CNWRA
A center of excellence
in earth sciences
and engineering®

UNITED STATES NUCLEAR REGULATORY COMMISSION

EXPERIMENTAL STUDY AND NUMERICAL MODELING OF NATURAL CONVECTION WITH CONDENSATION

Kaushik Das,[1] Randall Fedors,[2] Chandrika Manepally,[1] and Debashis Basu[1]

[1]Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute®
San Antonio, TX

[2]U.S. Nuclear Regulatory Commission
Washington, DC

12th April 2011
International High-Level Radioactive Waste Management Conference
Albuquerque, NM

CNWRA
A center of excellence in earth sciences and engineering®

Outline

UNITED STATES NUCLEAR REGULATORY COMMISSION

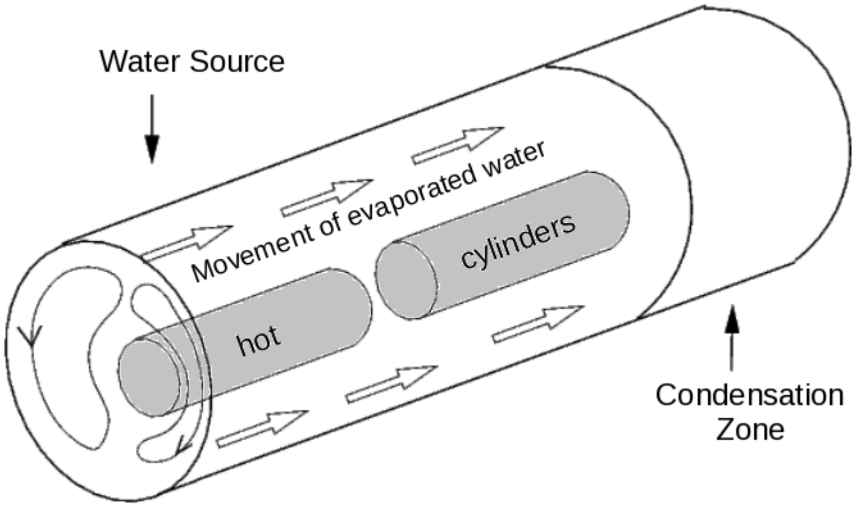
- Background
- Methodology
- Experimental Setup and Results
- Numerical Model Development
- Results of Numerical Study
- Comparison Between Experimental and Numerical Data
- Conclusions

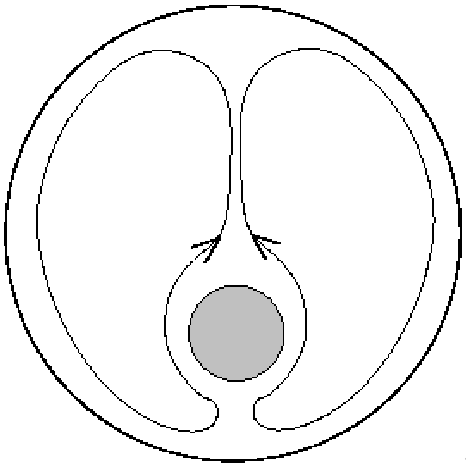
CNWRA
A center of excellence in earth sciences and engineering®

Background: Relevant Processes

- Cold Trap Process
  - Seepage water
  - Radioactive decay heat
  - Evaporation on heated surface
  - Condensation on cold surfaces
  - Redistribution of water

- Physical Processes and Mechanisms
  - Natural convection
    - Driven by the thermal perturbation
  - Surface Condensation
  - Volumetric Condensation
    - Interphase heat transfer





CNWRA
A center of excellence in earth sciences and engineering®

Background: Objective of the Current Study

UNITED STATES NUCLEAR REGULATORY COMMISSION

- Develop a Validated Numerical Tool
  - Capable of handling the physics
  - Eventual application to study cold trap process
- Technical Requirements of the Tool
  - Resolution of conjugate heat and mass transfer
  - Solution of species transport equations for water vapor
  - Simulation of surface condensation and evaporation
  - Simulation of volumetric condensation and latent heat transfer
  - Radiation heat transfer
- Validation Technique
  - Controlled experiment with single condensation-evaporation cycle

CNWRA
A center of excellence in earth sciences and engineering®

Methodology

- Numerical Simulations Using ANSYS® FLUENT® Version 12.1
- Customized Function Development for
  - Surface evaporation and condensation
  - Volumetric condensation
  - Interphase mass transfer between the liquid and vapor phase
- Experimental Study
  - Single source of water for evaporation
  - Measured condensation rate and temperature
- Comparison of Experimental Observation With Computed Data

