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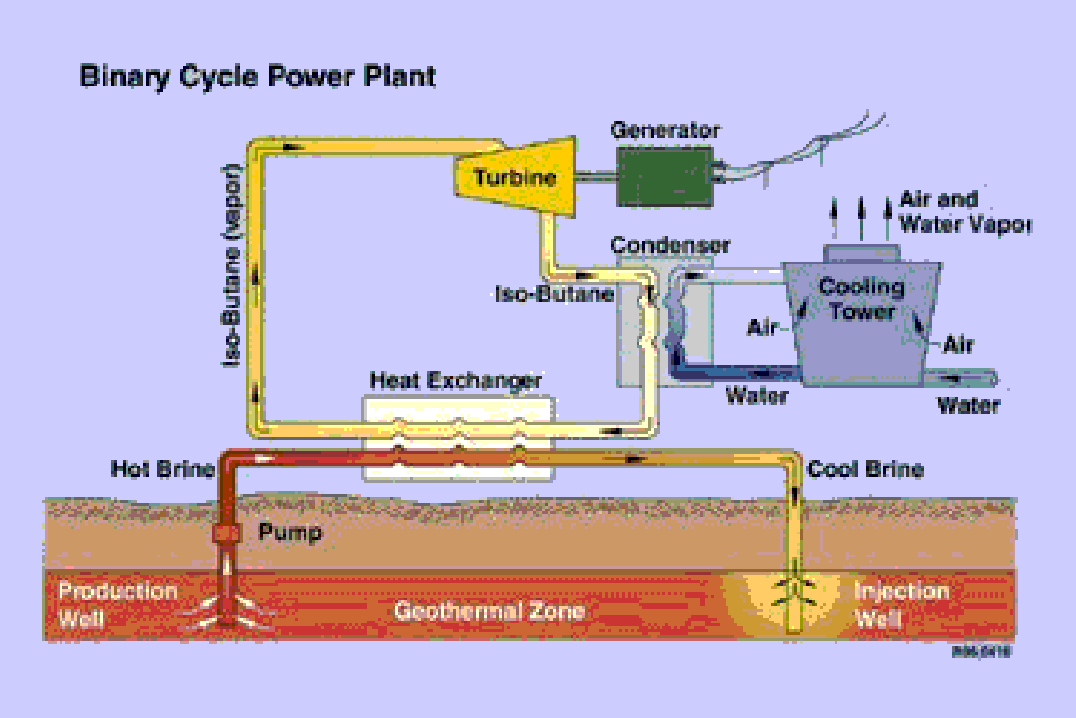

Project team

Amy Childress, Ph.D., Civil & Env. Engineering

Miles Greiner, Ph.D., Mechanical Engineering

Kwang Kim, Ph.D., Mechanical Engineering

Chanwoo Park, Ph.D., Mechanical Engineering

Paul Laca, Ph. D., Mechanical Engineering

Advanced Heat/Mass Exchanger Technology for Geothermal and Solar Renewable Energy Systems

Project Officer: Bill Vandermeer

Total Project Funding: $1.2M (Cost Share $300K)

April 23 2013

PI: Miles Greiner

Presenter: Chanwoo Park

University of Nevada, Reno

Track 1

Relevance/Impact of Research

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Motivation

- Existing binary-fluid geothermal power plants achieve only about 30% of their ideal efficiency whereas fossil fueled plants reach ~60%.
- A most important source of irreversibility in a power plant is the heat/mass exchange process.

Relevance

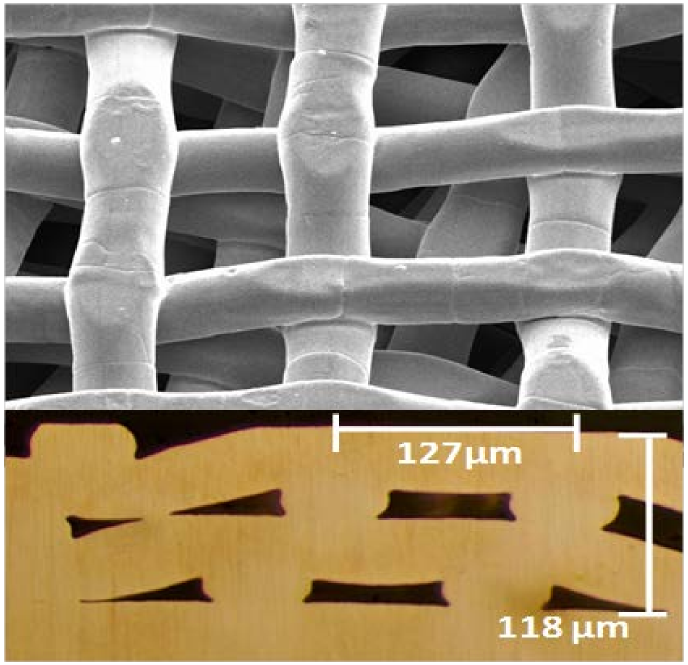
- Heat/Mass exchangers are essential to any energy conversion system.
- Improvements in the exchange process will lead to smaller, more efficient and less costly systems.

