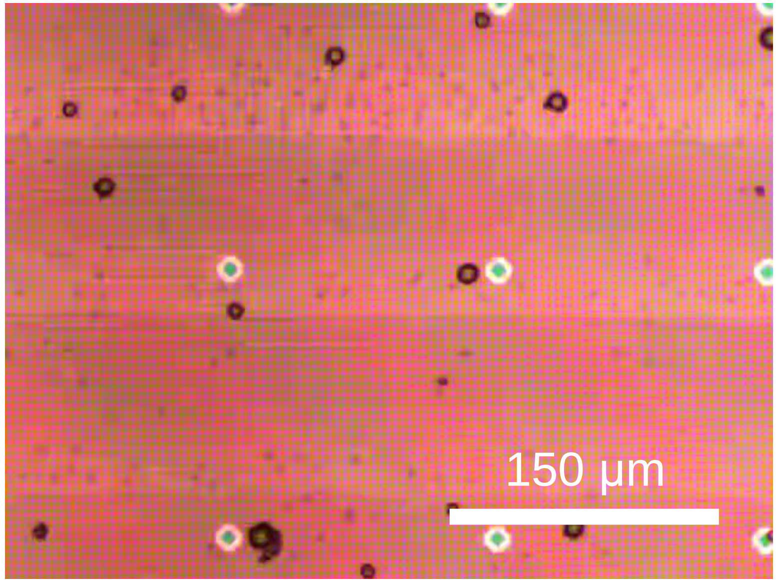
Imaging under optical microscope

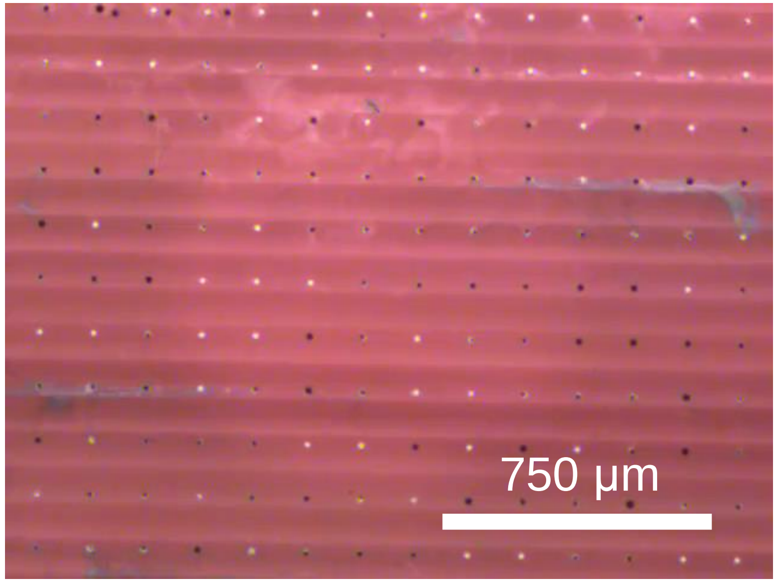


wick and membrane are hydrophobic



wick hydrophilic; membrane hydrophobic

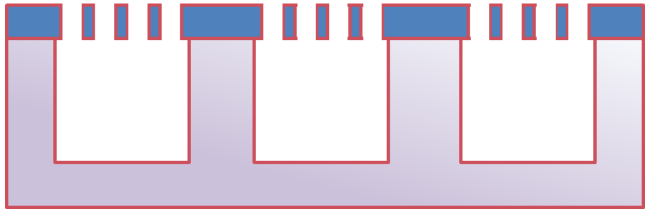




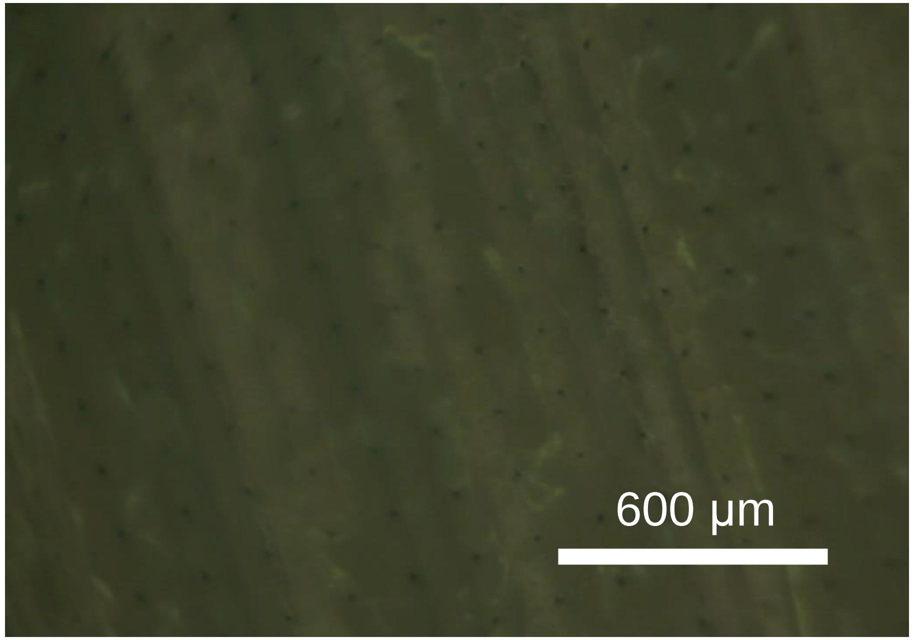
Pure vapor condensation

Challenge with completely hydrophobic structure

- Not clear if nucleation happens on top of membrane or in the wick
- Droplets are both absorbed into structure and pin on the surface
- Wick does not fill completely
- Bursting/flooding droplets pin strongly on membrane