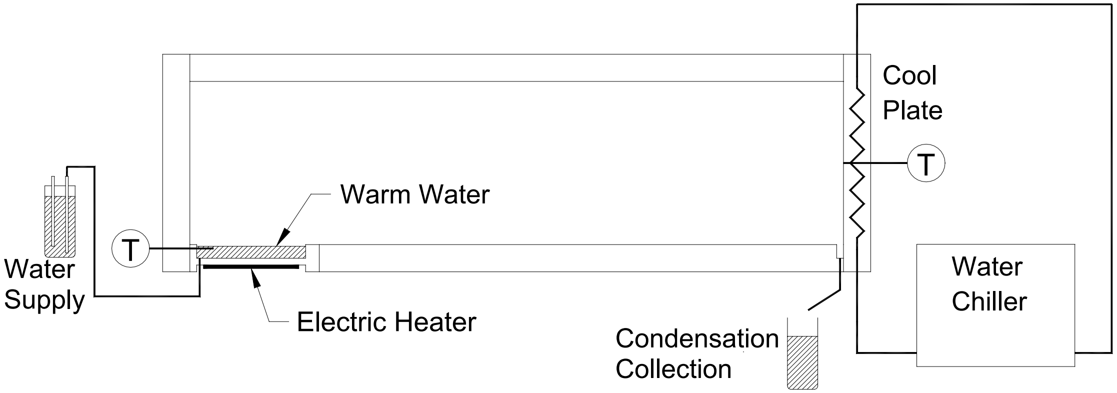
Experimental Setup

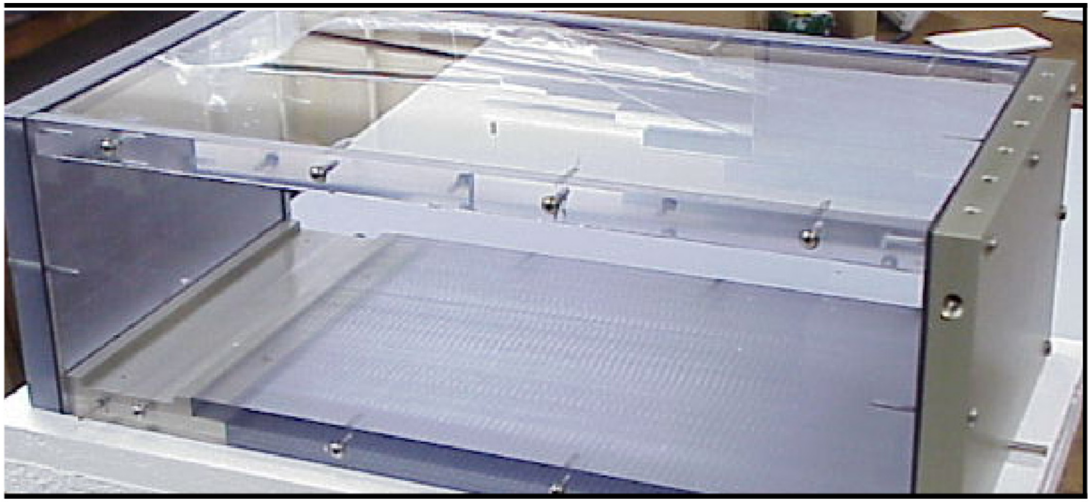
- Overall Enclosure Dimension: 23 × 6 × 12 Inches
- Materials: Polycarbonate Sheet and Acrylic Sheet
- Heated Tray for Evaporating Water With Continuous Supply
- Condensate Flow Collected in Graduated Cylinder
- Water Source Dimension

  3 × 12 Inches
- Whole Chamber Covered With Polystyrene to Reduce Heat Loss
- Cooling Wall Material: Aluminum

1 in = [0.0254 m]

