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

Advanced Cooling Technologies, Inc.

Richard W. Bonner (PI), Sean H. Hoenig, Chien-Hua Chen, Michael C. Ellis

Suez Water Technologies & Solutions

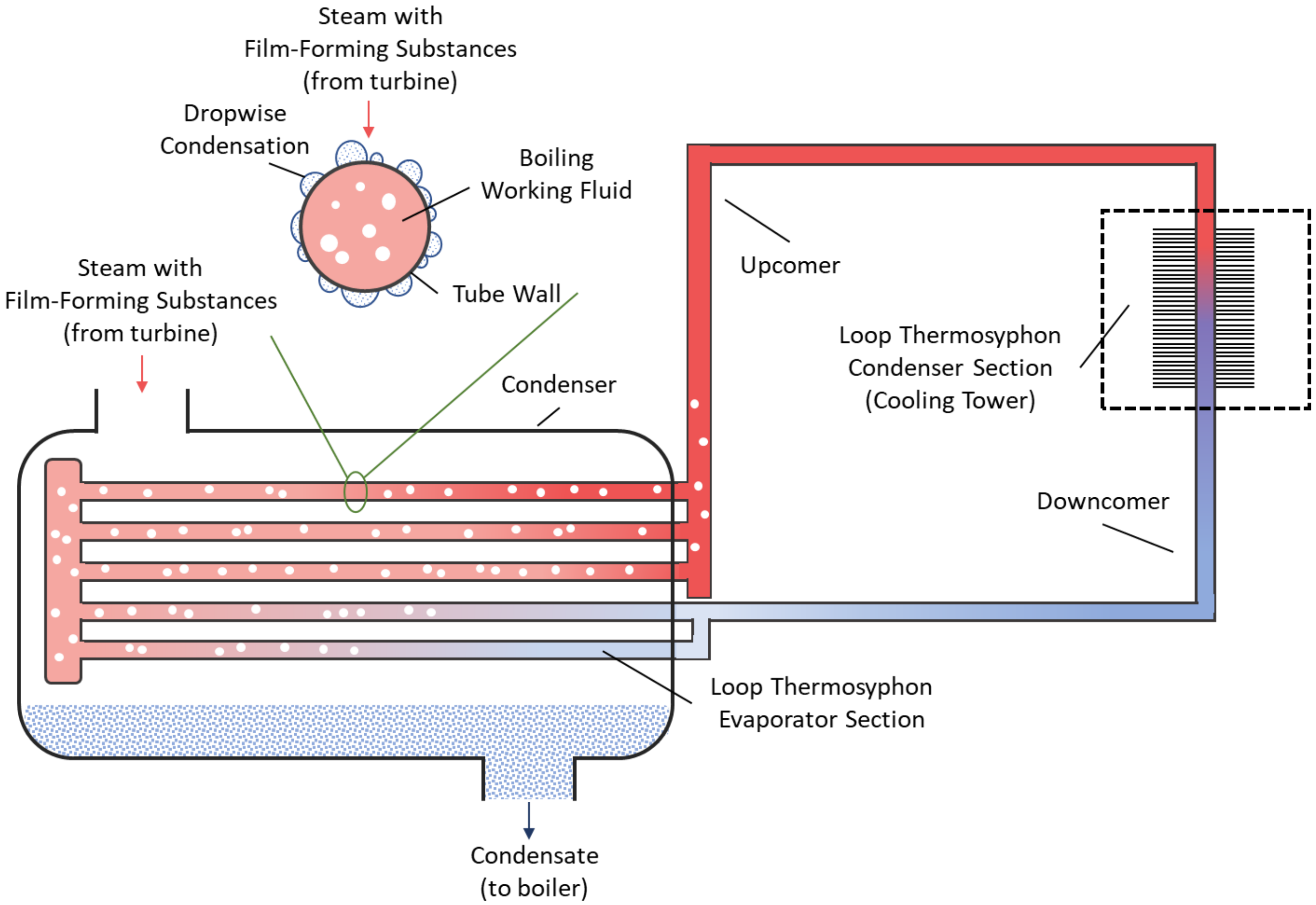
Don Meskers, Claudia Pierce, Mahesh Budhathoki, Gregg Robinson

In Year 2 of 3, finishing up Quarter 8

Project Overview

Concepts

- #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

Concept

- FFA 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 FFA using materials found in power plants and for power plant conditions