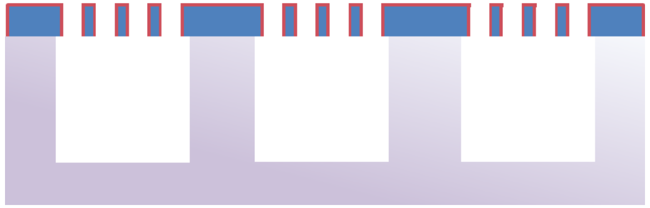
wick and membrane are hydrophobic



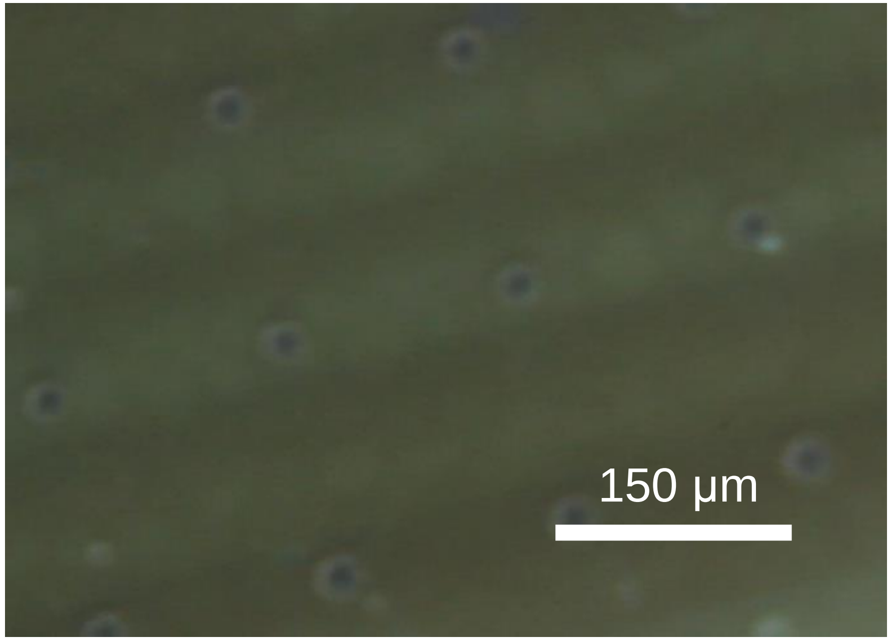
Pure vapor condensation

Successful demonstration of capillary-driven condensation

- Wick fills completely
  - No dry spots
- Small droplets are absorbed continually
- Surface appears “dry”
- Droplet on pillars are continually absorbed
- Heat transfer measurements ongoing



wick hydrophilic; membrane hydrophobic



Project update on scalable approach

NATIONAL ENERGY TECHNOLOGY LABORATORY

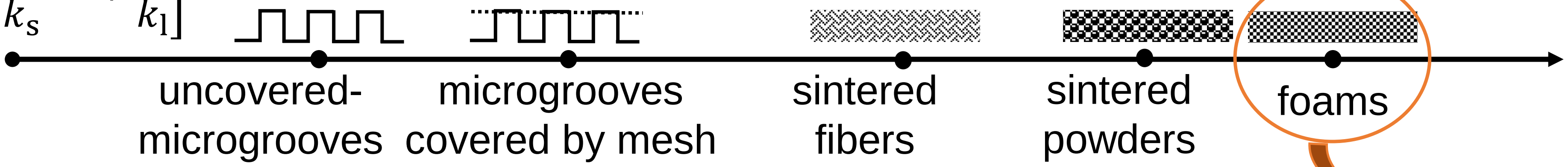
Scalable Surfaces for Capillary-Driven Condensation

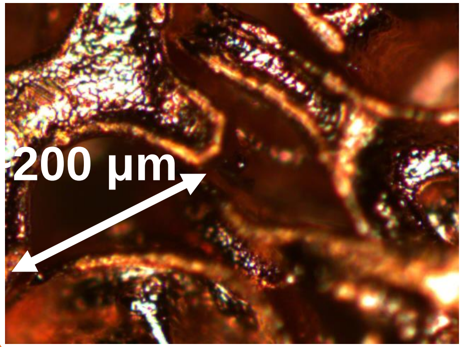
➢ Wick layer materials selection

$k_{\mathrm{eff,min}} = \left[\frac{(1-\phi)}{k_s} + \frac{\phi}{k_l}\right]^{-1}$

k_{eff} of different porous metal wick

$k_{\mathrm{eff,max}} = k_s(1-\phi)+k_l\phi$





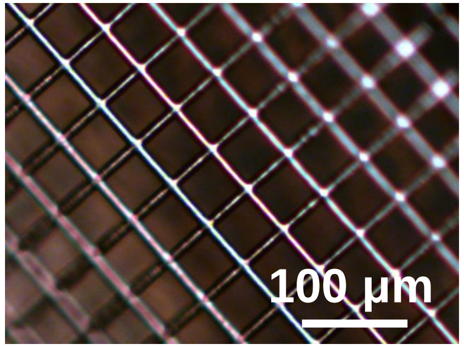
Cu foam

➢ Membrane layer materials selection

- Commercially available and hydrophobic
- Easy to bond with wick layer
- Well-defined pore size (model validation)

} hydrophobized copper mesh →

- Alternative membrane material being considered for <u>robust hydrophobicity</u>:
  - electrospun hydrophobic membranes



