ACTIVE THERMOSYPHONS
FOR POWER-PLANT COOLING:
MODELING AND EXPERIMENTS

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2018 Advanced Energy Conference

New York, NY
March 27, 2018
ARPA-E

• Advanced Research Program Agency for Energy (ARPA-E)
• Modeled after DARPA
  • Strategic, well-defined programs
  • Substantial resources
  • Milestone-driven; not basic research
  • Commercialization is essential
• Focused themes or programs
  • Typical: $20~35 M; 8 ~ 14 teams; 2 ~ 3 year projects
• This program: ARID (Advanced Research In Dry cooling)
  • Goal: Technologies to improve performance of dry-cooled power plants, especially in arid regions (e.g., Southwest)
Why Dry Cooling

Wet cooling thermoelectric plants
- Withdraw large amounts of fresh surface water
- Water loss through evaporation
- Adverse impact on ecosystems
- Drought threatens continued operation

Dry cooling thermoelectric plants
- Only 1% of all plants in U.S
- Higher cost due to lower heat transfer performance
- 2% production loss of steam turbine
- Extremely hot days: power production reduced 10% ~ 15%

• **Goal:** Improve cooling performance of air cooled condenser by using evaporative cooling
  
  - Combustion of fossil fuels produces water vapor
  - Condense some of this water vapor for evaporation

• **DEW-COOL:** *Deferred Evaporation of Water Condensate Obtained Locally*
Water Harvesting using Active Thermosyphon

- Water as the working fluid inside the thermosyphon (environment-friendly, inexpensive)
- Pump actively circulates water, unlike traditional thermosyphon
- High–k polymer material evaporator
- Air-cooled condenser
- Optional low-lift blower – increase performance in very hot conditions
Modeling of the Thermosyphon

Flue Gas

Condensate Film

Evaporator

Condenser

Vapor

Loop Thermosyphon

\( T_{fg} \)

\( R_{dif} \)

\( R_{f} \)

\( R_{conv} \)

\( R_{ew} \)

\( R_{ef} \)

\( R_{cf} \)

\( R_{cw} \)

\( T_{air} \)

\( Q_{latent} \)

\( Q_{conv} \)

\( Q_{tot} \)
Modeling Work (cont)

• Analytical model developed that includes
  • Interior thermosyphon physics (flow, evaporation, condensation)
  • Exterior heat transfer and condensation (using NTU method + literature correlations)

• Model predicts
  • Heat transfer
  • Internal temperatures
  • Condensed water collection rate

• Full power plant simulation done in Aspen™
  • Plant efficiency vs. temperature
  • Levelized cost of electricity
Graphite-polymer composite for evaporator tubes

- Commercially available: Technoform Kunststoffprofile, GMBH (Germany)
- Polypropylene (PP) or Polyphenylene sulfide (PPS)
- Thermal conductivity: 15 ~ 16 W/m·K in radial direction (similar to stainless steel)
- Excellent corrosion properties

**THERMAL PROPERTIES OF PP-GRAFHITE**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat resistance long term</td>
<td>90 °C</td>
</tr>
<tr>
<td>Specific heat capacity $c_p$</td>
<td>1.21 J/(g*K)</td>
</tr>
<tr>
<td>Thermal elongation</td>
<td>$29 \times 10^{-6}$ 1/K</td>
</tr>
<tr>
<td>Thermal conductivity in plane (injection moulding)</td>
<td>26.6 W/(m*K)</td>
</tr>
<tr>
<td>Thermal conductivity through plane (injection moulding)</td>
<td>4.5 W/(m*K)</td>
</tr>
<tr>
<td>Thermal conductivity through plane (extruded tube)*</td>
<td>10-15 W/(m*K)</td>
</tr>
<tr>
<td>Heat transfer coefficient on tube **</td>
<td>2316 W/(m²*K)</td>
</tr>
</tbody>
</table>

* calculated out of practical heat transfer coefficient measurement, no direct measurement possible.
** Measured on test rig under following conditions: Salinity 65g/kg, mass flow water 0.1kg/(s*m), Temperature heating vapour 80°C, Temperature evaporation: 75.8 °C
Experimental Setup

Two annular gas flow channels each with one evaporator tubes inside
Experimental Details

- PC (left) and TKP (right)
- Added 3 in diameter extension tube to measure velocity profile (mass flow)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>TKP section</th>
<th>PC section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5 m/s</td>
<td>5.0 m/s</td>
</tr>
<tr>
<td>2</td>
<td>4.6 m/s</td>
<td>5.1 m/s</td>
</tr>
</tbody>
</table>

- The following test conditions were conducted:

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>45°C</td>
<td>85 %</td>
</tr>
<tr>
<td>Condition 2</td>
<td>45°C</td>
<td>75 %</td>
</tr>
<tr>
<td>Condition 3</td>
<td>45°C</td>
<td>65 %</td>
</tr>
</tbody>
</table>

- Condensation rates (gm/hr) for both TKP and PC tube measured over several hours at each condition.
Experimental Results

- The condensate rate increases with the relative humidity for both types of tubes.

- For PC tube, the condensate rate increased by 35% and 89%.

- For TKP tube, the condensate rate increased by 22% and 67%.

- Condensate ratio between TKP tube and PC tube is between 2.2 and 2.5.
**Compare Results with Simulation**

**TKP tubes**
- 4.5 m/s velocity
- Experiment within 93 ~ 95% of model predictions
- Experimental data is lower than the model
- Trend is accurately captured

**PC tubes**
- 5.0 m/s velocity
- Experiment within 76 ~ 85% of model predictions
- Experimental data is lower than the model
- Trend is accurately captured
Compare Results with Simulation

• Agreement with TKP tubes is very good; PC acceptable.
• Possible reasons for low values with PC
  o Presence of non-condensable gas in system
    - Will reduce heat transfer and condensation rate for both tubes
  o Thermal conductivity of PC tube not confirmed.
    - Literature $k = 0.187 \text{ W/m\cdot K}$ and $k = 0.20 \text{ W/m\cdot K} \rightarrow$ condensation too high
    - Thermal conductivity of polycarbonate may be reduced during extrude process (alignment of polymer strands)
      - $k = 0.15 \text{ W/m\cdot K}$ gives good fit
  o Presence of droplets on the tube wall not accounted for
    - TKP tube is hydrophilic; thinner droplets
Future work for BNL-Scale Test

A larger scale prototype will be built in Brookhaven National Laboratory (BNL).
Summary

- Thermosyphon-based technology to harvest water from power plant flue gas
- Analytical model developed to predict the condensation performance.
- Lab-scale thermosyphon prototype built to investigate performance using high-performance polymer-graphite tubes as the evaporators.
- Model agreement with composite polymer tube agrees well.
- Larger 10 kW prototype being designed and fabricated at Brookhaven National Laboratory (Dr. Tom Butcher)
- Other applications for technology?
  - Water harvesting for other?
  - High performance heat recovery in combustion systems and buildings?
  - Other applications?
Acknowledgments

• Advanced Research In Dry cooling (ARID) project, funded by Advanced Research Projects Agency-Energy (ARPA-E).