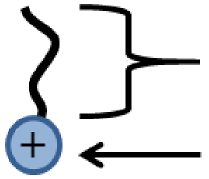
<u>Film-Forming Amine Composition</u>

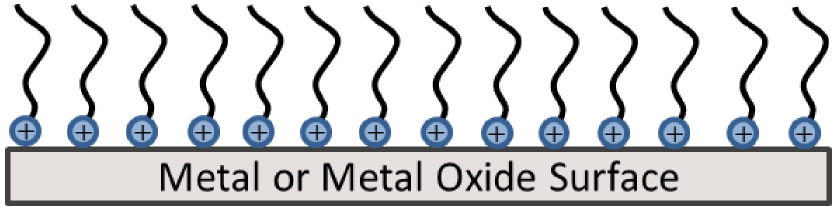
R_1-[NH-(R_2)-]$_n$-NH_2

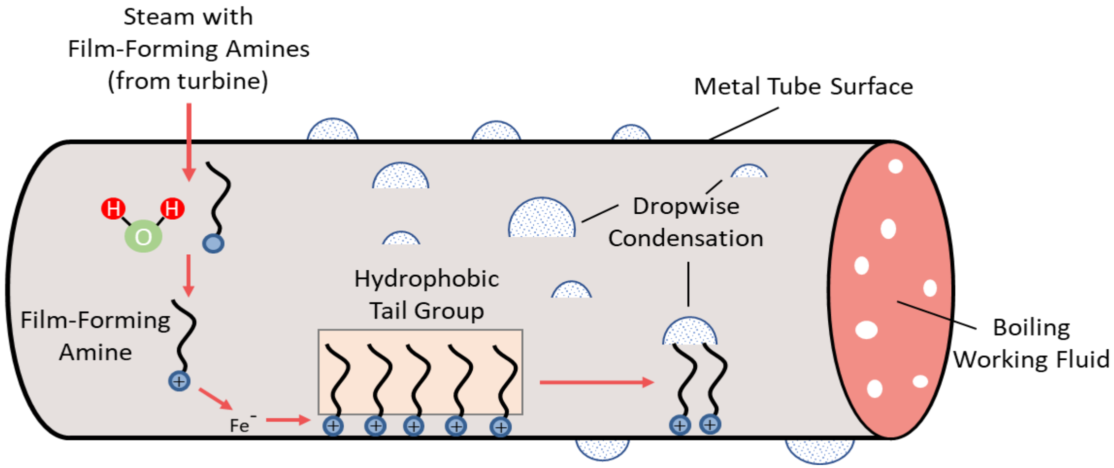
n is a whole number between 0 and 7

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







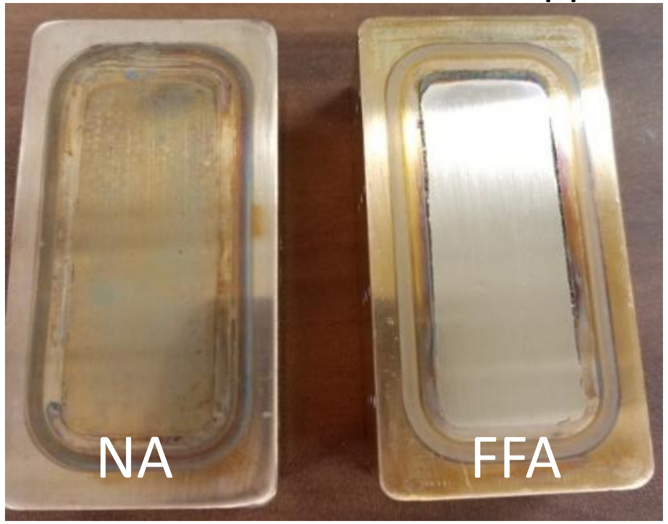
Testing Update

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

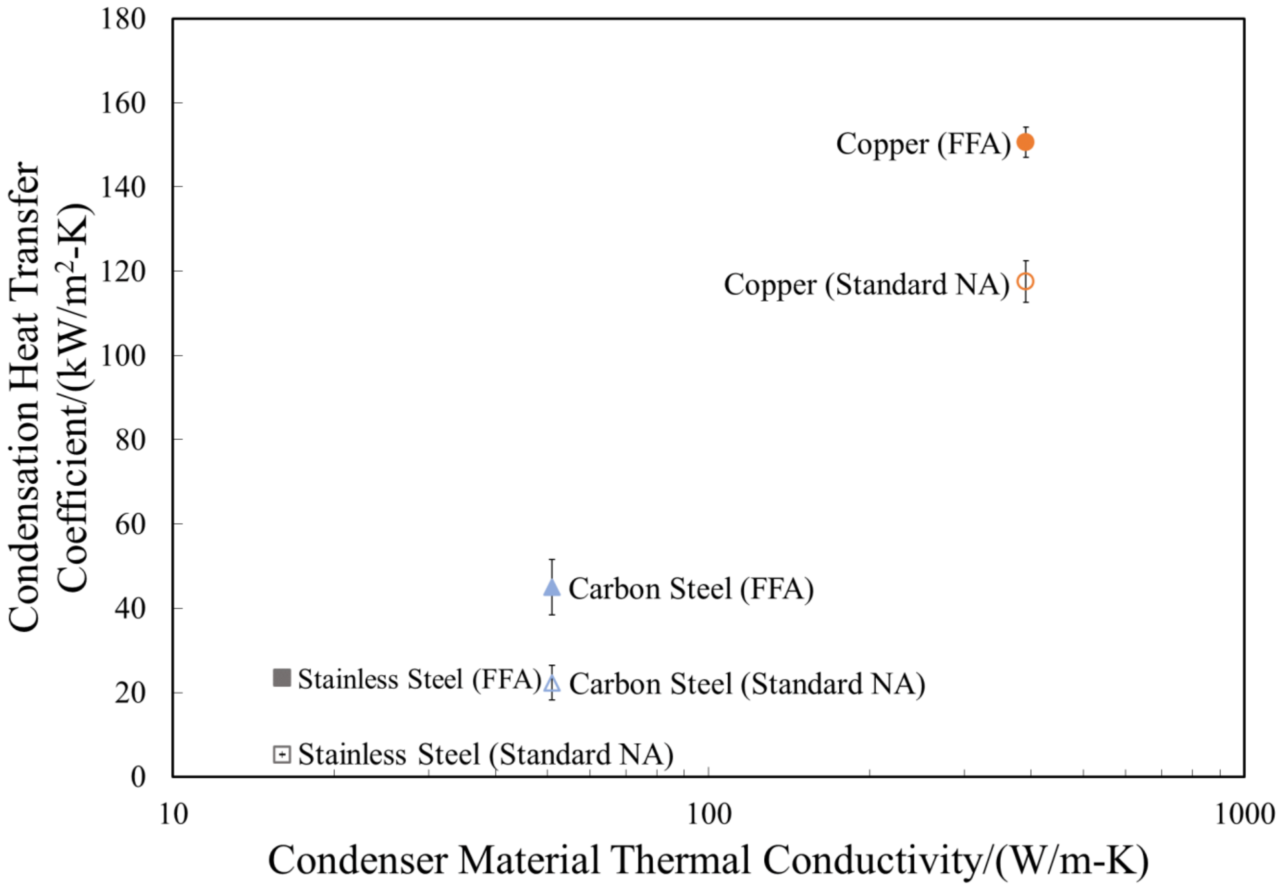
