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, Michael C. Ellis, Chien-Hua Chen

Suez Water Technologies & Solutions

Don Meskers, Claudia Pierce, Mahesh Budhathoki

Project Overview

Goal

- To improve steam surface condenser performance & reliability in wet and dry cooling systems for coal-fired power plants

Fossil Energy Objectives

- Develop cost-effective, reliable technologies to improve the efficiency of new and existing coal-fired power plants
- Water management through reduction in freshwater use

Specific Problems for this Project

- Steam condenser thermal performance and reliability
- Excessive operational costs, parasitic power consumption, and maintenance of cooling water recirculation pumps

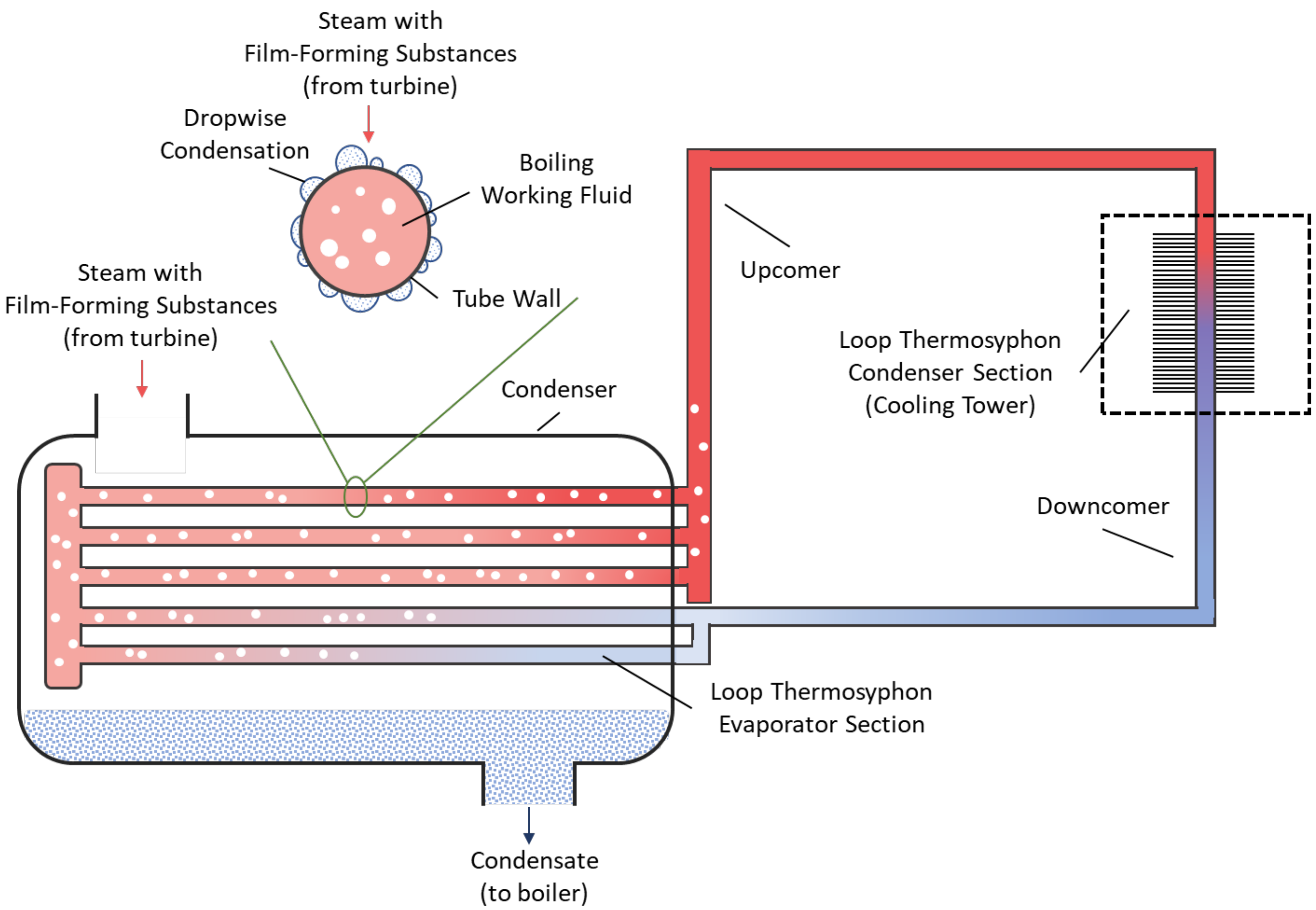
Status

- In Year 1 of 3, recently finished Quarter 2

Concept Overview

Concepts

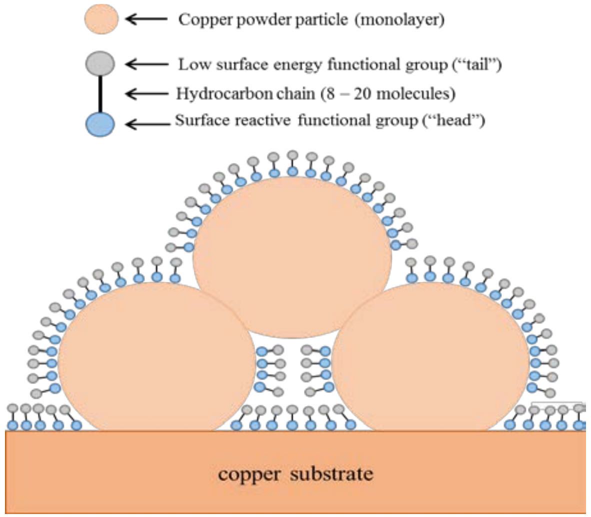
- #1 Develop *film-forming amine (FFA) coatings* applied to steam surface condensers to improve the reliability of dropwise condensation coatings and realize the efficiency improvements made possible by better performance
- #2 Replace pumped cooling water systems with passive *loop thermosyphons* (no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



Previous Condensation Work

Dropwise Condensation Background

- Funded through DOE SBIR Program
- Dropwise condensation thermal performance is 5-20x greater than filmwise condensation

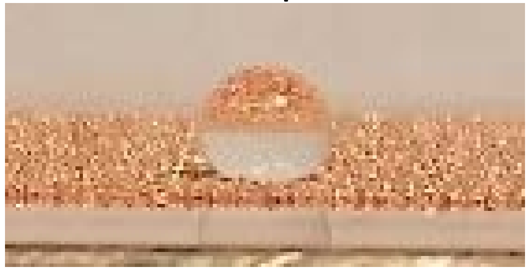


Highlights

- We demonstrated high condensation heat transfer coefficients using reliable and economical fabrication processes