Overall Objectives

- Apply micro/nano/molecular-scale science to heat/mass exchanger design used in geothermal power plants.
- A 10-fold increase in heat/mass exchanger performance via phase change processes (re-boilers, evaporators, condensers), single phase heat and mass transport (heat exchangers, purification systems).
- Five sub-projects sharing a common goal:
  - Efficient Boiling Surfaces for Geothermal Power Cycles (P. Laca, R.A. Wirtz)
  - Heat and Mass Transfer in Membrane Contactor Processes (A. Childress)
  - Enhanced Single Phase Heat Transfer in Intermittently-Grooved Channels (M. Greiner)
  - Reinforced Super-hydrophobic Surfaces for High-Performance Condensers (K. Kim)
  - Nano-Coating, Structured Porous Surfaces for Evaporation/Boiling Heat Transfer Enhancement (C. Park)

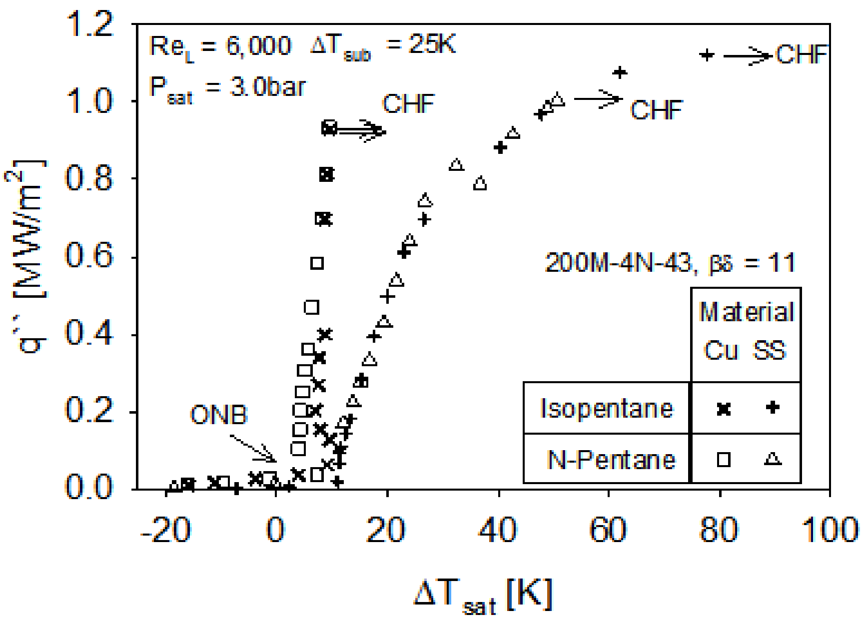
Efficient Boiling Surfaces for Geothermal Power Cycles
P. Laca, R.A. Wirtz

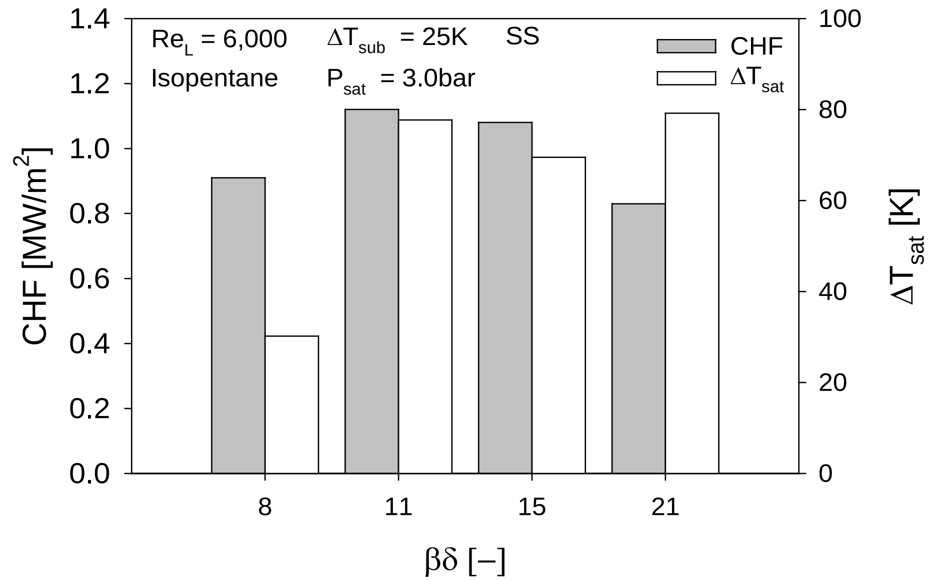
- A reduction in re-boiler tube superheat will lead to a reduction in entropy generation rate, which translates to an improvement in power plant thermal efficiency.
- Compressed laminations of fine filament metallic screen overlaying a heat transfer surface in sub-cooled flow boiling of water at 0.2atm have been shown to be able to accommodate in excess of 4.5MW/m^2 with very small wall superheats of approximately 5.0K.



