ACTIVE THERMOSYPHONS FOR POWER-PLANT COOLING: MODELING AND EXPERIMENTS

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AEC 2018

The Premier New York State Advanced Energy Conference

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)

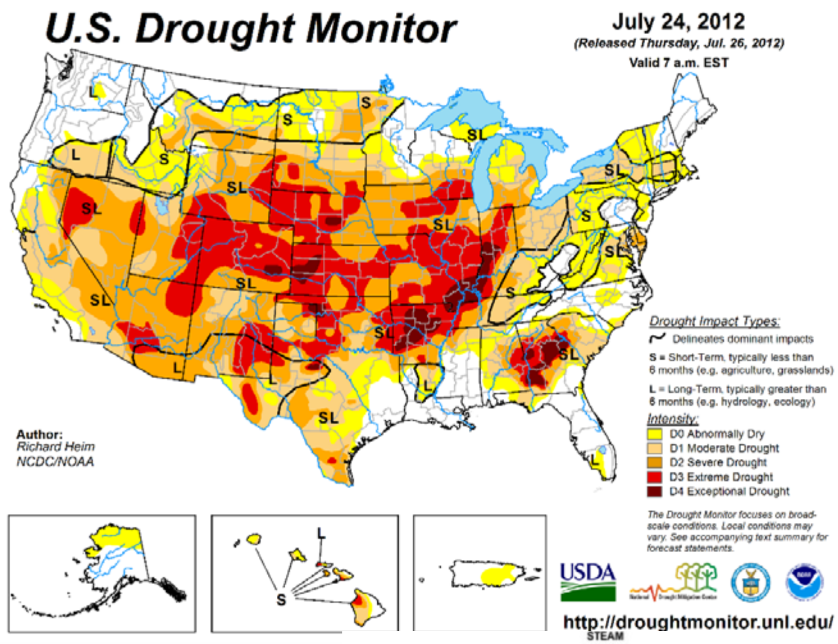
Why Dry Cooling

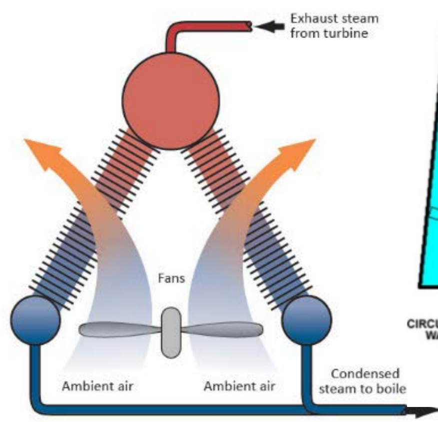
Wet cooling thermoelectric plants

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

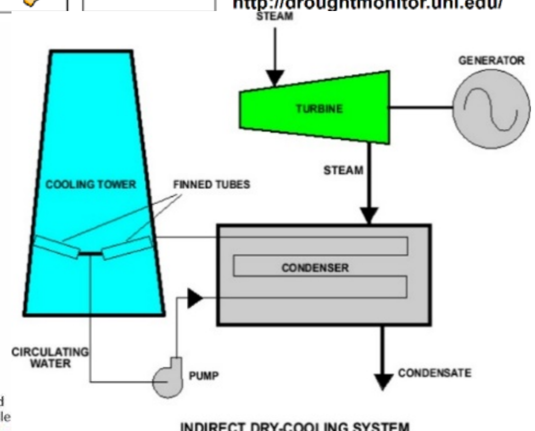
Dry cooling thermoelectric plants

- 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%





Direct dry cooling[1]



Indirect dry cooling[2]