43µm

119µm



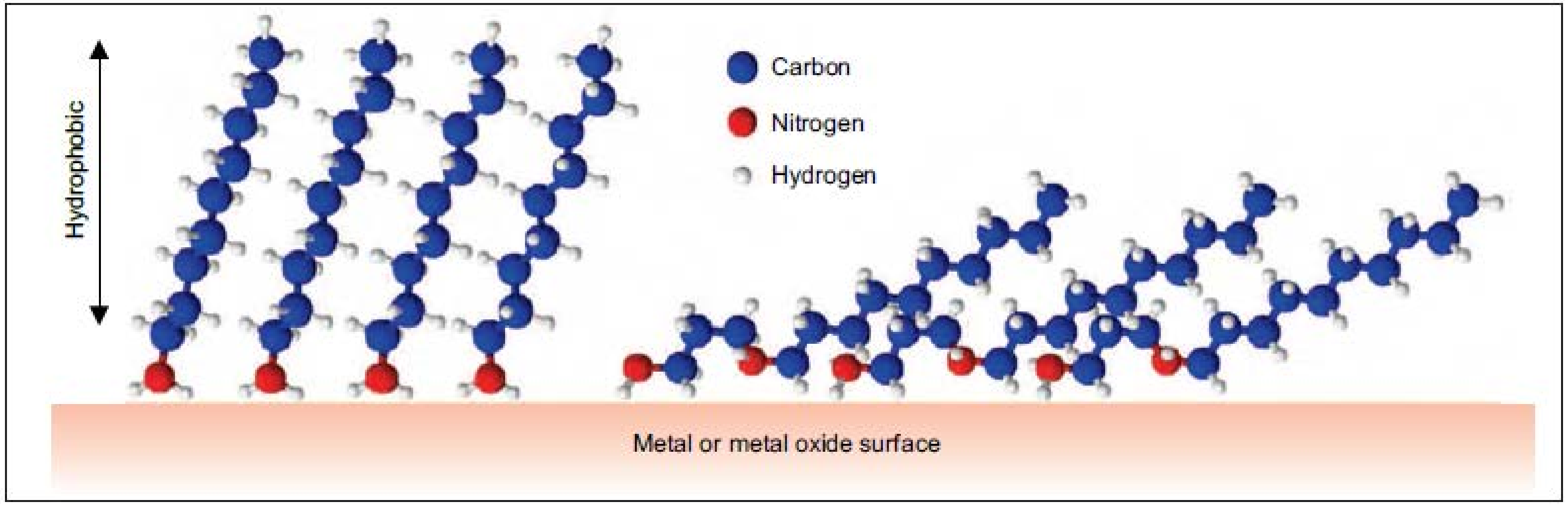
Remaining Challenges

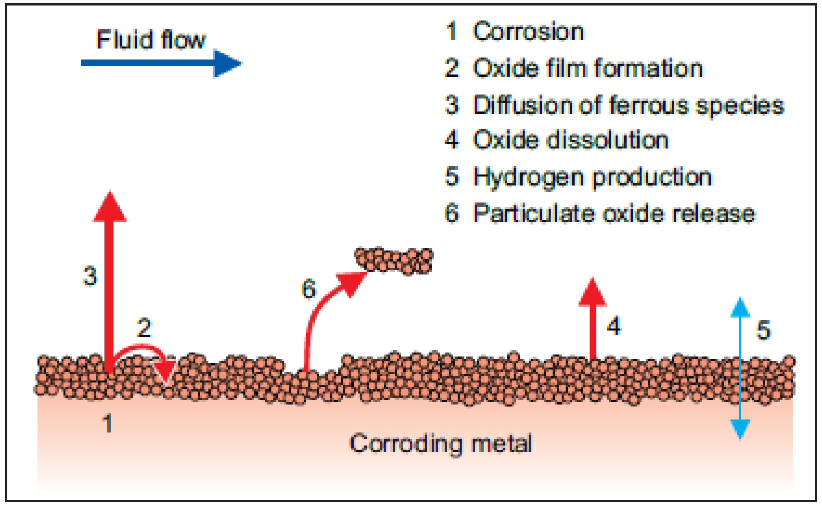
- Life of coatings, particularly on carbon steel surfaces under power plant steam conditions
- Current coating methods cannot be replenished

Dropwise and Amine Films

Concept

- FFA are self-healing, hydrophobic coatings that can be continuously applied to steam to protect steel tubing
- Suez uses this family of coatings to prevent corrosion in power plant boilers
- Our goal is to characterize the thermal performance and life of FFA using materials found in power plants and for power plant conditions



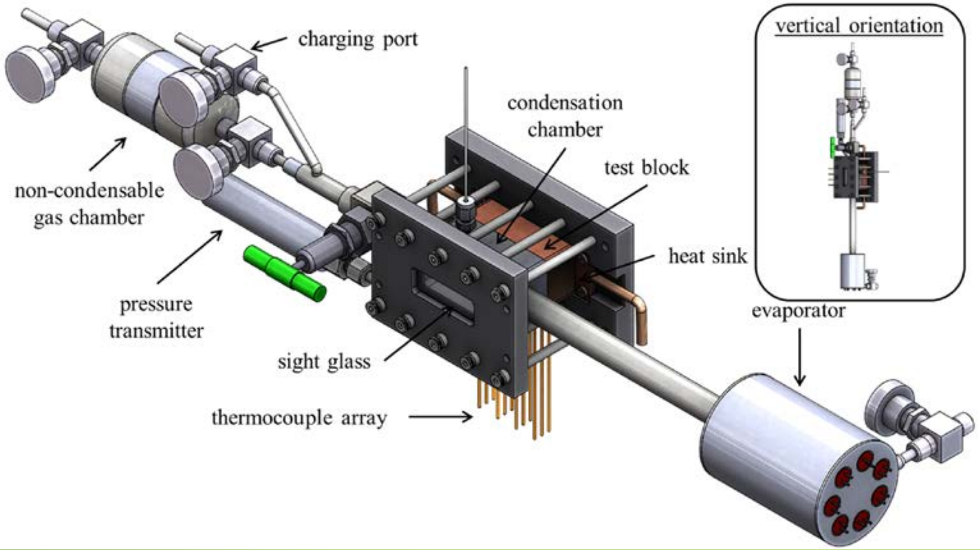


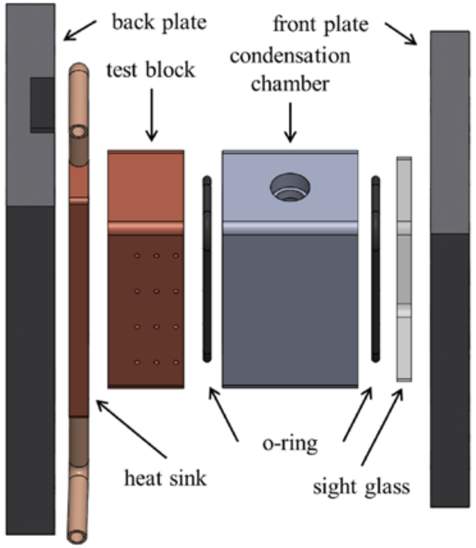
Source: Dooley, et. al.

Testing Update

Experimental Test Setup

- To accelerate testing, we are using a flat plate condenser test apparatus for thermal performance evaluation
- We evaluate the local heat transfer coefficient (h_l) via interpolation of the condenser surface temperature
- Currently transitioning to a tube-based test setup