- Flow-boiling experiments on plane and tubular, copper and steel screen-laminate surfaces are conducted. Boiling characteristics of Isopentane and n-pentane are documented

Accomplishments, Results and Progress Project 1





- Isopentane and n-Pentane are found to produce nearly identical boiling characteristic curves.
- At the same applied heat flux, the superheat of copper filament coatings are much smaller than the steel filament coating superheats. This is due to the much greater thermal conductivity of copper.
- Increased sub-cooling and flow intensity (Reynolds number) shift boiling performance curves upward; the most notable effect being an increase in Critical Heat Flux.

- CHF enhancement is found to be intrinsically linked to the surface area enhancement ratio (βδ), which has an optimum value for the present coating material and fluid of 11.
- Since this is essentially the same value obtained by Penley and Wirtz in their experiments with copper coatings boiling water, the implication is that the area enhancement factor is the dominate parameter in the determination of surface performance.
- The fluid properties and coating material properties are of secondary importance.

Future Directions & Summary
Project 1

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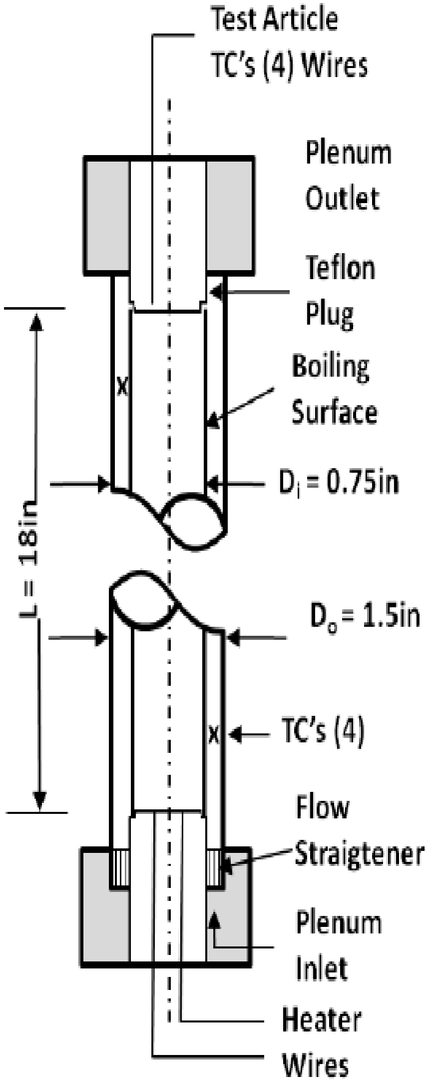
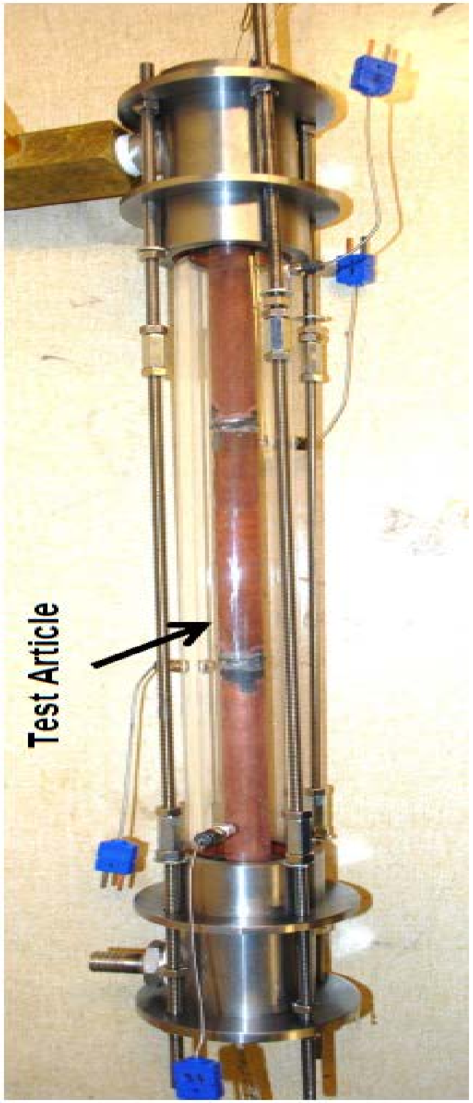
- A tubular test assembly was built to conduct flow boiling experiments on our best performing screen laminate surface.
  - Test article Cu200M-4N-43, βδ=11 was diffusion-bonded an a copper tube (18 inch long) as boiling surface.
  - The copper tube is heated by a cartridge heater (4.5kW, 5/8 in diameter) and instrumented with thermocouples.
  - Tests can be run to verify that plane surface boiling performance results are applicable to tubular surfaces.





