Project Review

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

Project ID: DE-FE0031677

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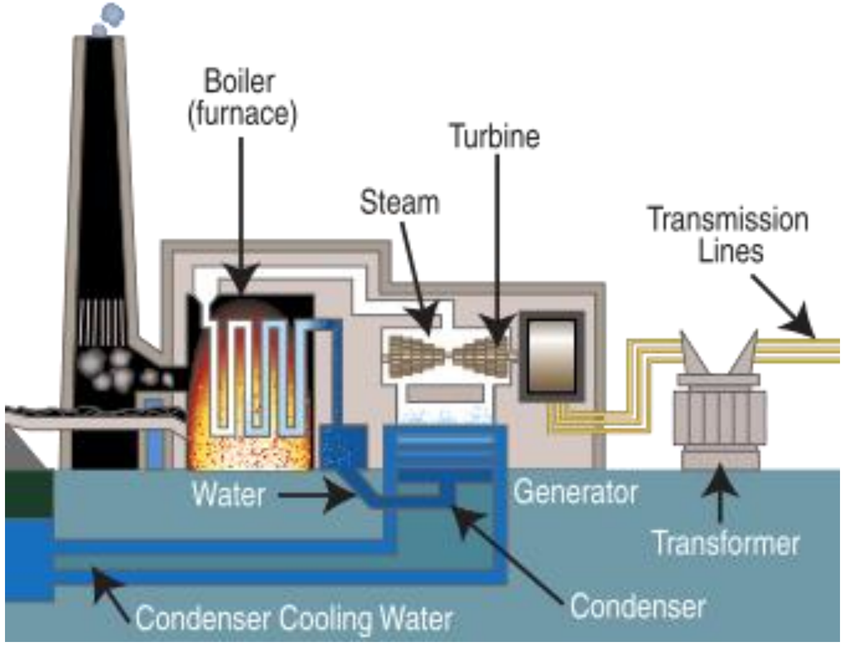
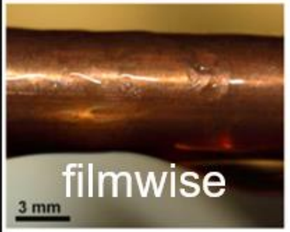
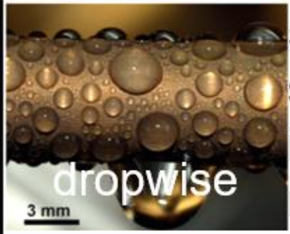
Project Description and Objectives

Motivation

- Steam power plants are responsible for the largest amount of water[1] withdrawn from U.S. water bodies: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

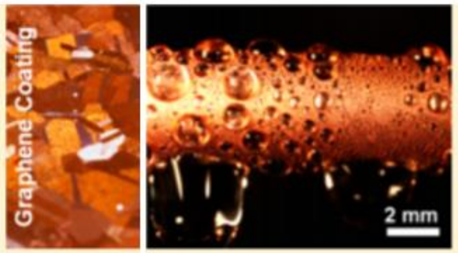


- Industrial condensers rely on conventional filmwise condensation:

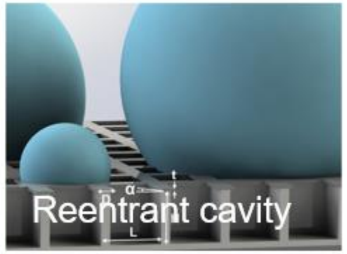
	prevalent in industry; barriers to heat transfer		5-7x HTC shown in lab; insufficient robustness

- Scalability and robustness remain challenging for dropwise condensers:

lubricant infused surface[2]



graphene coating[3]



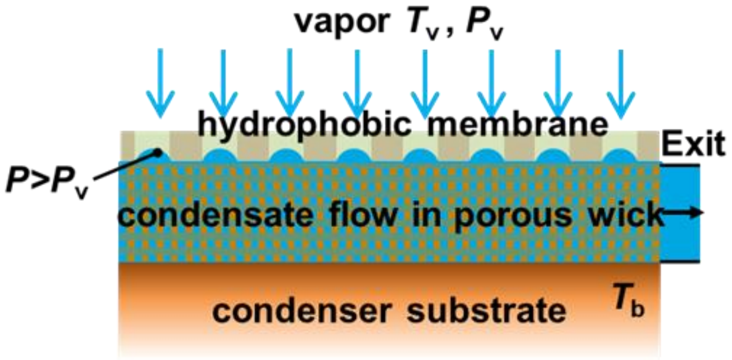
reentrant surface[4]

[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

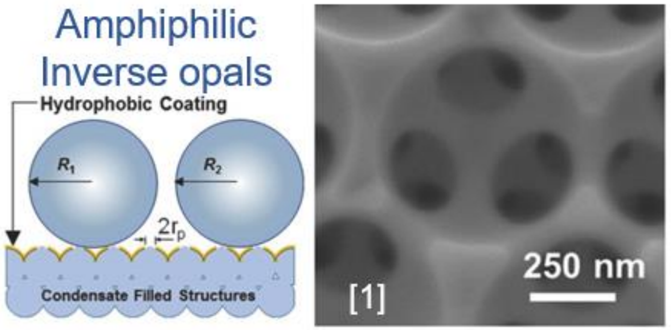


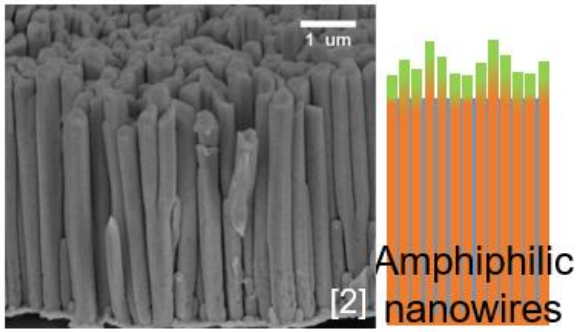
- Hierarchical surface consisting of a robust hydrophobic membrane and high thermal conductivity wick
- Vapor transports through membrane pores and condenses at the wick-membrane interface
- Capillary pressure at the membrane-wick interface provides additional driving-force to push condensate from the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