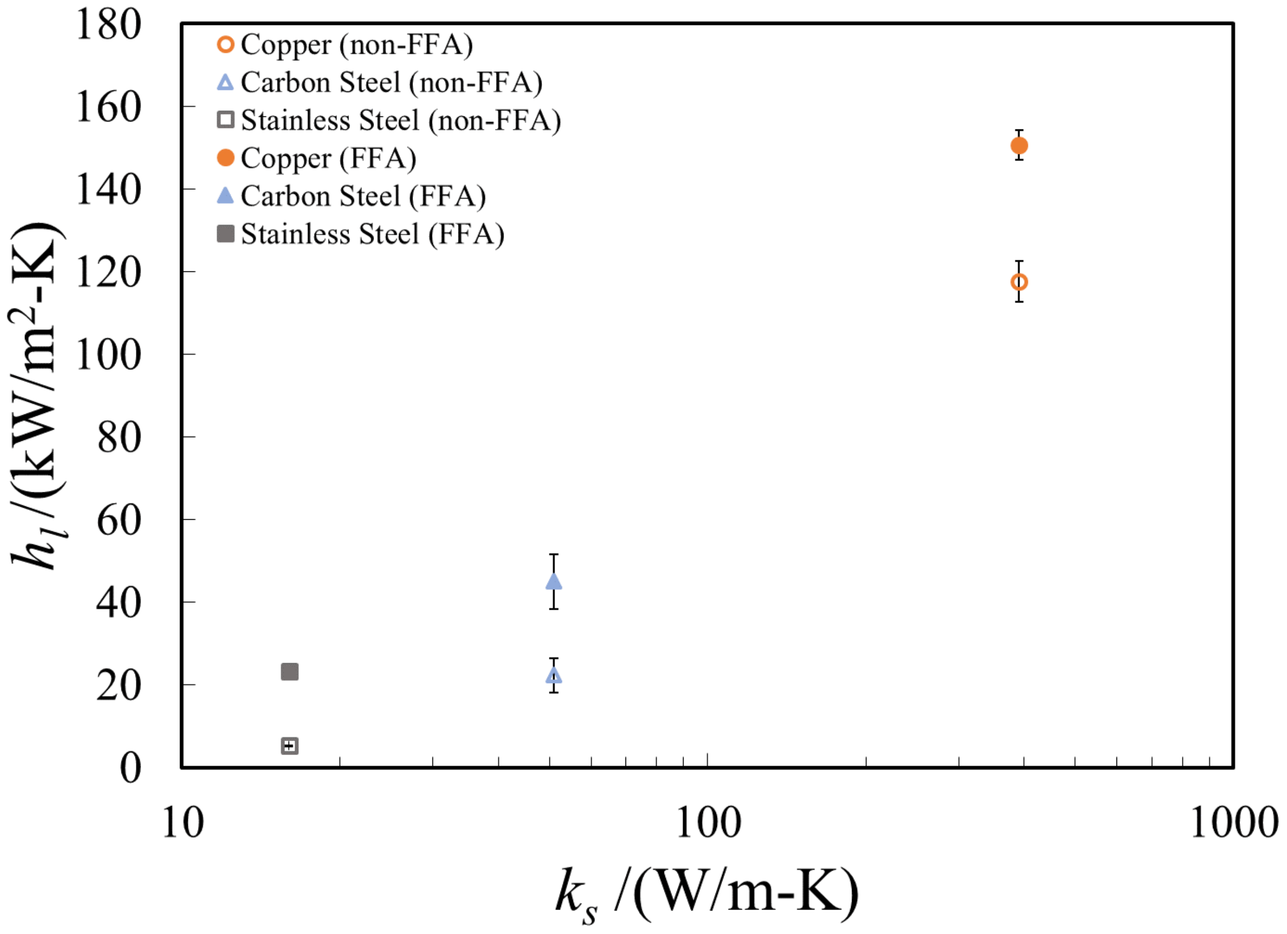




Thermal Performance

Results to Date

- Copper has demonstrated sustained enhanced DWC where h_l = 160 kW/m^2-K, similar to other studies
- Carbon Steel and Stainless Steel also show typical dropwise condensation performance while promoted
- The FFA coated samples outperform neutralizing amine surfaces, although some DWC is exhibited by the neutralizing amines for copper and even carbon steel



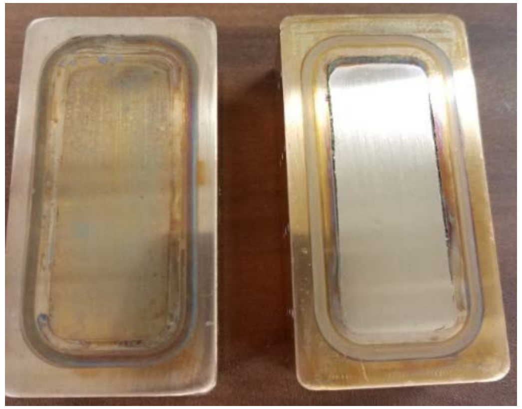
Coating Reliability

Initial Coating Reliability Results

- FFA coated copper showed strong resistance to oxidation compared to baseline
- Using a deoxygenated coating apparatus has proven to coat the surface to prevent oxidation of carbon steel during testing
- Carbon steel and stainless steel have exhibited short term enhanced DWC due to batch mode operation…need to replenish continuously or find a more optimal concentration