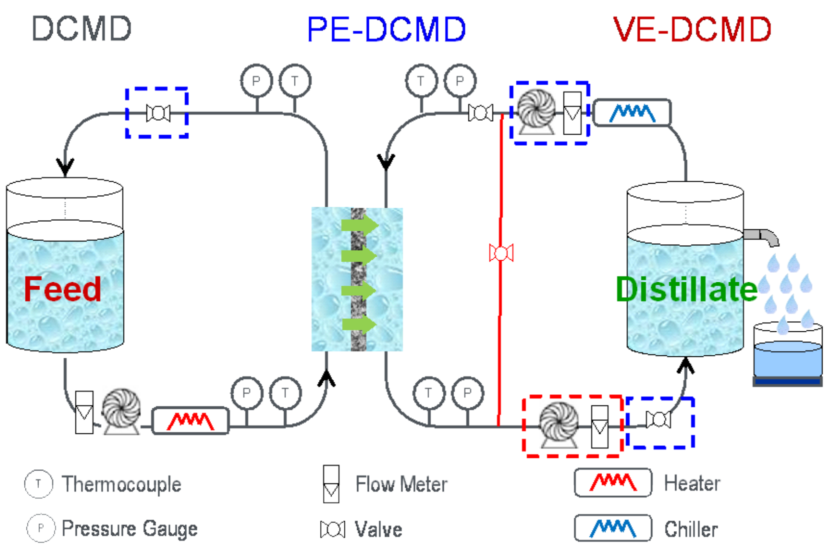
Heat and Mass Transfer in Membrane Contactor Processes
A. Childress

- Understanding the mass transfer mechanisms of membrane distillation (MD) is key to improving productivity
- Schofield mass transfer model was used to predict water flux
  - Factors affecting mass transfer include membrane structure properties and vapor pressure inside membrane pores
- Direct contact MD (DCMD), pressure enhanced DCMD (PE-DCMD), and vacuum enhanced DCMD (VE-DCMD) were tested; experimental results and model results were compared

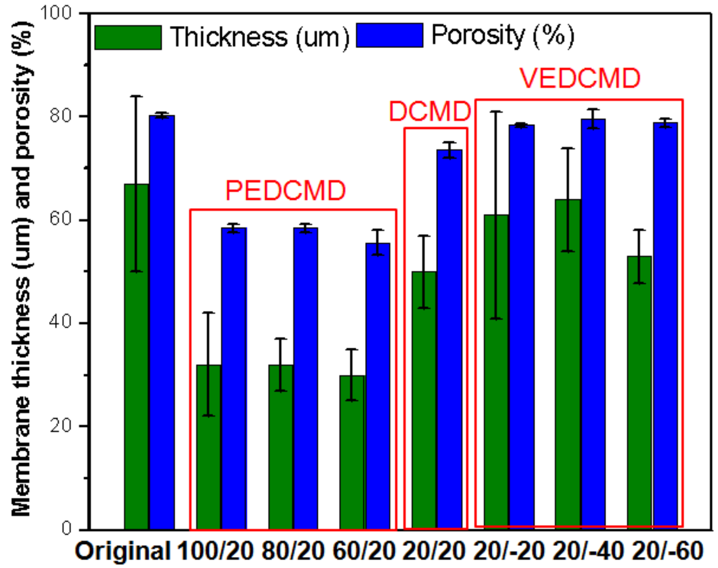
$$N_K = \frac{2r\varepsilon}{3\delta\tau}\left(\frac{8M}{\pi RT}\right)^{0.5}\Delta P_i \qquad N_V = \frac{r^2\varepsilon}{8\tau\delta}\frac{MP_i}{RT\eta}\Delta P_i$$