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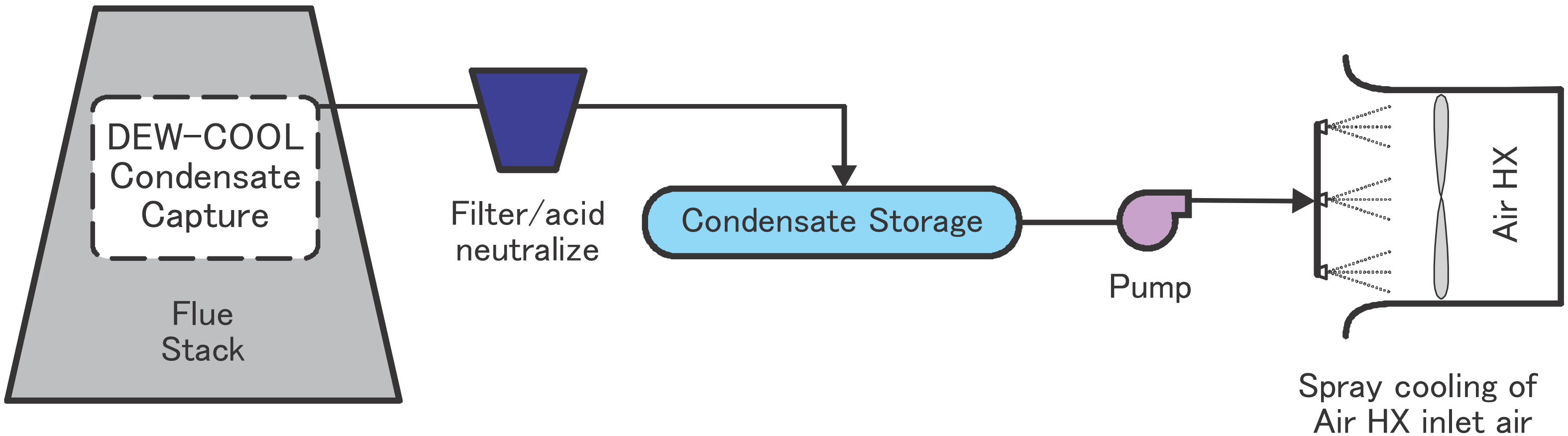
1. http://cornerstonemag.net/advanced-cooling-technologies-for-water-savings-at-coal-fired-power-plants/
2. http://decarboni.se/publications/evaluation-and-analysis-water-usage-power-plants-co2-capture/14-state-art-technology