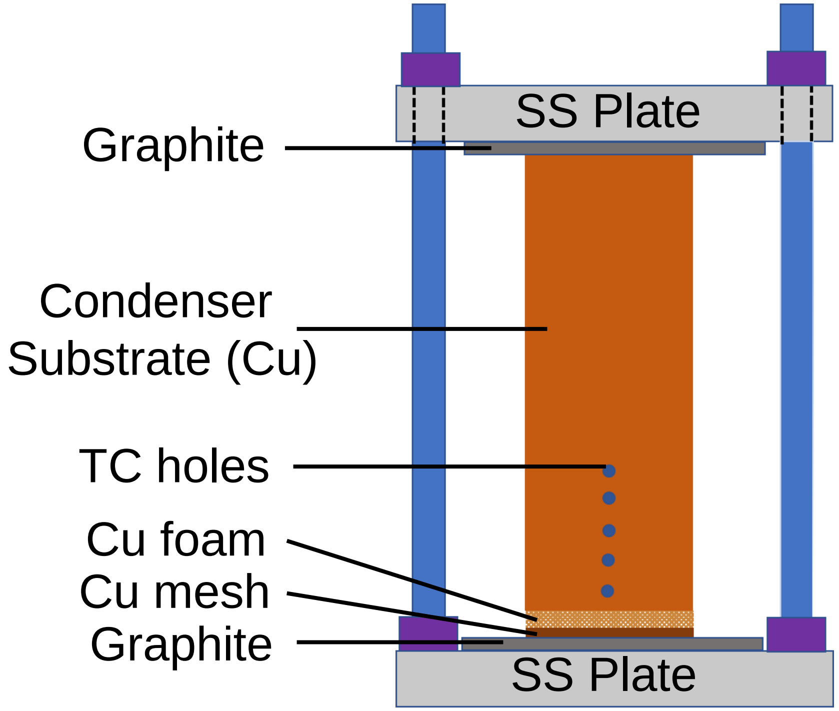
Cu mesh

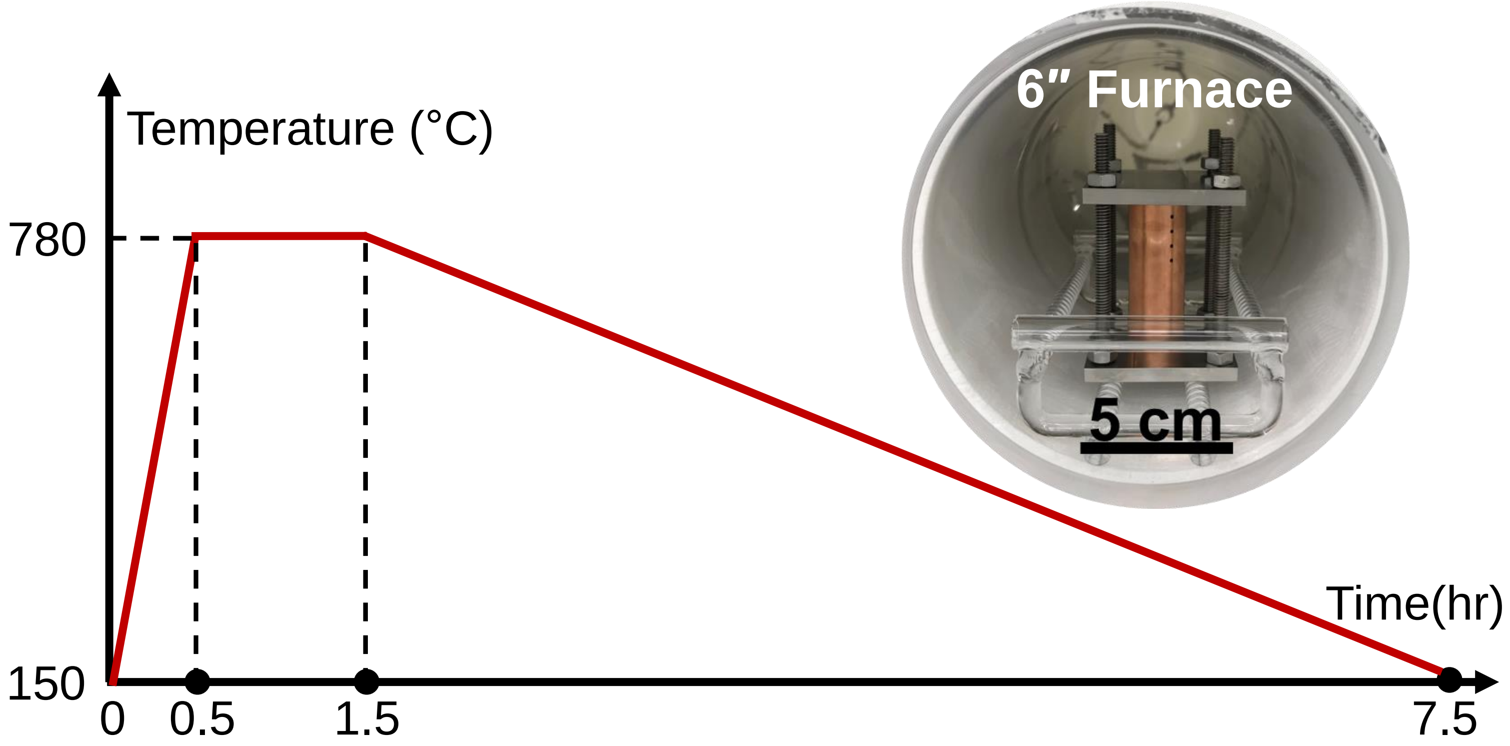
Fabrication of hierarchical Cu condenser

Surface fabrication — diffusion bonding

Three Cu meshes of different size bonded with same Cu foam and hydrophobized:

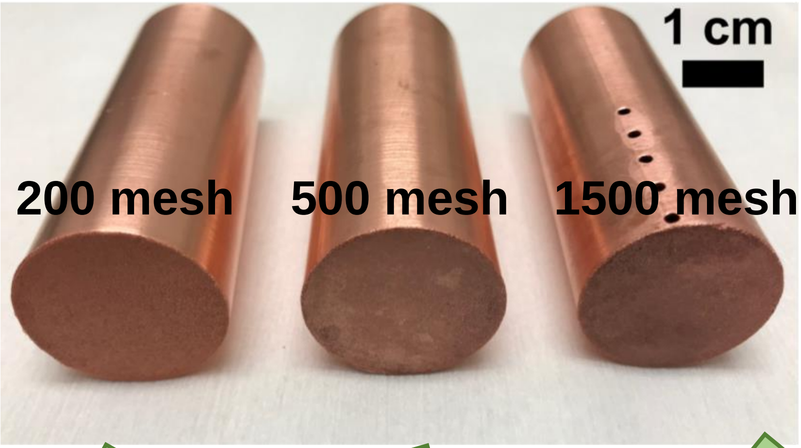
200/500/1500 mesh size, corresponding to ~80/40/10 μm membrane pore size