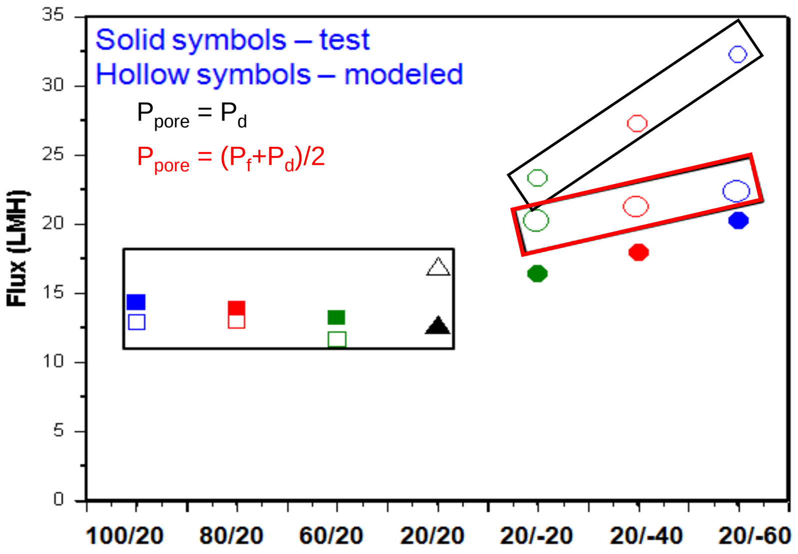
$$N_M = \frac{DP\varepsilon}{P_a\tau\delta}\frac{M}{RT}\Delta P_i$$

$$\frac{1}{N_{total}} = \frac{1}{N_K + N_V} + \frac{1}{N_M}$$



- Decreased thickness and porosity observed with PE-DCMD membranes
  - DCMD and VE-DCMD membranes similar to each other
- Experimental results indicate DCMD and PE-DCMD behave similar to each other
  - VE-DCMD has increased mass transfer
- Air pressure inside membrane pores must be estimated
  - Literature suggests $P_{pore} = P_d$
- VE-DCMD requires improved estimate of membrane pore pressure
  - $P_{pore} = (P_f + P_d) / 2$ provides much better agreement with experimental data





Future Directions & Summary Project 2

- Vacuum enhanced DCMD has increased mass transfer due to decreased air pressure within membrane pores
  - DCMD ideal process for utilizing low-grade waste heat for water purification
- Comprehensive comparison of specific energy consumptions of MD processes with Organic Rankine Cycle (ORC)-RO processes to determine optimal use of waste heat sources is underway
- Dissemination of project results

	FY 2012	FY 2013
Target/Milestone	**• Water flux tests with DCMD, PE-DCMD, and VE-DCMD** **• Predict MD water flux using mass transfer models**	**Compare energy consumption of three DCMD processes with RO processes driven by power cycles using the same low-grade heat sources**
Results	**Completed** ***(two manuscripts in progress)***	**Complete by 9/30/13**

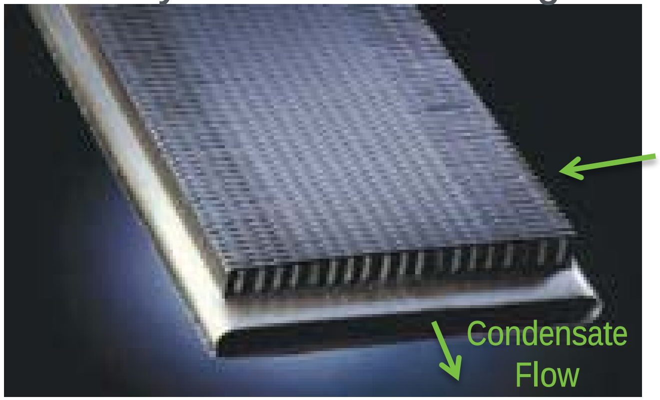
Scientific/Technical Approach, Project 3