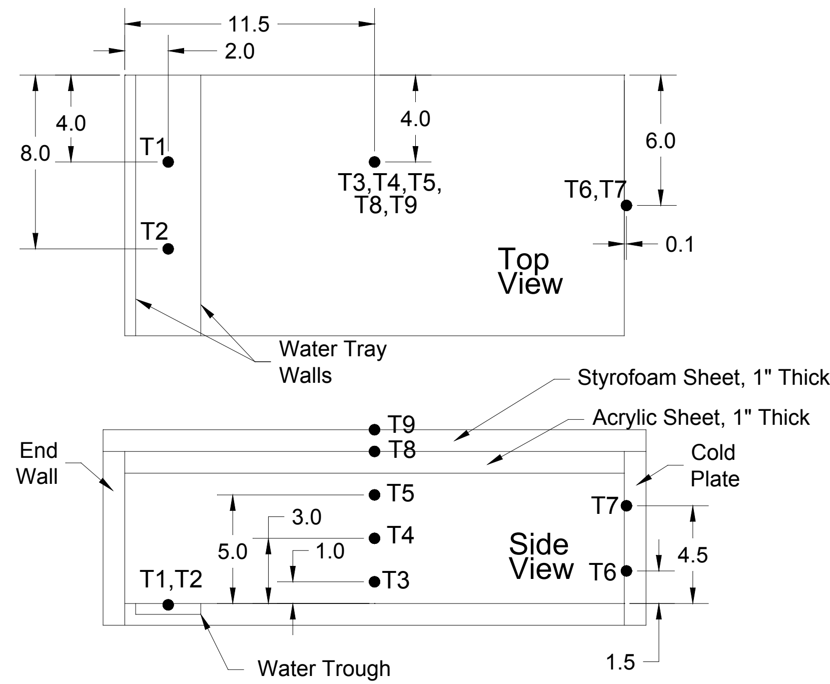
Schematic of the Setup





Experimental Setup: Instrumentation

- Heater Pad for Water Source
  - — Powered by variable AC supply
- Cooling Wall
  - — Drilled channels with circulating cooling fluid
- Thermocouple Locations
  - — Air temperatures at three locations
  - — Evaporator temperature
  - — Condenser temperature



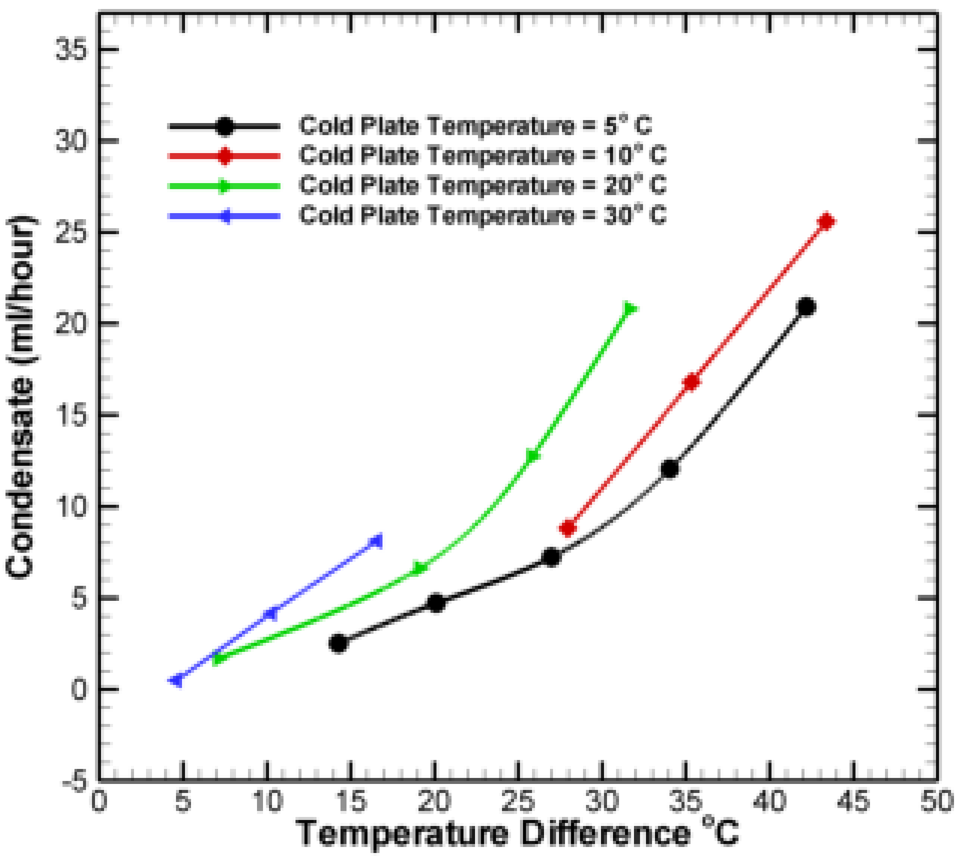
all units are in inches

1 in = [0.0254 m]

