Comparisons of Mixed-Phase Icing Cloud Simulations with Experiments Conducted at the NASA Propulsion Systems Laboratory

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Outline

- Introduction
- PSL and model description
- Supersaturation and Aerosol Condensation
- Model/Experiment Comparisons
  - Supersaturation/Condensation Cloud Tests
  - 4 RH Sweeps
- Summary

Introduction

- Many engine power-loss events reported since the 1990's
- Ice crystals entering the engine core – Mason et al.
- Ingestion of ice into engine studied at NASA PSL and elsewhere
- Observed environmental conditions changed with cloud activation
  - Gas temperature change
  - Humidity change
- Hypothesis: Thermal interaction between air and cloud
- Building on previously written model to simulate PSL
- Objective: Understand the air - cloud interactions in PSL tunnel

General Description of Model

- Model Simulates PSL icing tunnel
  - Air and cloud conservation equations (mass, energy) fully coupled
  - Air is treated as ideal compressible gas
  - Isentropic equations used to solve ρ_{air}, v_{air}, T_{air}, P
  - Air and particle flow are steady and one dimensional
  - Temperature is uniform within the perfectly spherical particle
  - Full particle size distributions used

Air		**Cloud**
$\frac{\partial m_{air}}{\partial x}$	$\Leftrightarrow$	$\frac{\partial m_p}{\partial x}$
$\frac{\partial T_{air}}{\partial x}$	$\Leftrightarrow$	$\frac{\partial T_p}{\partial x}$ or $\frac{\partial \eta_p}{\partial x}$
$\frac{\partial v_{air}}{\partial x}$	$\Rightarrow$	$\frac{\partial v_p}{\partial x}$

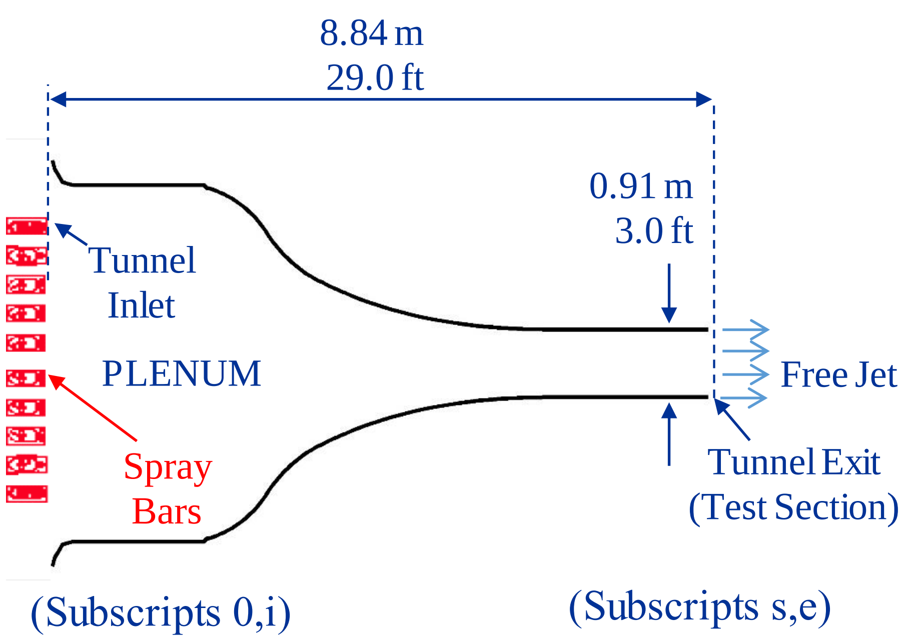
PSL Geometry and Capabilities

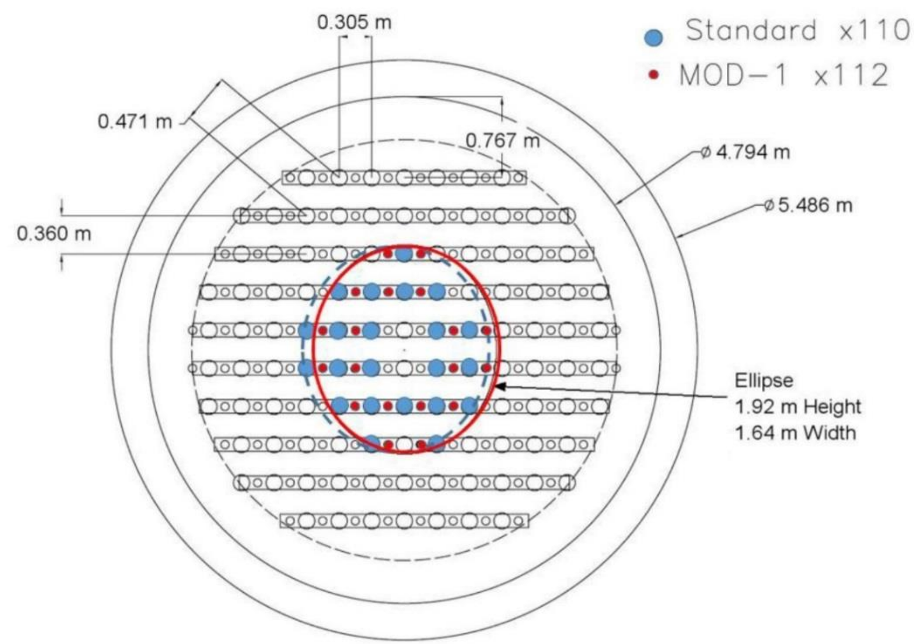
Tunnel Capability

- Freeze out liquid cloud
- 12 parameters can be varied
  - P, V, T_{air}, T_{water}, RH, MVD, TWC, Water Type, Nozzle Pattern…