Enhanced Single-Phase Heat Transfer in Intermittently-Grooved Channels

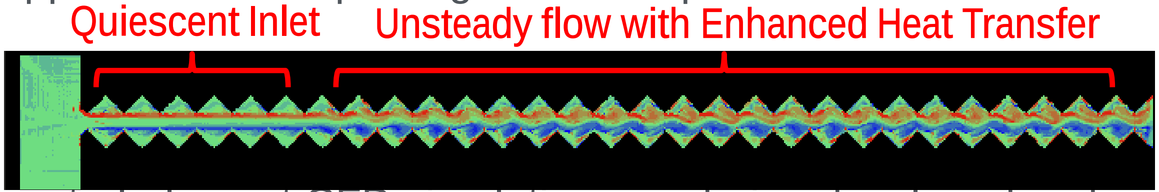
Miles Greiner

Direct Dry-Cooled Condensing Unit

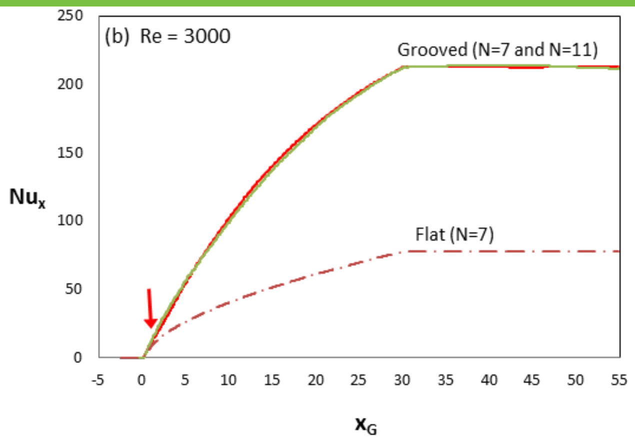
Externally-Finned Condensing Tube

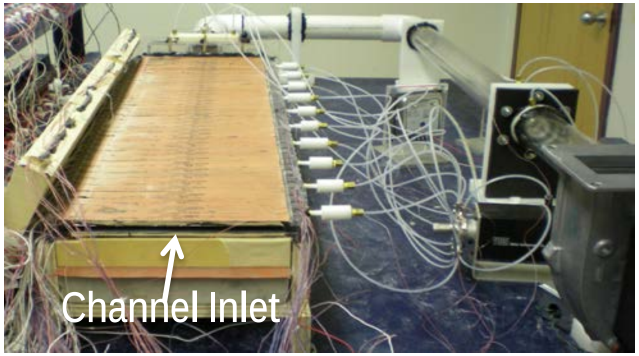


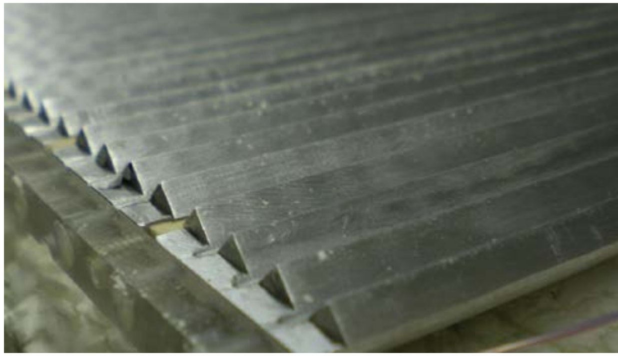
- Air-Cooled condensers are used to reduce water consumption at geothermal power plant.
  - Low heat transfer in the flat passages on the *air side* of condenser tubes limits power plant performance
- Grooved passages have been shown to enhance heat transfer by triggering flow instabilities and unsteady mixing, without the need for larger fans
- High-order spectral-element computational fluid dynamics (CFD) simulation shows unsteadiness appears near the passage inlet and persist downstream



- In this work, spectral-element CFD simulations are being developed and experimentally benchmarked, so they can be used to design high performance air-cooled condensing tubes







- The left hand figure shows the average heat transfer within groove and flat passages versus the passage length from two-dimensional CFD simulations.
- These simulations show that
  - Heat transfer augmentation appears at the same location were unsteadiness first appears, and persists to the end of the passage.
  - The location where unsteadiness and heat transfer augmentation appear moves closer to the inlet as the flow rate increases.
- Earlier work shows that three-dimension simulations are required to accurately predict grooved passage heat transfer versus pumping power performance.
- The middle figure shows a wind tunnel experiment that is being constructed to compare the heat transfer versus pumping power performance in the developing regions of grooved and flat passages.
- The right hand figure show one of the grooved surfaces that is installed in the wind tunnel test section.

Future Directions & Summary Project 3

- The heat transfer versus pumping power performance of grooved and flat passages is being measured for a range of flow rates using the experimental wind tunnel.
- The two-dimensional simulations will be used as initial conditions for computationally-intensive three-dimensional calculations, and the results will be compared to the experimental data.
- The benchmarked spectral-element simulations will be a useful tool for designing and optimizing high performance grooved passages for air cooled condensers.

	FY 2013	FY 2014
Target/Milestone	**Complete apparatus construction and initiate 3-dimensional simulations**	**Benchmark simulation using exponential data and develop design tools.**
Results	**Complete by 9/30/13**	**Will be completed by 9/30/14**

Reinforced Super-hydrophobic Surfaces for High-Performance Condensers

K. Kim

- A reduction in condenser tube superheat can lead to a reduction in entropy generation rate, which translates to an improvement in power plant thermal efficiency.
- Dropwise condensation is an effective way to enhance the performance of steam condensation.
- The objective of this project is to develop a material-engineered and long-term, performance-effective technique for enhancing heat transfer rates in steam condensation, which would dramatically reduce the footprint and manufacturing cost of industrial condensers.