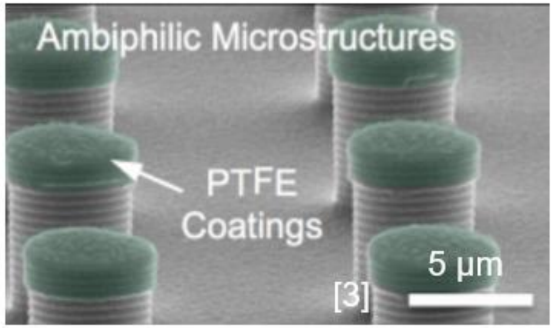
Project Description and Objectives

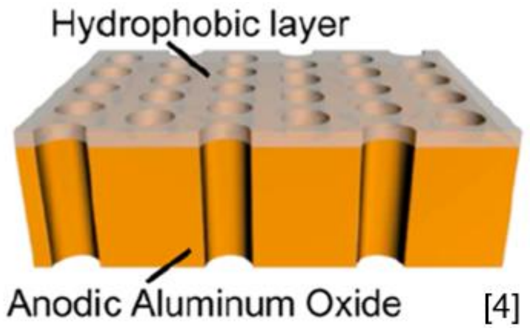
Technology Benchmarking

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









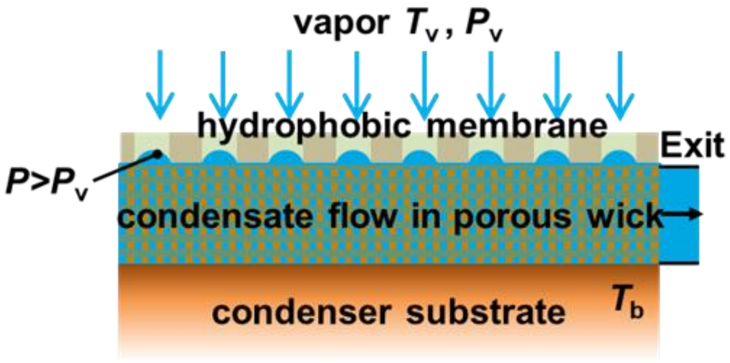
Challenges

- 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] Ölçeroğlu, E. *et al*. (2017) [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

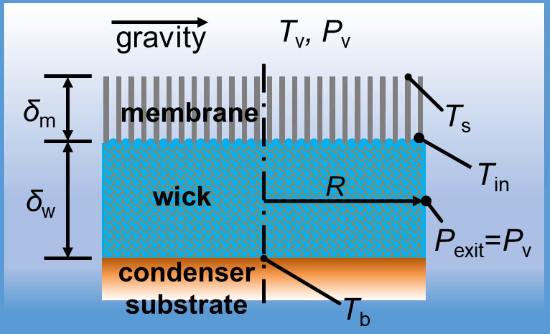
Approach

Model Development

Design parameters:

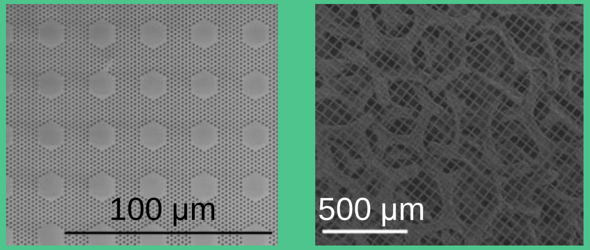
Wick: permeability, thickness, porosity, thermal conductivity