Tunnel Controllability

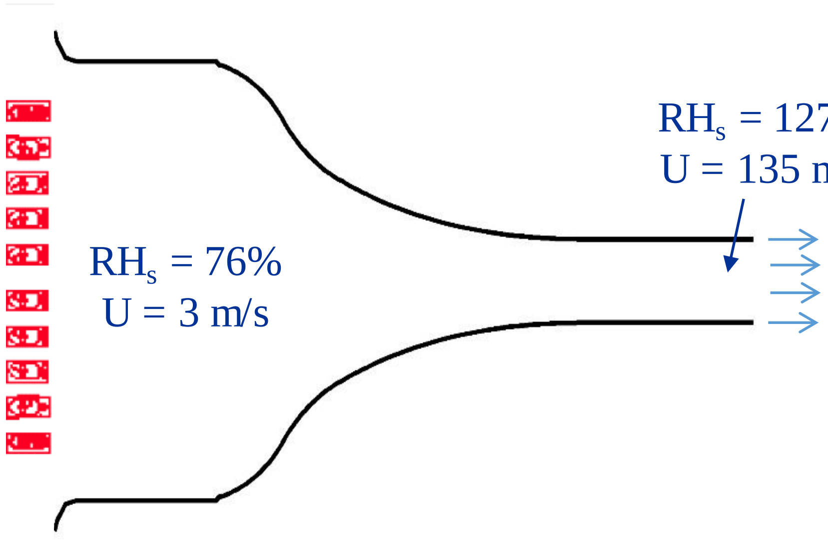
- ±0.3 kPa (.05 psia)
- ± 0.5 ^{O}C (1 ^{O}F)
- ± 1% RH