- **<u>Goal</u>: 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*

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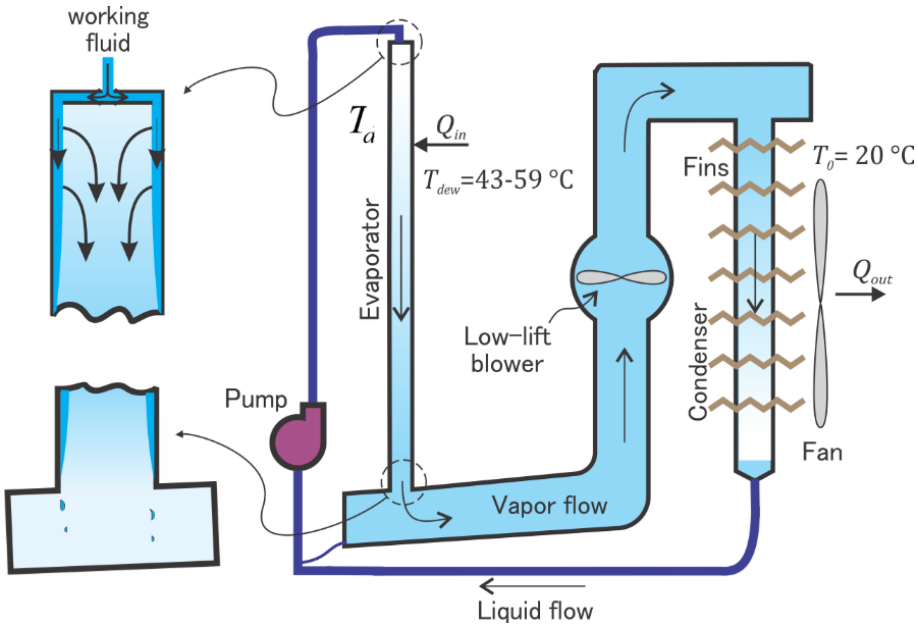