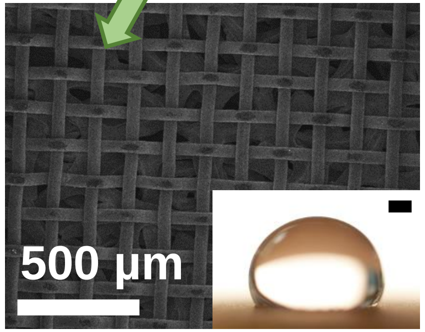


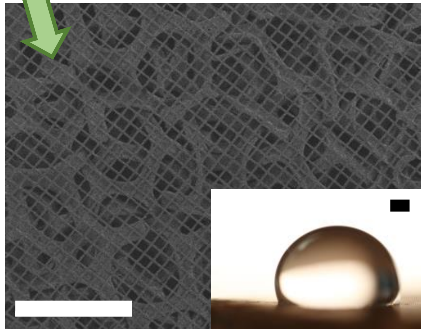


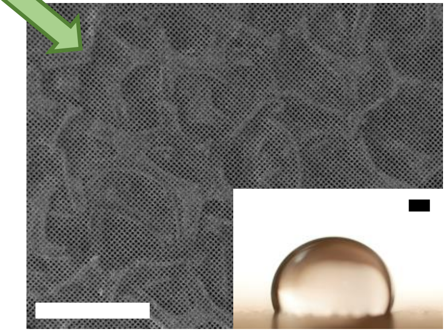
Fabrication of hierarchical Cu condenser

Surface characterization: integrity of pore geometry



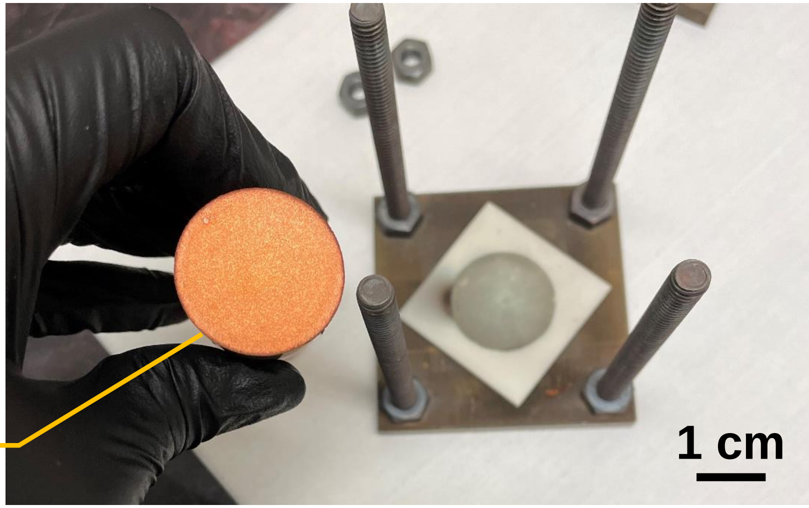






Solution to graphite powder:

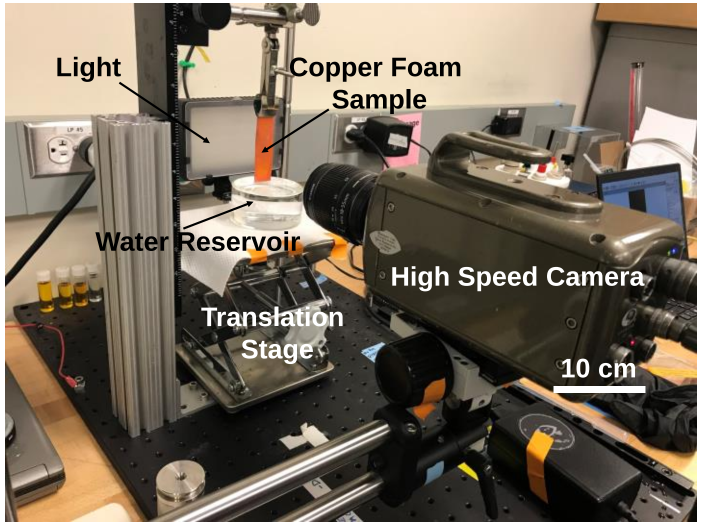
Graphite-free sample fabricated by diffusion bonding with ceramic molds

