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A Novel Steam Condenser with Loop Thermosyphons and Film-Forming Agents for Improved Heat Transfer Efficiency and Durability

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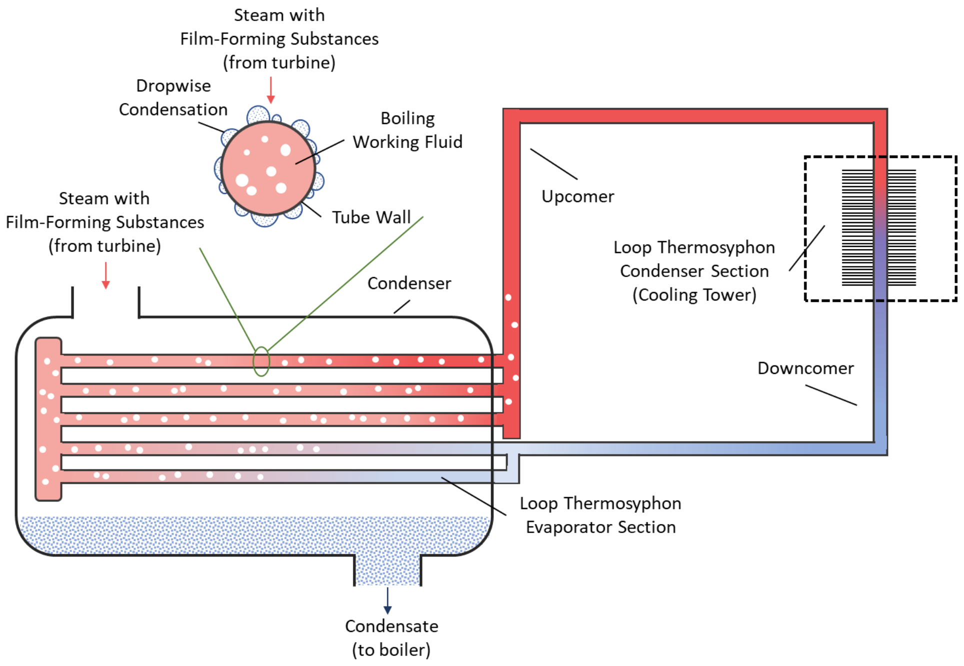
In Year 3 of 3, in Quarter 11



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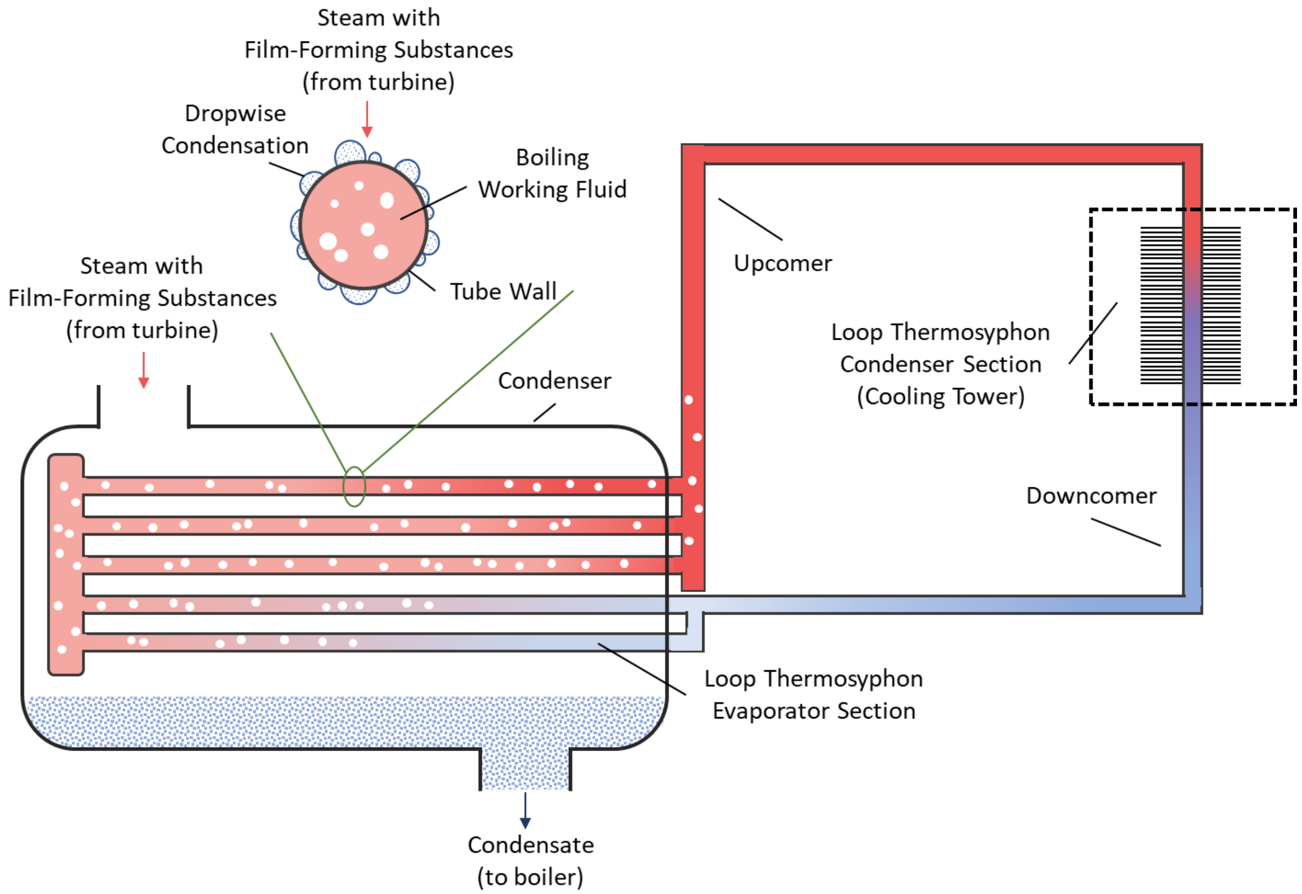
Project Overview

- #1 Develop *film-forming amine (FFA) coatings* applied to steam surface condensers to improve the reliability of dropwise condensation coatings and realize the efficiency improvements made possible by self-healing properties
- #2 Replace pumped cooling water systems with passive *loop thermosyphons* (no pumps) to save on energy & maintenance costs and improve reliability



Dropwise and Amine Films

- FFAs are self-healing, hydrophobic coatings that can be continuously applied to steam to protect metal (i.e. steel) tubing
- Suez uses this family of coatings to prevent corrosion in power plant boiler systems
- Our goal is to characterize the thermal performance and life of FFAs using materials found in power plants and for power plant conditions

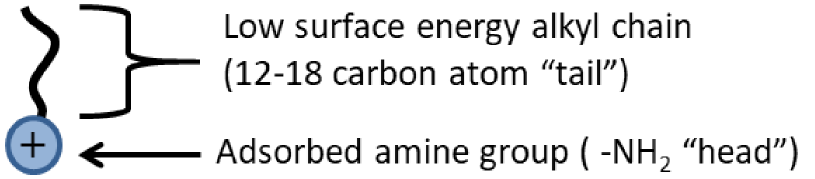
<u>Film-Forming Amine Composition</u>

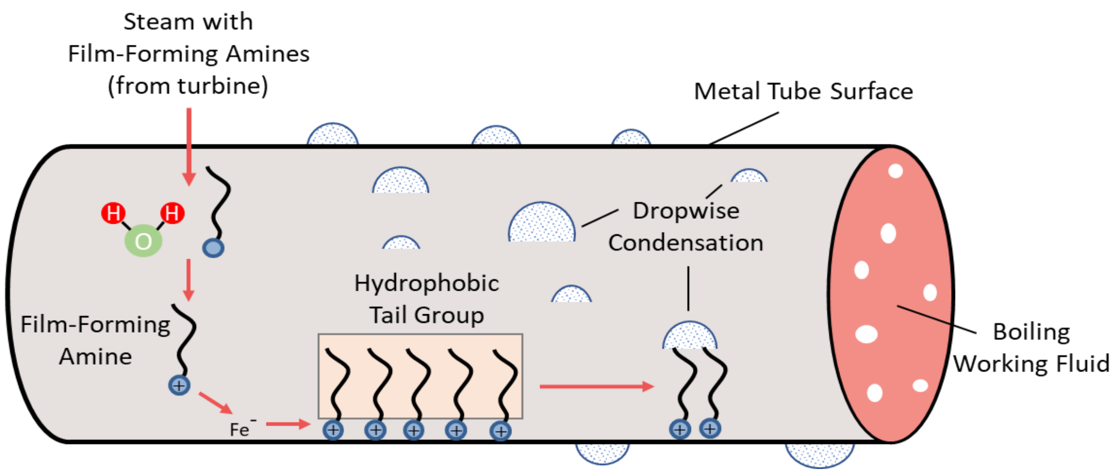
R_1-[NH-(R_2)-]$_n$-NH_2

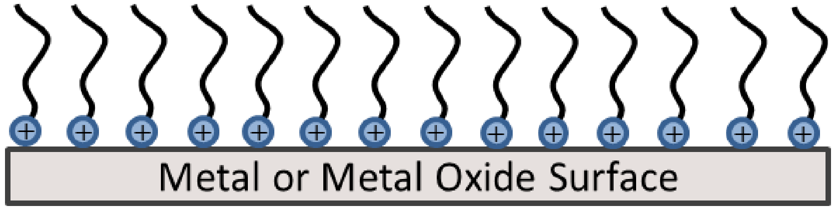
n is a whole number between 0 and 7

R_1 is an unbranched alkyl chain with 12-18 carbon atoms

R_2 is a short-chain alkyl group with 1-4 carbon atoms







Why are Power Plants utilizing film-forming chemistry?