After Several Hours on Copper



Testing Update

Initial Results

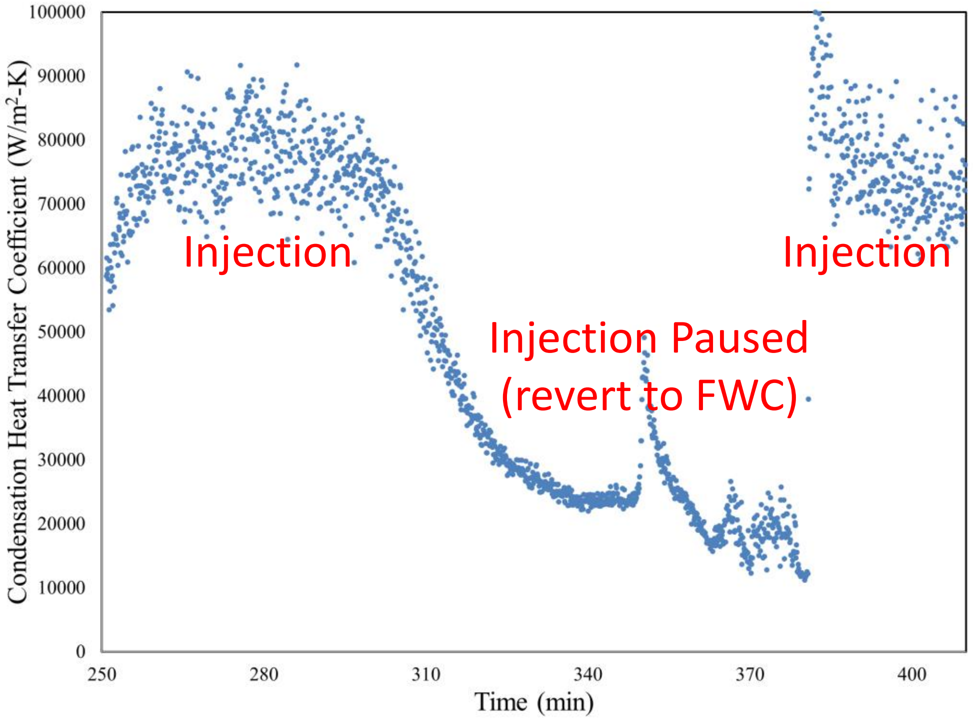
- Copper, carbon steel, and stainless steel showed performance results expected when compared to similar past studies using self-assembled monolayers
  - Confirmed by: Hoenig, S.H., R.W. Bonner, et. al. “Role of Substrate Thermal Conductivity and Vapor Pressure in Dropwise Condensation”. *Appl. Therm. 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