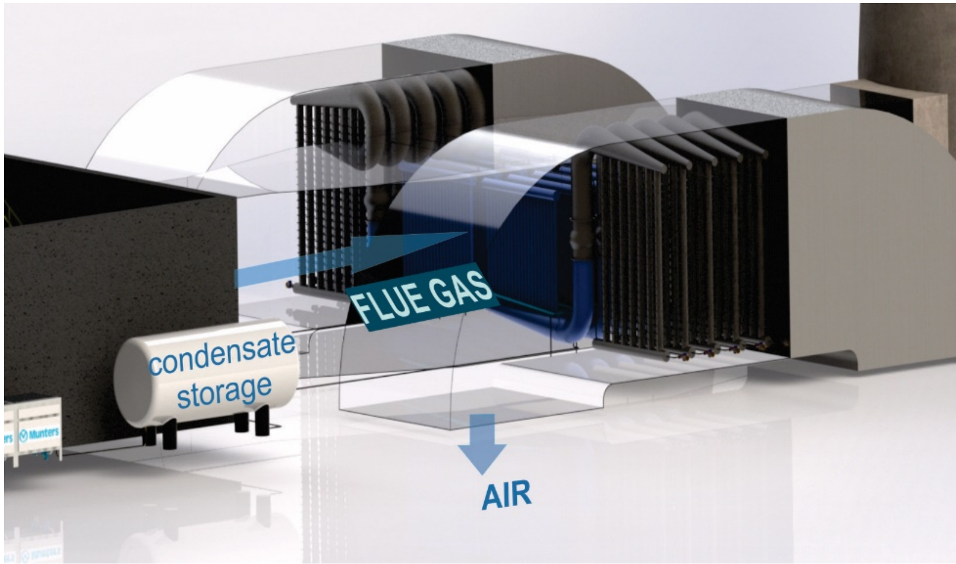
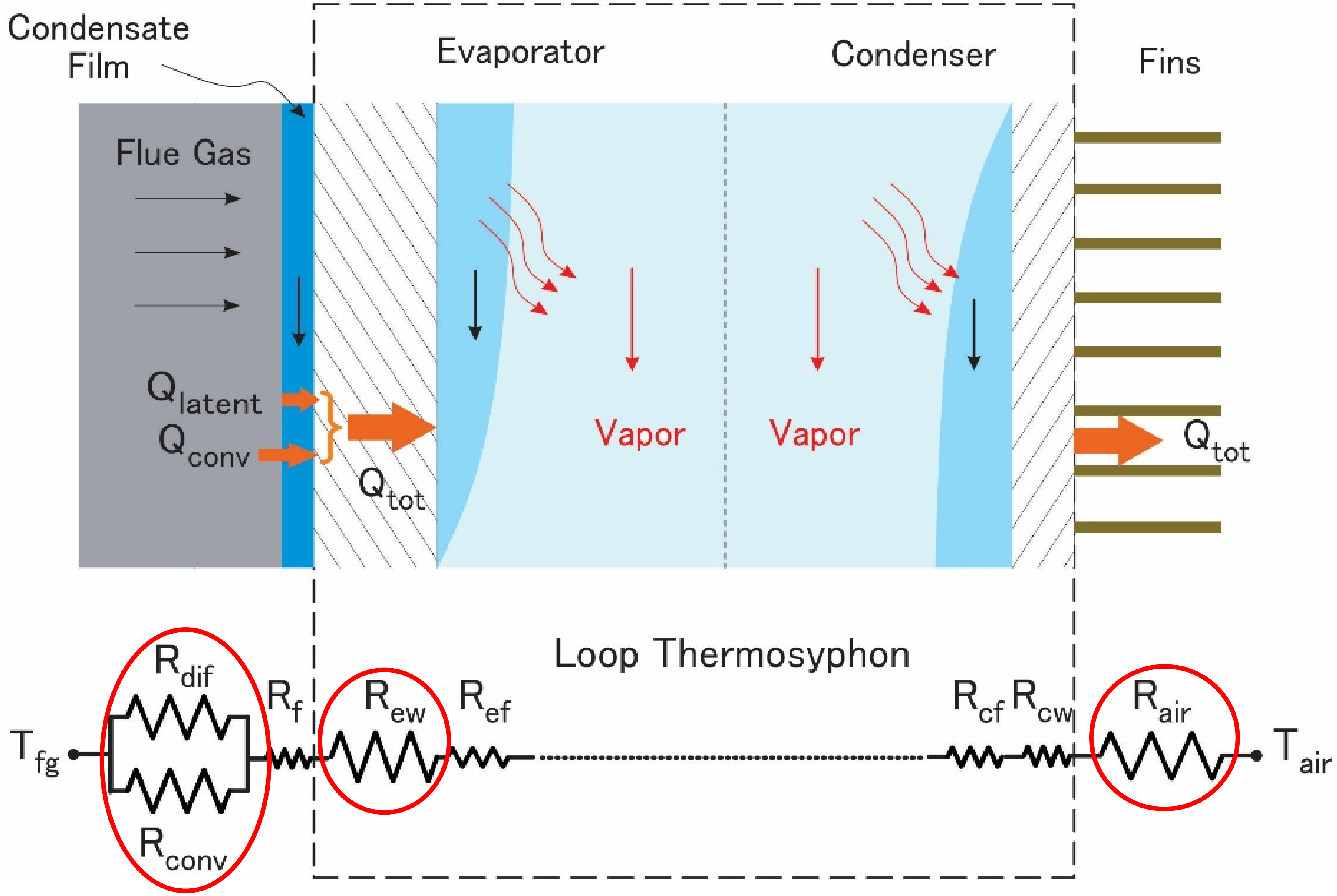
Water Harvesting using Active Thermosyphon