- #1 Reason for Power = cycling load/downtime storage protection
  - Reduced corrosion of all steam & water touched circuits
  - Lower metal oxide transport during start/stop operation and load transients
- General and Flow Accelerated Corrosion (FAC) reduction
  - Lower iron/copper transport
- Cleaner heat transfer surfaces/efficiency
  - Fewer boiler cleanings
  - Lower risk of under-deposit corrosion (UDC)
  - Improved heat transfer

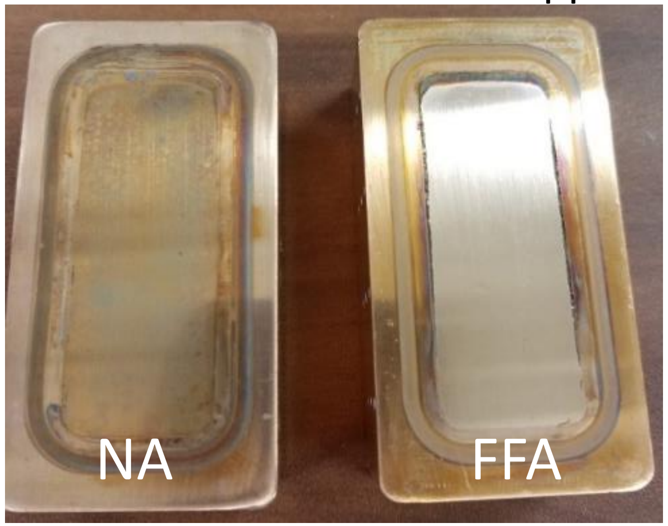
Testing Update – Initial Results

- For Y1 testing, we used a flat plate condenser test apparatus for thermal performance evaluation
  - Measured condensation heat transfer coefficients

- We determined that batch mode was insufficient to sustain dropwise condensation continuously on any metal surface
- Protection from oxidation is sustained using FFA compared to standard Neutralizing Amines (NA) (used for pH control)

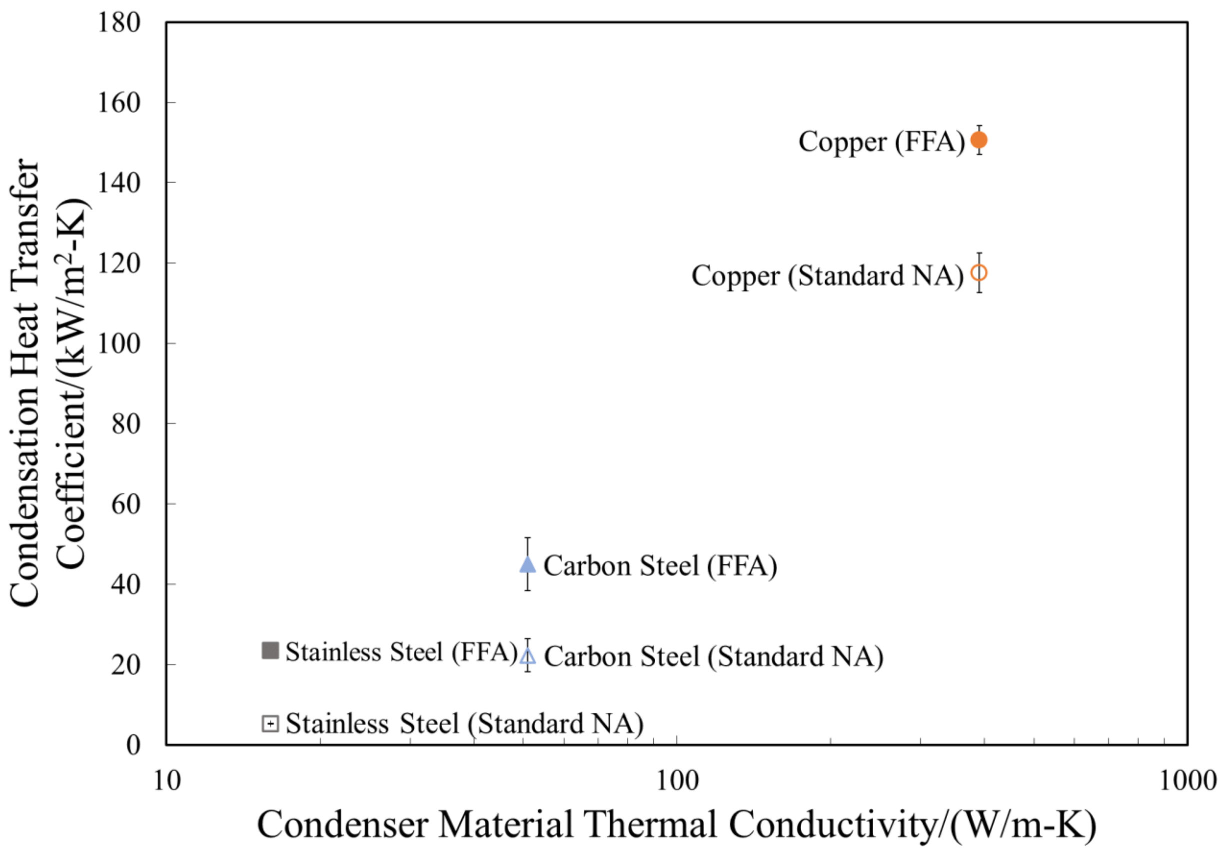
Minutes of DWC on Carbon Steel

After Several Hours on Copper



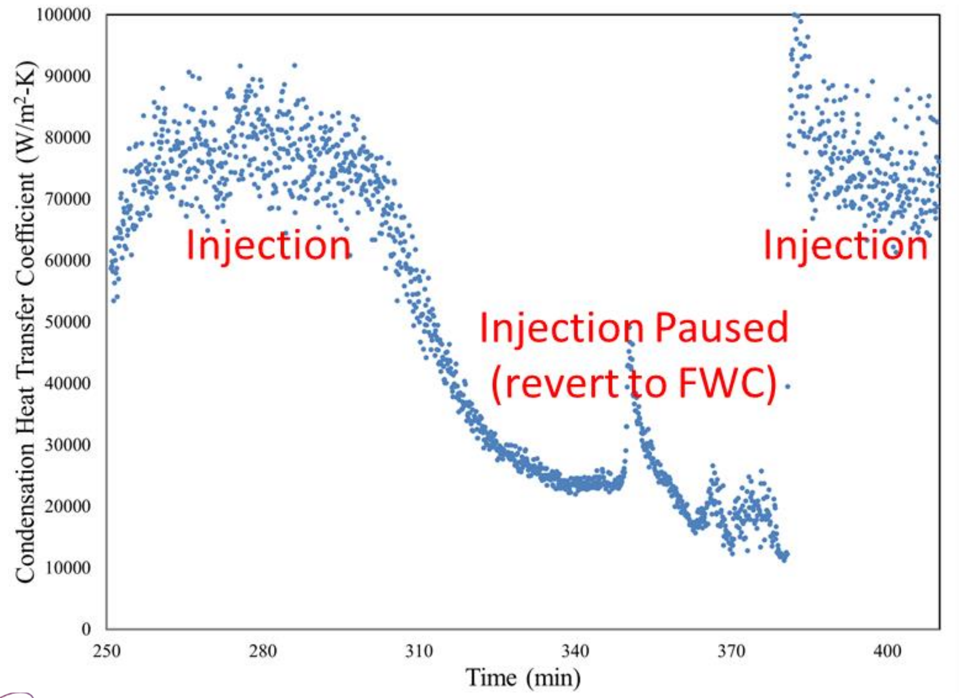
Testing Update – Initial Results

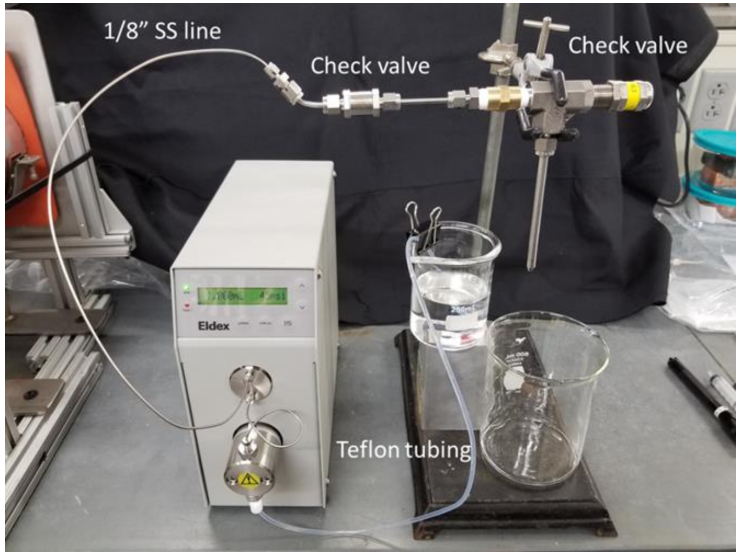
- Copper, carbon steel, and stainless steel showed performance results expected when compared to similar past studies using self-assembled monolayers
  - Confirmed by: Hoenig, S.H., R.W. Bonner, et. al. "Role of Substrate Thermal Conductivity and Vapor Pressure in Dropwise Condensation". *Appl. Therm. Engr.* 178C (2020) 115529.
- Results compare condensation heat transfer coefficients for each material for FFA and standard NA
  - FFA coatings provided a consistent hydrophobic surface for DWC
  - Standard NA led to mixed modes of condensation (primarily filmwise behavior on steel surfaces due to low affinity) and no oxidative protection of the surface