Membrane: pore size, porosity, thickness, thermal conductivity



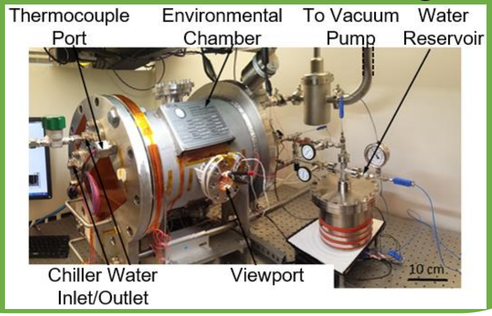
Surface Fabrication

- 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

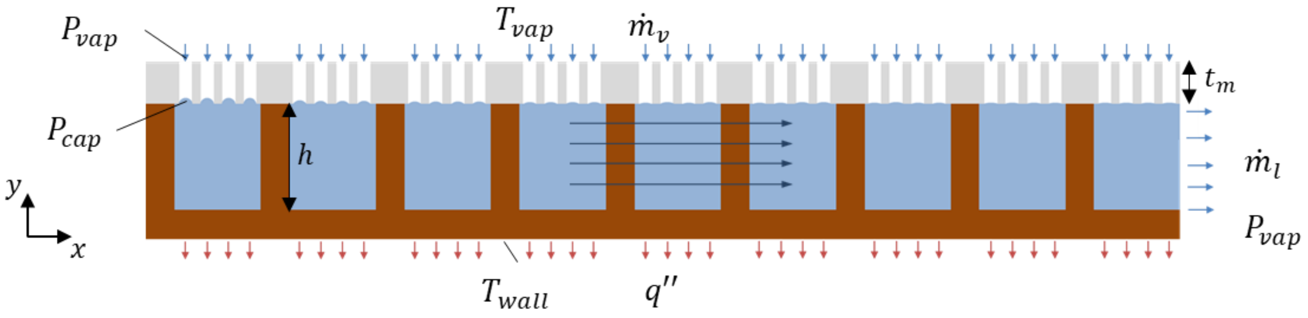


Project Update

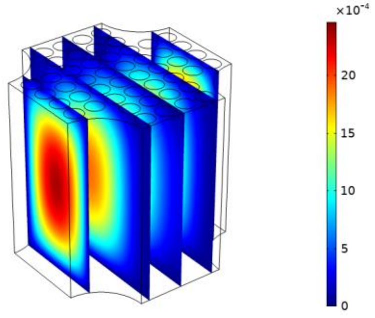
High-Performance Design Utilizing Highly Defined Geometry

- 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

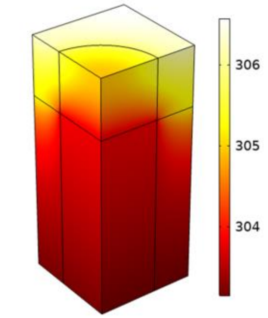
- Device geometry



present case: micropillar wick, through-pore porous membrane



permeability of COMSOL unit cell

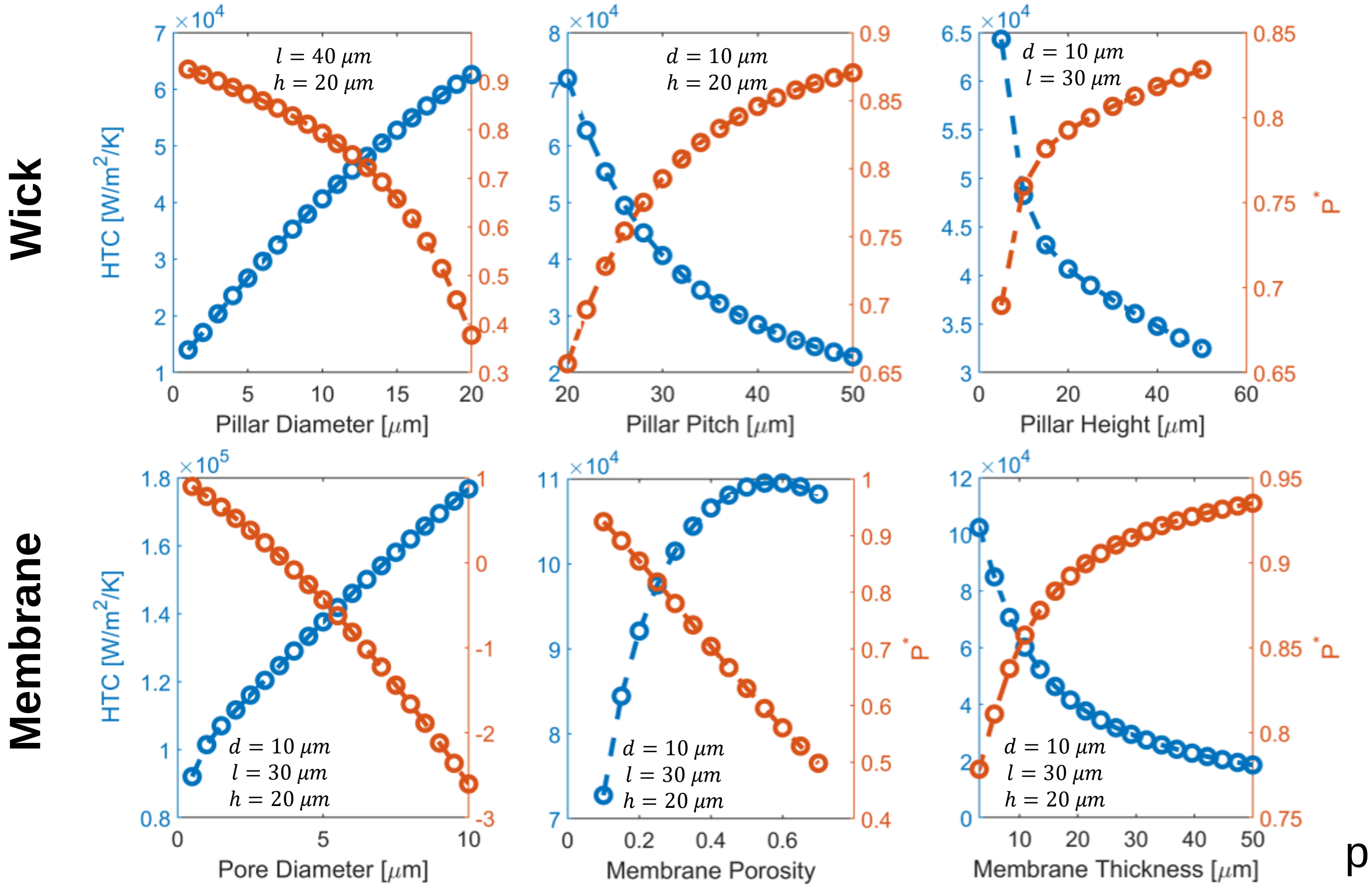


HTC of COMSOL unit cell

Project Update

High-Performance Design Utilizing Highly Defined Geometry

- Performed **parametric studies** to better understand factors that drive performance



