Overview of NSF-EPRI Power Plant Dry Cooling Science and Technology Innovation Program (2014-2017)

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Program Objective

Develop *innovative* dry cooling ideas, science and technologies ***to dramatically reduce or eliminate the water use in steam condensation through the use of air cooled condensers*** with the following optional approaches:

- Develop more efficient, cost effective, and compact alternative dry and dry-wet hybrid cooling solutions for power plant steam condensation cooling systems
- Significantly increase the air side heat transfer coefficient
- Reduce steam side pressure drop, size, and steam condensation temperatures

* Note the importance of steam condensation temperature as a key performance metric (lowering it increases power generation efficiency) and it’s relationship to ambient temperatures.

How did we get here?

- MOU established between NSF and EPRI in 2012
- Joint technical workshop held in ASME IMECE 2012 to define most favorable research opportunities for water saving advanced cooling technology development
- $6 M joint solicitation developed and issued in 2013
- Keys to successfully attract exceptional proposals
  - Strong technical guidance
    - ✓ Comprehensive background info. and data provided to potential researchers
    - ✓ Well defined selection criteria
  - Engagement of the thermal-science community towards this important societal problem

NSF vs. EPRI Research Interests

- NSF

  Transformational ideas and gaining fundamental understanding of the associated fundamentals involving:
  - Modeling
  - Lab scale testing
  - Fundamental technology development

- EPRI

  Applied research and development
  - Game changing idea development
  - Modeling, design optimization, and prototype testing
  - Technical and economical feasibility study

What was the selection process?

- NSF Panel prioritized selections
  - NSF selected all the academic experts
  - EPRI chose majority of the industry experts
  - Panel was conducted at NSF following the merit review guidelines of NSF plus additional criteria as established by the NSF-EPRI solicitation
  - EPRI observed the panel deliberations
  - Proposals were rated by individual reviewers and ranked by the panel in three groups –Highly Recommended (HR), Recommended (R)and Not Recommended (NR)
  - NSF Funding is typically for proposals in the HR and R category.
- EPRI internal panel independently reviewed and prioritized its selections
- EPRI and NSF compared recommendations and developed joint plan for funding top proposals

10 Proposals Selected for Funding Collaboratively by NSF and EPRI

Summary of Projects with $6 M Total Funding

Project Title	Orgnization	Funder
Direct Contact Liquid on String Heat Exchangers for Dry Cooling of Power Plants	UCLA	NSF
On-demand Sweating-Boosted Air Cooled Heat-Pipe Condensers for Green Power Plants	U of S Carolina	NSF
Ejector Cooling Systems with Evaporation/Condensation Compact Condensers	Univ of Missouri Columbia/SPX	NSF
Novel Thermosyphon/Heat Pipe Heat Exchangers with Low Air-Side Thermal Resistance	Univ of Kansas /Univ of Connecticut	NSF
Auto Flutter Enhanced Air Cooled Condensers	GaTech/Johns Hopkins/Southern Company/SPX	NSF-EPRI
Advanced Air Cooled Condensers with Vortex-Generator Arrays between Fins	UIUC	NSF-EPRI
Indirect Dry Cooling Towers with Phase-Change Materials as Intermediate Coolants	Drexel/ACT/Worley Parsons	NSF-EPRI
Novel Heat-driven Microemulsion-based Adsorption Green Chillers for Steam Condensation	UMD/Worley Parsons	EPRI
Nanostructure Enhanced Air-Cooled Steam Condensers	MIT/HTRI	EPRI
Porous Structures With 3D Manifolds For Ultra-Compact Air Side Dry Cooling	Stanford	EPRI

Alternative Dry Cooling Projects

Air and/or Steam Side Enhancement Projects for Air Cooled Condensers

Indirect Dry Cooling Towers with Phase-Change Materials as Intermediate Coolants (Drexel University/ACT)