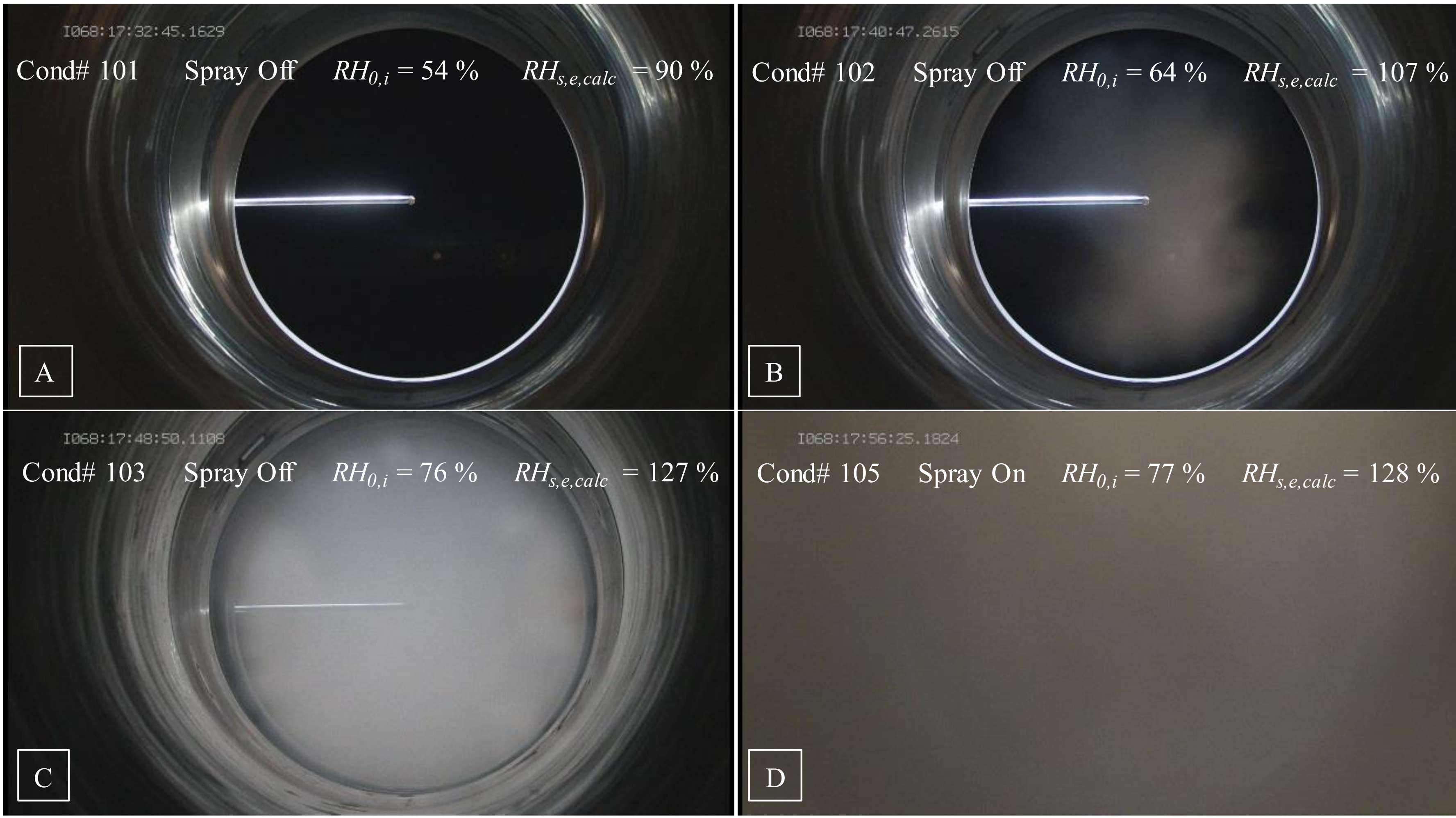


Supersaturation and Condensation

- Vapor saturation can be exceed for certain conditions
- Condense on cloud particles through diffusion not sufficient
- Supersaturated? Condense? Combination?
- 2 type of condensation
  - Homogeneous - RH >> 100% (very clean air)
  - Heterogeneous - RH >100% (nucleation / seeding)
- Nature ~ 101% RH



Condensation Cloud Experiments



Aerosol Particulates Background

- Organic and inorganic in composition
- Size distribution from 0.003 µm to 2.5 µm
- # density variations
  - 3,100/cm^3 (Alps)
  - 100,00/cm^3 (city background)
  - Diurnal variation (peak traffic hours)
  - Seasonal variation (heating in winter)
- Aerosol particulates considered in condensation

Aerosol Condensation Subroutine

- Implemented only when RH>100%
- Treat aerosol like any other water droplet / ice particle

- Initial # Density: 22,000/cm^3 (Pittsburg, PA paper)
- Initial Size: 0.04 µm (Pittsburg, PA paper)
- Initial Velocity: 99.99% of air velocity
- Initial Temperature: Twb
- Twb > 0 ^{O}C : Condense as liquid
- Twb <= 0 ^{O}C : Deposit as ice

- Effects of charged particles neglected

Model Formulation - *Algorithm*

- Written in MATLAB version R2016b
- Solves conservation differential equations using built-in ODE45 solver
- *Numerical* relative and absolute convergence tolerance of 10^{-8}
- Mass transferred between the gas and particle(s) balanced to 10^{-15}
- Energy transferred between the gas and particle(s) balanced to 10^{-4}
  - *Physical* accuracy dependent on accuracy of property values (C_p, L_{heat}, etc.)