Wick

- HTC↑ with denser wicks:
  - (l constant) HTC↑ as d ↑
  - (d constant) HTC ↑ as l ↓
- HTC↑ with thinner wicks i.e., h ↓

Membrane

- HTC ↑ generally as t_m ↓ and ϕ_m ↑
- HTC ↑ as d_p ↑ due to less vapor transport resistance; However P^* ↓ as d_p ↑ such that the membrane floods when $P^* < 0$

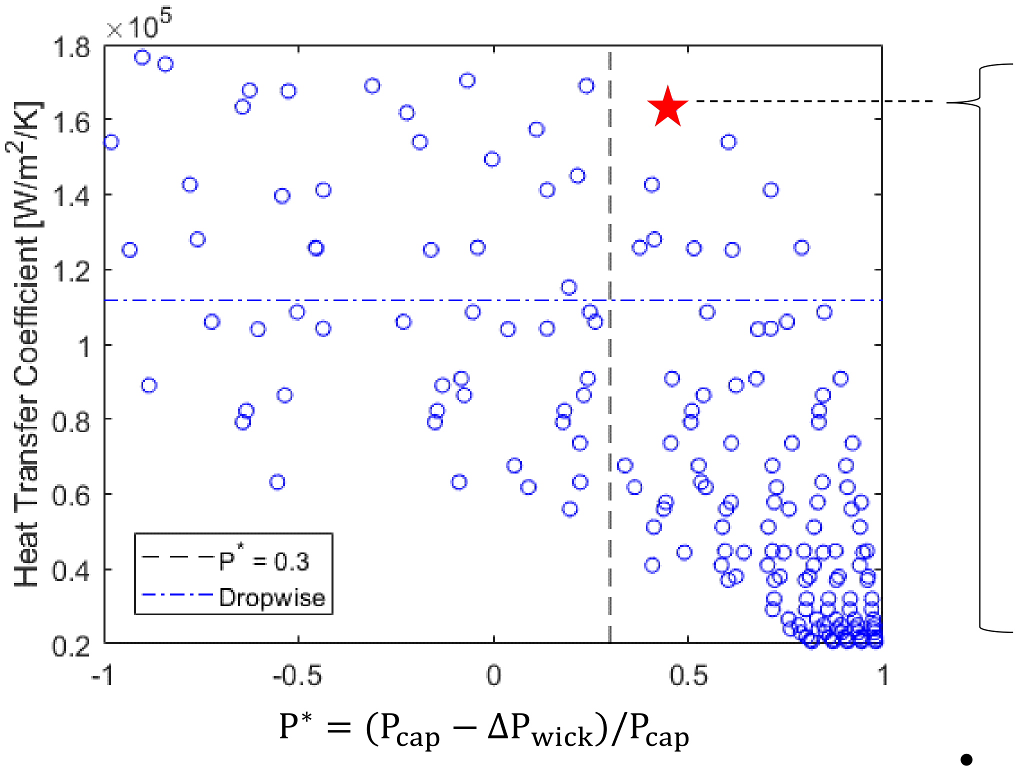
**All computations are at 5K subcool*

pressure budget: $P^* = (P_{cap} - \Delta P_{wick})/P_{cap}$

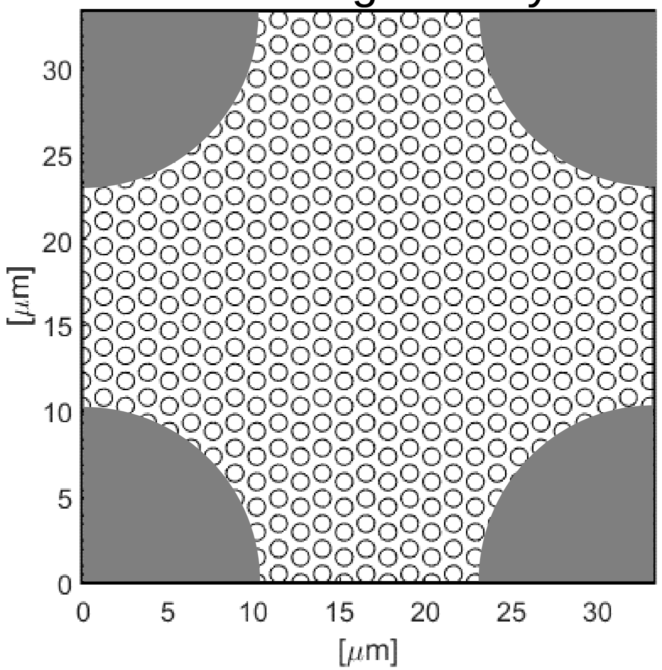
Project Update

High-Performance Design Utilizing Highly Defined Geometry

- Performed **global optimization** to select high-performance rational designs
- Selected designs within a pressure budget $P^* > 0.3$ to avoid flooding