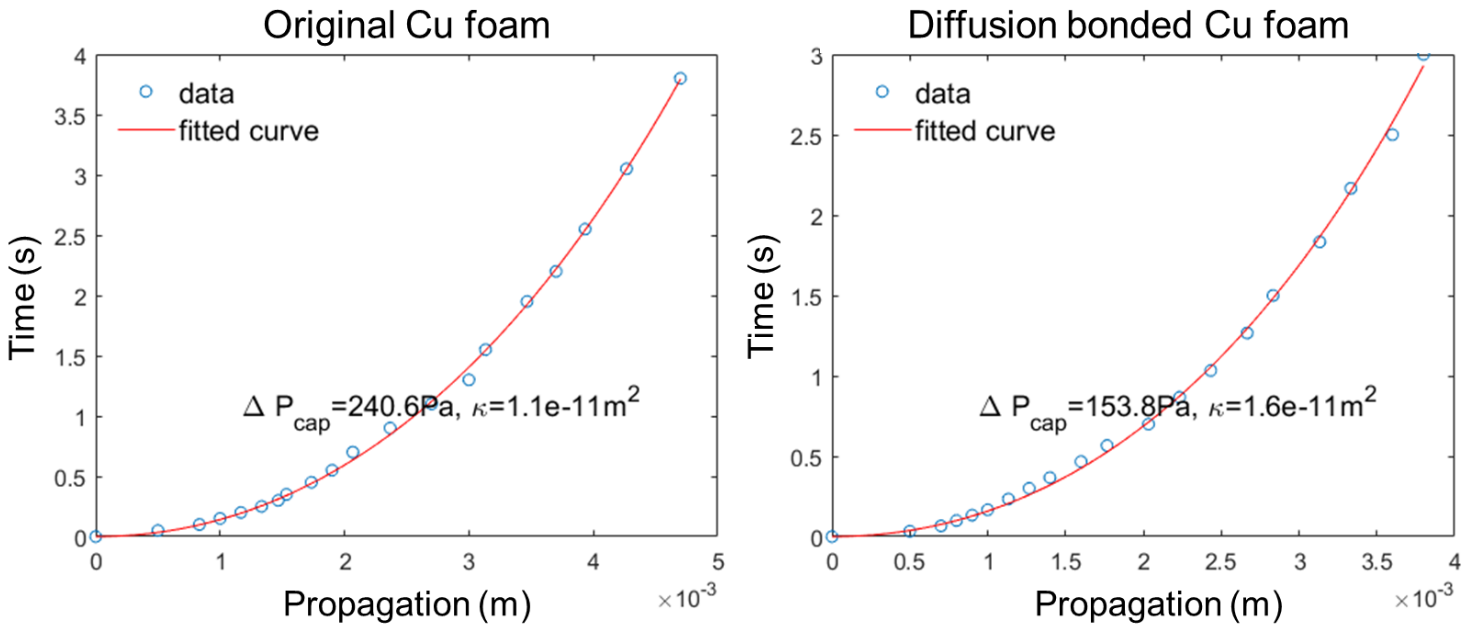


- Pore geometry retained after bonding
- Uniform hydrophobicity validated via condensation under optical microscope
- Small traces of black deposits were found--graphite powders

Fabrication of hierarchical Cu condenser

Surface characterization: permeability measurements





One-dimensional Darcy's Law:

$$\frac{dy}{dt} = \frac{-\kappa}{\mu\varphi}\left(\frac{-\Delta P_{cap}}{y} + \rho g\right)$$

Solution:

$$t = -\frac{A\ln(A - By) + By - A\ln(A)}{B^2},$$

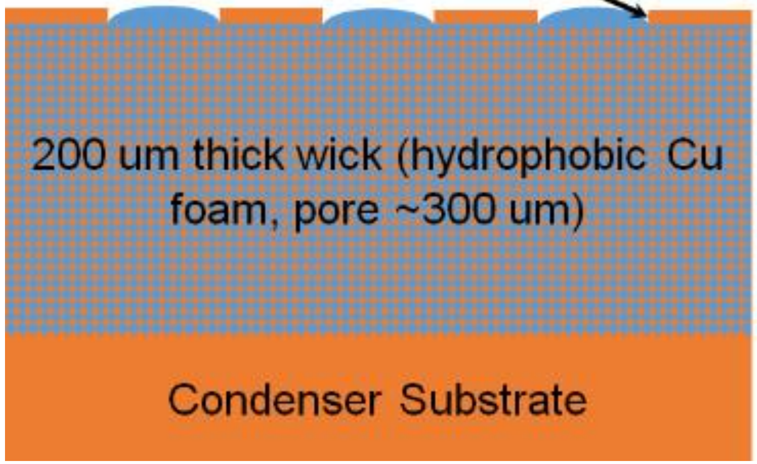
where $A = \frac{\kappa \Delta P_{cap}}{\mu\varphi}, B = \frac{\kappa \rho g}{\mu\varphi}$

- Permeability $\boldsymbol{\kappa}$ measured before & after diffusion bonding
- 1E-11m^2 would be a conservative estimation for $\boldsymbol{\kappa}$
- Increase in $\boldsymbol{\kappa}$ may be due to etched copper oxide

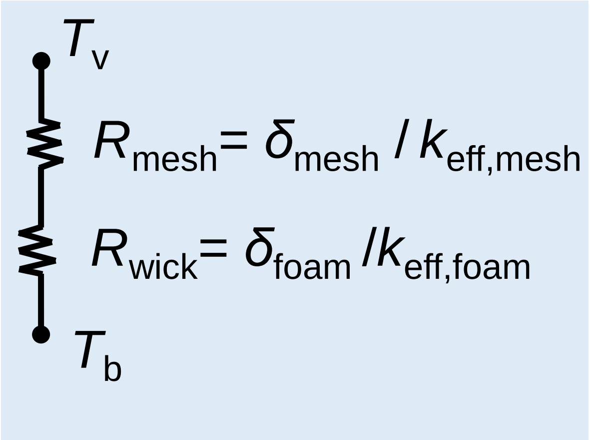
Modeling of hierarchical Cu surfaces

Modeling framework for HTC and flooding prediction

- Simplified model based on exp. observation:



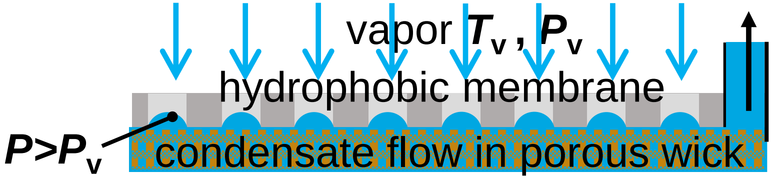
Thermal resistance network



$$k_{eff,mesh} = \frac{\beta - \varepsilon}{\beta + \varepsilon} k_l \qquad \beta = \left(1 + \frac{k_s}{k_l}\right) / \left(1 - \frac{k_s}{k_l}\right)$$

$$k_{eff,wick} = \varepsilon k_s + (1 - k_s) k_l$$

- Flooding criterion *P**:



Capillary driving force: $P_{cap} = \frac{-4\gamma\cos\theta}{d_p}$

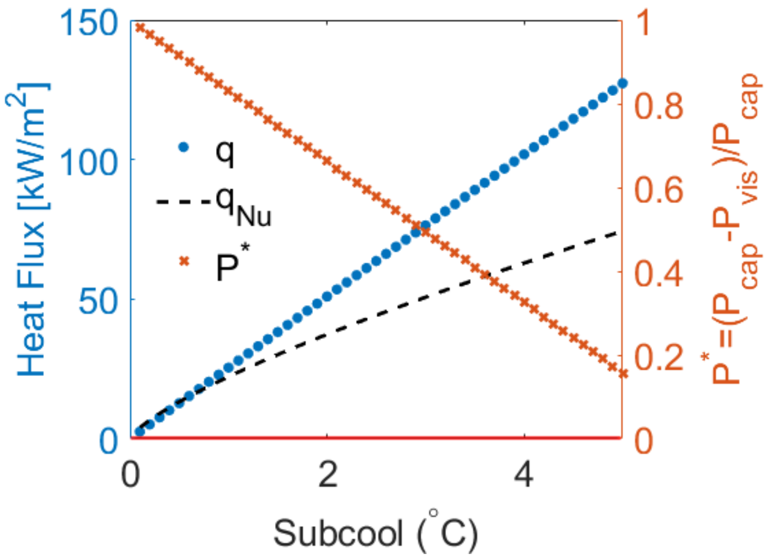
Viscous pressure loss: $P_{vis} = \frac{k_w \mu (T_{in} - T_b) R^2}{4\rho\kappa h_{fg} \delta_w{}^2}$