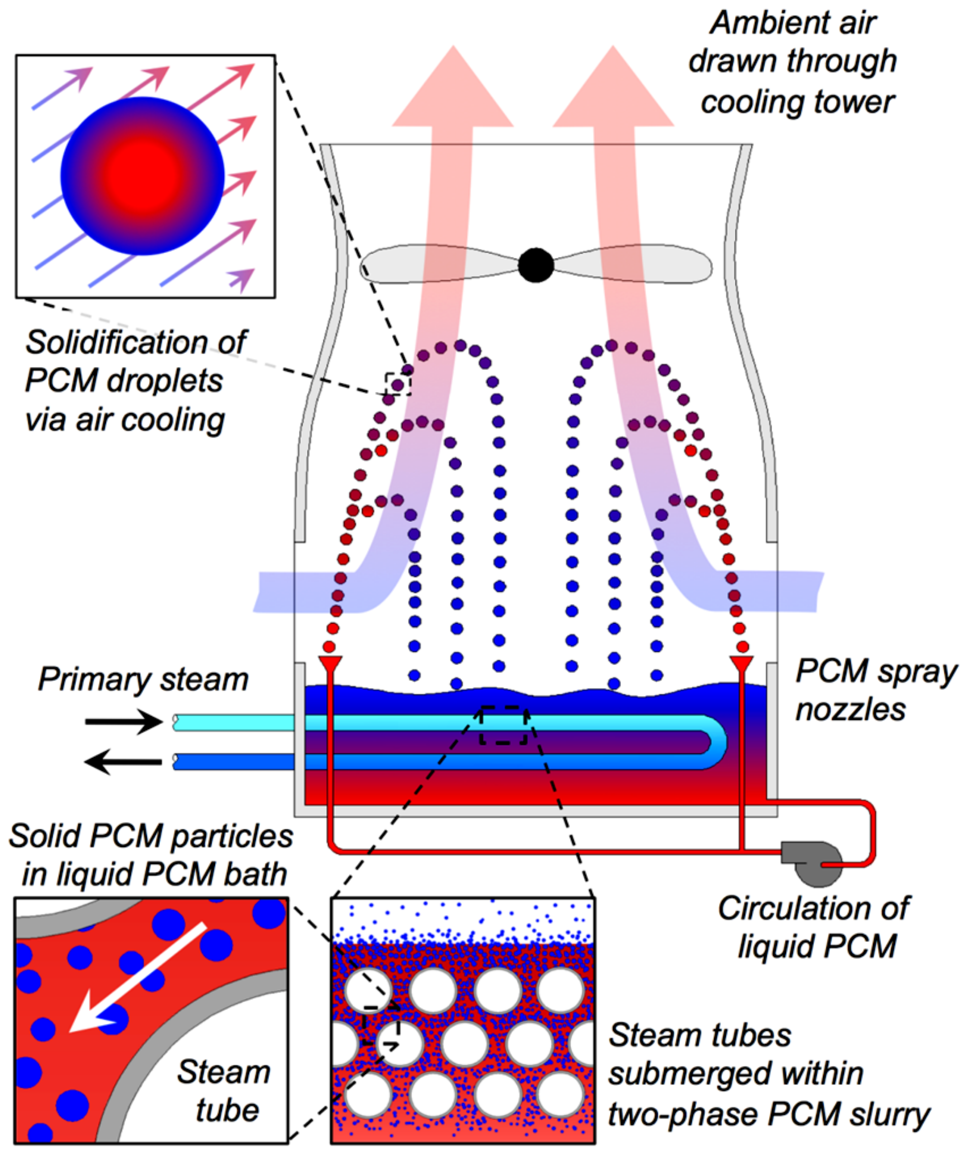
Project Scope

- Develop air-cooled PCM spray-freezing technology with enhanced thermal and fluidic performance.
- Perform technical & economic feasibility evaluation including environmental impact study.
- Perform testing and characterization of components and scaled prototype.

Key Potential Benefits

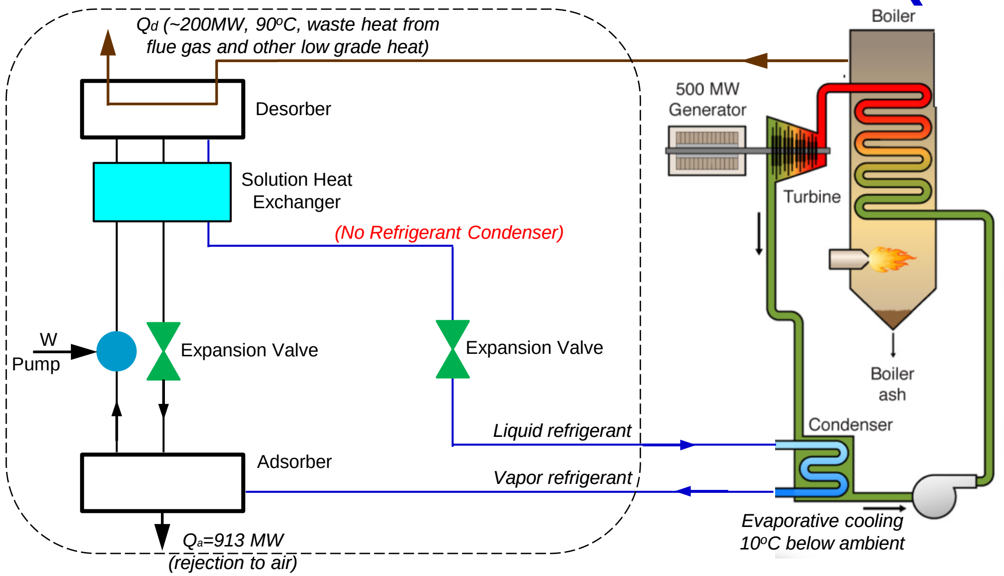
Compared to traditional ACCs

- Improved air-side heat transfer coefficient due to use of sprayed droplets.
- Reduced steam condensation temperature in hot weather would lead to significant production gain
- Reduced primary steam tubing and pressure drop.
- Significantly reduced system cost and size