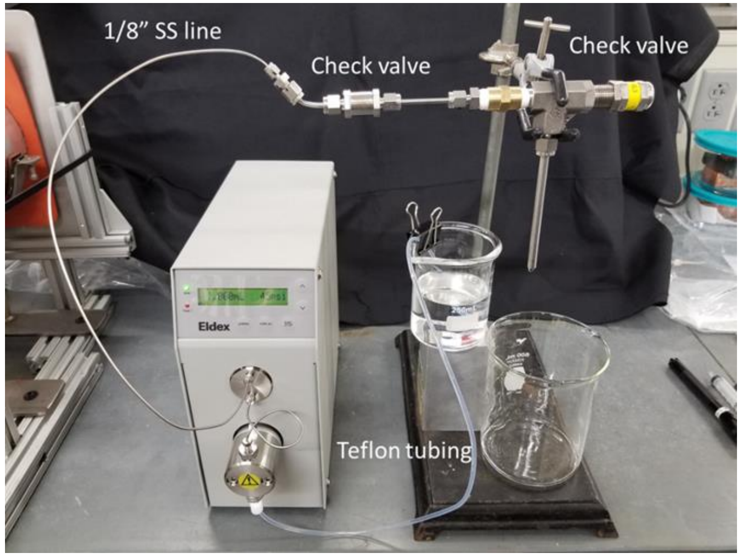


Testing Update

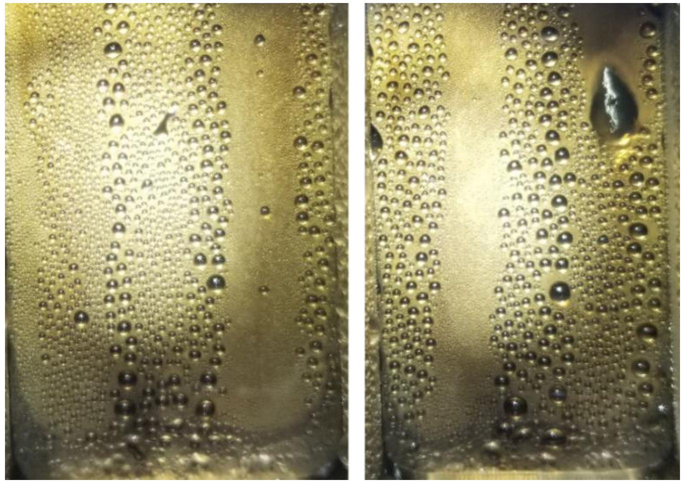
Subsequent Findings

- 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)!