Flooding criterion: $0 < \boldsymbol{P}^* = \frac{(P_{cap} - P_{vis})}{P_{cap}} < 1$

Modeling results hierarchical Cu surfaces

HTC enhancement and flooding regime predicted by model

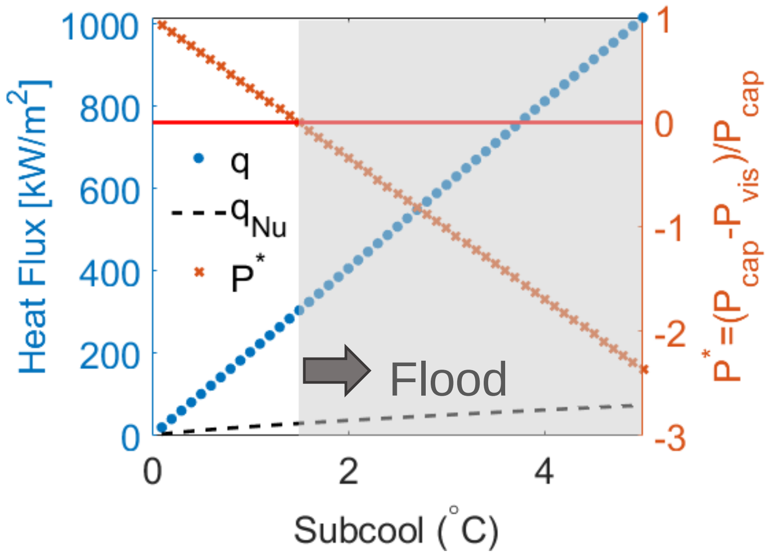
Model prediction for T_v=35°C



200 mesh size sample

No flooding

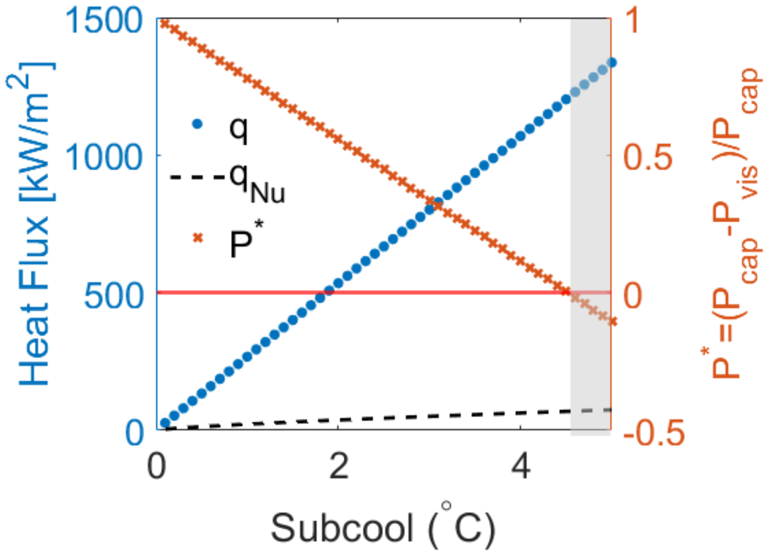
1-2x htc



500 mesh size sample

No flooding up to ΔT ~ 1.5°C

1-10x htc



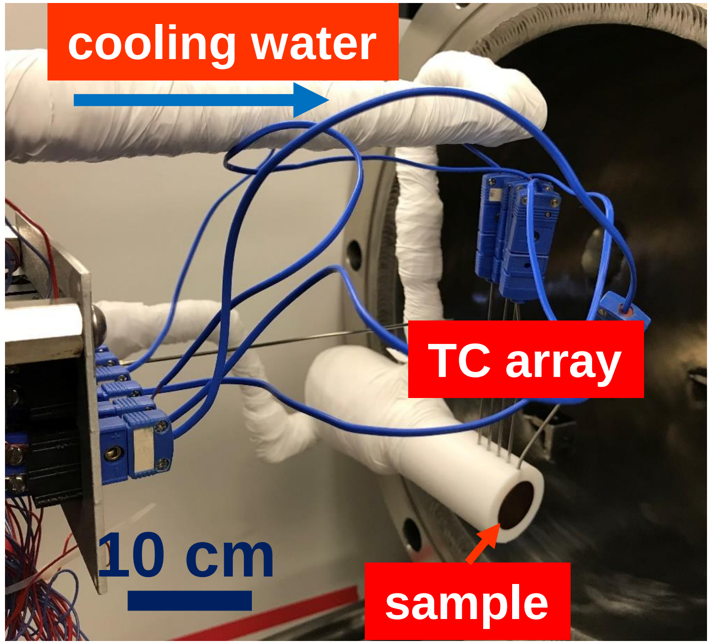
1500 mesh size sample

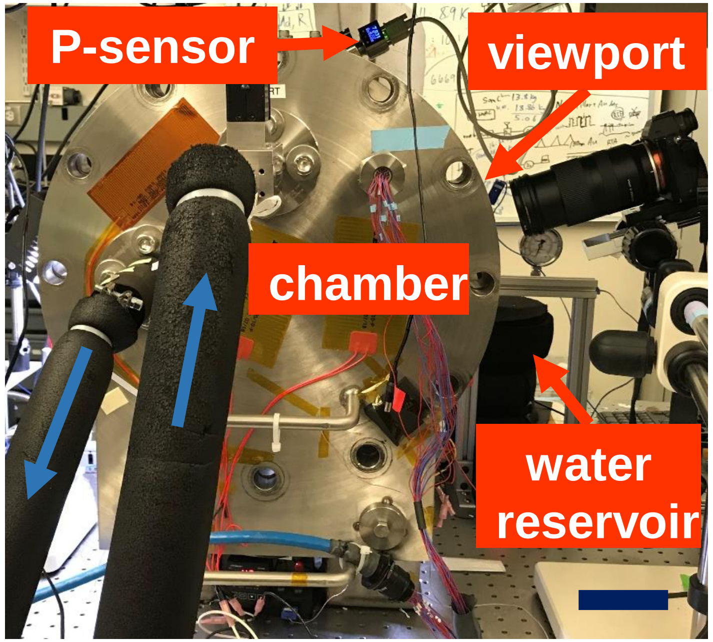
No flooding up to ΔT ~ 4.5°C

1-17x htc

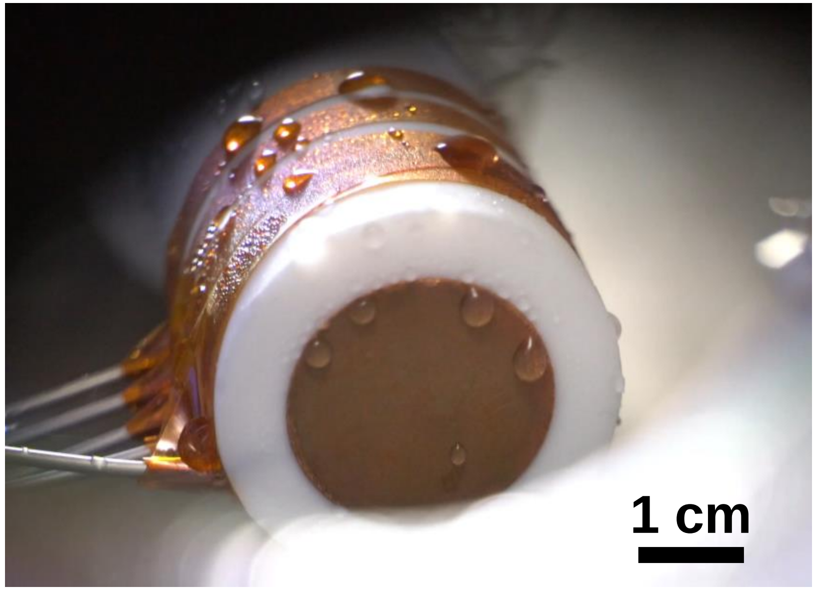