Novel Heat-driven Microemulsion-based Adsorption Green Chillers for Steam Condensation (UMD)

Joint UMD-EPRI Patent Pending



Novel Microemulsion-based Adsorption Chiller

Project Scope

- Develop advanced microemulsion adsorbents
- Develop advanced microemulsion-based adsorption chillers for power plant steam condensation
- Perform system integration energy and mass flow balance analysis for 500 MWe coal plant
- Perform prototype testing
- Perform technical and economic feasibility evaluation

Key Potential Benefits

Compared to the currently used ACCs
- More efficient evaporative cooling
- Reduced condensation temperature

Compared to the conventional green chillers
- No refrigerant condenser needed -Smaller size
- Reduced waste heat requirement (10X predicted)
- 4X higher COP and lower cost

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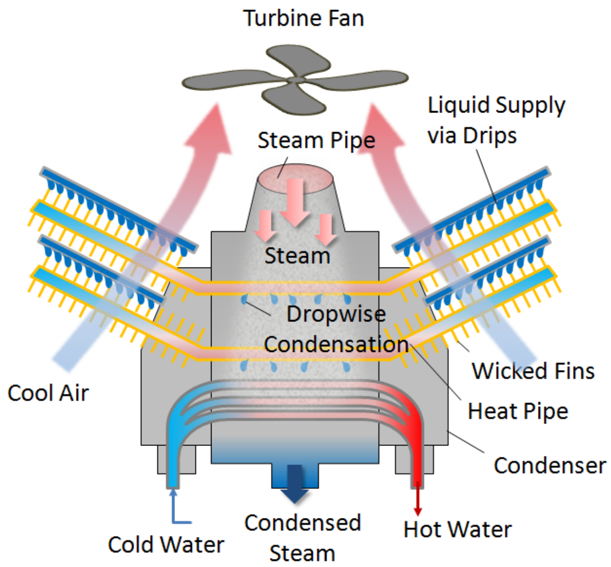
On-demand Sweating-Boosted Air Cooled Heat-Pipe Condensers for Green Power Plants

UNIVERSITY OF SOUTH CAROLINA

Project Scope

- Develop highly efficient alternative dry cooling systems by optimizing heat acquisition via long-lasting dropwise condensation (DWC), heat transport from steam to the air-side through highly conductive heat pipes, and finally heat rejection by sweating-boosted air cooling
- Design and evaluate impacts of the proposed air cooled heat-pipe condensers on power plants in a VTB
- Develop sweating-boosted air cooling
- Achieve long-lasting DWC with Ni coatings using atmospheric plasma spray (APS)
- Develop high performance heat pipes with microscale hybrid wicks
- Test a lab-scale ACC prototype



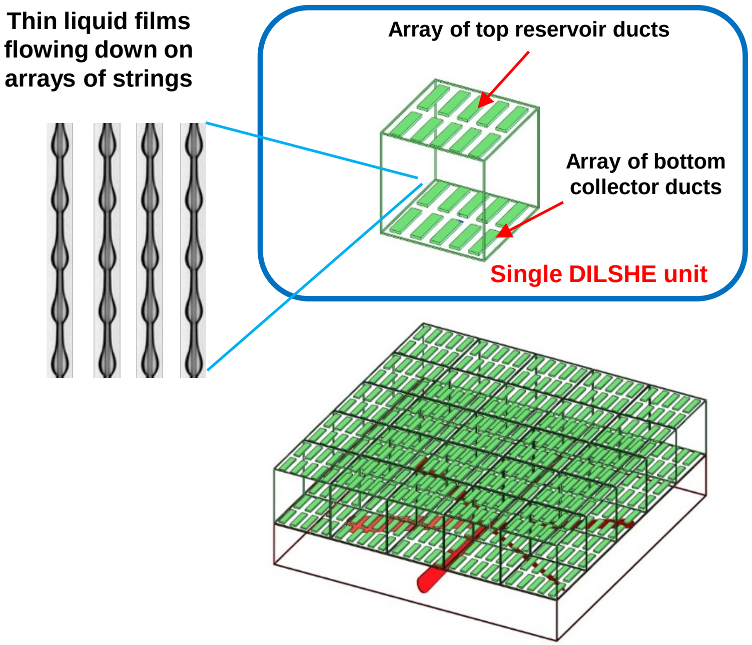
Key Potential Benefits

- 4X better air side heat transfer coefficient up to ~ 200 W/m^2K
- 2X higher steam side heat transfer coefficient
- Reduced air side heat transfer area up to 68%
- Reduced footprint up to 50%
- Potentially save nearly 70% water using dripping system compared to cooling towers
- Reduced capital and maintenance costs of ACC