CNWRA
A center of excellence
in earth sciences
and engineering®

Experimental Results

UNITED STATES NUCLEAR REGULATORY COMMISSION

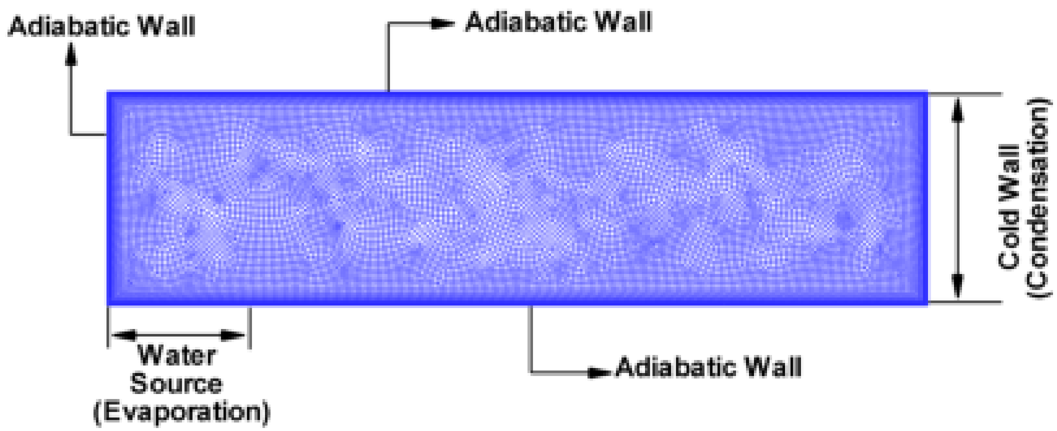


- Experiment Conducted for Four Sets of Cold Plate Temperatures
- Temperature Difference = (Evaporator Temperature – Condenser Temperature)
- Condensation Rate Increases With Increased Temperature Difference

Temperature Difference: F = 1.8 C
Temperature: F = 1.8 C + 32
1 ml/hr = 2.64 10^{-4} gal/hr

CNWRA
A center of excellence in earth sciences and engineering®

Numerical Model Development



- ANSYS FLUENT 12.1
- Two-Dimensional Model
- Density-Driven Natural Convection Flow
- Approximated as Incompressible Fluid
  — Boussinesq approximation for density
- Navier-Stokes Equations
  — Momentum, species, and energy
- SIMPLEC for Pressure Velocity Coupling
- Shear Stress Transport (SST) k-ω Turbulence Model

CNWRA
A center of excellence in earth sciences and engineering®

Numerical Model Development: Treatment of Mass Transfer Process

- Three Distinct Mass-Transfer-Related Processes

- Mass Transfer at the Walls Due to Condensation and Evaporation
  - Modeled using user-defined functions at the wall
  - Assumes equilibrium conditions adjacent to the wall
  - Only film condensation is considered
  - Latent heat exchange takes place from the source (i.e., wall)
  - Diffusion through mass transfer boundary layer
  - Mass, momentum, and energy source terms calculated based on condensation or evaporation rate and accounted for in the respective transport equations
  - Assumes equilibrium conditions adjacent to the wall

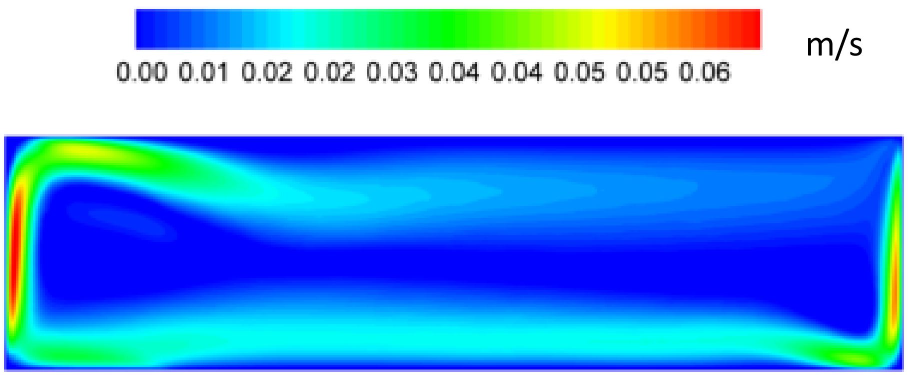
- Transport of Evaporated Water Vapor From the Hot Source Location
  - Solved the species transport equations using the mixture model

Numerical Model Development: Treatment of Mass Transfer Process (cont.)