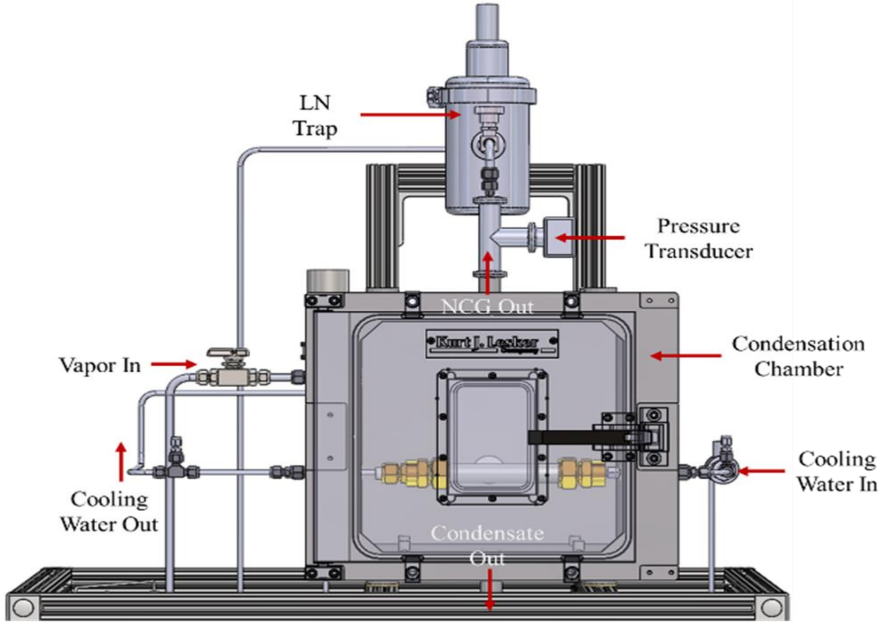
Continuous DWC on Carbon Steel

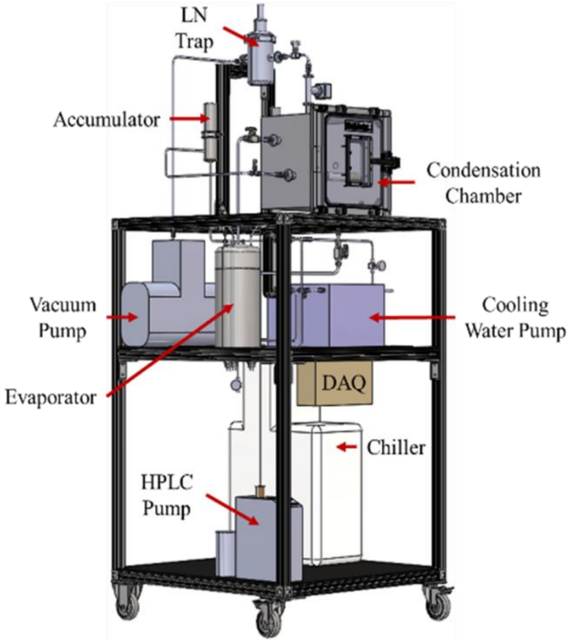


Experimental Setup

Progress

- Transition to a tube-based experimental apparatus to measure condensation heat transfer coefficients
  - 1" OD tube mimics conventional steam surface condenser
- Condensation chamber is hermetic and will be used to test at power plant operating conditions (i.e. vacuum)
- Calorimetry is used to evaluate thermal performance

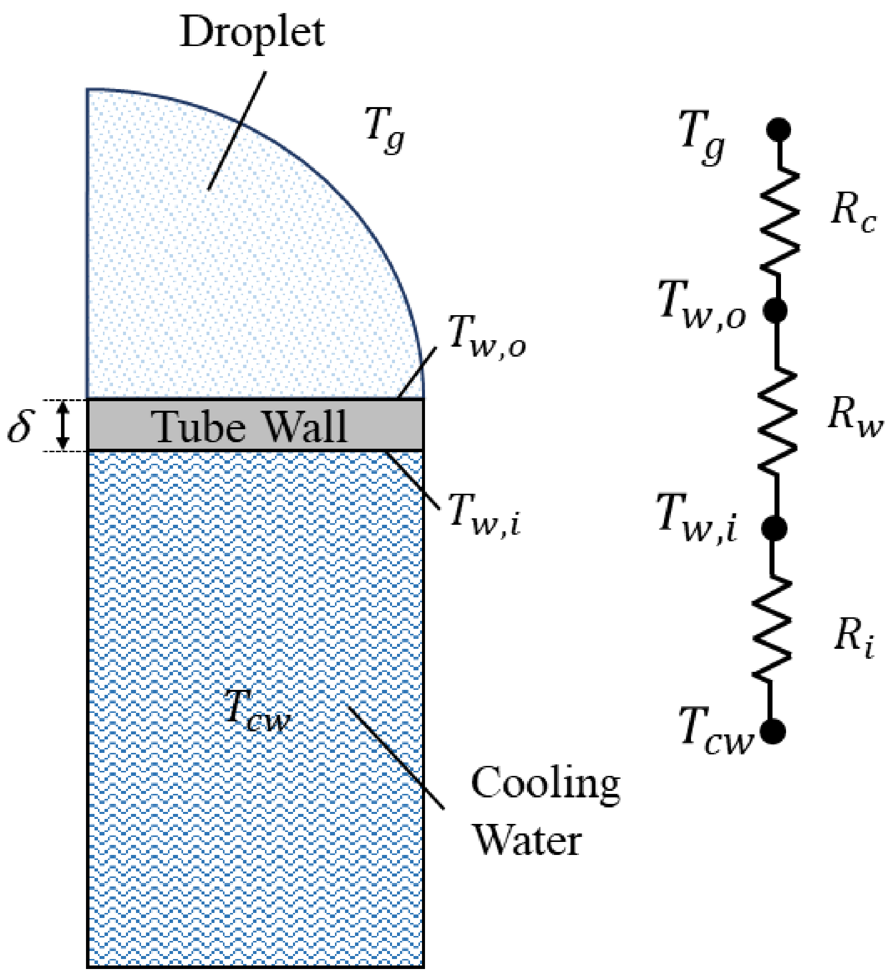




Technoeconomic Analysis

FFA Coating Technoeconomic Analysis

- Quantify the improvement in plant process parameters due to the enhancement in the condensation heat transfer coefficient with using FFA coatings
  - 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 FFA use
  - 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 under review at PPCHEM
  - Hoenig, S., et. al. "*Technoeconomic Benefits of Film-Forming Amine Coatings Applied to Steam Surface Condensers*" …