Experiments

Experimental setup & preliminary testing





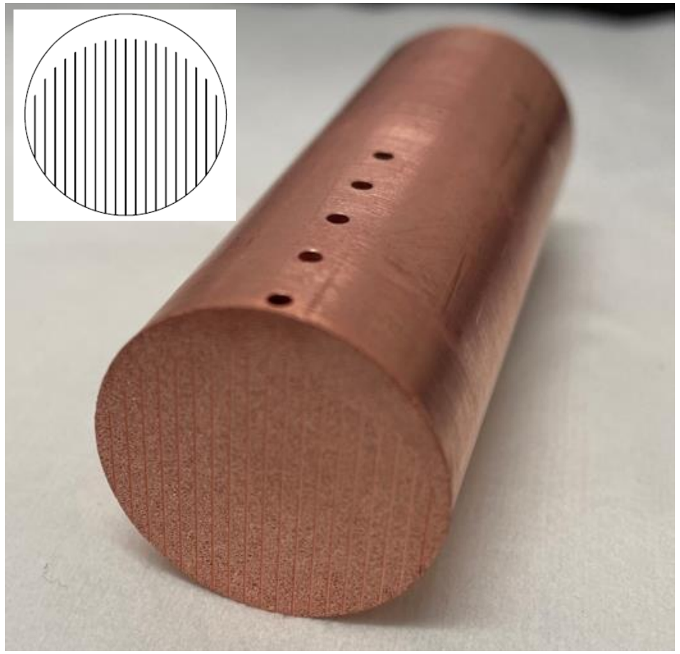
Preliminary test:



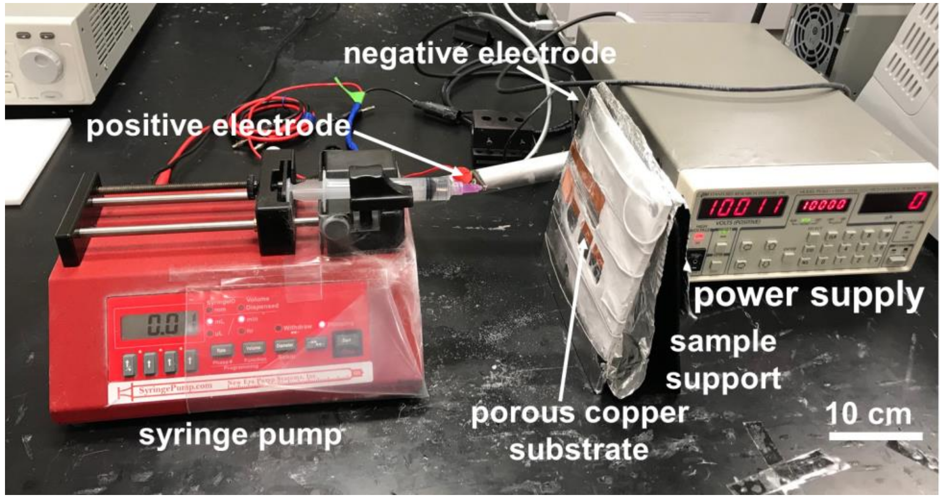
- Experimental setup for condensation HTC characterization with industrial-level vapor conditions
- HTC measurements being conducted and will be compared to model prediction
- Flooding/bursting of droplets occurred—attributed to local defects in coating/mesh
  - Design of exit port/channels to guide the condensate flow
  - Application of selective coating/intrinsic hydrophobic membrane to keep the wick hydrophilic