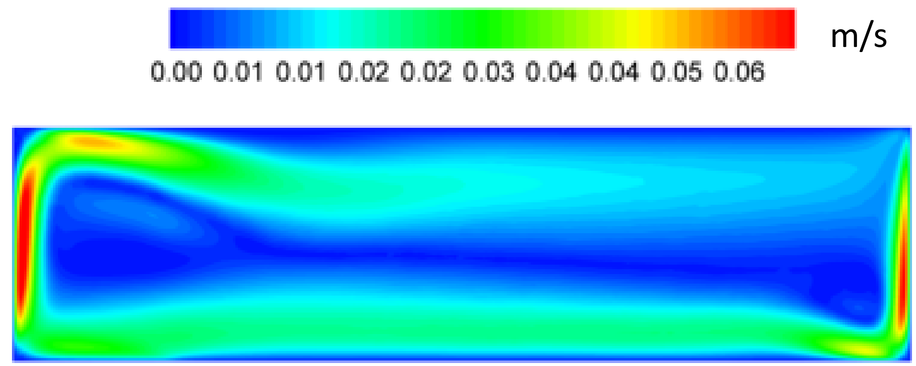
- Condensation of Water Vapor Within the Flow Domain: Two Different Modeling Approaches
  - Nonequilibrium model: Domain allowed to supersaturate (i.e., relative humidity can be more than 100%)
    - Supersaturation limit determined based on kinetic theory
  - Equilibrium Model: Volumetric Condensation Of Water Takes Place And Relative Humidity Restricted To 100%
    - Maximum mass transferred: Difference between the saturation and supersaturation limit
    - Condensed water flows with the air-vapor mixture
    - Rainout of droplets is not considered
    - Volumetric fraction of condensed liquid is significantly less compared to the main mixture