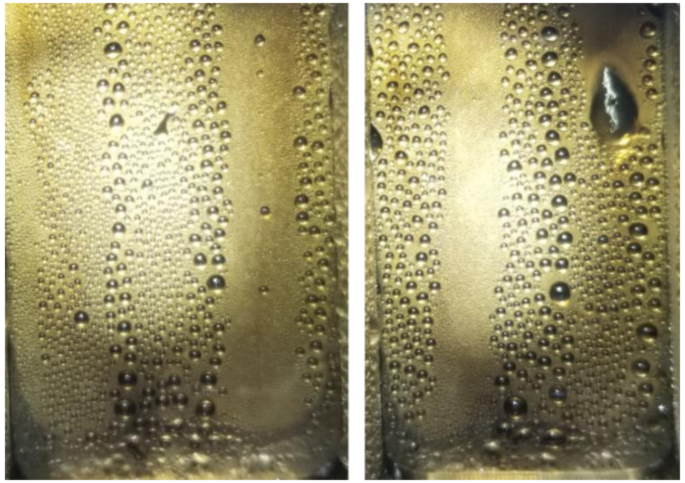
Testing Update – Initial Results

- Continuous injection is required to sustain DWC on the condenser surface
- First time successfully sustaining dropwise condensation on a steel surface at high performance (h_l = ~70 kW/m^2-K)!