NSF

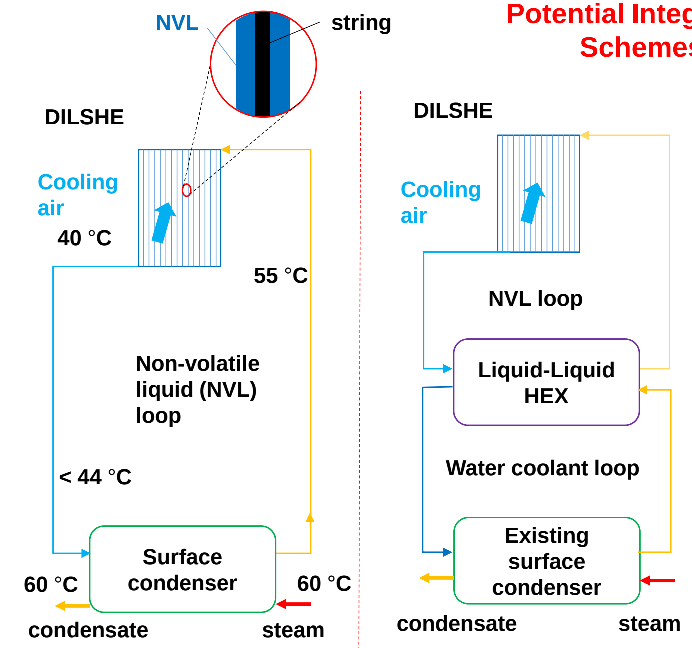
Direct Contact Liquid on String Heat Exchangers for Dry Cooling of Power Plants

UCLA



DISLHE module assembly with a central cooling air fan

Potential Integration Schemes



(a) Direct Connection

(b) Indirect Connection

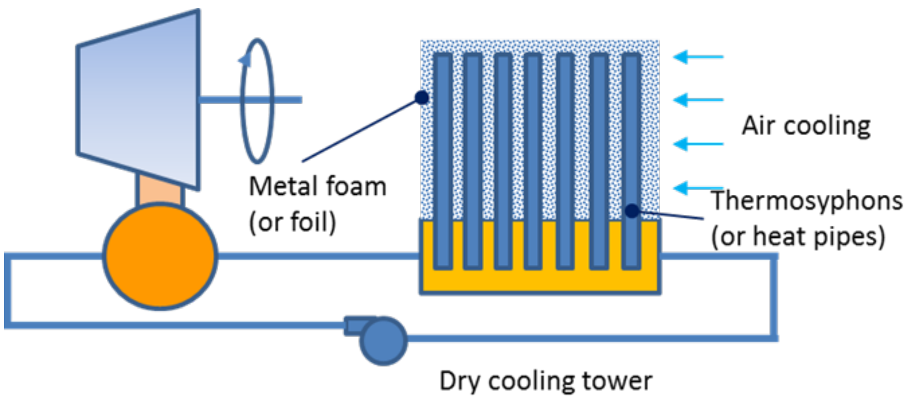
Project Scope

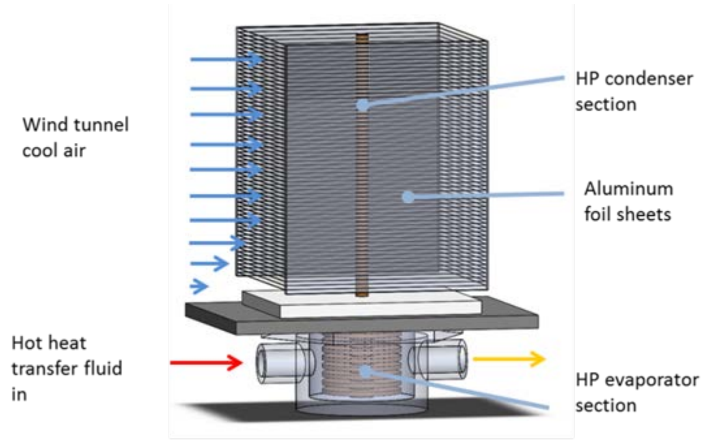
- Develop DIrect-contact Liquid-on-String Heat Exchangers (DILSHE) for indirect dry cooling of a steam power plant.
- Perform fundamental studies of the fluid mechanics of thin liquid film flows on high-curvature surfaces and associated heat/mass transfer phenomena.
- Perform design, construction, and testing of a scaled-down DILSHE prototype.