top view schematic of optimal device geometry



Wick design

- $d/l = 0.6$
- $d = 20\ \mu m$
- $l = 33.3\ \mu m$

Membrane design

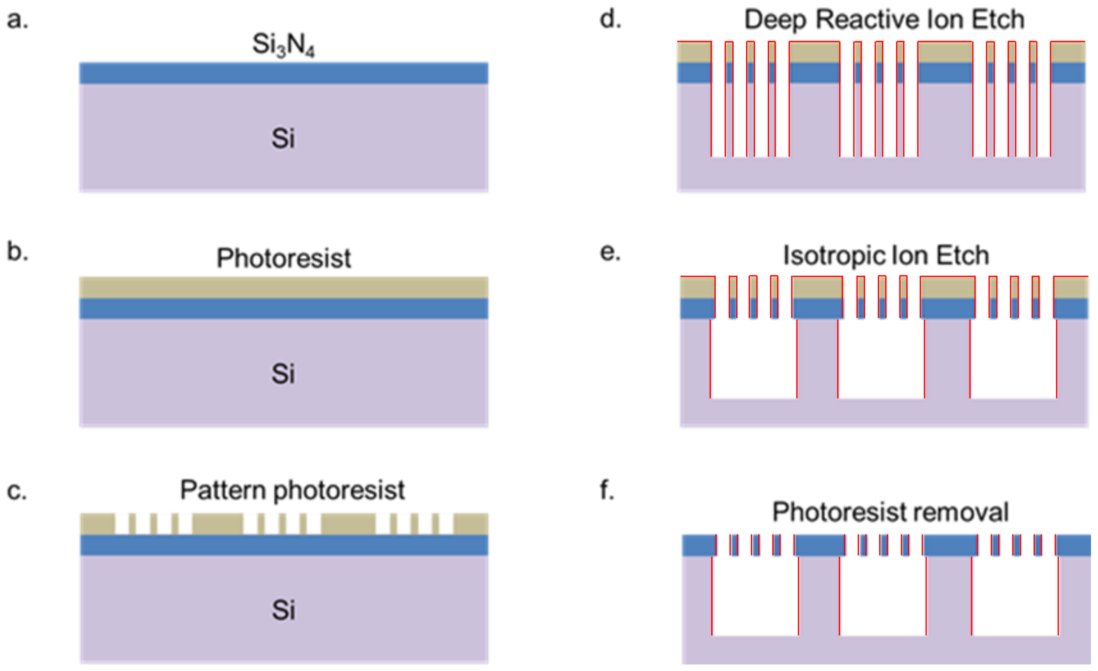
- $d_p = 1\ \mu m$
- $t_m = 0.5\ \mu m$
- $\phi_m = 0.2$

- ~8x HTC enhancement expected at 5K subcool

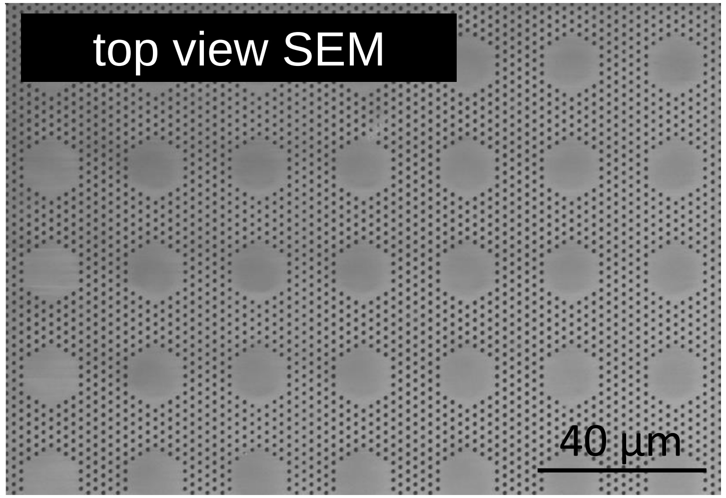
Project Update

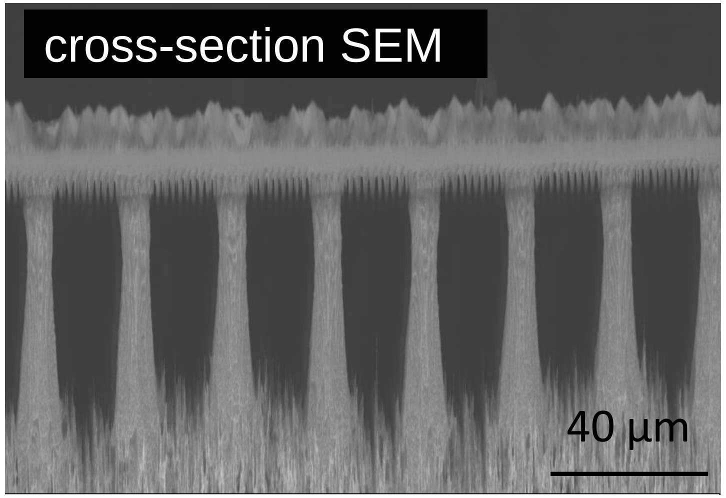
Structure Fabrication of Highly Defined Geometry

- Developed novel fabrication method to validate model
    - Potential applications in silicon vapor chamber technology
- Demonstrated feasibility of fabrication approach at small scale
- Next steps: scale up device and experimentally validate model



= C_4F_8
hydrophobic layer
(Bosch Process)