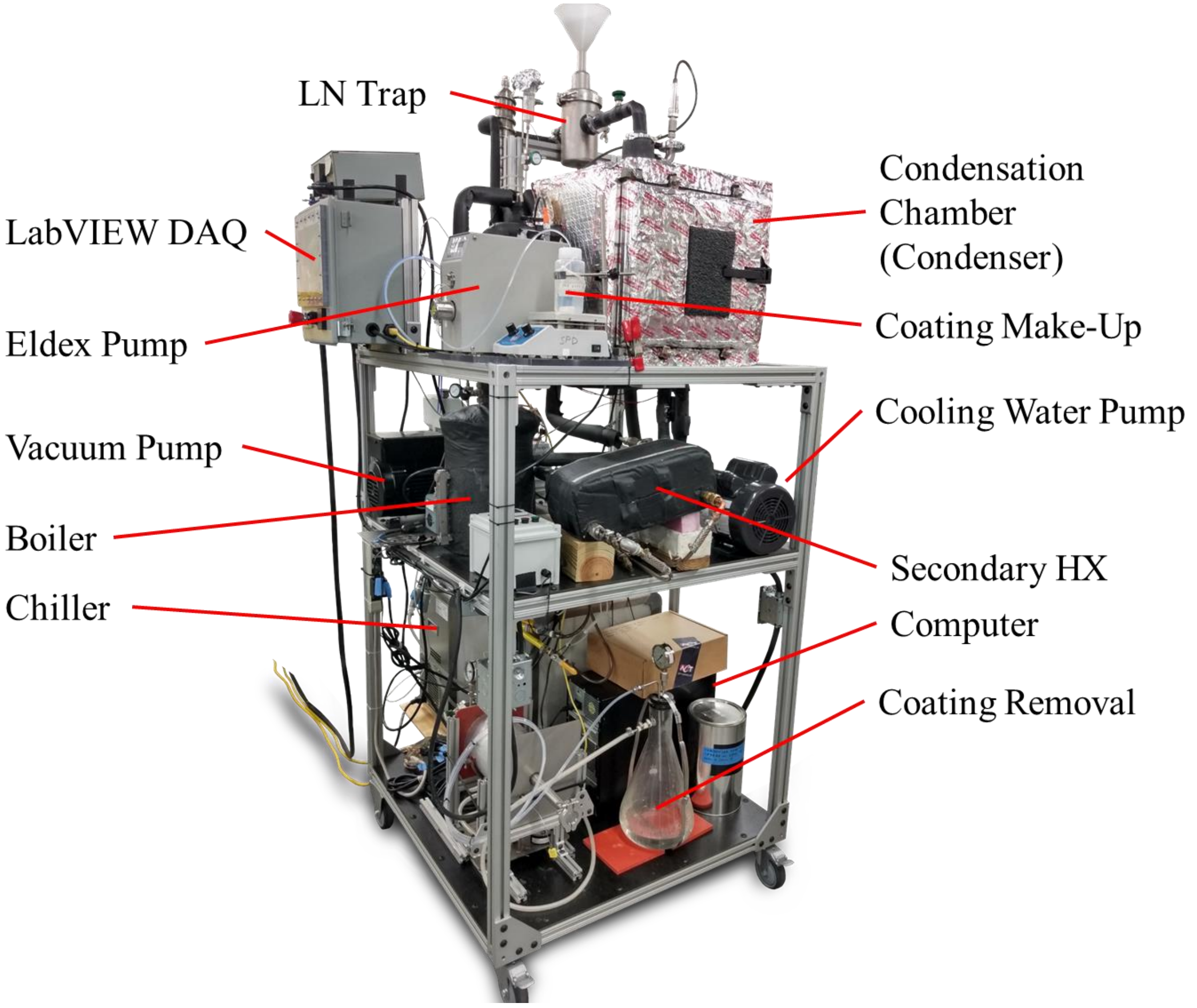


Continuous DWC on Carbon Steel



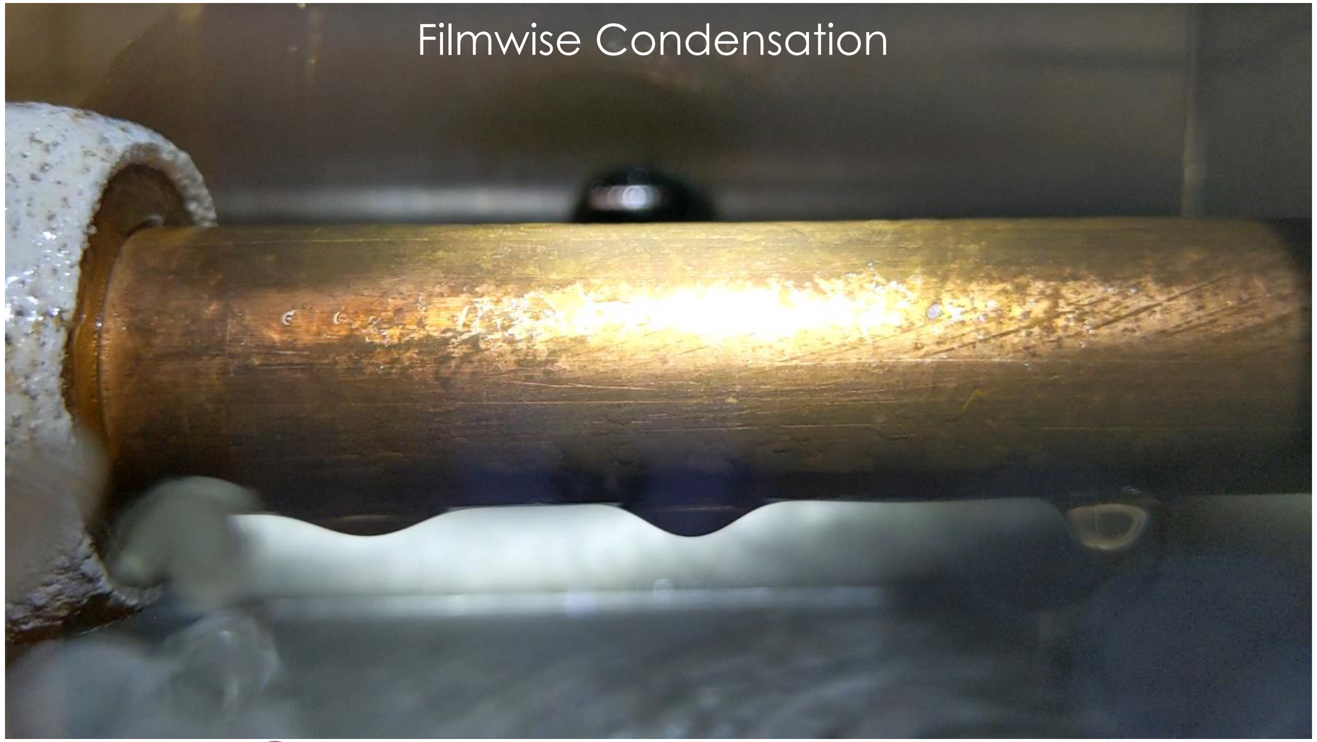
New Experimental Setup

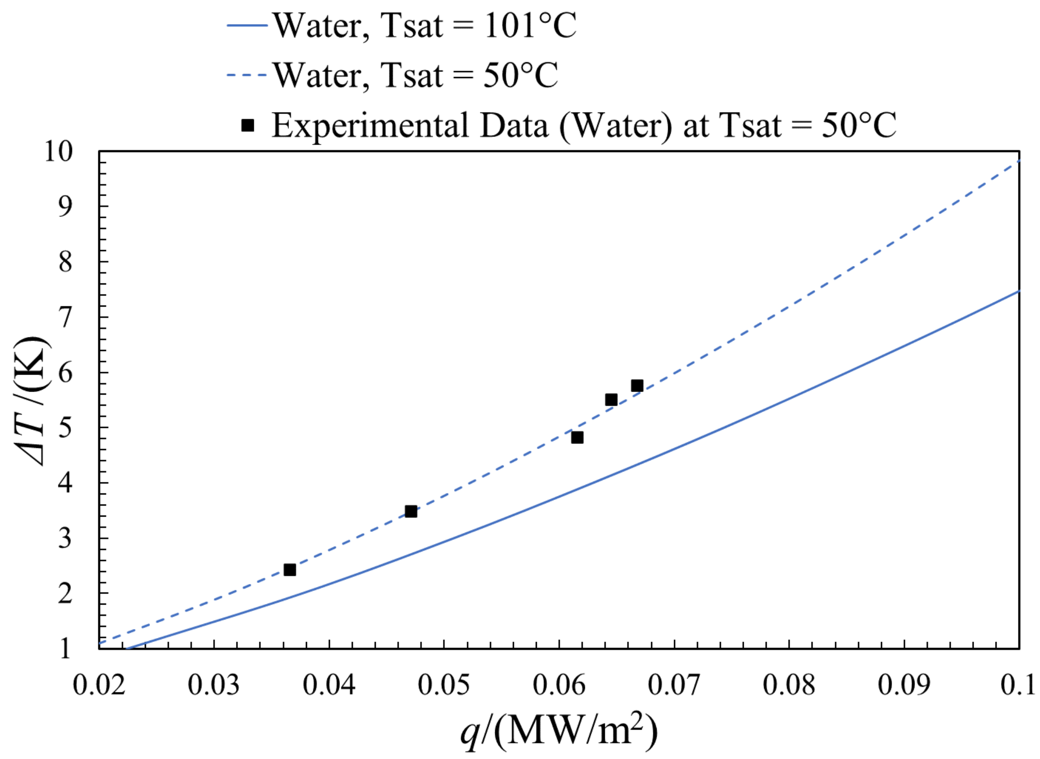
- Transition to a tube-based experimental apparatus to measure condensation heat transfer coefficients
  - 1" OD tube mimics conventional steam surface condenser size
- Condensation chamber is hermetic and is used to test at power plant operating conditions (i.e. vacuum pressures)
- Calorimetry is used to evaluate thermal performance
- Make-up FFA coating is injected into the system to replenish the surface coverage on the tubing



Experimental Setup Validation

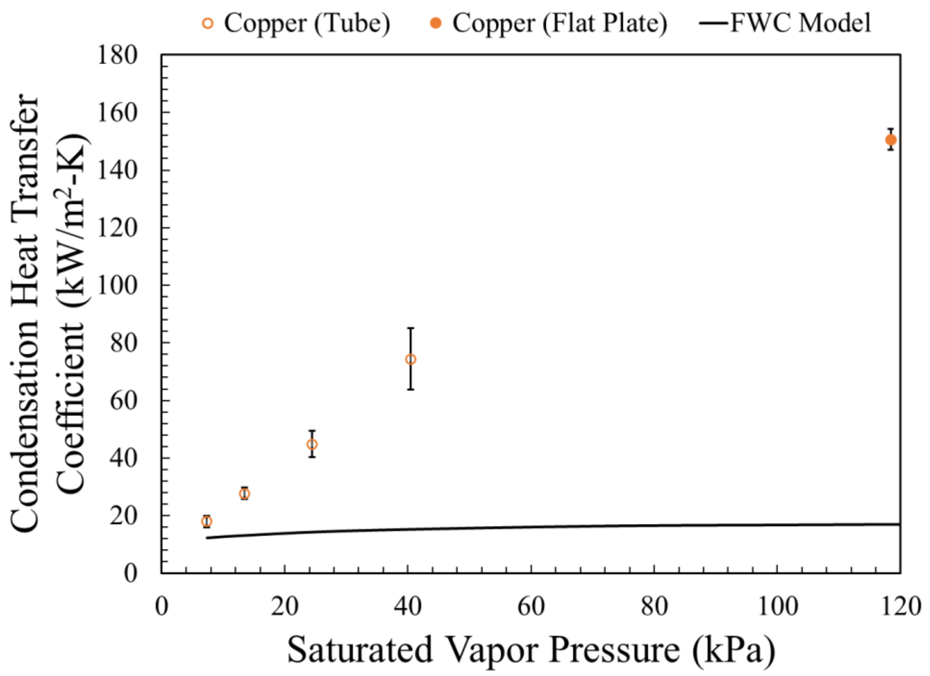
- Verified operation of test setup using the Nusselt filmwise condensation model
  - Experimental results completed with DI Water
  - Successfully oxidized copper tubing using OTC hydrogen peroxide
  - Only completed at low vapor pressure (and low heat flux) due to design limitations

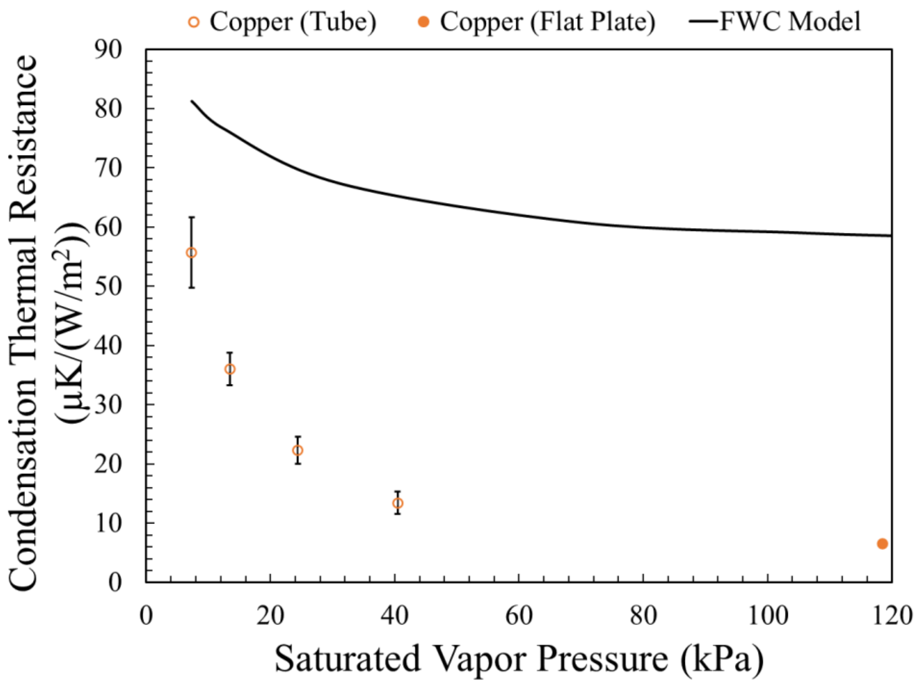




New Experimental Results on Copper Tubing

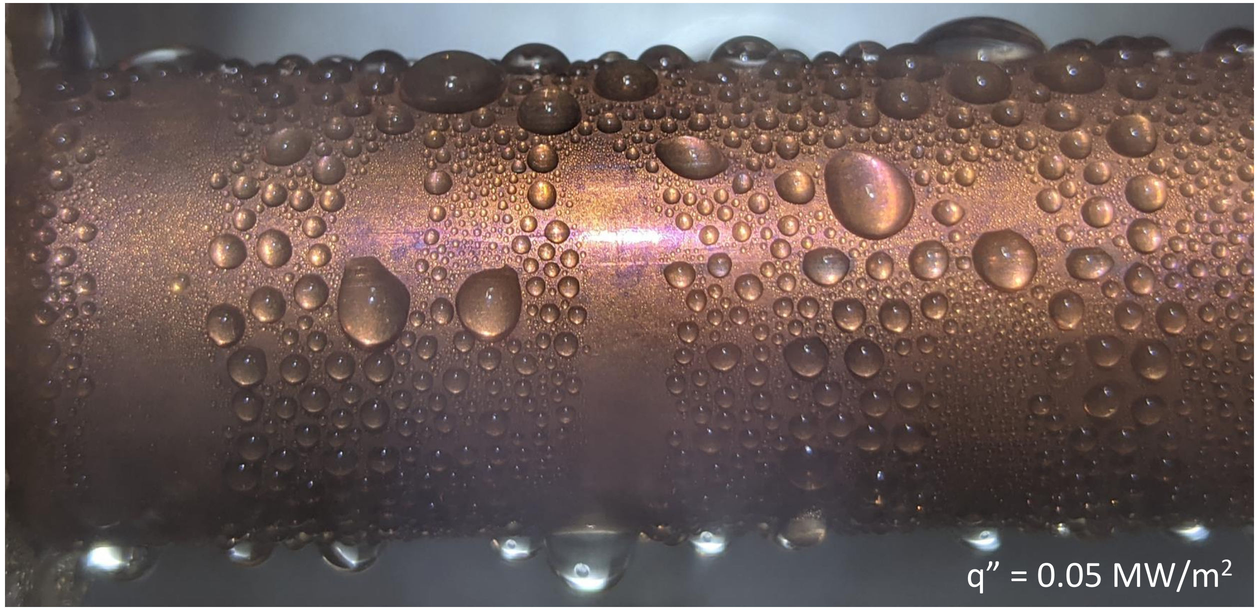
- Thermal performance results are consistent with previous studies
  - Confirmed in: Hoenig, S.H., R.W. Bonner, et. al. "Role of Substrate Thermal Conductivity and Vapor Pressure in Dropwise Condensation". *Appl. Therm. Engr.* 178C (2020) 115529.
  - All results evaluated at a heat flux approximately, q" = 0.05 MW/m^2 (this is consistent with power plant condensers)
    - Grol, E., et. al. "NETL Crosscutting Program Research Guidance – Condensers and Wastewater Treatment Projects," National Energy Technology Laboratory, Pittsburgh, PA, 2019.