Technoeconomic Analysis Summary

FFA Coating TEA Summary

- 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 100,000 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

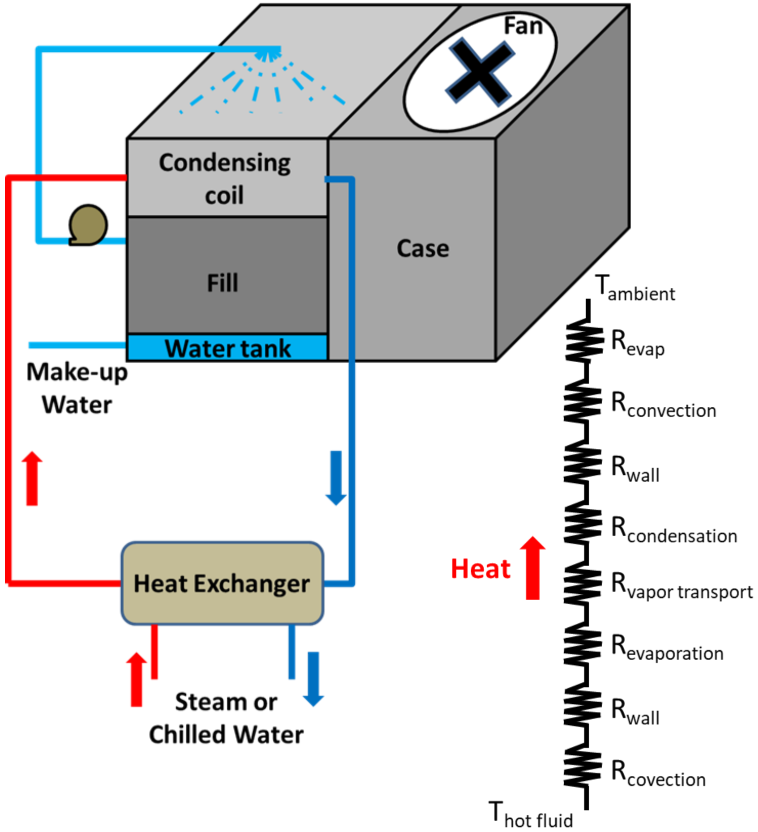
Loop Thermosyphon with Closed Cooling Tower