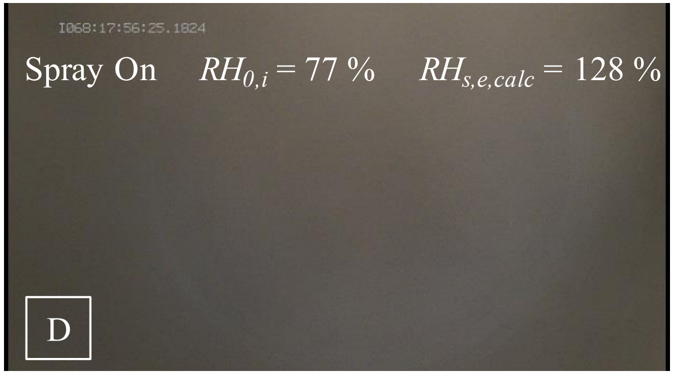
Supersaturation Simulation Profiles

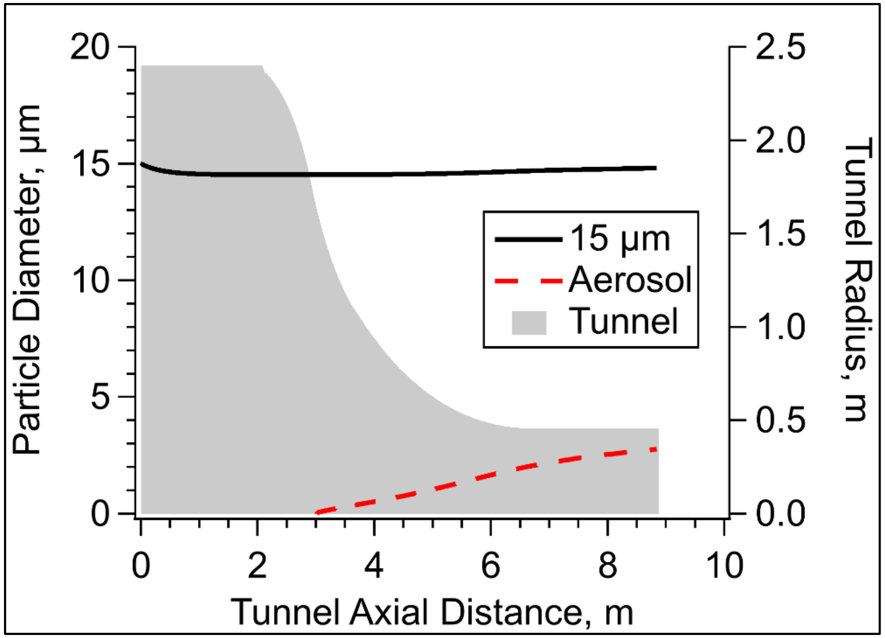
Test Conditions

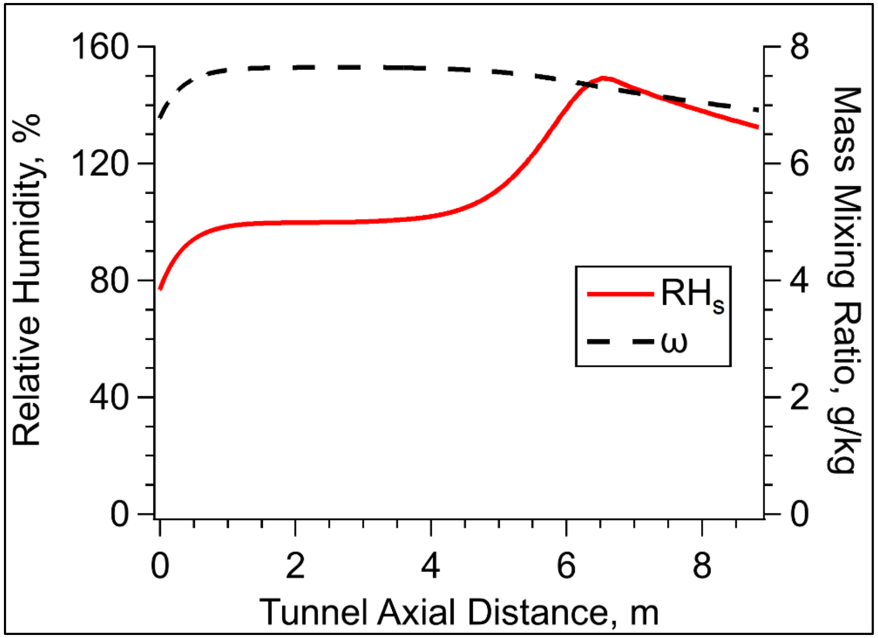
$T_{0,i} = 10.0\ ^0C$ $U_e = 135$ m/s

$P_{0,i} = 78.2$ kPa $MVD_i = 15\ \mu m$

$RH_{0,i} = 77\%$ $TWC_i = 7.1\ g/m^3$



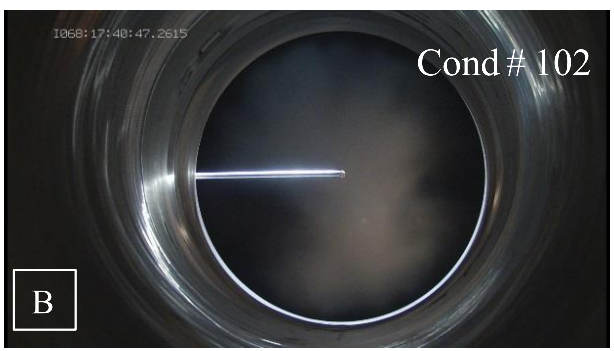


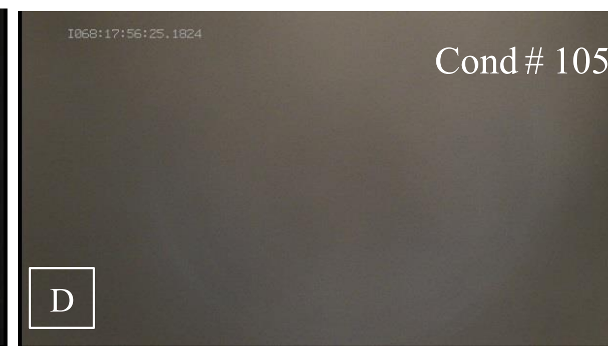


Supersaturation Simulation Comparisons

(ω= mass mixing ratio)

1	2	3	4	5	6	7	8	9	10	11
Cond #	Spray On/Off	$T_{0,i}$ °C	$T_{s,e,calc}$ °C	$RH_{0,i}$ %	$RH_{s,e,calc}$ %	$\omega_{100\%RH}$ g/kg	$\omega_{i,exp}$ g/kg	$\omega_{e,exp}$ g/kg	$\omega_{e,sim,none}$ g/kg	$\omega_{e,sim,aero}$ g/kg
102	Off	10.9	1.8	64	107	5.61	6.01	5.99	6.01	6.00
103	Off	10.1	1.1	76	127	5.34	6.87	6.35	6.87	6.79
105	On	10.0	1.0	77	128	5.30	6.81	6.42	7.15	6.94