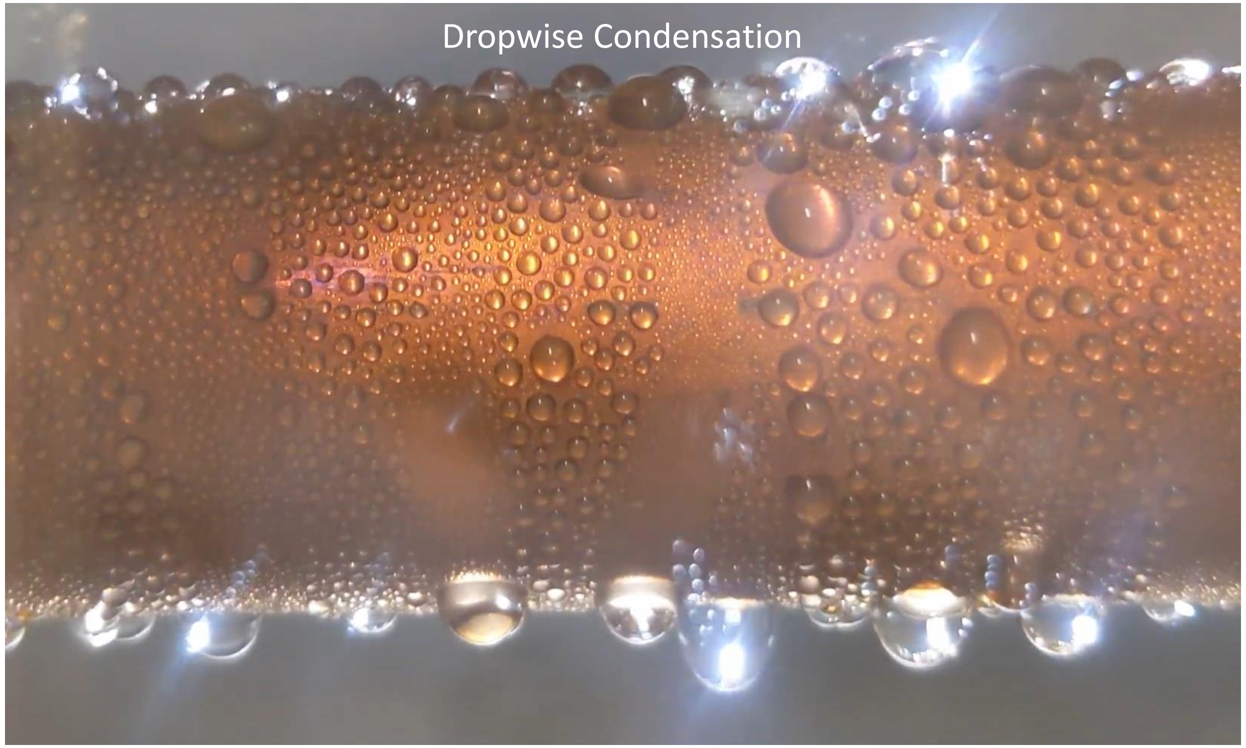




Droplet Images on Copper Tubing

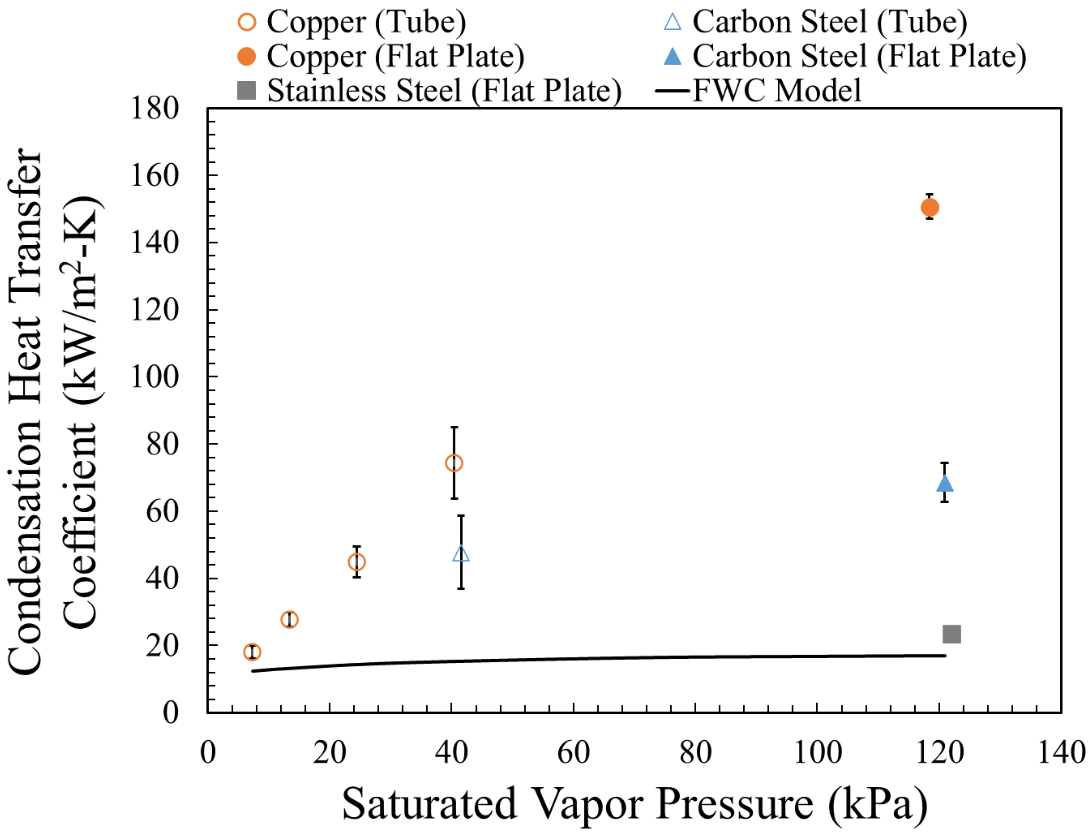
- Observation: large, stagnant droplets on the top & bottom tubing surfaces
  - Regardless, the large interfacial vapor resistance seems to dominate at low vapor pressure





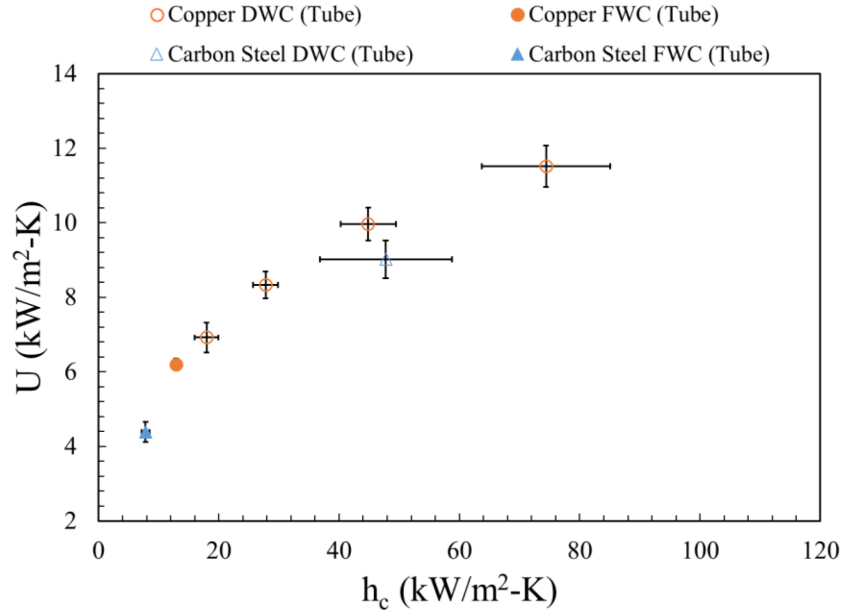
New Experimental Results on Carbon Steel Tubing