Key Potential Benefits

- The DILSHE uses inexpensive polymer strings to create very large heat transfer areas.
- By reducing the use of heavy metals, highly economic and light-weight dry cooling heat exchangers with zero water consumption can be achieved.
- Each DILSHE unit is also readily field serviceable and/or replaceable without disrupting plant operation.

Novel Thermosyphon/Heat Pipe Heat Exchangers with Low Air-Side Thermal Resistance (KU/UConn)





- 3D computational domain of experimental test section.
- Test section is snapped into the bottom wall of a wind tunnel.
- Full 3D mixed convection, conjugate heat transfer, evaporation, condensation, and condensable vapor flow inside the heat pipe.

Project Scope

- Integrate high capacity thermosyphons/heat pipes with air-side metal foil/foam to minimize overall thermal resistances of heat exchangers.
- Perform experiments and develop multi-phase physical models
  - To measure and predict thermal performance
  - To enable a simulation capability for full-scale design.
- Assess the economic viability of a scaled-up design (500 MWe).

Key Potential Benefits

- Develop the knowledge base that will enable the design of a economical, high-performance, completely-dry cooling towers *or condensers*.
- Estimated improved performance at half the cost of conventional dry cooling towers or condensers.
- Specifically, integrate high capacity heat pipes/thermosyphons with air-side metal foil/foam .

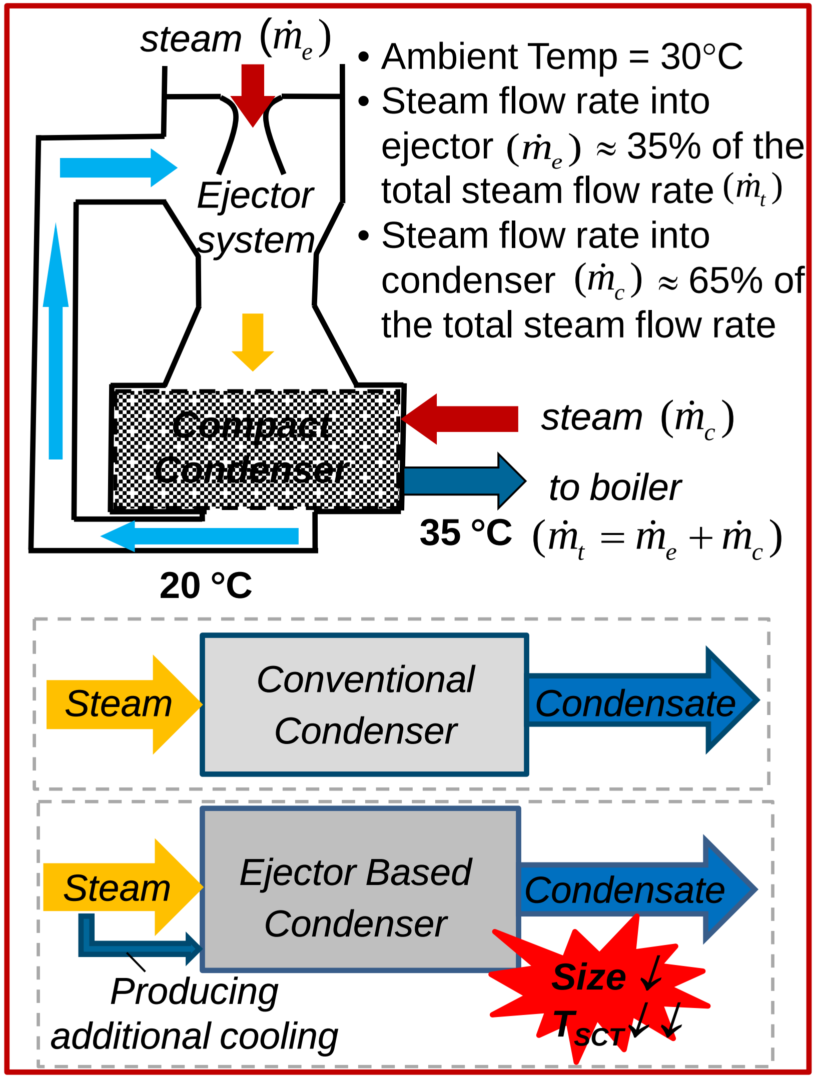
Ejector Cooling Systems with Evaporation/Condensation Compact Condensers (University of Missouri)