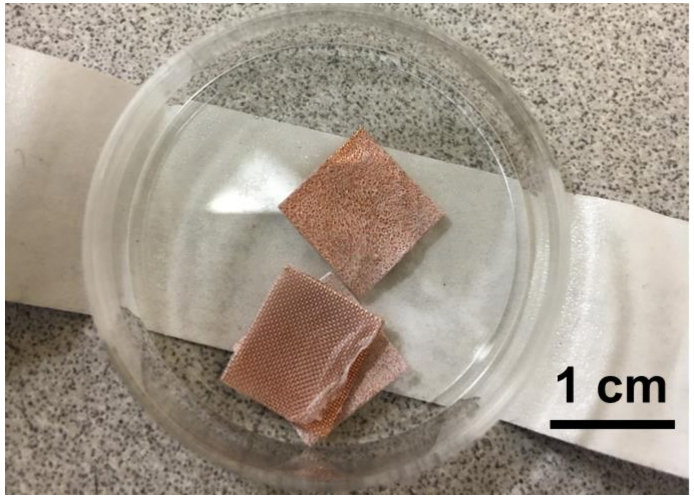
Exploration of reliable & robust surfaces

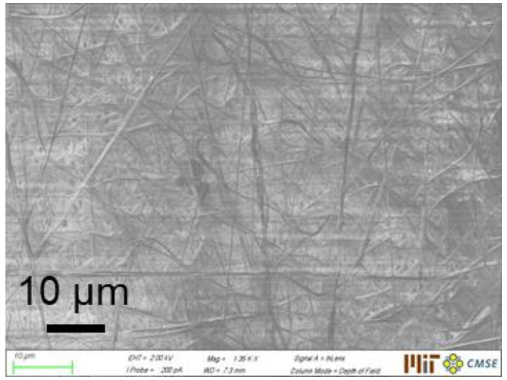
Exit port design, scalable and robust membranes

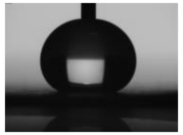


Cu foam with microchannels (before diffusion bonding)

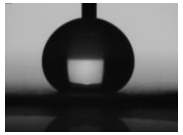








$\theta_{adv} \approx 142.1^{\circ}$



$\theta_{rec} \approx 140.2^{\circ}$

Electrospinning PVDF membrane:

- Intrinsically hydrophobic
- Low cost
- Tunable geometry (e.g., pore size)
- Different porous Cu substrate tested
- Bonding remains a challenge

Preparing Project for Next Steps

NATIONAL ENERGY TECHNOLOGY LABORATORY

Next steps

- Determine if configuration where the top of the membrane and the pore sidewalls is hydrophobic, and where the entire membrane is hydrophobic, are desired configurations
- Develop a superior sample-condenser bonding technique for heat transfer measurements
- Heat transfer measurements of hierarchical copper condenser and microfabricated condenser
- Fabrication of scalable condenser surfaces on tube geometry utilizing gained knowledge
  - 1) bonding intrinsic hydrophobic membrane to wick 2) develop exit port design

Tech to market

- Continue to develop fabrication strategies for scalable structure
- Testing at larger scale—Heat Transfer Research, Inc

End goals of the project

- Scalable and robust capillary-driven condensers for HTC enhancement
- Model framework to guide the rational design of capillary-driven condensers

Concluding Remarks

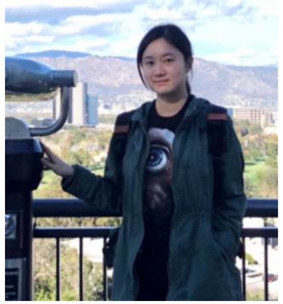
Summary

- Successfully micro-fabricated large-area engineered sample and demonstrated our proof-of-concept
    - Successful micro-fabrication of large area structures on silicon
    - Developed selective coating technique to show variation in physics over non-selective configuration
    - Conducted condensation visualization experiments in air and pure vapor ambient
    - Found preferred configuration consists of a hydrophilic wick and a top coated hydrophobic membrane
- Successfully fabricated scalable capillary-driven condensers
    - Hierarchical copper condensers of different geometry were fabricated by diffusion bonding
    - Over 10x HTC enhancement with a subcool up to 4.5 K given by fabricated sample is predicted
    - Fabrication of robust and scalable condensers based on electro-spun PVDF
- Ongoing heat transfer characterization

Acknowledgement

We gratefully acknowledge funding support from the National Energy Technology Laboratory (NETL) of the U.S. Department of Energy with Richard Dunst as project manager.

Samuel Cruz



Yajing Zhao

Market Benefits/Assessment

Integrating capillary-driven condensers into existing industry

Techno-economic Evaluation for a typical 950 MW fossil fueled power plant[1]

Estimated material costs to modify an existing condenser with 23,150 tubes (made of 90/10 cupronickel alloy) with dimensions D_o=28.6 mm and L=13.4 m are shown below:

- Porous copper powder wick (0.2mm thick)
- PVDF membrane (pore size ~1 μm)
  - Alternative materials: PTFE, PP

Material	Material Cost	Required Amount	Total Cost
Sintered copper powder (Φ = 70%)	135 [$/kg]	34963 [kg]	$ 4.72 Million USD
PVDF membrane	400 [$/m^2]	27872 [m^2]	$11.15 Million USD
Fabrication cost (assuming C_{Mater}/3)	-	-	$ 5.29 Million USD
Total	-	-	21.16 Million USD

[1] Webb, R.L.(2010)

Market Benefits/Assessment

Porous Cu foam and PVDF membrane modified condensers

Thermo-economic Evaluation for a typical 950 MW fossil fueled power plant[1]

Item	Plain Condenser	Capillary-driven Condenser	Unit
Boiler heat input Q_h	2,223	2,223	MW
Condenser water T_{in}	20	20	^oC
Condenser water T_{out}	30	30	^oC
Condenser saturation temperature	38.95	34.20	^oC
Condenser external HTC	8.183	46.127	kW/m^2K
Condenser overall HTC	3.426	5.226	kW/m^2K
Condenser heat rejection/MW	1,273	1,195	MW
Condenser water volume flow rate	30.53	28.66	m^3/s
Reduced condenser water flow rate	-	**1.87**	m^3/s
Turbine output W_t	950	1,028	MW
Increased power output	-	**78**	MW
Capital value of increased generation	-	7.8E+07	$/year
Tube modification cost	-	2.12E+07	$
Simple payback on increased generation	-	**0.27**	year

[1] Webb, R.L.(2010)