Copper

non-FFA FFA

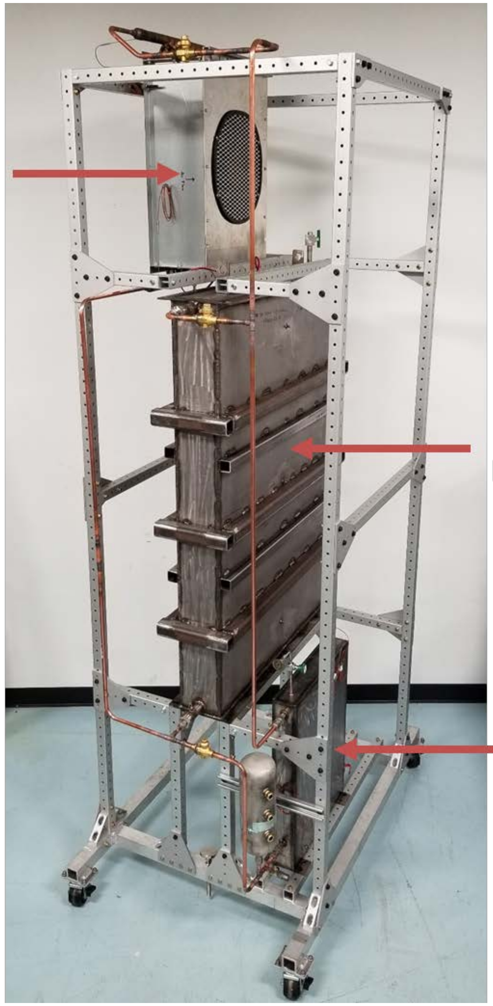


Short term DWC on Carbon Steel

Previous Loop Thermosyphon Work

Heat Pipe – PCM Based Cool Storage for ACC Systems

- Funded through ARPA-E ARID Program
- Improve the cooling capacity of air-cooled condenser system using salt-hydrate based thermal energy storage solution



<u>Highlights</u>

- A single loop thermosyphon with a system of valves was used to effectively shuttle heat from the steam to the phase change material (PCM) thermal storage tank during the day, and from the PCM storage tank to air at night
- Loop thermosyphons are passive, cost effective, and high performance thermal transport systems