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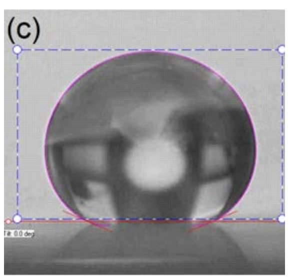
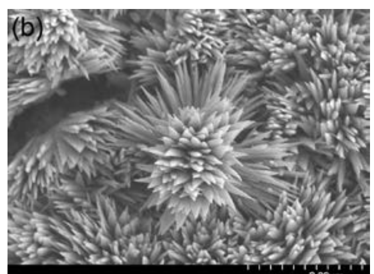
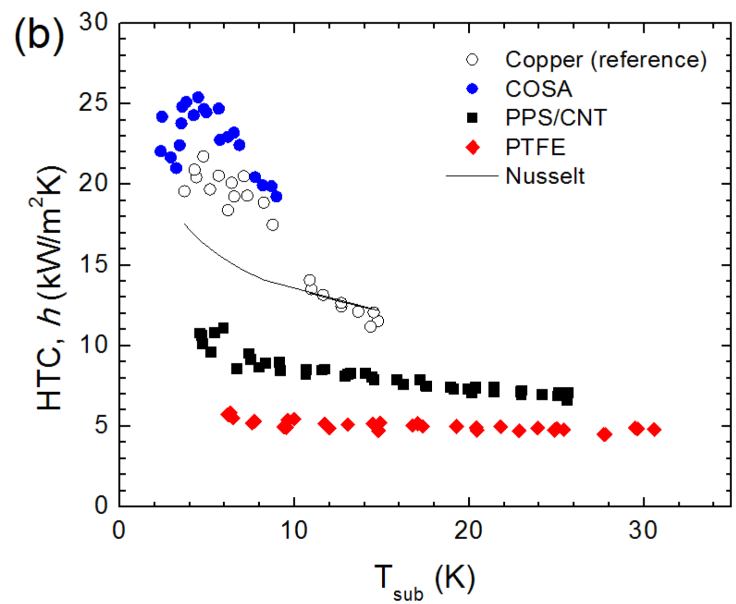
- Among a few promising coating techniques, we found that copper oxide self-assembly (COSA) is a promising candidate to fabricate dropwise condensers. COSA shows different morphologies, which are controlled by thermodynamically and/or kinetically controlled oxidation conditions. Under a certain oxidation condition, micro- and nano-hybridized double tier structure is shown.
- COSA can effectively prevent water droplets from impinging on a condensing surface→ Enhancing condensation heat transfer.



COSA





Future Directions & Summary Project 4

- Expected outcome of this effort
  - Copper oxide self-assembly (COSA) surfaces have demonstrated an improvement in steam condensation. A further optimized surface is expected to achieve more than 50% improvement over conventional industrial condensers.
- Planned milestones
  - We expect to complete long-term testing (over 1,000 hours of operation) of a few promising condensing surfaces.
- Summary
  - A successful condenser surface has been established.
  - Condensation testing is underway.

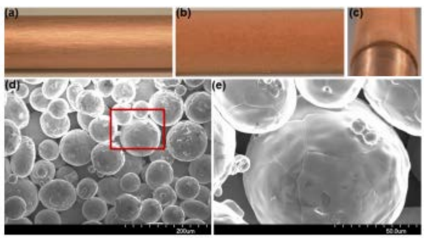
	FY 2013	FY 2014
Target/Milestone	**Effective condenser surface developed and characterized**	**Long-term condensation testing**
Results	**Completed by 9/30/13**	**Will be completed by 9/30/14**