Project Update

Scalable Surfaces for Capillary-Driven Condensation

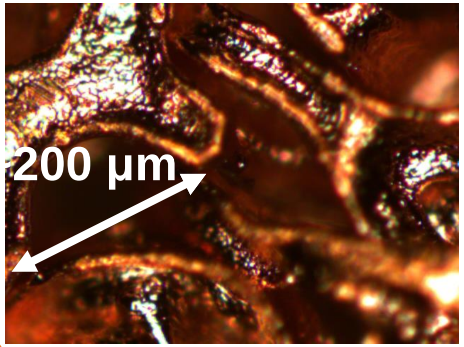
- Wick layer materials selection

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

k_{eff} of different porous metal wick

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

uncovered-microgrooves | microgrooves covered by mesh | sintered fibers | sintered powders | foams

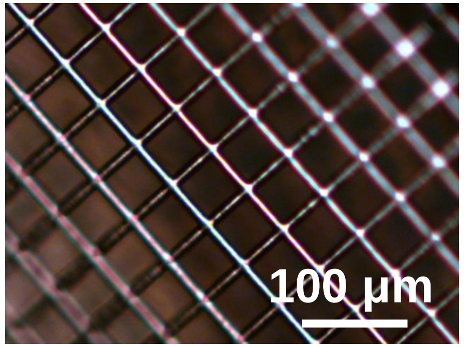


Cu foam

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

  hydrophobized copper mesh

  - Other materials being considered for robust hydrophobicity:
    - polymer-infused porous copper
    - electrospun hydrophobic membranes



Cu mesh

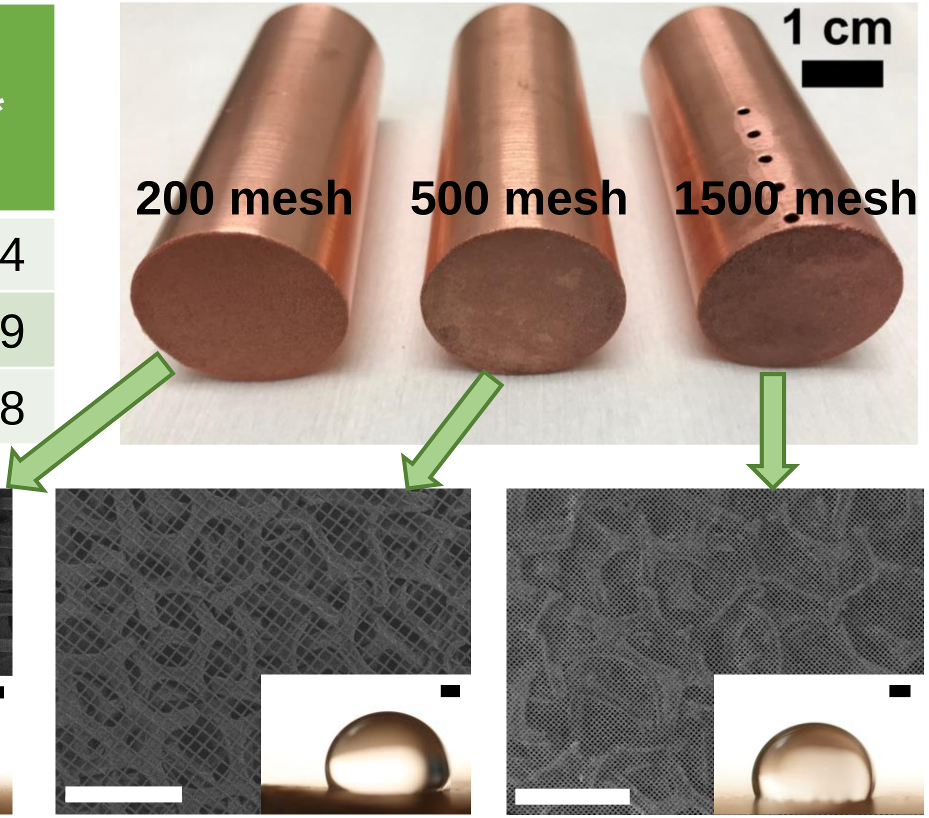
Project Update

Scalable Surfaces for Capillary-Driven Condensation

- Surface design and fabrication

Model prediction for T_v=45°C ,T_b=42°C: q_{Nu}=50 kW/m^2

Cu mesh					Cu foam			q (kW/m^2)	P^*
size	d_{wire}/ μm	d_p/ μm	ϕ_m	δ_m	κ/m^2	ϕ_w	δ_w/ μm		
200	50.8	80	0.35	112				**280**	0.54
500	11.4	39	0.6	5	5E-11	0.7	220	**290**	0.89
1500	5.6	11	0.44	5				**280**	0.98