- 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



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

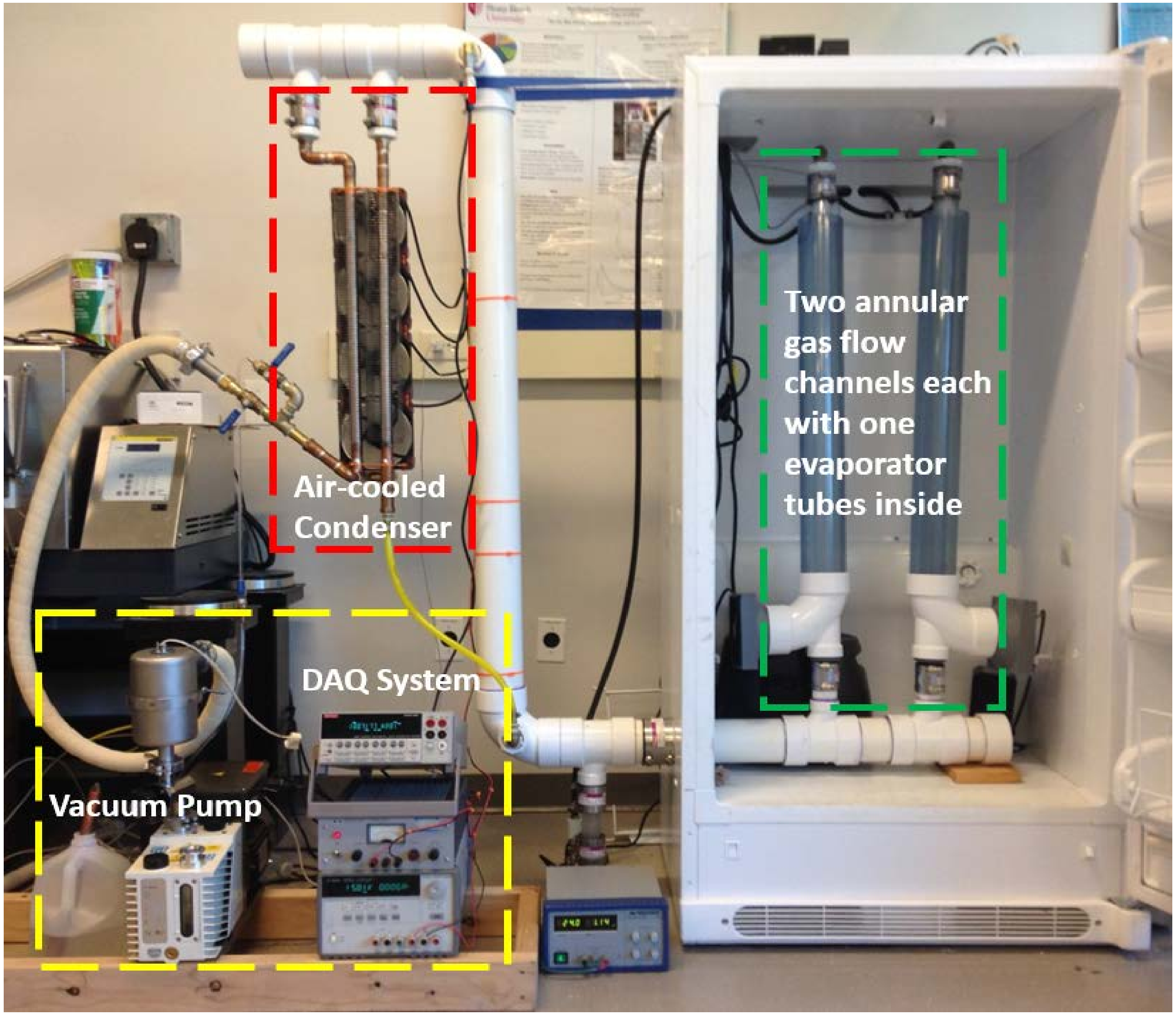
THERMAL PROPERTIES OF PP-GRAPHITE

Heat resistance long term	90	°C
Specific heat capacity c_p	1.21	J/(g*K)
Thermal elongation	29×10^{-6}	1/K
Thermal conductivity in plane (injection moulding)	26.6	W/(m*K)
Thermal conductivity through plane (injection moulding)	4.5	W/(m*K)
Thermal conductivity through plane (extruded tube)*	10-15	W/(m*K)
Heat transfer coefficient on tube **	2316	W/(m²*K)

* calculated out of practical heat transfer coefficient measurement, no direct measurement possible
** Measured on test rig under follwing conditions: Salinity 65g/kg, mass flow water 0,1kg/(s*m), Temperature heating vapour 80°C, Temperature evaporation: 75,8 °C

- Commercially available: *Technoform Kunstsoffprofile, 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

Experimental Setup



Experimental Details

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

Measurement	TKP section	PC section
1	4.5 m/s	5.0 m/s
2	4.6 m/s	5.1 m/s

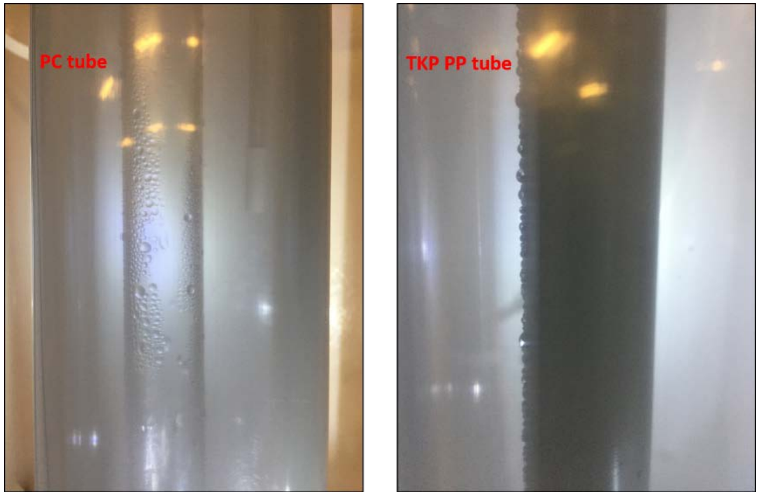
- The following test conditions were conducted