NATIONAL ENERGY TECHNOLOGY LABORATORY

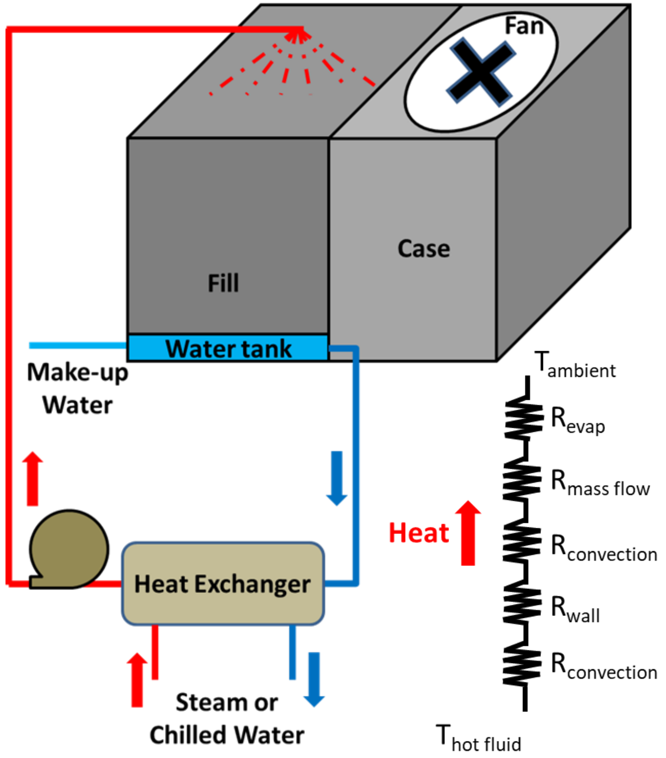
Loop Thermosyphon vs. Pumped Water Loop

Loop Thermosyphon with Closed Cooling Tower

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



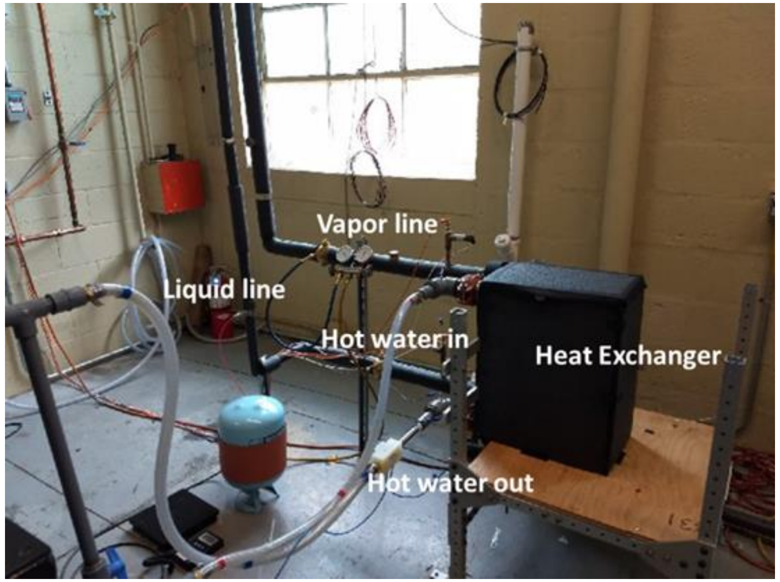
Pumped Water Loop with Open Cooling Tower



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

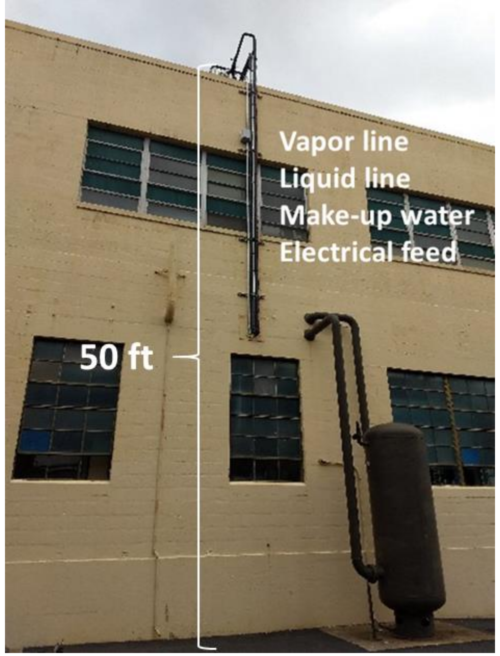
Demonstration Setup

- 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)