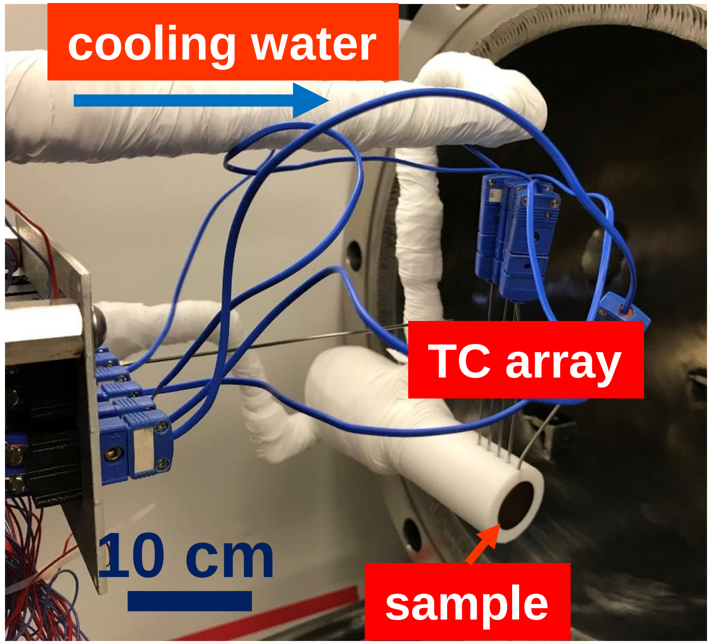


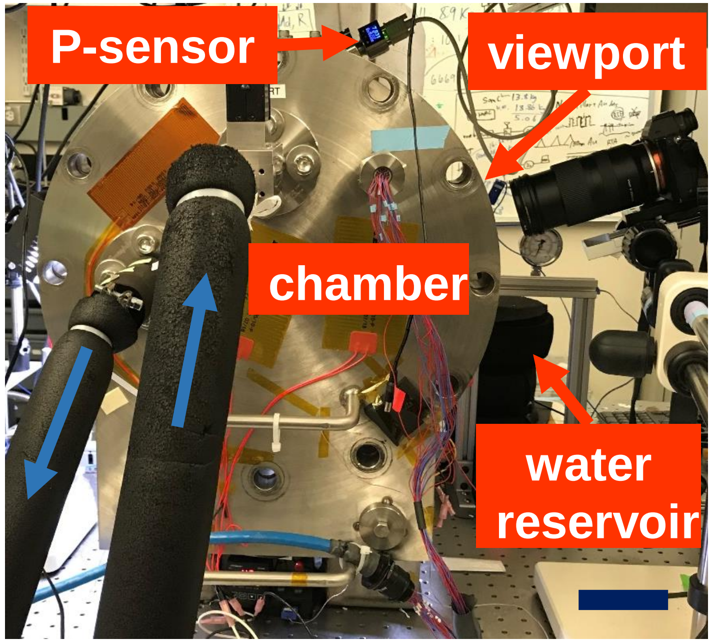
- 3 samples with different d_p were fabricated via diffusion bonding and hydrophobized
- Model predicts a >5x HTC enhancement
- 200-mesh sample floods more easily

Project Update

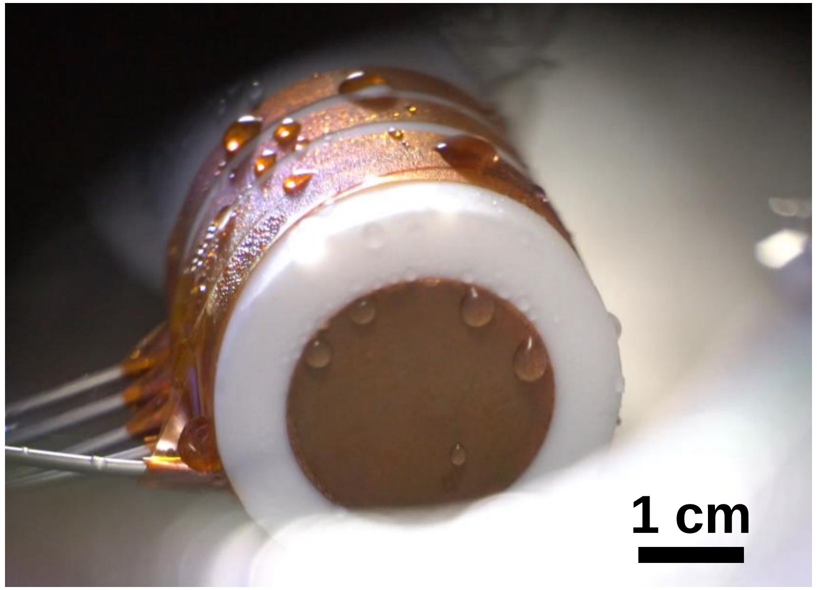
Scalable Surfaces for Capillary-Driven Condensation

Experimental setup & testing





Preliminary test:



- Experimental setup for condensation HTC characterization with industrial-level vapor conditions
- Flooding/bursting of droplets occurred—attributed to local defects in coating/mesh
- HTC measurements being conducted and will be compared to model prediction (>5x expected)

Preparing Project for Next Steps

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

Technology-to-Market Path

- Knowledge of combining micro-structured wicks and hydrophobic membrane developed during the project can be directly employed in industrial condensers
- Remaining challenges include:
  - Fabrication of porous metal wicks on tube condensers
  - Integration of structured metal wick with hydrophobic membrane layer
  - Design of exit port strategies for the drainage of condensed water

  } ongoing experiments
- Industry collaborator: Heat Transfer Research Inc. to provide testing services for the condenser designs in industrial conditions
- Potential research: new fabrication strategies to make structured wicks and membranes bonded in one step; exit port design for other applications (e.g., information encryption)

Market Benefits/Assessment

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Integrating capillary-driven condensers into existing industry

Thermo-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)

Concluding Remarks

NATIONAL ENERGY TECHNOLOGY LABORATORY

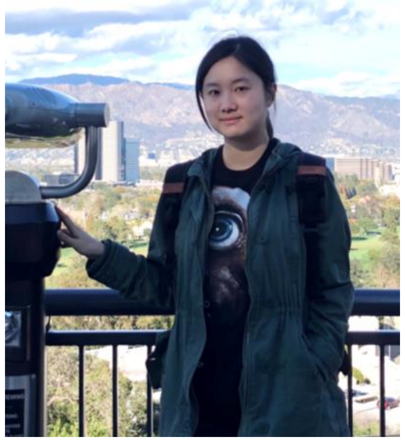
Summary

- Developed HTC models based on the concept of capillary-driven condensation
- Fabricated highly-defined geometry and scalable surfaces in parallel
- Ongoing experiments for HTC characterization and model validation
- Expecting a 5x HTC for durable condensation under industrial settings and 8x for highly defined geometries