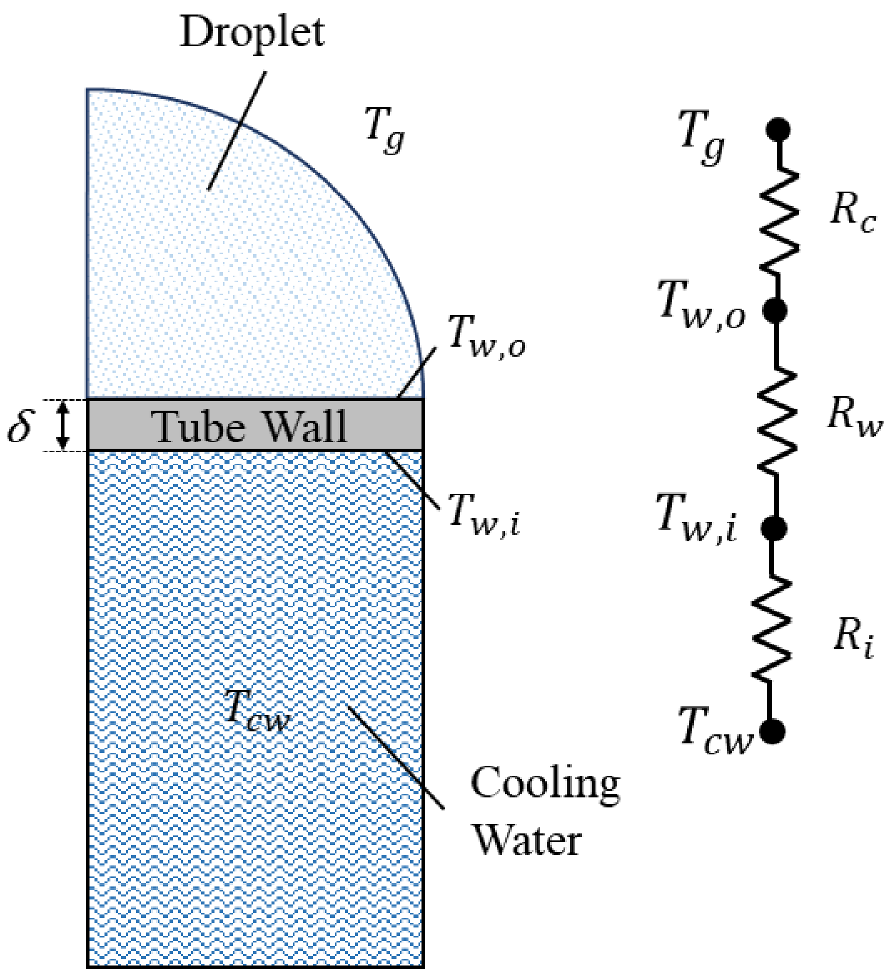
- Initial results at low vacuum pressure show a comparable trend in improvement in the condensation heat transfer coefficient
  - Constriction resistance leads to a lower condensation heat transfer coefficient with a lower thermal conductivity material
    - Hoenig, S.H., R.W. Bonner, et. al. "Role of Substrate Thermal Conductivity and Vapor Pressure in Dropwise Condensation". *Appl. Therm. Engr.* 178C (2020) 115529.
  - Additional results at low vacuum pressure will complete the study, including a life test on carbon steel tubing



Overall Heat Exchanger Thermal Performance

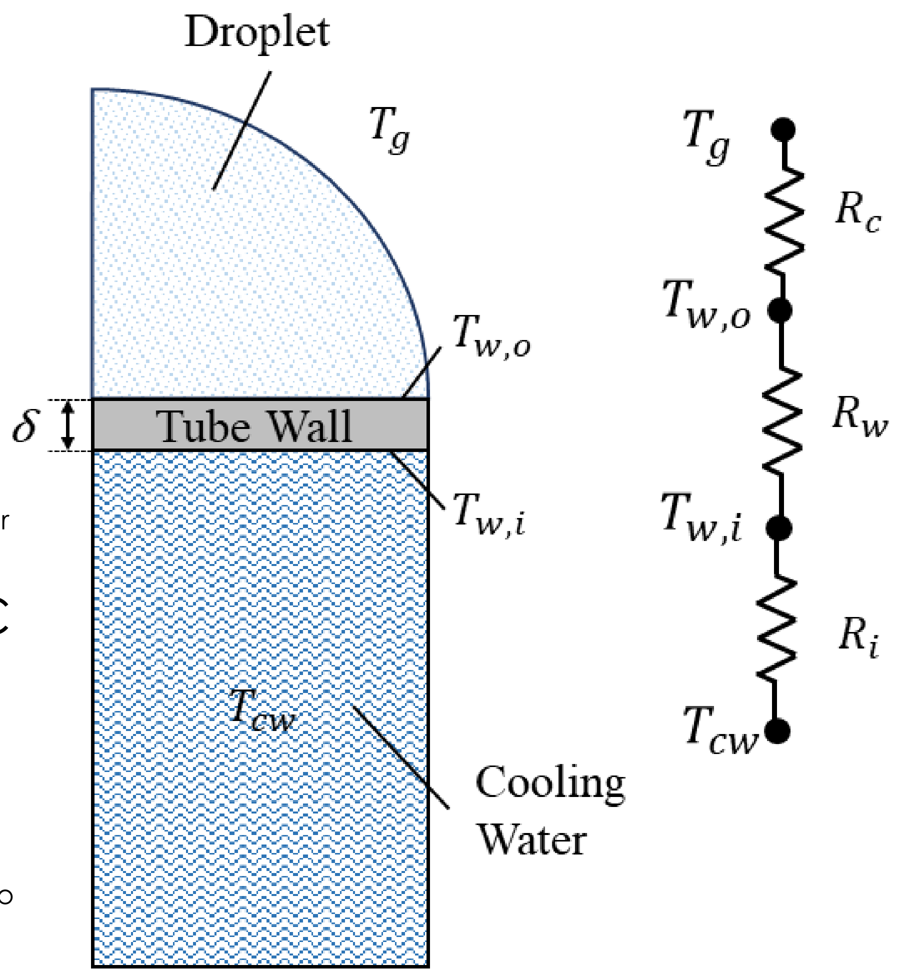
- Although R_i generally dominates, an appreciable improvement in the overall heat exchanger thermal performance (U) is shown for small increases in h_c
  - U has less experimental error associated with its calculation and is a well-known method to compare HX performance
  - Our experimental setup has a larger R_i than what is typically seen in power plant condensers, so this measured improvement is considerable





Technoeconomic Analysis of Film-Forming Amine Products

- Quantify the improvement in plant process parameters due to the enhancement in the condensation heat transfer coefficient with using FFAP
  - Determine how the reduction in the condensation thermal resistance affects the entire resistance pathway
  - Examine turbine backpressure, net plant efficiency, cooling water consumption, and overall heat transfer coefficient (*U*)
- Used NETL Research to guide dimensional & flow assumptions for the power plant scale condenser
  - Grol, E., et. al. "NETL Crosscutting Program Research Guidance – Condensers and Wastewater Treatment Projects," National Energy Technology Laboratory, Pittsburgh, PA, 2019.
- Used a journal paper on the feasibility of long-term DWC to create a cost model for FFAP
  - Ahlers, M., et. al. "Is dropwise condensation feasible? A review on surface modifications for continuous dropwise condensation and a profitability analysis," Journal of Advanced Research, vol. 16, pp. 1-13, 2019.
- Manuscript published in PPCHEM
  - Hoenig, S.H., et al. "Technoeconomic Benefits of Film-Forming Amine Products Applied to Steam Surface Condensers". *PPCHEM* **2021**, 23(1), 4.