CNWRA
A center of excellence in earth sciences and engineering®

Results of Numerical Study: Velocity Field



Nonequilibrium Model

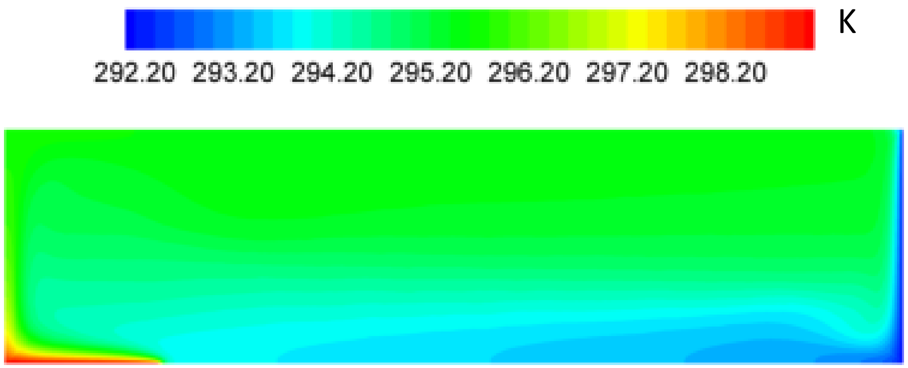


Equilibrium Model

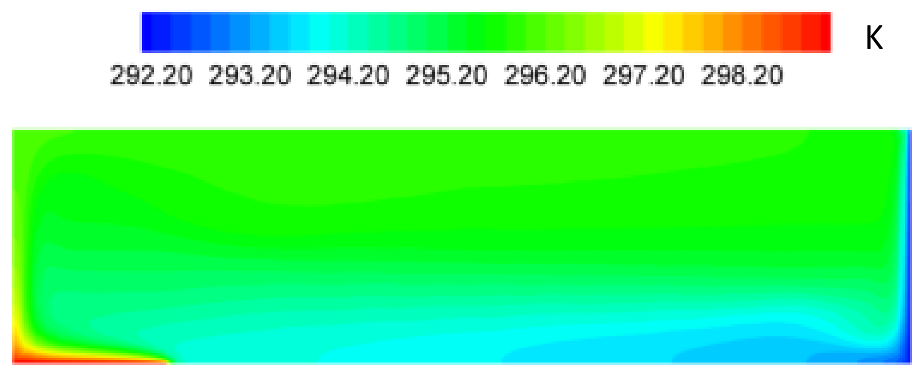
1 m/s = 3.28 ft/s

CNWRA
A center of excellence in earth sciences and engineering®

Results: Temperature Field



Nonequilibrium Model

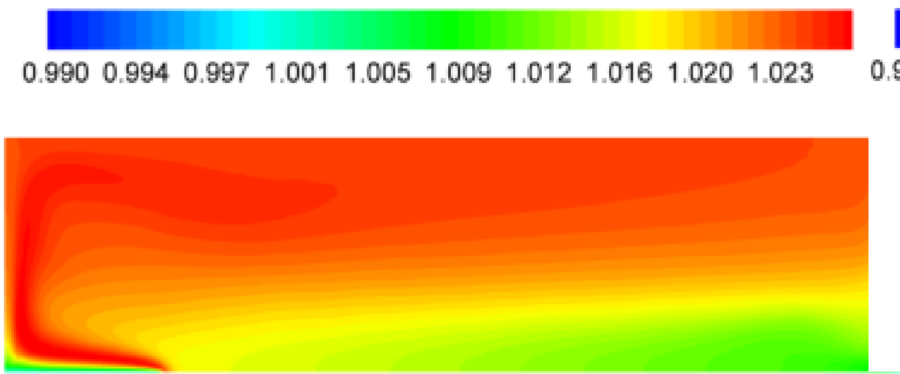


Equilibrium Model