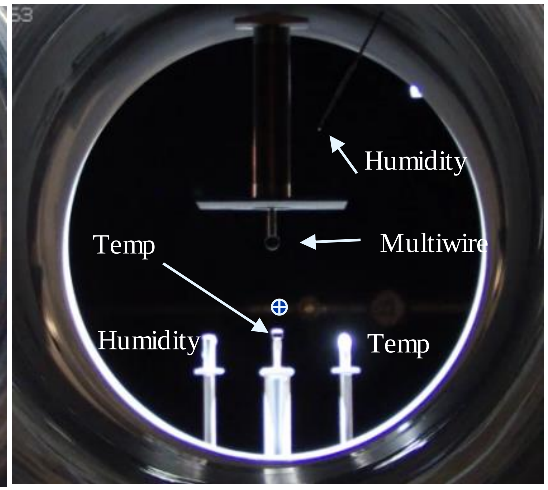




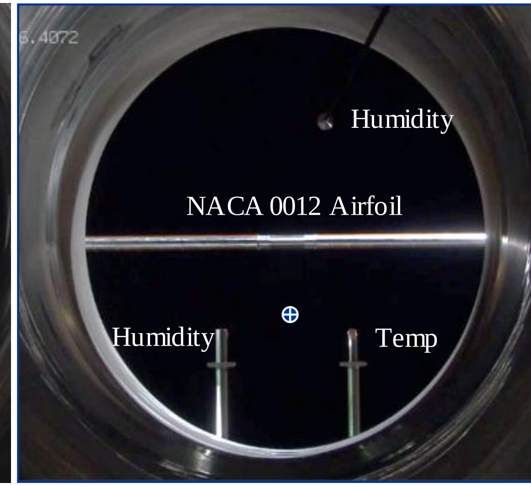
Experiment Configurations

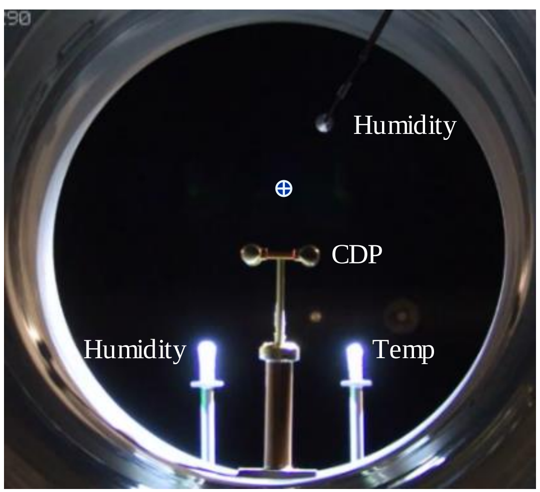
Temp + Humidity

Melt Fraction

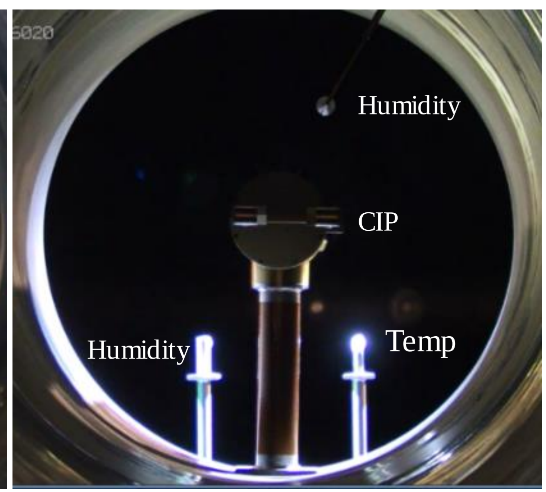


Airfoil Icing