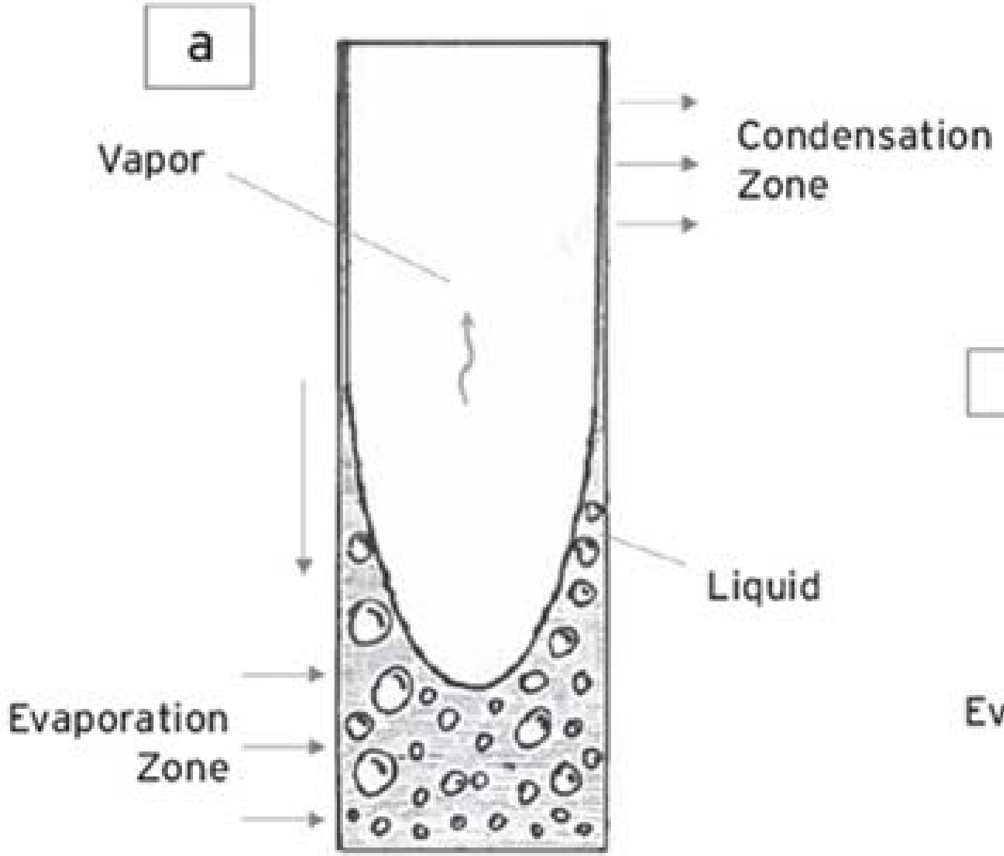
<u>Remaining Challenges</u>

- Need to develop better validated design tools

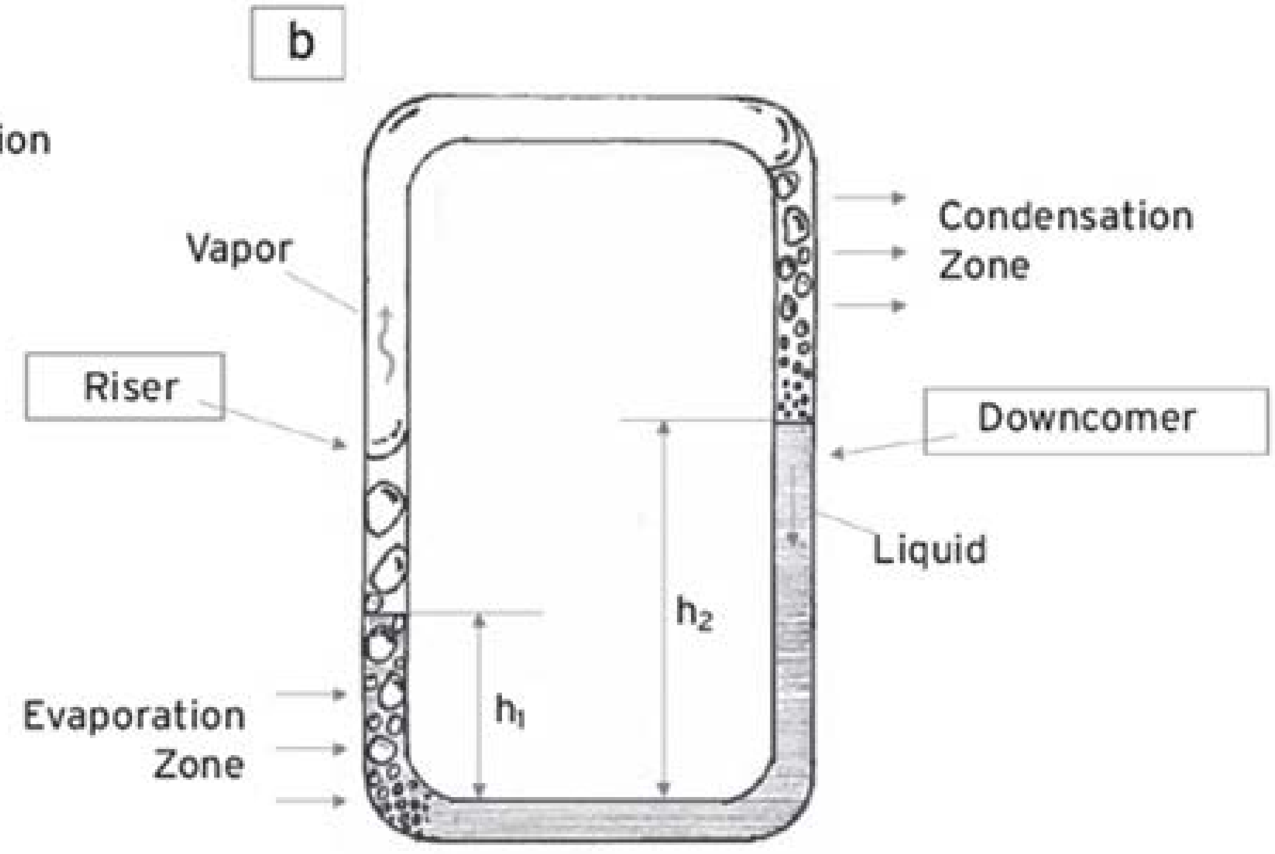
Loop Thermosyphon Overview

Operation

Thermosyphon



Loop Thermosyphon

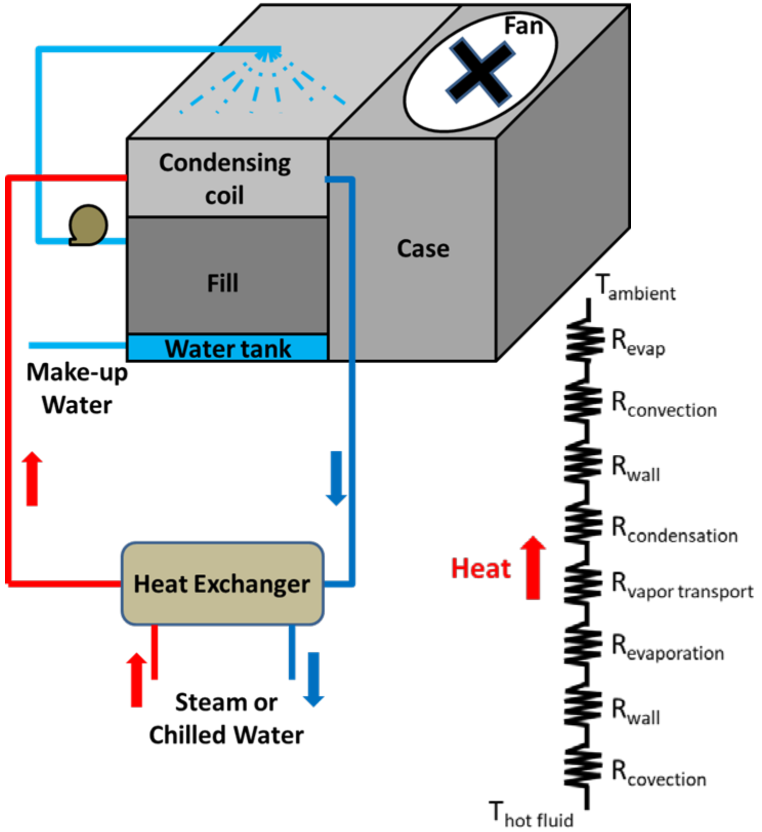


Comparison to State-of-the-Art

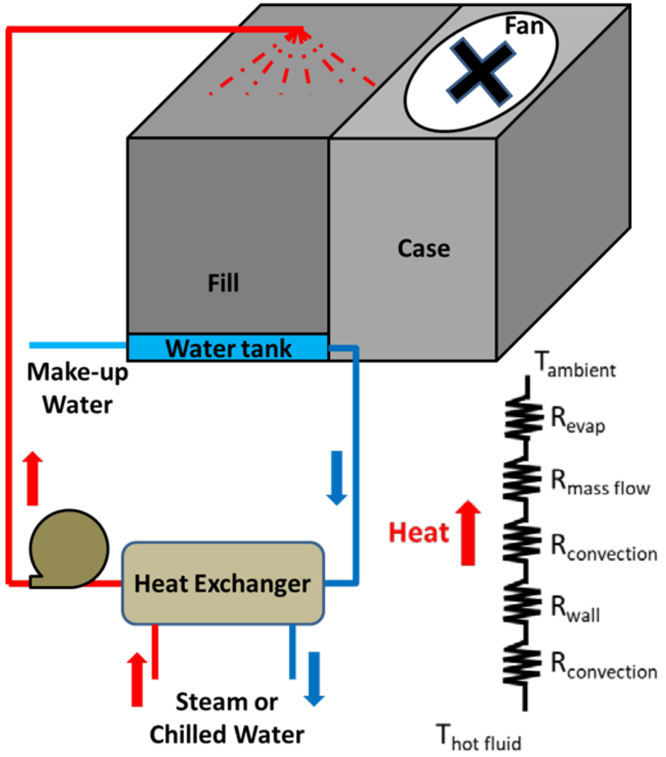
Loop Thermosyphon vs. Pumped Water Loop

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

Loop Thermosyphon with Closed Circuit Cooling Tower



Pumped Water Loop with Open Circuit Cooling Tower



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

Design Model

Loop Thermosyphon Modeling

- Driving pressure (the in-balance of gravity head created by the thermal input) has to overcome the overall pressure drop

Pressure balance: $\sum \Delta P_{friction} + \sum \Delta P_{gravitational} = 0$

Mass balance: $\dot{m}_{tot} = \sum \dot{m}_{vapor} + \sum \dot{m}_{liquid}$