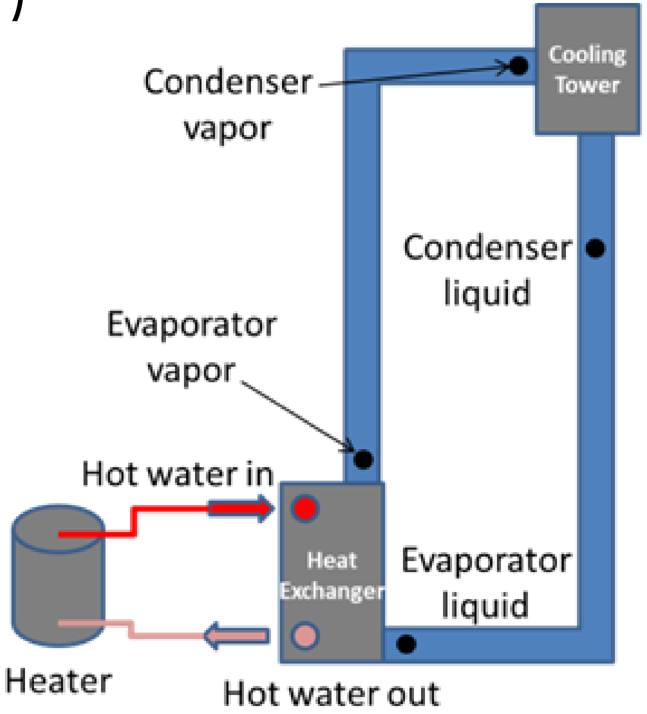


Evaporator

Condenser

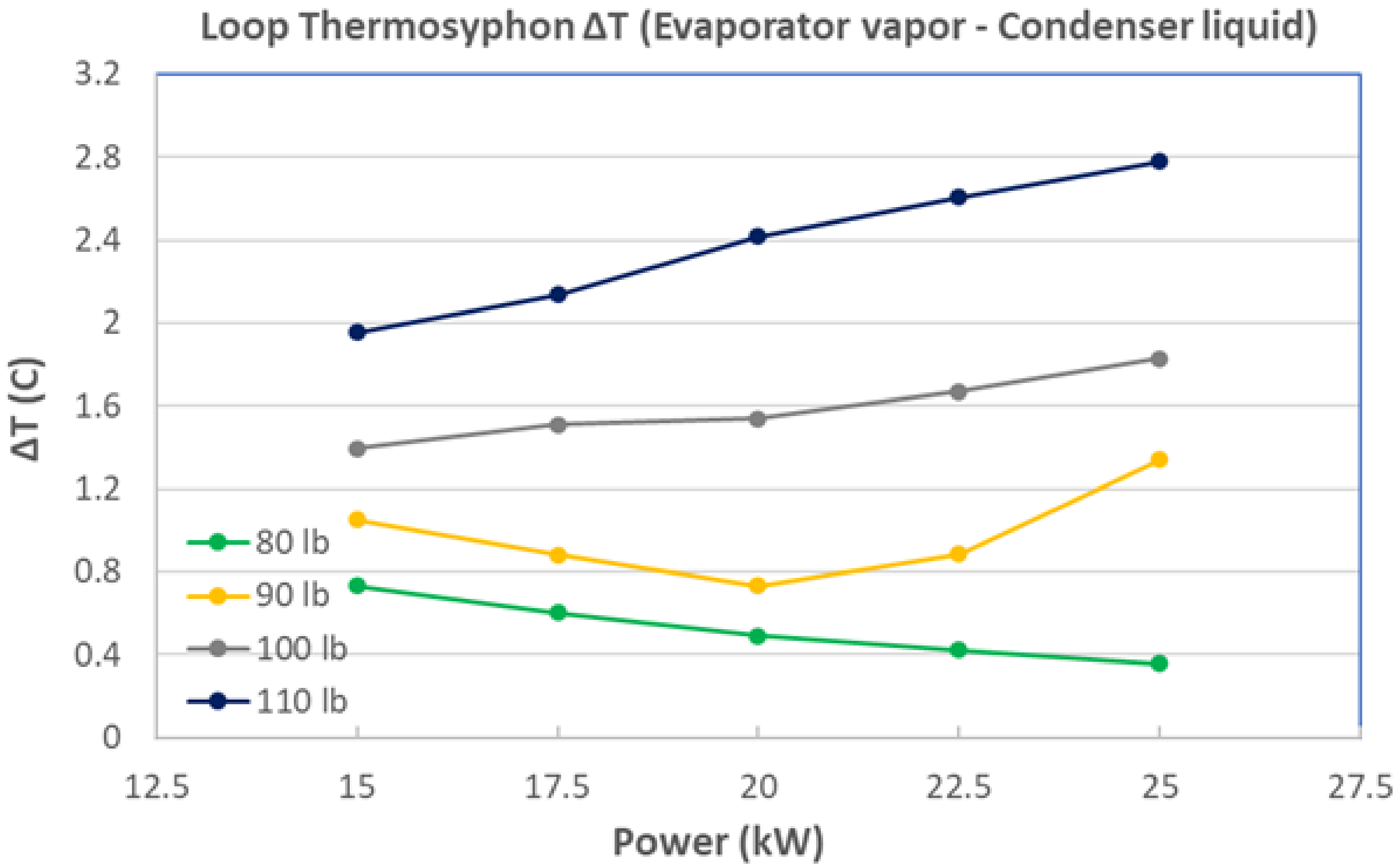


Vapor and Liquid lines



Testing Summary

- The refrigerant filled loop thermosyphon was able to transfer 25 kW of waste heat 50ft vertically, passively, with ΔT < 1°C



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.
  - Note: enables the selling of ACT's other DWC coating structures
- Loop thermosyphons for coal and other power plant cooling systems
  - Start with the "addressable" HVAC, power electronics, renewables markets…work with BAC
    - 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

Product Development at ACT

- 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
  - TEA demonstrates 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
  - Determine thermal performance results in tube-based test apparatus
  - Verify results with multiple FFA coating chemistries relevant to Suez's product offerings
  - Life Testing
- Loop Thermosyphon
  - Re-instrument and test, and develop improved design models

Tech to Market

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

Acknowledgments

Thank You!

- Barbara Carney (NETL) for their generous funding and technical support of the current program
- Recent Program Managers on related energy-water nexus programs including Robie Lewis (DOE SBIR) and James Klausner, Addison Stark, and Michael Ohadi (ARPA-E ARID), and Mark Lausten (SETO)