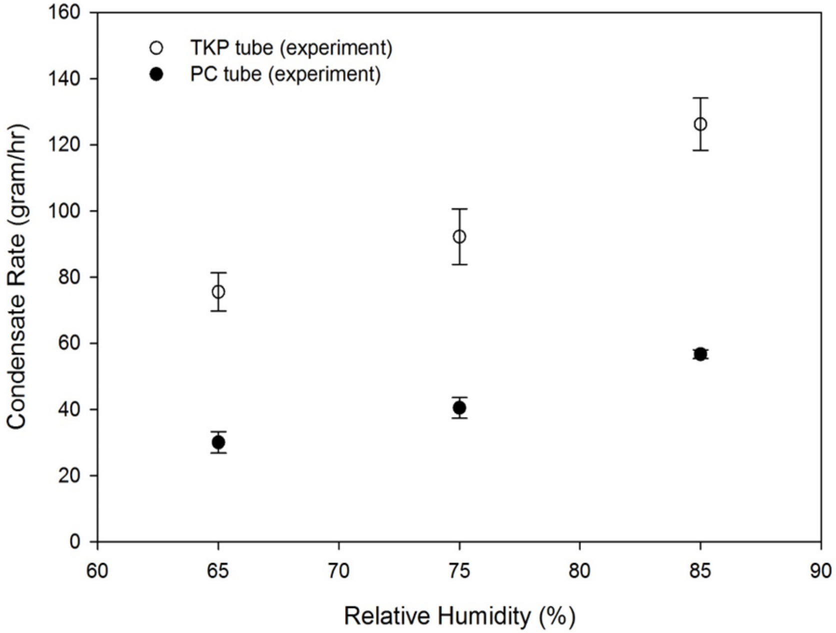
Component	Temperature	Relative Humidity
Condition 1	45°C	85 %
Condition 2	45°C	75 %
Condition 3	45°C	65 %