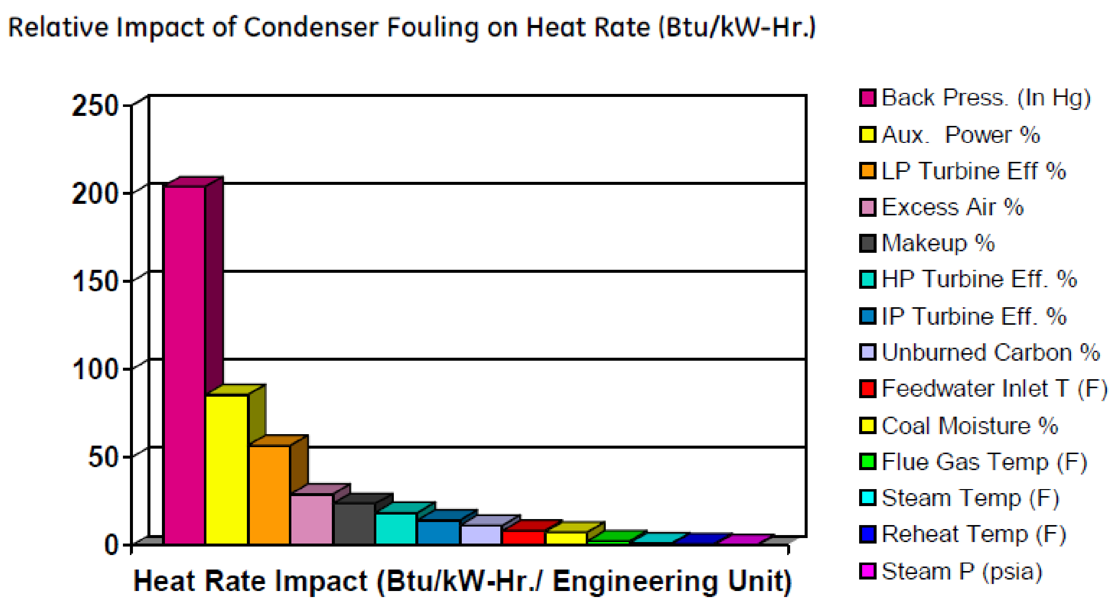


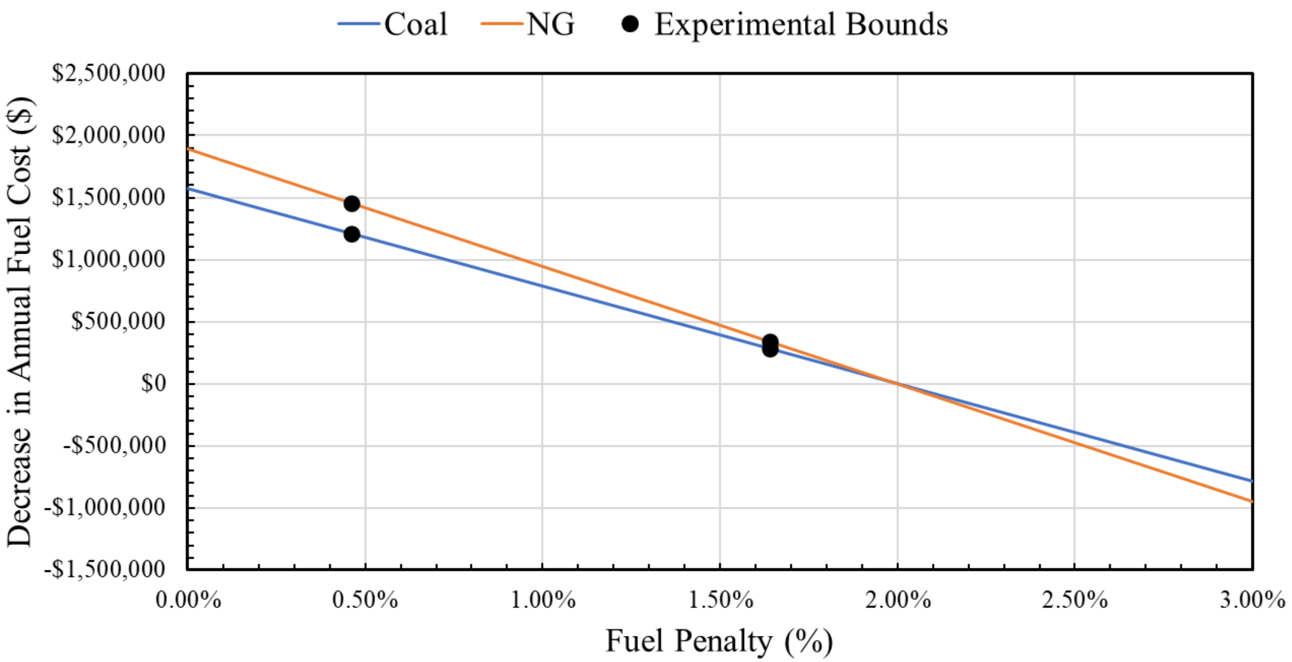
Technoeconomic Analysis of Film-Forming Amine Products

- All comparisons made between a baseline carbon steel tube with a filmwise heat transfer coefficient (HTC) of 10,000 W/m^2K and a FFA coated carbon steel tube with a dropwise HTC of 70,000 W/m^2K
- The comparisons show that a FFA coated condenser would have a:
  - 38% reduction in the condenser thermal resistance (size)
  - 59% improvement in the overall heat exchanger performance
  - 0.54 inches of Hg reduction in back pressure
  - 0.84% increase in power plant efficiency
  - 24% reduction in net levelized condenser cost

Technoeconomic Analysis of Film-Forming Amine Products

- "A 1.0" Hg increase in condenser backpressure relates to a 200 BTU/hr. increase in heat rate"…"divided by an avg. heat rate of 10,000 BTU/kW-hr is approximately a 2% fuel penalty"
- Determine fuel cost savings based on reduction in turbine backpressure
  - Assumption: 500MW power plant operating 300 days/year using standard fuel costs
  - Potential annual fuel cost savings is between $300K - $1.5M per year

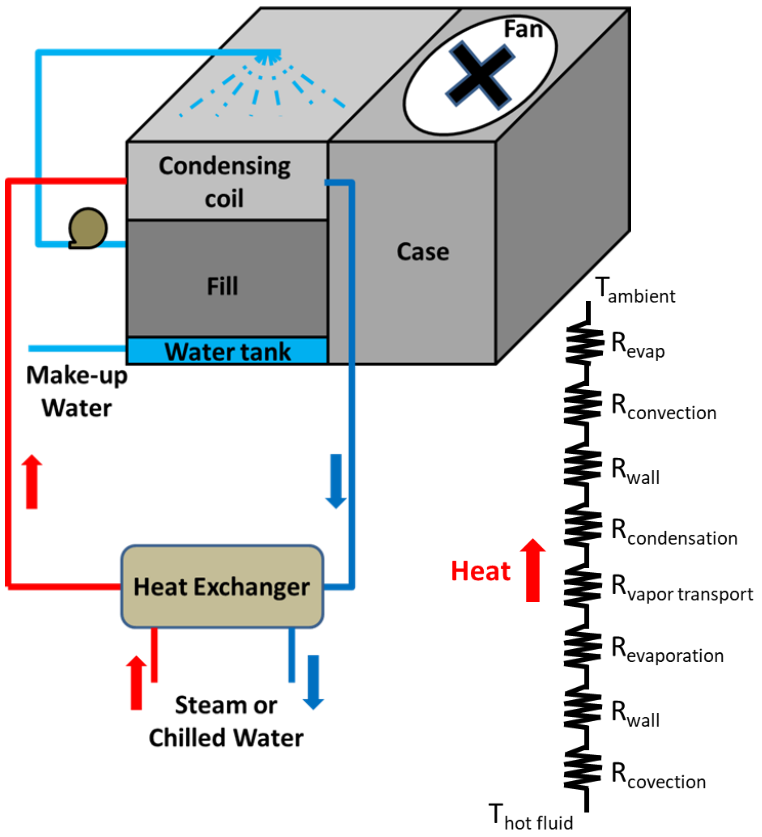




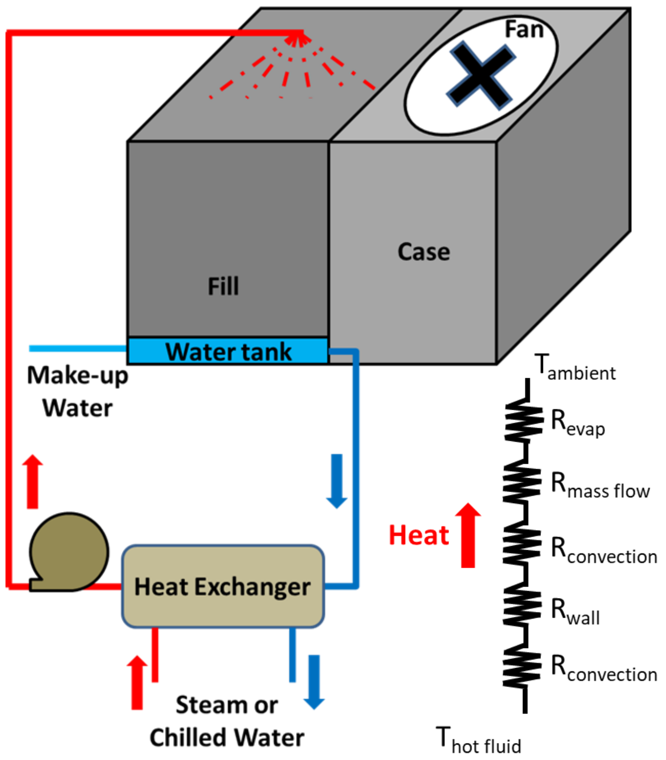
Loop Thermosyphon with Closed Cooling Tower

Loop Thermosyphon with Closed Cooling Tower

- No circulation pump
- No circulation power consumption
- Less maintenance
- Higher number of thermal resistances on the condenser side



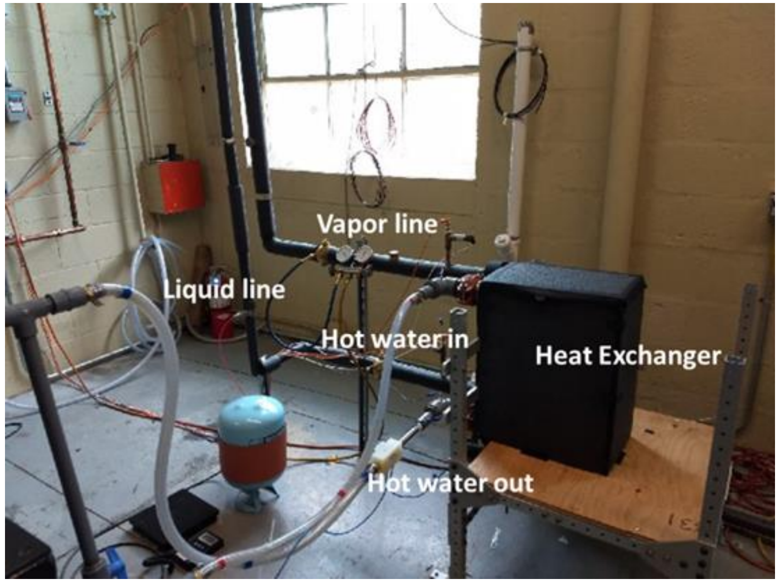
Pumped Water Loop with Open Cooling Tower



- Less number of thermal resistances on the condenser side
- Circulation pumping power requirement
- Cooling water and water pipe maintenance

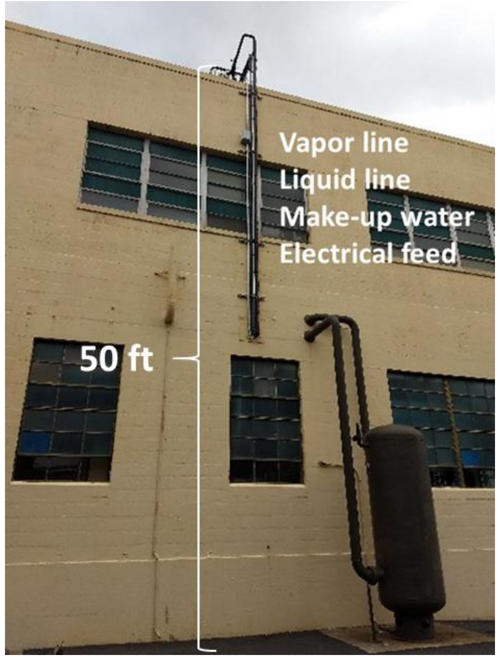
Demonstration Setup

- Evaporator – Flat plate heat exchanger
- Condenser – Closed cooling tower (Evaporative Cooler from BAC)
- Vapor and liquid lines – ~50 feet tall
- Heating method – Circulation Water heater (up to 25 kW)