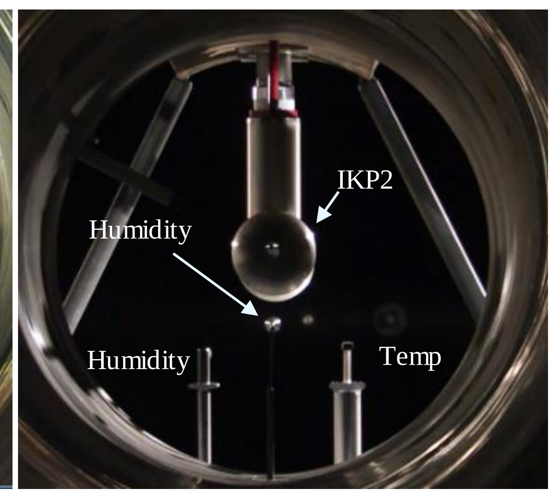




Particle Size

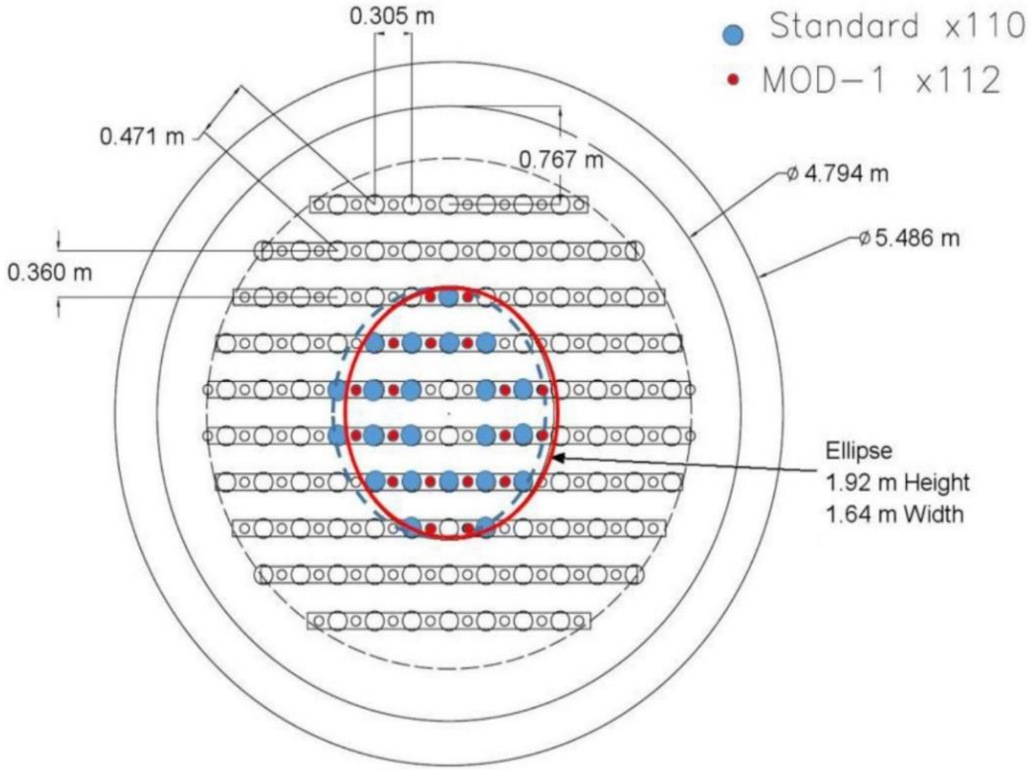


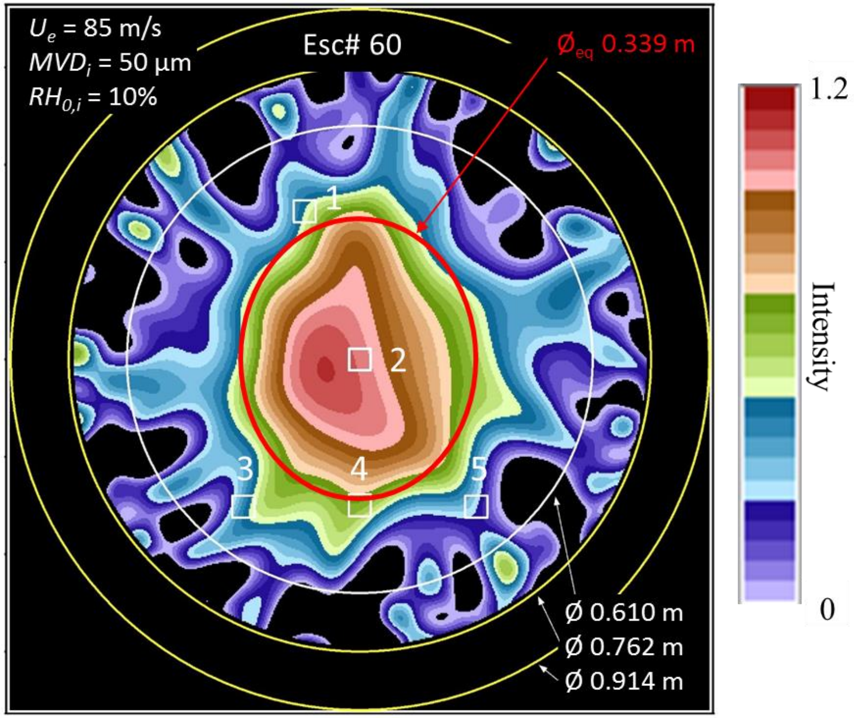
Particle Size



Total Water Content

Tomography – Icing Cloud Spread





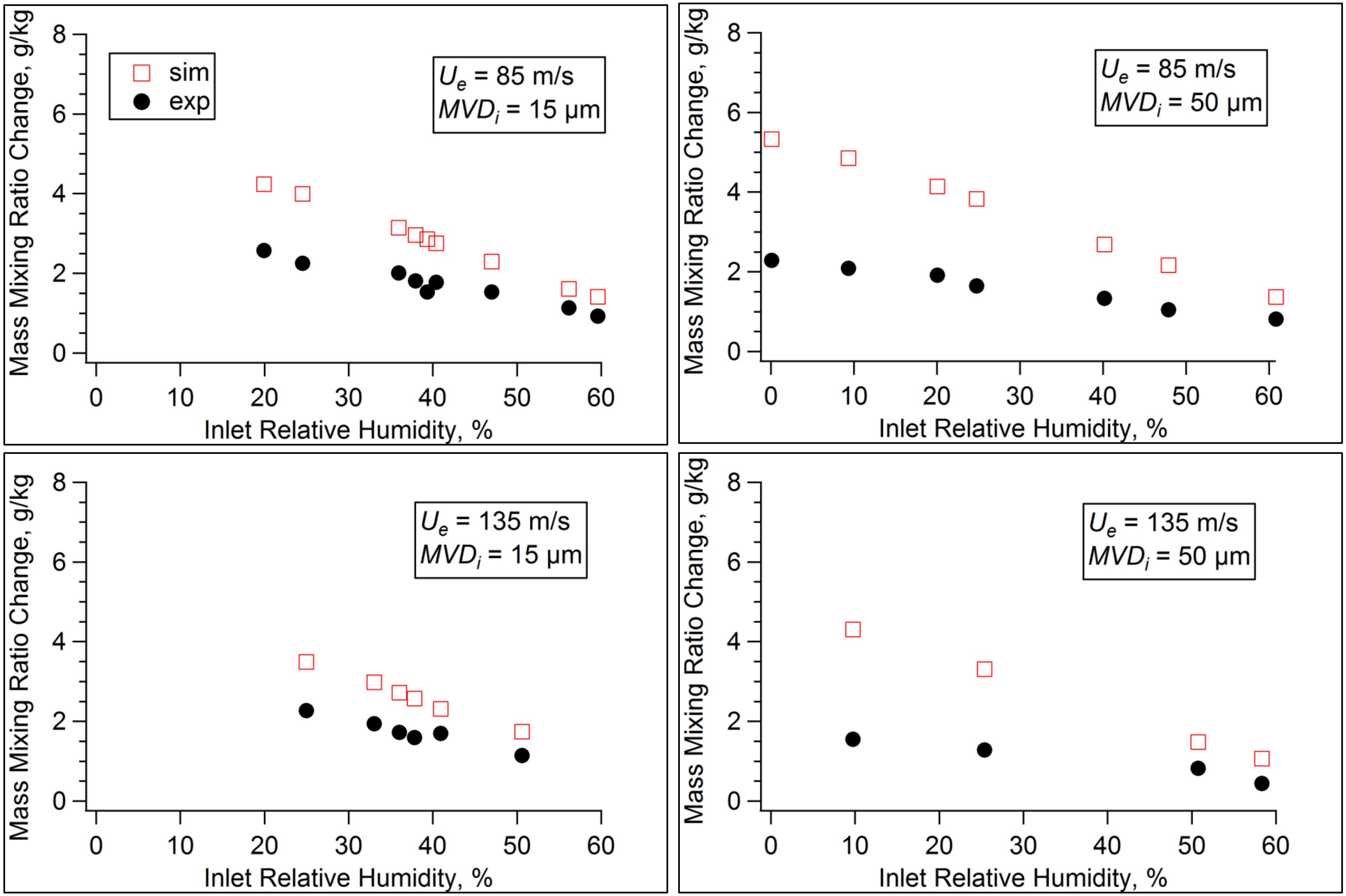
Experimental Test Conditions for 4 RH Sweeps