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

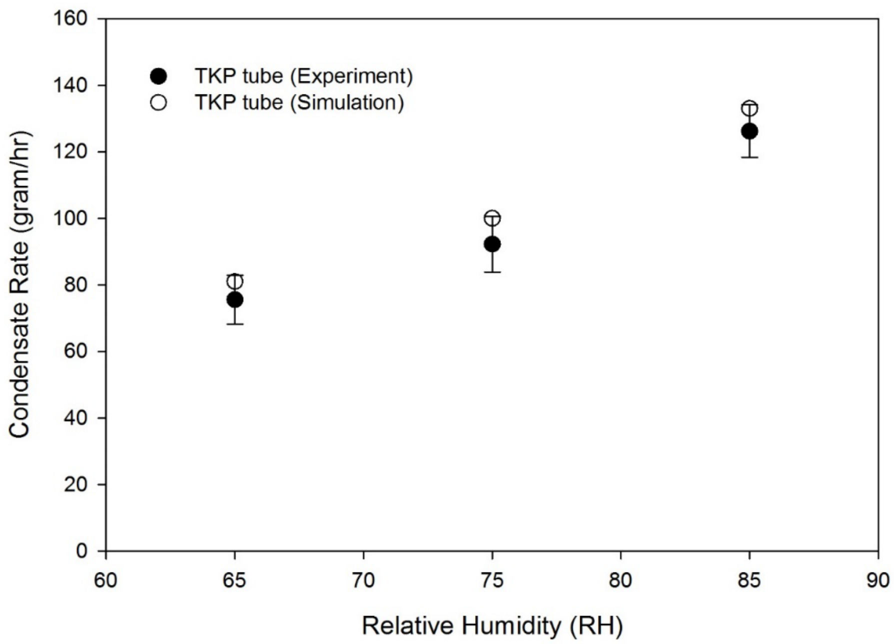
Experimental Results

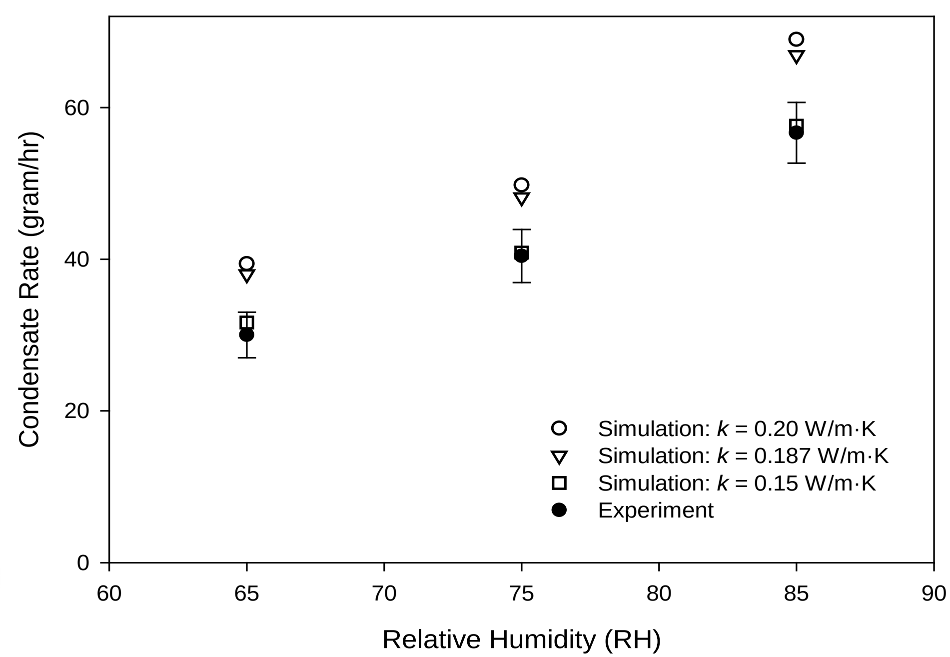
- The condensate rate increases with the relative humidity for both types of tubes.
- For PC tube, the condensate rate increased by 35% and 89%.
- For TKP tube, the condensate rate increased by 22% and 67%.
- Condensate ratio between TKP tube and PC tube is between 2.2 and 2.5.