$\Delta P_{friction}$	**Rising 2ϕ tube** (evap. outlet -> cond. Inlet)	**Horiz. 2ϕ tube** (evap. outlet -> condenser Inlet)	**Fall 1ϕ vertical tube** (condenser out -> evap. Inlet)	**Fall 1ϕ horizontal tube** (condenser outlet -> evap. Inlet)
Density (ρ_i)	$\bar{\rho}_{2\phi}(T) = \left[\frac{x}{\rho_v(T)} + \frac{1-x}{\rho_L(T)}\right]^{-1}$	$\bar{\rho}_{2\phi}(T) = \left[\frac{x}{\rho_v(T)} + \frac{1-x}{\rho_L(T)}\right]^{-1}$	$\rho_L(T)$	$\rho_L(T)$
Viscosity (μ_i)	$\bar{\mu}_{2\phi}(T) = \left[\frac{x}{\mu_v(T)} + \frac{1-x}{\mu_L(T)}\right]^{-1}$	$\bar{\mu}_{2\phi}(T) = \left[\frac{x}{\mu_v(T)} + \frac{1-x}{\mu_L(T)}\right]^{-1}$	$\mu_L(T)$	$\mu_L(T)$
Length (L_i)	$L_{2\phi,v}$	$L_{2\phi,H}$	$L_{1\phi,v}$	$L_{1\phi,H}$
Diameter (D_i)	$D_{2\phi,v}$	$D_{2\phi,H}$	$D_{1\phi,v}$	$D_{1\phi,H}$
Velocity (V_i)	$\frac{\dot{m}_{total}}{\bar{\rho}_{2\phi}(T)\left(\frac{\pi}{4}(D_{2\phi,v})^2\right)}$	$\frac{\dot{m}_{total}}{\bar{\rho}_{2\phi}(T)\left(\frac{\pi}{4}(D_{2\phi,H})^2\right)}$	$\frac{\dot{m}_{total}}{\rho_L(T)\left(\frac{\pi}{4}(D_{1\phi,v})^2\right)}$	$\frac{\dot{m}_{total}}{\rho_L(T)\left(\frac{\pi}{4}(D_{1\phi,H})^2\right)}$