- Varied Parameters
  - $RH_{0,i}$ = 0% to 60%
  - MVD_i = 15 µm or 50 µm
  - U_e = 85 m/s and 135 m/s

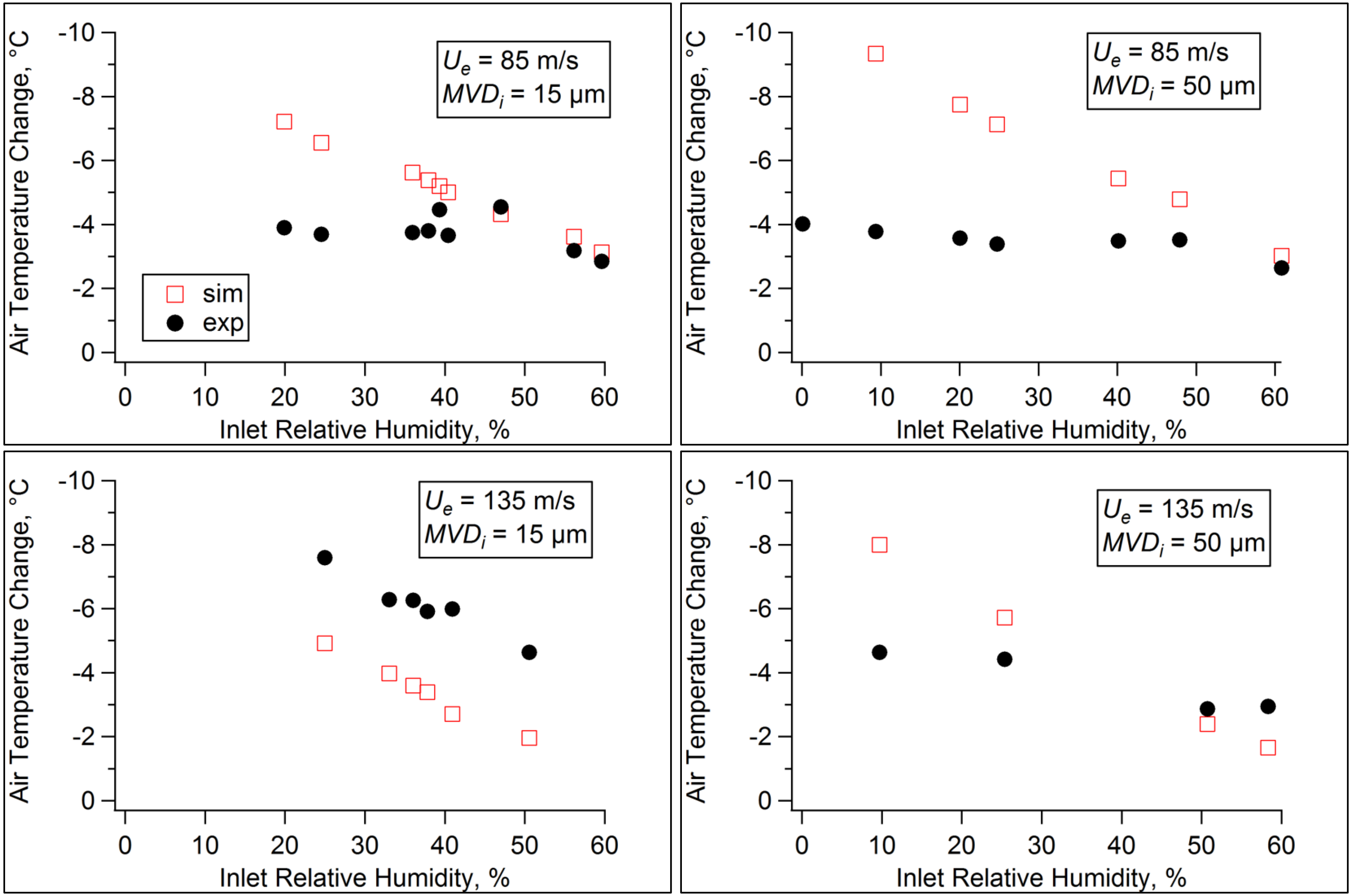
- Constant Parameters
  - $T_{0,i}$ = 7.2 ^{0}C
  - $P_{0,i}$ = 44.6 kPa
  - TWC_i = 7.0 g/m^3