Project Scope

- Demonstrate a new generation of ejector-based cooling technology resulting in significant reduction or elimination of the use of water for cooling power plants
- Develop mathematical model predicting the heat transfer performance
- Demonstrate a 5 kW prototype

Key <u>Potential</u> Benefits $\dot{m}_e$

- Effective utilization of low grade thermal energy of steam for cooling
- Significant cost reduction of the ACC system
- Significant reduction (35% for wet cooling) or elimination (100% for dry cooling) of the use of water
- Condensation temperature decrease from 50 °C to 35 °C at an ambient temperature of 30 °C
- Easy integration of ongoing cooling systems
- Simple, reliable and compact cooling system
- SPX assessment ensuring satisfaction in real world needs

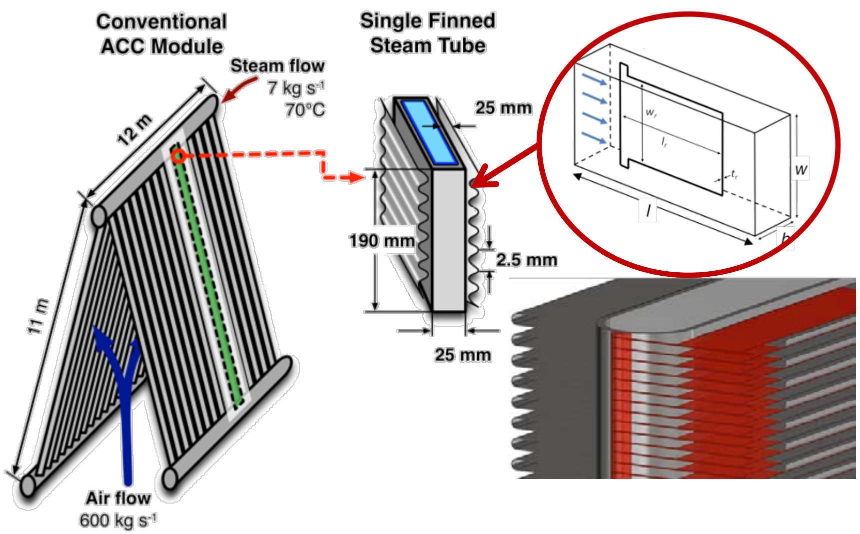


Alternative Dry Cooling Projects

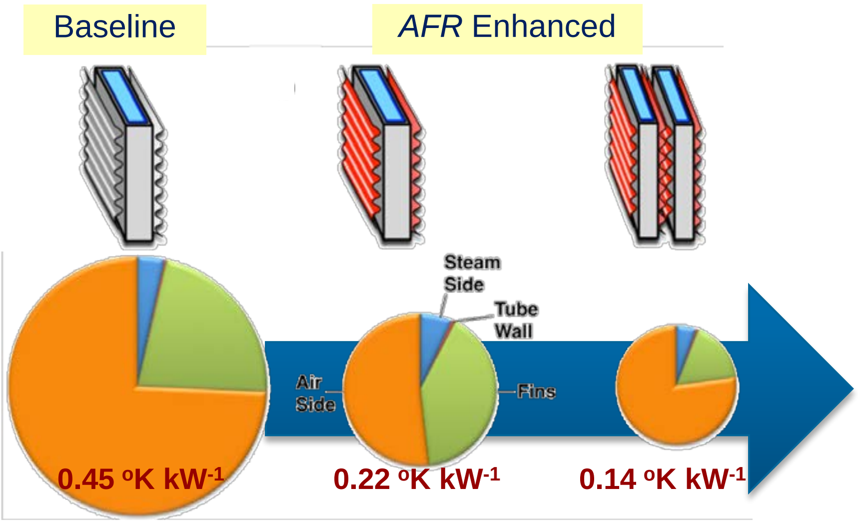
Air and/or Steam Side Enhancement Projects for Air Cooled Condensers

Auto Flutter Enhanced Air Cooled Condensers (Georgia Tech/Johns Hopkins)