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

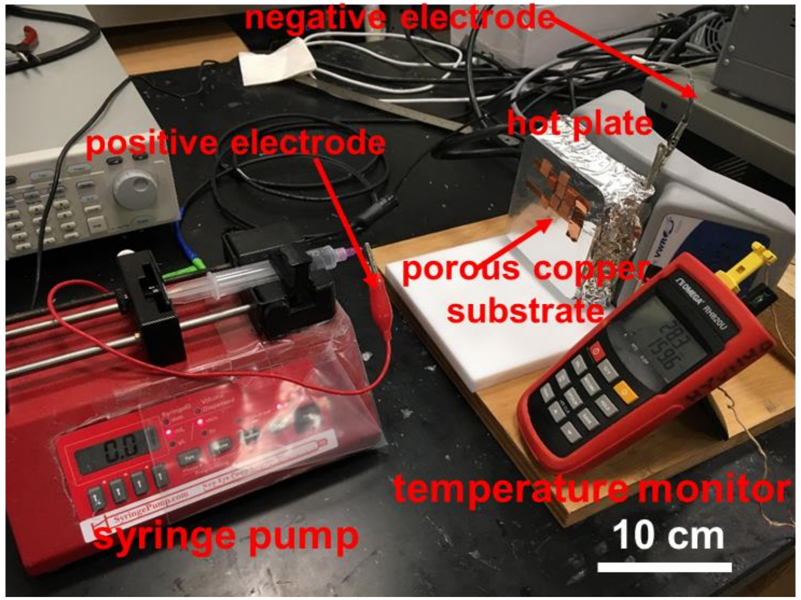


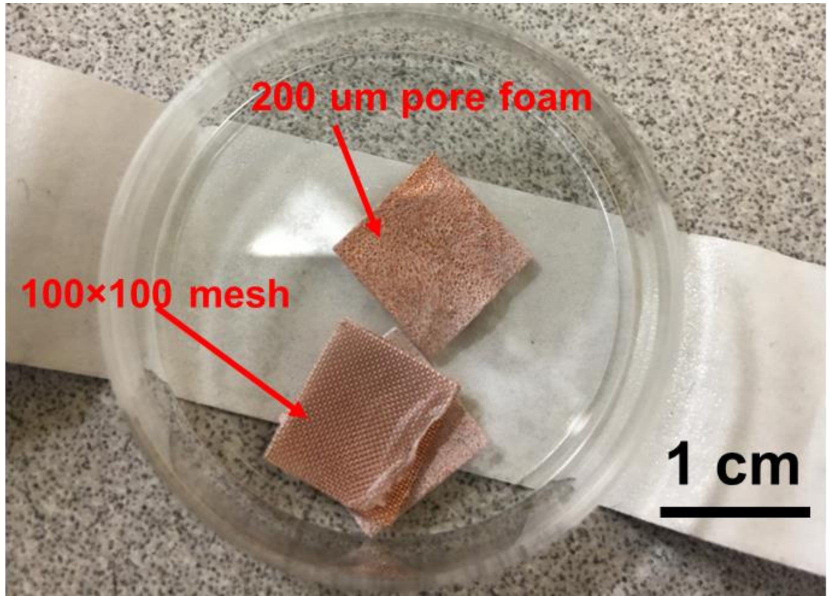
Yajing Zhao

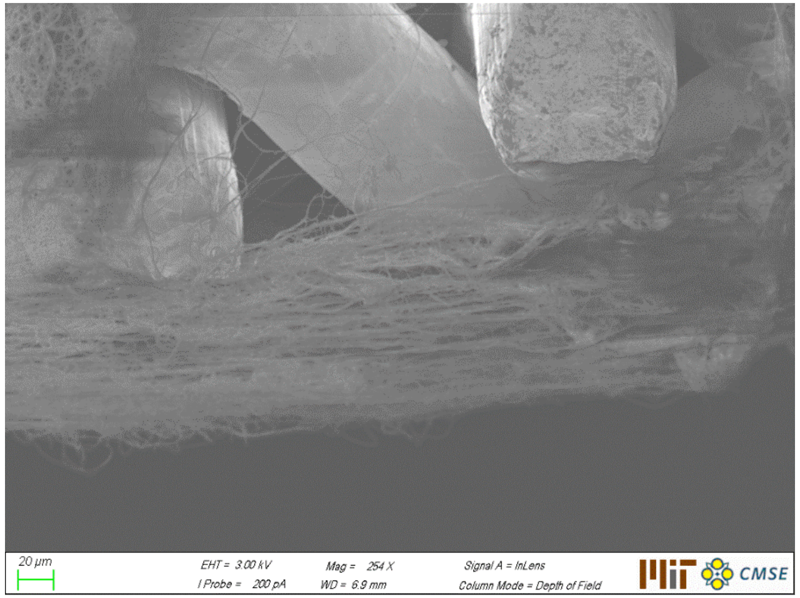
Electrospin PVDF on porous Cu

Preliminary fabrication: electrospin PVDF-HFP on porous copper

- Intrinsic hydrophobic
- Scalable
- Potential to bond robustly upon heating







Diffusion Bonded Hierarchical Cu