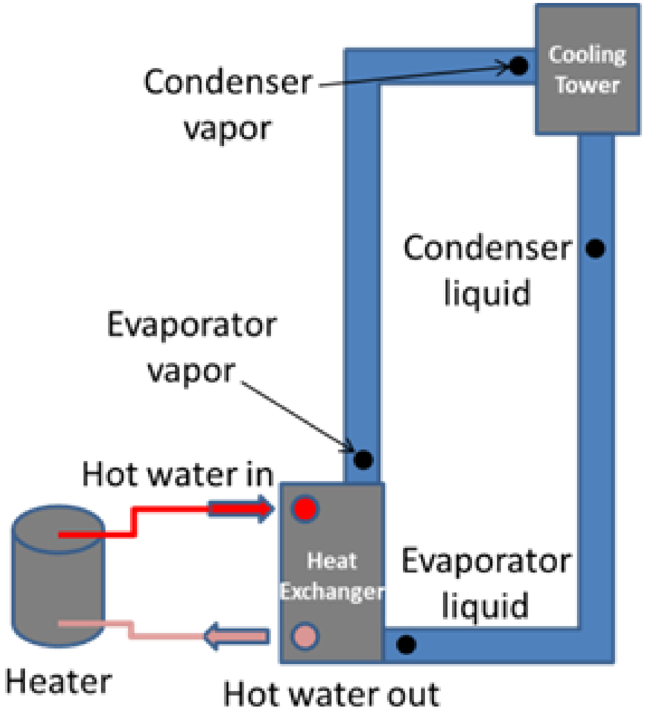


Evaporator

Condenser

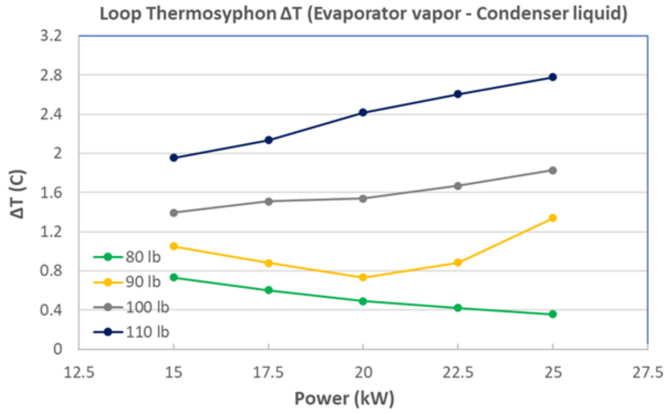


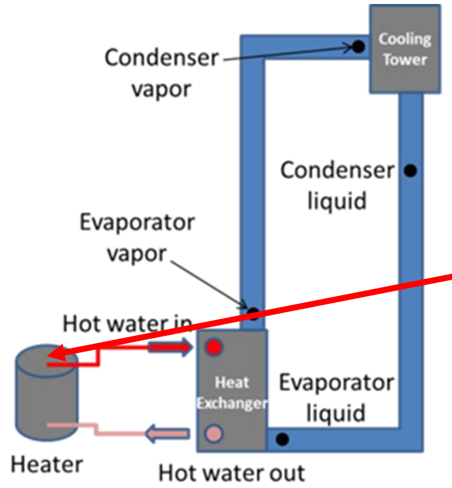
Vapor and Liquid lines

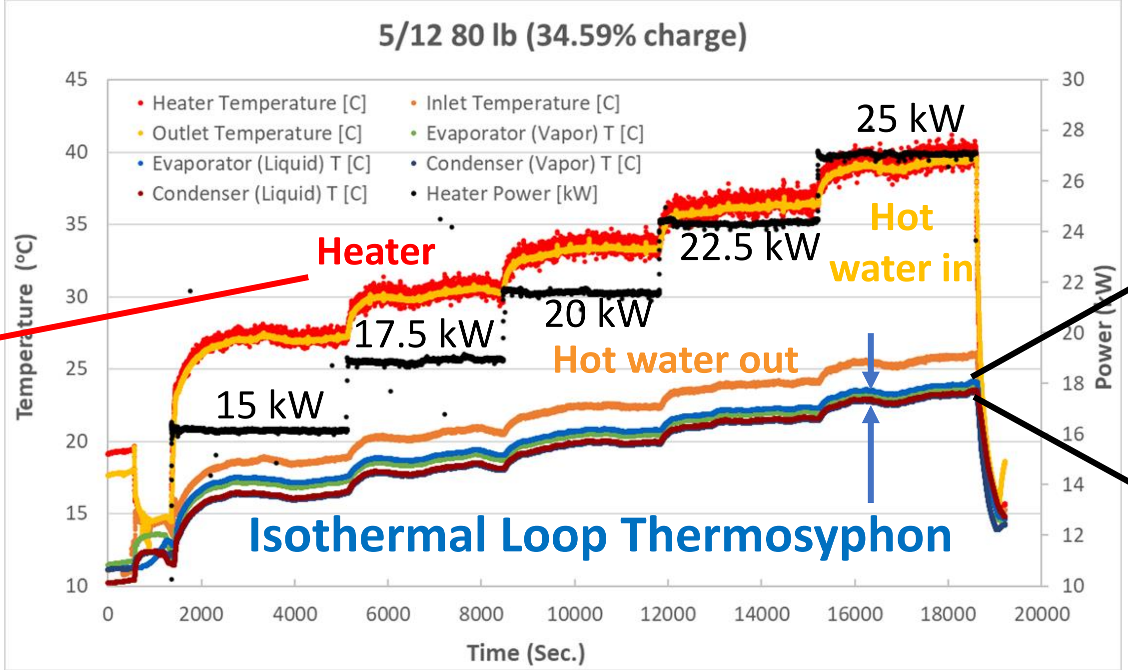


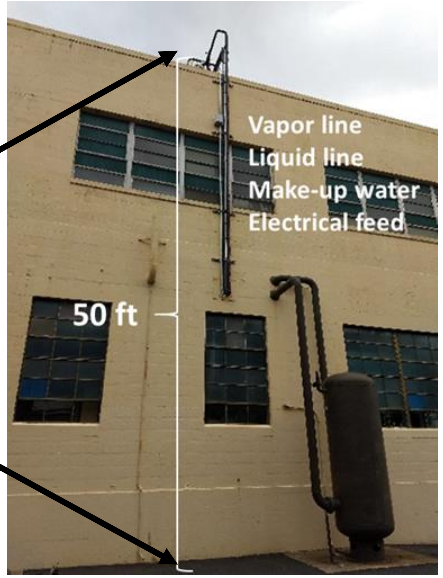
Testing Summary

- The refrigerant filled loop thermosyphon was able to transfer 25 kW of waste heat 50ft vertically, passively
- With proper charge, the ΔT within the loop thermosyphon is < 1°C
- Excess charge can slightly increase the ΔT due to the subcooling of the condensate









Tech-to-Market Assessment

- FFA Coatings to promote enhanced DWC
  - Work with Suez to promote the FFA coating technology for power plants by adding the condensation performance as an additional selling point
    - Reduction in turbine pressure, improvement in net plant efficiency, etc.
    - Engaged in discussions to implement a field test with a natural-gas combined cycle plant
- Loop thermosyphons for coal and other power plant cooling systems
  - Start with the "addressable" HVAC, power electronics, renewables markets…
    - Similar requirements but at a manageable scale
    - Apply models to split loop energy recovery systems
  - Collaboration with a larger scale cooling tower company to address coal fired power plant market

Loop Thermosyphon Commercialization Path

<u>Product Development at ACT</u>

- Loop thermosyphons integrated into radiators for air-to-air heat exchange
    - ACT has built units capable of 100’s of kW’s
    - Typically integrated in large building air handlers
    - Payback period 2-3 years
- New production business with a wind turbine manufacturer that will use 75kW loop thermosyphons to passively cool gear oil using R-134a as the working fluid

Results Summary

Technical Summary

- Film-forming amine coating technology can be used to improve steam surface condenser thermal performance
  - Demonstrated high DWC performance typical of monolayer type promoters
  - Continuous coating injection sustains hydrophobicity on all condenser materials & leads to replenishable DWC
  - New test results on tubing confirms comparable thermal performance benefits
  - TEA demonstrates condenser improvement in size, performance and costs
- Loop thermosyphon technology can replace pumped cooling water
  - Two-story (50 ft.), loop thermosyphon with a 7-ton (25 kW) cooling tower has high thermal performance & can replace pumped cooling water
  - Commercialization opportunities have expanded our company's operations in loop thermosyphon technology
  - Models are under development for use as quick design tools

Next Steps

Next Technical Steps

- Dropwise Condensation
  - Investigate results with other FFA chemistries in Suez's product offerings
  - Life Testing (on carbon steel)
- Loop Thermosyphon
  - Re-instrument and test; improve design models

Tech to Market

- Continue working with Suez on FFA coating development
  - Field test
- Develop HVAC, Wind and Power Electronics market as initial addressable markets for loop thermosyphons
- Continue to develop relationships with power plant condenser and cooling tower suppliers at conferences

Acknowledgements

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  - This material is based upon work supported by the Department of Energy Award Number DE-FE0031657
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