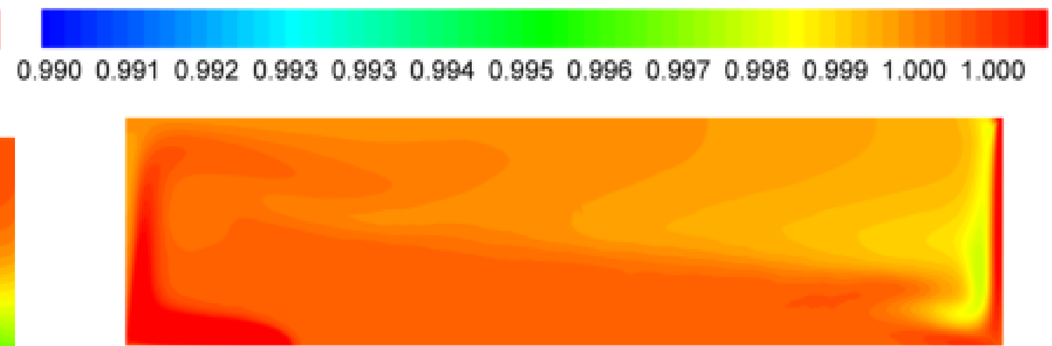
Temperature: $F = 1.8\ (K) - 459.4$

CNWRA
A center of excellence in earth sciences and engineering®

Results: Relative Humidity

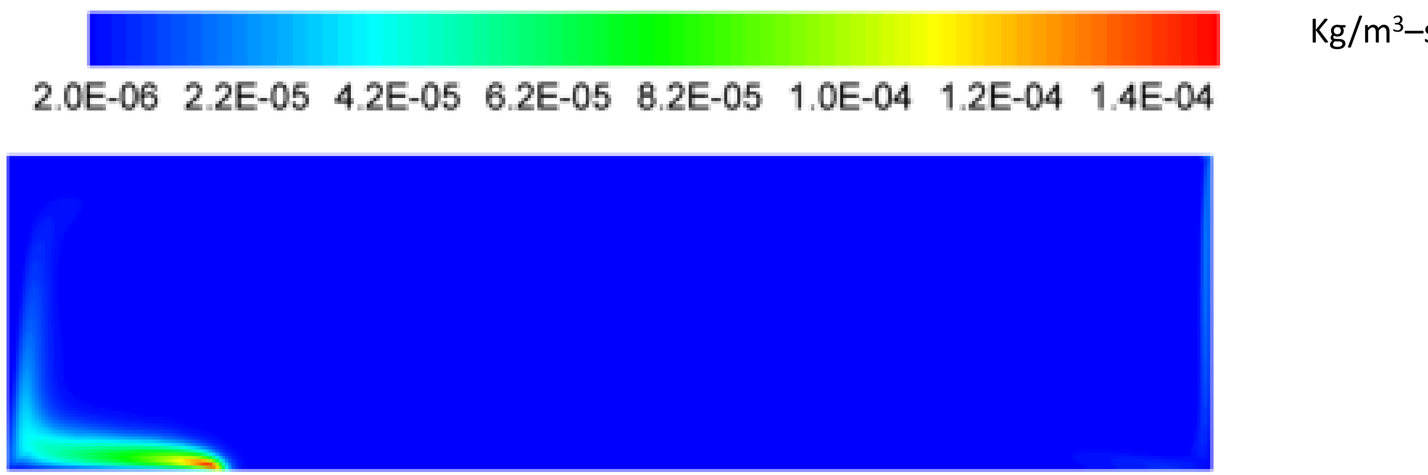


Nonequilibrium Model



Equilibrium Model

Results:
Interphase Mass Transfer Rate

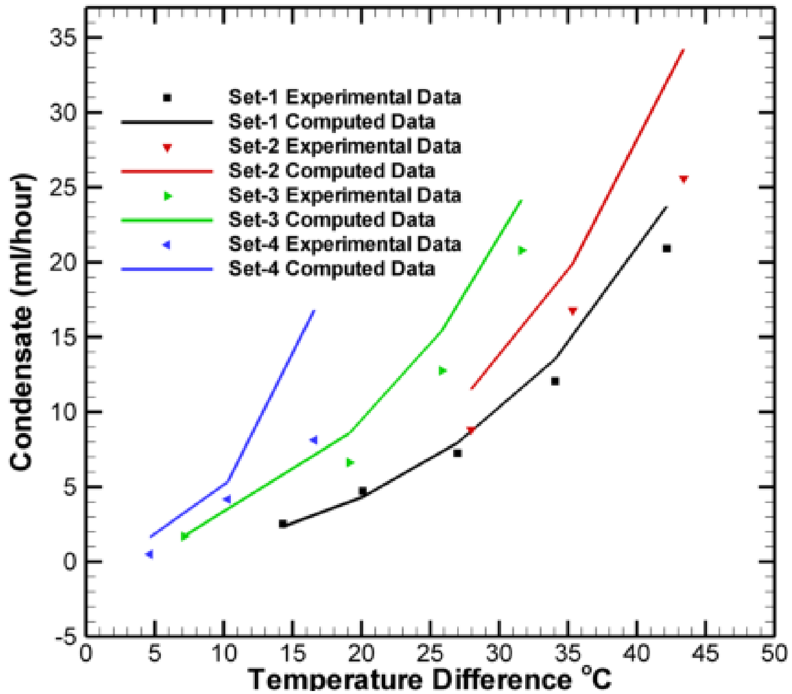


Equilibrium Model

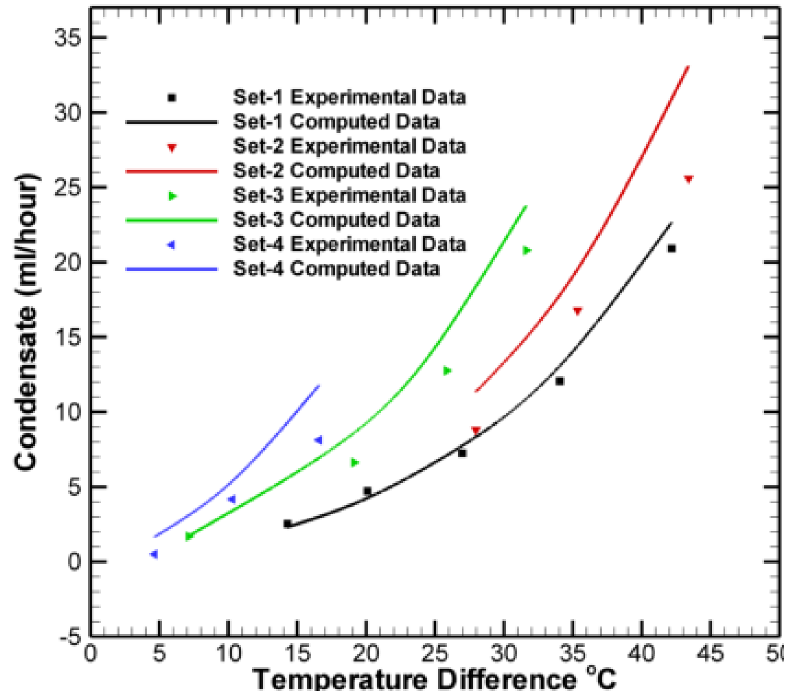
1 Kg/m^3–s = 6.242 × 10^{-2} lb$_m$/ft^3–s