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

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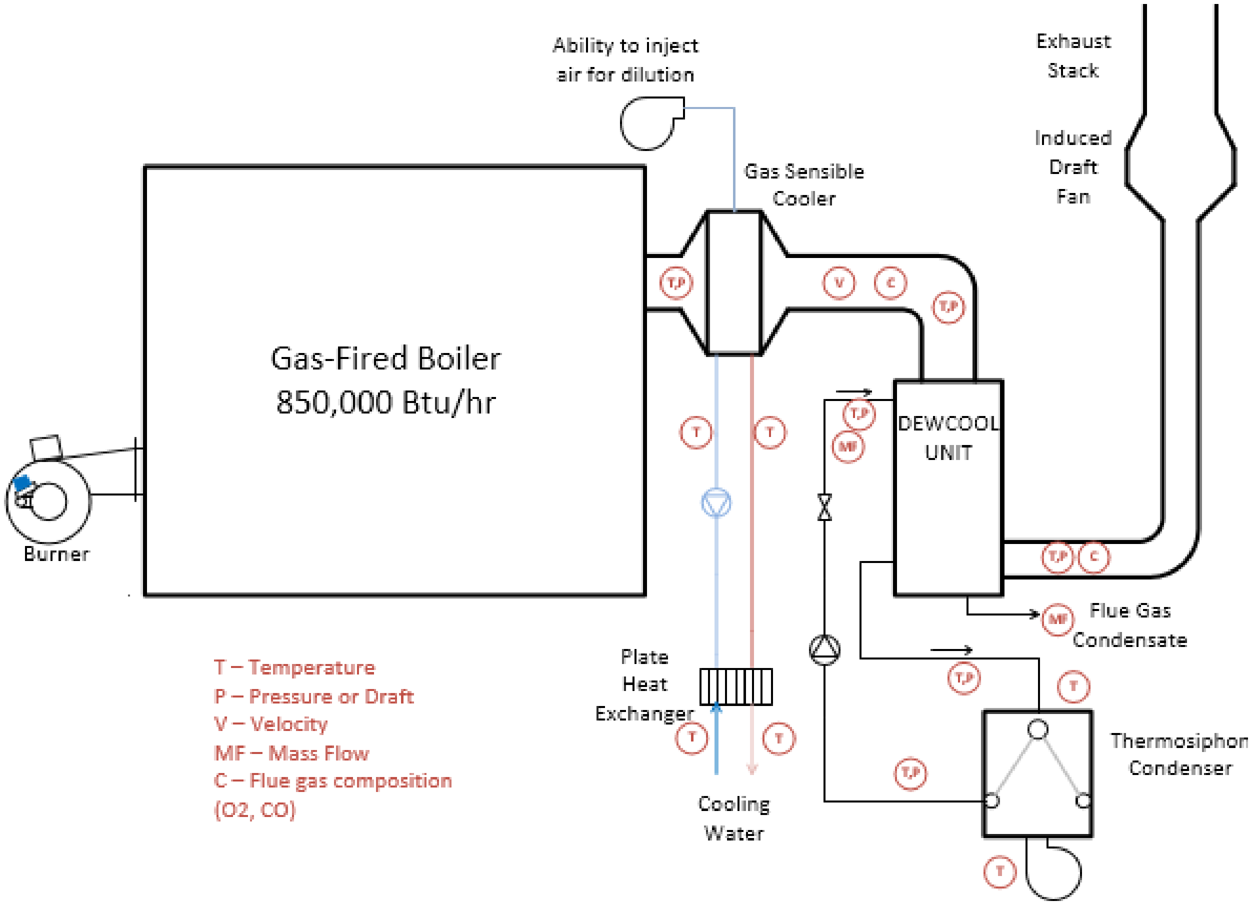
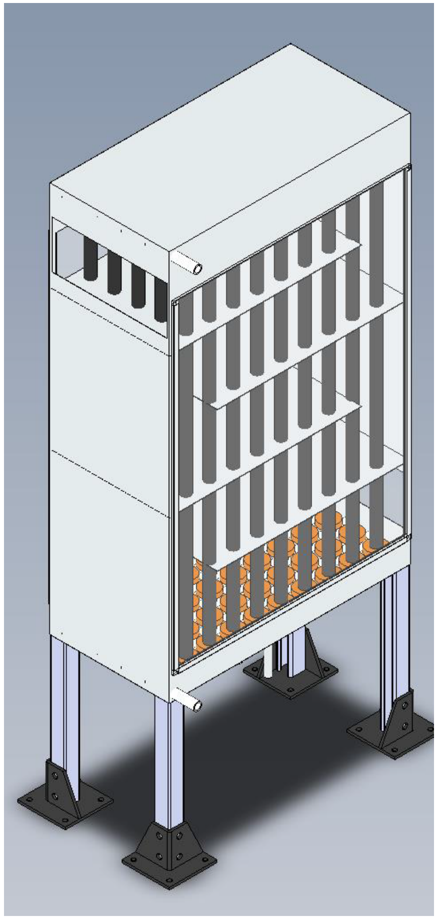
Compare Results with Simulation

- Agreement with TKP tubes is very good; PC acceptable.
- Possible reasons for low values with PC
  - Presence of non-condensable gas in system
    - Will reduce heat transfer and condensation rate for both tubes
  - Thermal conductivity of PC tube not confirmed.
    - Literature $k = 0.187$ W/m·K and $k = 0.20$ W/m·K $\rightarrow$ condensation too high
    - Thermal conductivity of polycarbonate may be reduced during extrude process (alignment of polymer strands)
    - $k = 0.15$ W/m·K gives good fit
  - 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

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