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

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Motivation

➢ Steam power plants are responsible for the largest amount of water withdrawn from U.S. water bodies:
  • HTC\textsubscript{condenser} ↑, power ↑, \( Q \)\textsubscript{consum}, water ↓

➢ Industrial condensers rely on conventional filmwise condensation:

➢ Scalability and robustness remain challenging for dropwise condensers:

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

Project Description and Objectives

Proposed Concept—Capillary-Driven Thin-Film Condensation

Key Advantages

• Decouples driving force \( (P_{\text{cap}} \sim 2\sigma/r_p) \) and viscous resistance \( (\kappa) \)
• 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
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
Geometry and Fabrication

micropillar wick with a silicon nitride membrane bonded on top

photoresist removal

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

- Achieved large area
- Qualitatively uniform

- Plane view SEM: qualitatively uniform; open pores
Large-scale fabrication

Cross section SEM

membrane
structure space open
pillar

~9.6 μm
~4.6 μm
~5 μm

Incomplete isotropic etching

open space at large scale

150 μm
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)

2 μm 2 μm 6 μm

bottom of wick
Ambient air condensation

Imaging under optical microscope

wick and membrane are hydrophobic

wick hydrophilic; membrane hydrophobic

150 μm

750 μm
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

600 μm
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

150 μm
Project update on scalable approach

Scalable Surfaces for Capillary-Driven Condensation

➢ Wick layer materials selection

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

\[k_{\text{eff,max}} = k_s(1 - \phi) + k_l\phi\]

- \(k_{\text{eff}}\) of different porous metal wick

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

➢ Membrane layer materials selection

- Commercially available and hydrophobic
- Easy to bond with wick layer
- Well-defined pore size (model validation)
- Alternative membrane material being considered for robust hydrophobicity:
  - electrospun hydrophobic membranes

- Hydrophobized copper mesh

- Cu foam: ~200 μm
- Cu mesh: 100 μm
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

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

Graphite-free sample fabricated by diffusion bonding with ceramic molds
Fabrication of hierarchical Cu condenser

Surface characterization: permeability measurements

One-dimensional Darcy’s Law:

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

Solution:

\[ t = -\frac{\text{Aln}(A - By) + By - \text{Aln}(A)}{B^2} \]

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

- Permeability \( \kappa \) measured before & after diffusion bonding
- 1E-11m² would be a conservative estimation for \( \kappa \)
- Increase in \( \kappa \) 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:
  - 200 um thick wick (hydrophobic Cu foam, pore ~300 um)
  - Condenser Substrate

Thermal resistance network

\[ R_{\text{mesh}} = \frac{\delta_{\text{mesh}}}{k_{\text{eff, mesh}}} \]
\[ R_{\text{wick}} = \frac{\delta_{\text{foam}}}{k_{\text{eff, foam}}} \]

- Flooding criterion \( P^* \):

\[ P = P^* > P_v \]

P > \( P_v \) condensate flow in porous wick

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

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

Flooding criterion: \( 0 < P^* = \frac{(P_{\text{cap}} - P_{\text{vis}})}{P_{\text{cap}}} < 1 \)
Modeling results hierarchical Cu surfaces

HTC enhancement and flooding regime predicted by model

Model prediction for $T_v=35^\circ C$

- **Subcool (°C)**
- **Heat Flux [kW/m²]**
- **q**, $q_{\text{Nu}}$, $P^*$

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Heat Flux (kW/m²)</th>
<th>No Flooding</th>
<th>Flooding</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 mesh</td>
<td>0</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>500 mesh</td>
<td>0</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>1500 mesh</td>
<td>0</td>
<td>1000</td>
<td>1500</td>
</tr>
</tbody>
</table>

- **Subcool (°C)**
- **Subcool (°C)**
- **Subcool (°C)**

- **Heat Flux (kW/m²)**
- **q**, $q_{\text{Nu}}$, $P^*$

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</tr>
</thead>
<tbody>
<tr>
<td>200 mesh</td>
<td>0</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>500 mesh</td>
<td>1</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>1500 mesh</td>
<td>1</td>
<td>1500</td>
<td>1000</td>
</tr>
</tbody>
</table>

- **No Flooding**
- **1-2x htc**
- **1-10x htc**
- **1-17x htc**

- **ΔT ~ 1.5°C**
- **ΔT ~ 4.5°C**

- **MIT Technology Review**
- **U.S. Department of Energy**
- **Massachusetts Institute of Technology**
- **DRL Device Research Laboratory**
• 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
Exit port design, scalable and robust membranes

Cu foam with microchannels (before diffusion bonding)

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

θ_{adv} ≈ 142.1°
θ_{rec} ≈ 140.2°
Preparing Project for Next Steps

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 $D_0=28.6$ 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

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Cost</th>
<th>Required Amount</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sintered copper powder ($\Phi = 70%$)</td>
<td>135 [$/kg$]</td>
<td>34963 [kg]</td>
<td>$4.72$ Million USD</td>
</tr>
<tr>
<td>PVDF membrane</td>
<td>400 [$/m^2$]</td>
<td>27872 [m$^2$]</td>
<td>$11.15$ Million USD</td>
</tr>
<tr>
<td>Fabrication cost (assuming $C_{\text{Mater}}/3$)</td>
<td>-</td>
<td>-</td>
<td>$5.29$ Million USD</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>$21.16$ Million USD</td>
</tr>
</tbody>
</table>

## Market Benefits/Assessment

**Porous Cu foam and PVDF membrane modified condensers**

### Thermo-economic Evaluation for a typical 950 MW fossil fueled power plant\(^{[1]}\)

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