ACC



ACC Thermal Resistance



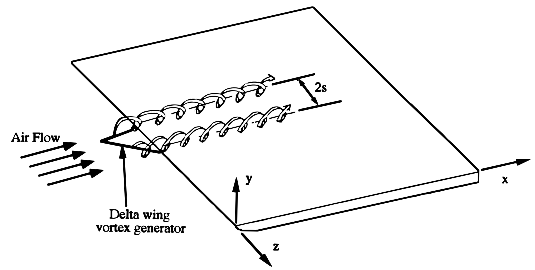
Project Scope

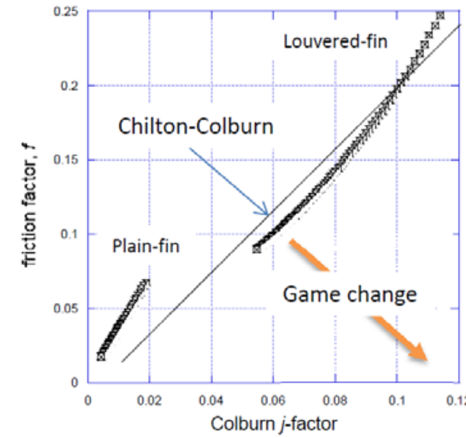
- Objective: Harness interactions between the cooling air flow and miniature, autonomously-fluttering reeds (*AFR*s) in innovative condensers.
- Development of design principles using laboratory experiments
- Performance evaluation in laboratory-scale condenser configurations.

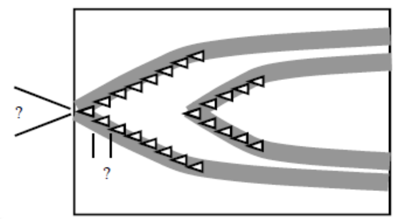
Key Potential Benefits

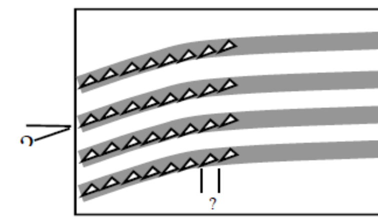
- Significantly increased heat transfer
- Power plant efficiency increased
- Inexpensive, off-the-shelf construction materials
- Retrofitable
- Clear commercialization pathway through collaborations with Southern and SPX

Advanced Air Cooled Condensers with Vortex-Generator Arrays between Fins (University of Illinois)









Project Scope

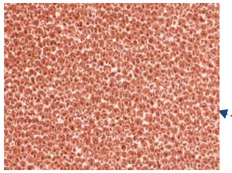
- Develop enhanced fin design for air-cooled condensers (ACC) based on vortex-generator arrays
- Using model experiments, validate CFD and achieve a near-optimal vortex-generator array
- Develop steam-side condensate management strategies to further enhance ACC performance
- Use system modeling to investigate integration
- Prototype fins to fine-tune design; prototype heat exchanger segment to validate predictions of performance improvements
- Conduct technical and economic feasibility evaluation

Key Potential Benefits

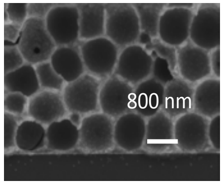
Compared to currently used ACCs

- 3X higher air-side heat transfer coefficient with no net fan power increase
- Improved steam-side heat transfer coefficient with decrease in steam pressure drop
- Significant cost reduction of ACC systems

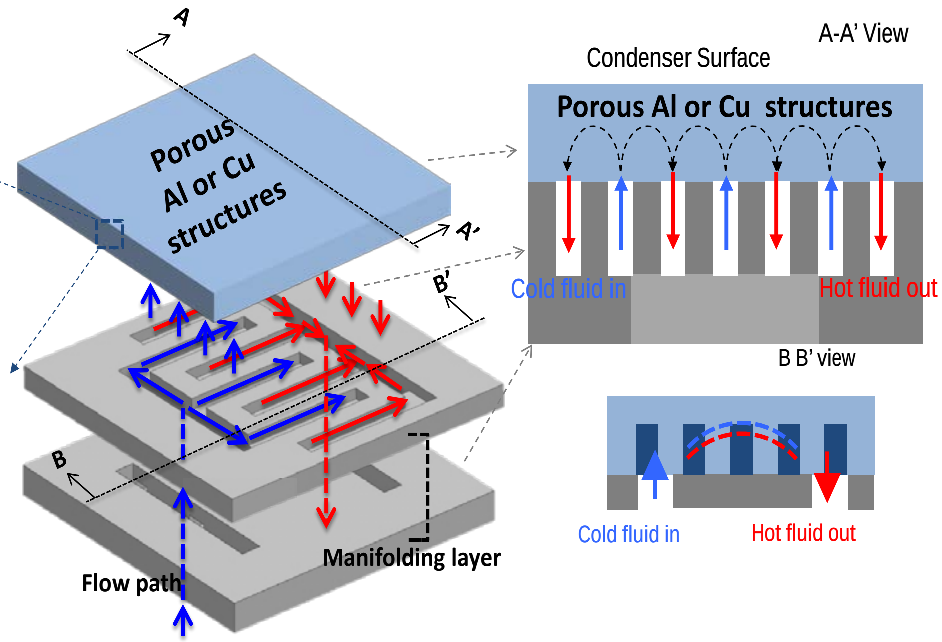
Porous Structures With 3D Manifolds For Ultra-Compact Air Side Dry Cooling (Stanford)



Duocel Copper (C10100) or Al Foam (6101-T6), 8% Density.