Reynolds Number (Re_i)	*Homogeneous model; S=1, Avg. 2ϕ properties* $Re_{2\phi} = \frac{(\bar{\rho}_{2\phi}(T))V_i D_{2\phi,v}}{\bar{\mu}_{2\phi}(T)}$	$Re_{2\phi} = \frac{(\bar{\rho}_{2\phi}(T))V_i D_{2\phi,H}}{\bar{\mu}_{2\phi}(T)}$	$\frac{(\rho_L(T))V_i D_{1\phi,v}}{\mu_L(T)}$	$\frac{(\rho_L(T))V_i D_{1\phi,H}}{\mu_L(T)}$
Friction Factor (f_i)	$Re_{2\phi} < 2300,\ f_{2\phi} = 64/Re_{tp}$, else $f_{2\phi} = 0.316\ Re_{2\phi}^{-0.25}$		$Re_{1\phi} < 2300,\ f_{1\phi} = 64/Re_{1\phi}$, else $f_{1\phi} = 0.316\ Re_{2\phi}^{-0.25}$	
Pressure gradient (dP/dz_i)	$\frac{dP}{dz}_{2\phi} = (\Phi_{LO}^2)\frac{dP}{dz_{LO}};\ \frac{dP}{dz_{LO}} = \frac{f_i \rho_L(T) V_i^2}{2D_{2\phi,v}}$ $\Phi_{LO}^2 = \left[1 + x\frac{(\rho_L - \rho_V)}{\rho_V}\right]\left[1 + x\frac{(\mu_L - \mu_V)}{\mu_V}\right]$		$\frac{dP}{dz}_{Liq.} = \frac{f_i \rho_L(T) V_i^2}{2D_{1\phi,v}}$	$\frac{dP}{dz}_{Liq.} = \frac{f_i \rho_L(T) V_i^2}{2D_{1\phi,H}}$