CNWRA
A center of excellence in earth sciences and engineering®

Comparison Between Experimental and Numerical Data: Temperature



Nonequilibrium Model

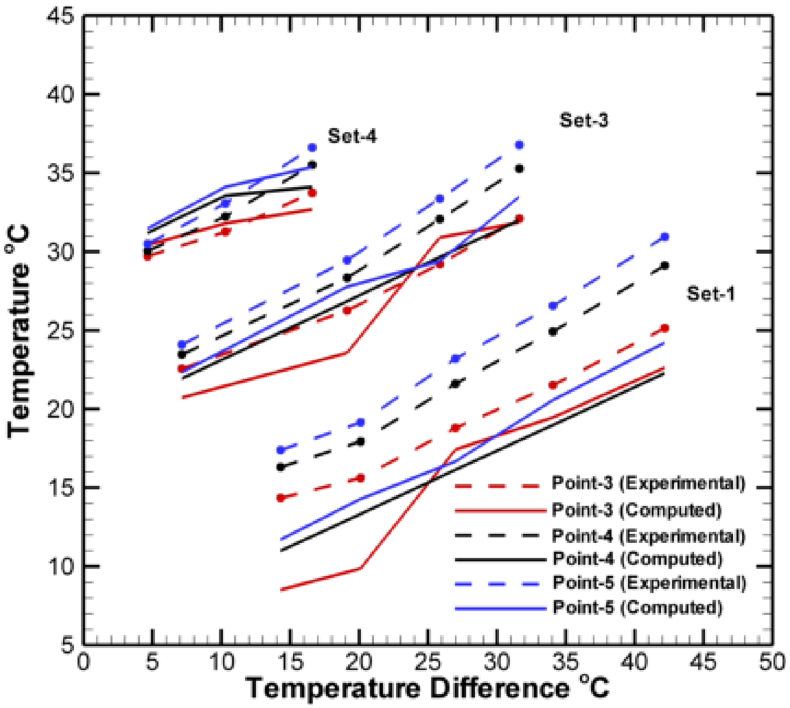


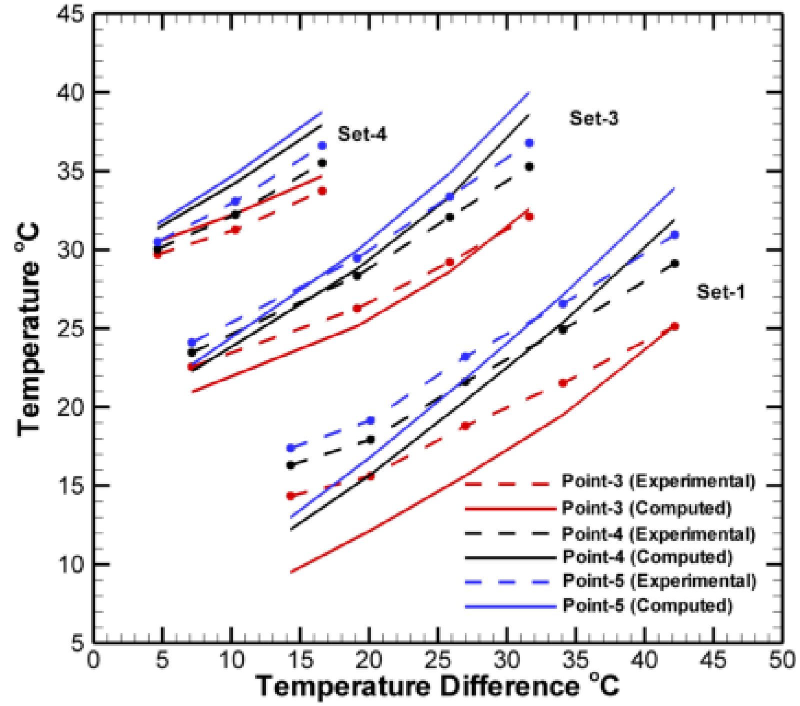
Equilibrium Model

1 ml/hr = 2.64 10^{-4} gal/hr
Temperature Difference: F = 1.8 C

CNWRA
A center of excellence in earth sciences and engineering®

Comparison Between Experimental and Numerical Data: Condensation Rates





Temperature Difference: F = 1.8 C
Temperature: F = 1.8 C + 32

CNWRA
A center of excellence
in earth sciences
and engineering®

Conclusions

- A Combined Experimental and Numerical Study Was Conducted to Validate the Numerical Study
- Volumetric and Surface Condensation Modeling Tools Developed
- Both Equilibrium and Nonequilibrium Numerical Models for Volumetric Condensation Studied
- Equilibrium Model Provided Better Match With Experimental Data

CNWRA
A center of excellence
in earth sciences
and engineering®

Disclaimer

This presentation is an independent product of the Center for Nuclear Waste Regulatory Analyses and does not necessarily reflect the view or Regulatory position of the U.S. Nuclear Regulatory Commission (USNRC). The USNRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of any licensing action that may be under consideration at the USNRC.