Copper porous structures



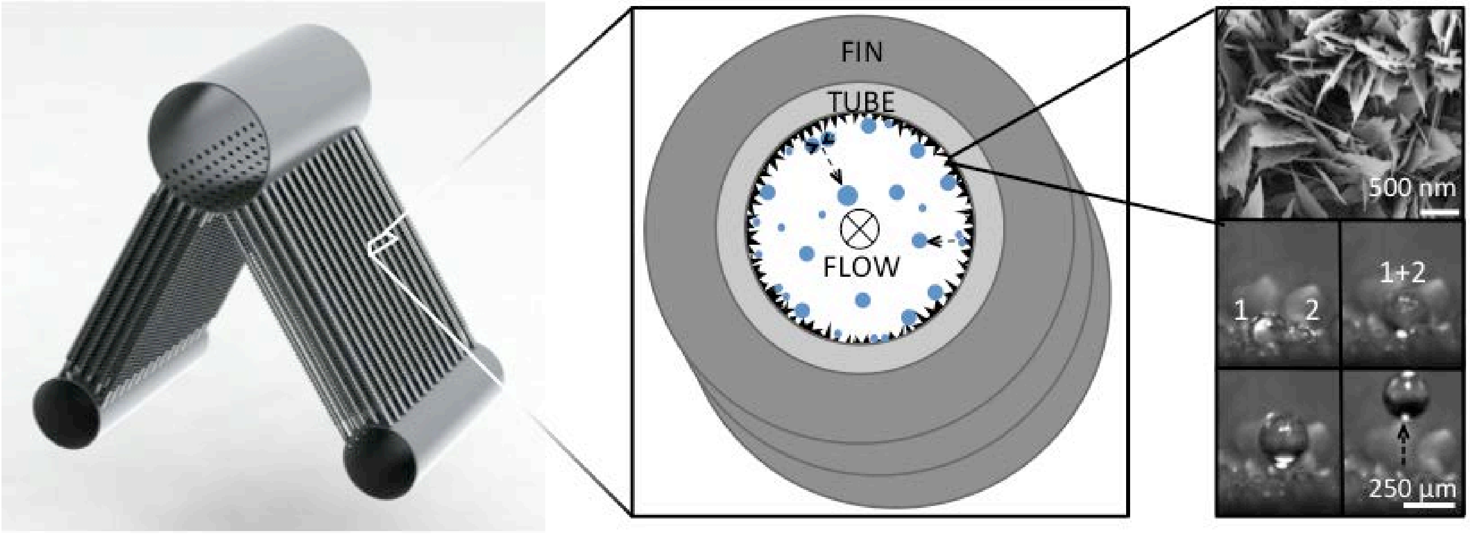
Project Scope

- Develop a breakthrough 3D manifold that delivers high velocity air to a porous metal structured I/O distributed inlets and outlets to revolutionize the design and performance of A-framed air cooled condensers.
- Validate pressure drop effects through prototype testing.

Key Potential Benefits

- Dry Cooling - No cooling water used
- More advanced than conventional air cooled condensers
  - ✓ > 20 X higher air side cooling rate
  - ✓ Lower condensation temperature (10 - 20 °C reduction) resulting in ~5% net production gain (~$11 M annual credit)
  - ✓ Minimal air side pressure drop or fan power consumption gain
  - ✓ 10x size/footprint reduction

Nanostructure Enhanced Air-Cooled Steam Condensers (MIT and HTRI)



Project Scope

- Develop nanostructure enhanced air-cooled A-frame design that maintains same overall dimensions, but with increased number of smaller tube diameters, and enhanced air-side fin surface areas.
- Develop and investigate scalable and robust superhydrophobic nanostructure surfaces that promote jumping droplets with enhanced heat transfer in internal flows
- Optimize the proposed A-frame design and to demonstrate performance enhancements in industrial steam condenser conditions

Key Potential Benefits

Compared to the currently used ACCs

- Order of magnitude higher condensation heat transfer coefficient
- Comparable steam side pressure drop to state-of-the art systems with smaller diameter tubes
- Lower condensation temperature resulting in net production gain
- Similar to state-of-the-art A-frame design to facilitate use in existing plants

Moving Forward Plan

- Funding all 10 projects soon
  - Coordinated but independent funding
    - ➢ NSF awards grants to 7 projects.
    - ➢ EPRI contracts to 6 projects.
  - Joint funding for 3 proposals
  - Independent funding
    - 4 projects by NSF
    - 3 projects by EPRI
- Provide continued technical guidance/supports to the project teams
- Holding a joint annual project review in every March-April time frame

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