Test Plan

Loop Thermosyphon Test Plan

- Working with cooling tower supplier to design a loop thermosyphon that can integrate into a commercially available closed circuit cooling tower (~4 ton)
- Refrigerant candidates
  - R134a – Can use regular condensing coil but lower thermal performance
  - R410a – Need high pressure condensing coil (heavier), better thermal and start up performance
- Objectives
  - Compare thermal performance with model
  - Study start-up/ transient behavior
  - Identify other integration issues


Potential Testing location (ACT's roof top)

Tech-to-Market

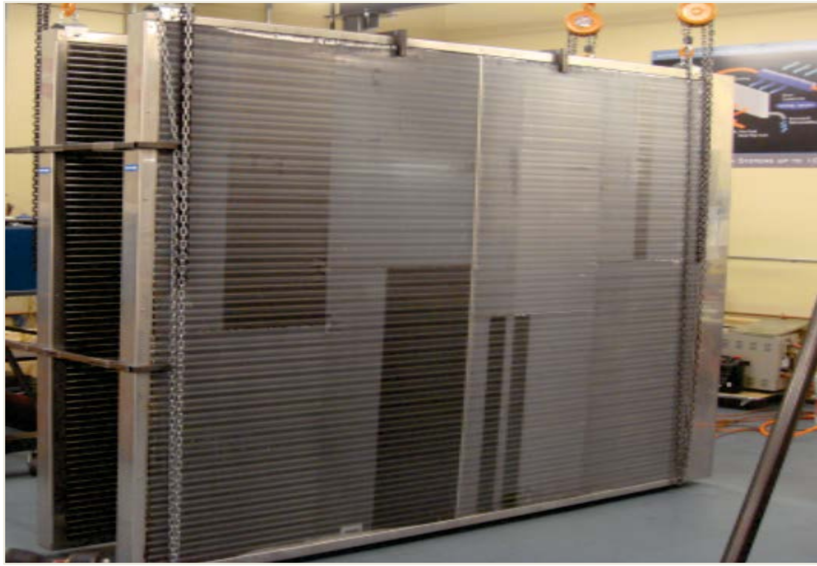
Assessment

- 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
  - 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 market
    - 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

HVAC Heat Exchangers

Loop Thermosyphon Commercialization Path

- 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
- Product Offerings
- Air-to-Air Heat Exchanger (AAHX)
- Wrap Around Heat Exchanger (WAHX)
- Pay back period < 2-3 years



Concluding Remarks

Technical Summary

- Film-forming amine coating technology can be used to improve steam surface condenser thermal performance
  - Demonstrated high performance typical of dropwise condensation
  - Copper has shown no sign of oxidation, De-oxygenated coating application has help prevent corrosion on carbon steel
  - Carbon steel and stainless steel have performed well, but show low life in batch mode operation
- Loop thermosyphon technology can replace pumped cooling water
  - Model under development
  - Plans to build a two-story, loop thermosyphon with a 4 ton cooling tower

Next Steps

Next Technical Steps

- Develop optimal concentration or continuous replenishment mode for FFA
- Build and test dropwise condensation performance on round tubes
- Integrate loop thermosyphons with a closed circuit cooling tower design and compare experimental data to model

Tech to Market

- Continue working with Suez on FFA coating development
- Develop HVAC market as first addressable market
- Develop relationship with power plant condenser and cooling tower suppliers

Acknowledgments

Thank You!

- Barbara Carney and NETL for their generous funding and technical support
- 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)