Nano-Coating, Structured Porous Surfaces for Evaporation/Boiling Heat Transfer

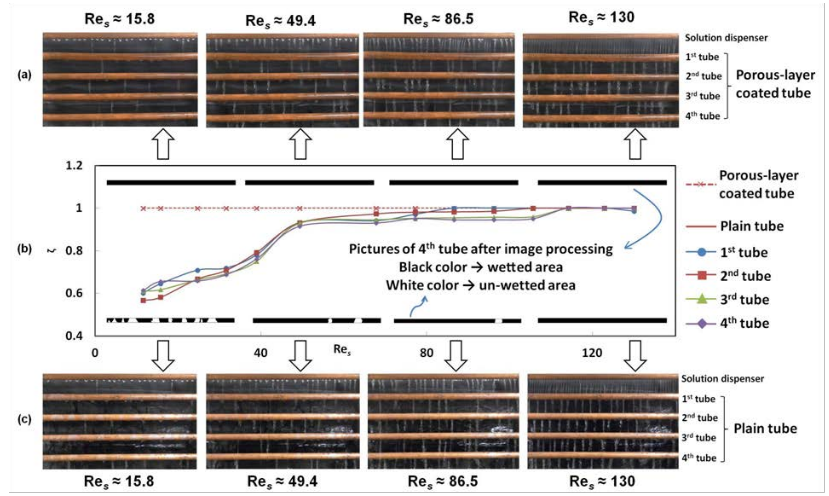
C. Park

- Incomplete solution wetting and its associated heat transfer deterioration are the inherent problem of horizontal-tube, falling -film heat exchangers.
- Thin-film evaporation using capillary-assisted liquid spreading in hydrophilic and porous surfaces can significantly enhance heat transfer performance.
- A micro-scale, porous-layer coating of sintered copper particle is built on the falling-film heat exchanger tubes.
- Visual observation and heat transfer experiments are performed to measure solution wetting and heat transfer coefficients for plain and porous-layer coated tubes using closed falling-film evaporators under saturated conditions.

- **Perfect Surface Wetting**
  - Achieved by using porous-layer coated falling-film evaporator tubes (sintered copper particles, $\varepsilon = 0.32$, $r_p = 73\sim98$ µm, $t = 0.8$ mm)

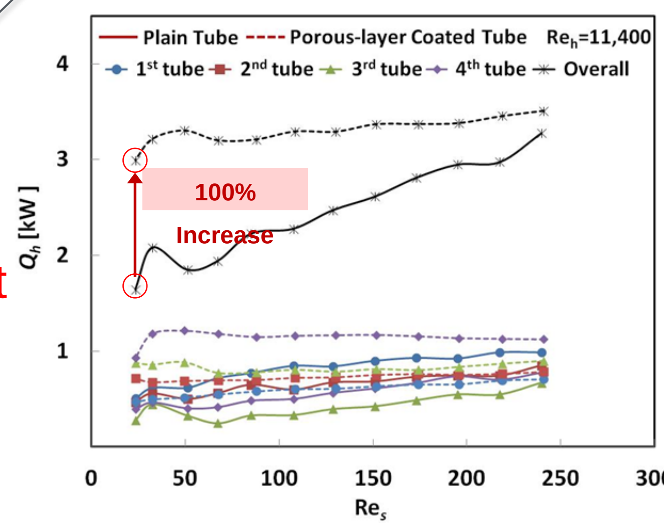


Micro-scale porous-layer coated tube (b-e)

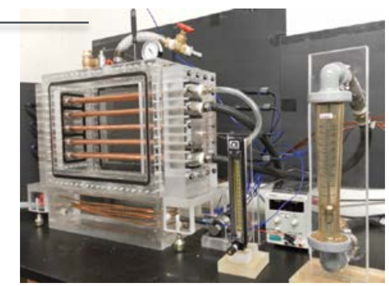


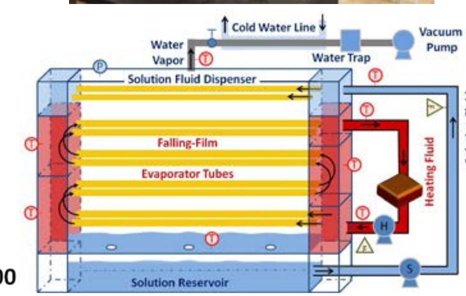
Surface wetting

- **Enhanced Heat Transfer**
  - 100 % increase in the heat transfer at the low solution flow rate using porous falling-film evaporator



Heat transfer measurement





Falling-film evaporation experimental setup

Future Directions and Summary Project 5

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- Outcomes
  - More than 100% improvement on heat transfer performance was achieved by using micro-scale, porous-layer coating fall-film evaporator.
- Planned milestones
  - Nano-scale surface modification for surface wetting control
  - Evaporator characterization experiment using various operating conditions (solution flow rate, wall superheat, subcooling).
- Summary
  - Micro-scale porous falling-film evaporator for enhanced heat transfer has been developed and tested. Evaporator characterization experiment is underway.

	FY2013	FY2014
Target/Milestone	**Nano-scale surface modification**	**Evaporator characterization experiment**
Results	**Complete by 9/30/2013**	**Will be completed by 9/30/2014**

Project Management

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- A one-year no-cost extension to this project (sub-projects:3,4,5 only) was requested to investigate interesting phenomena that were observed during the course of the work.

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
9/17/2010	9/17/2012	9/17/2010	9/17/2014

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$1.2M	$300,000	$852,226	$913,880	$1,160,377	$286,120