- Twb Ranges
  - $Twb_{0,i}$ = -6.9 ^{O}C (0% RH)
  - $Twb_{0,i}$ = +2.4 ^{O}C (60% RH)

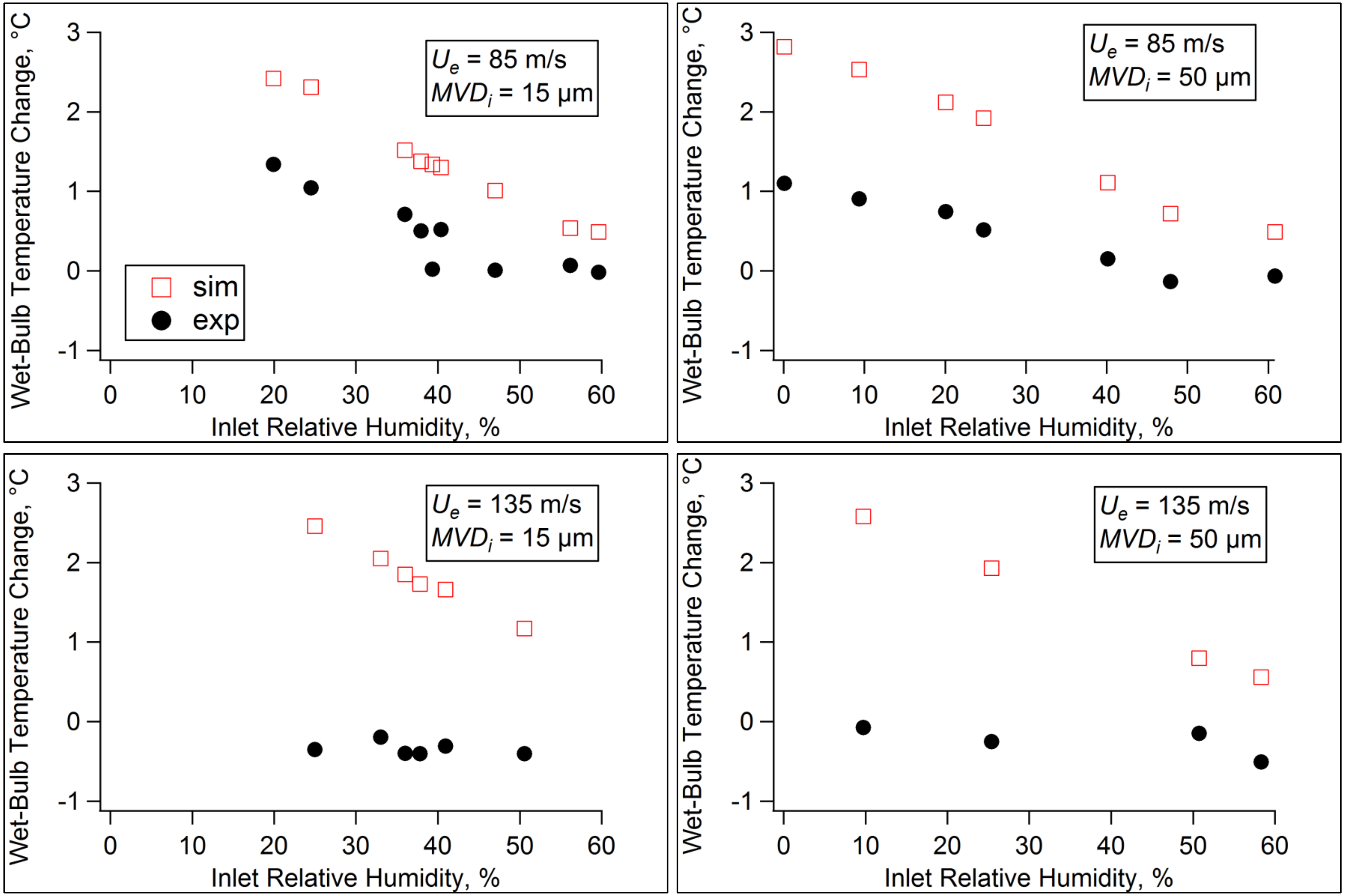
Plenum RH Sweeps - ΔHumidity



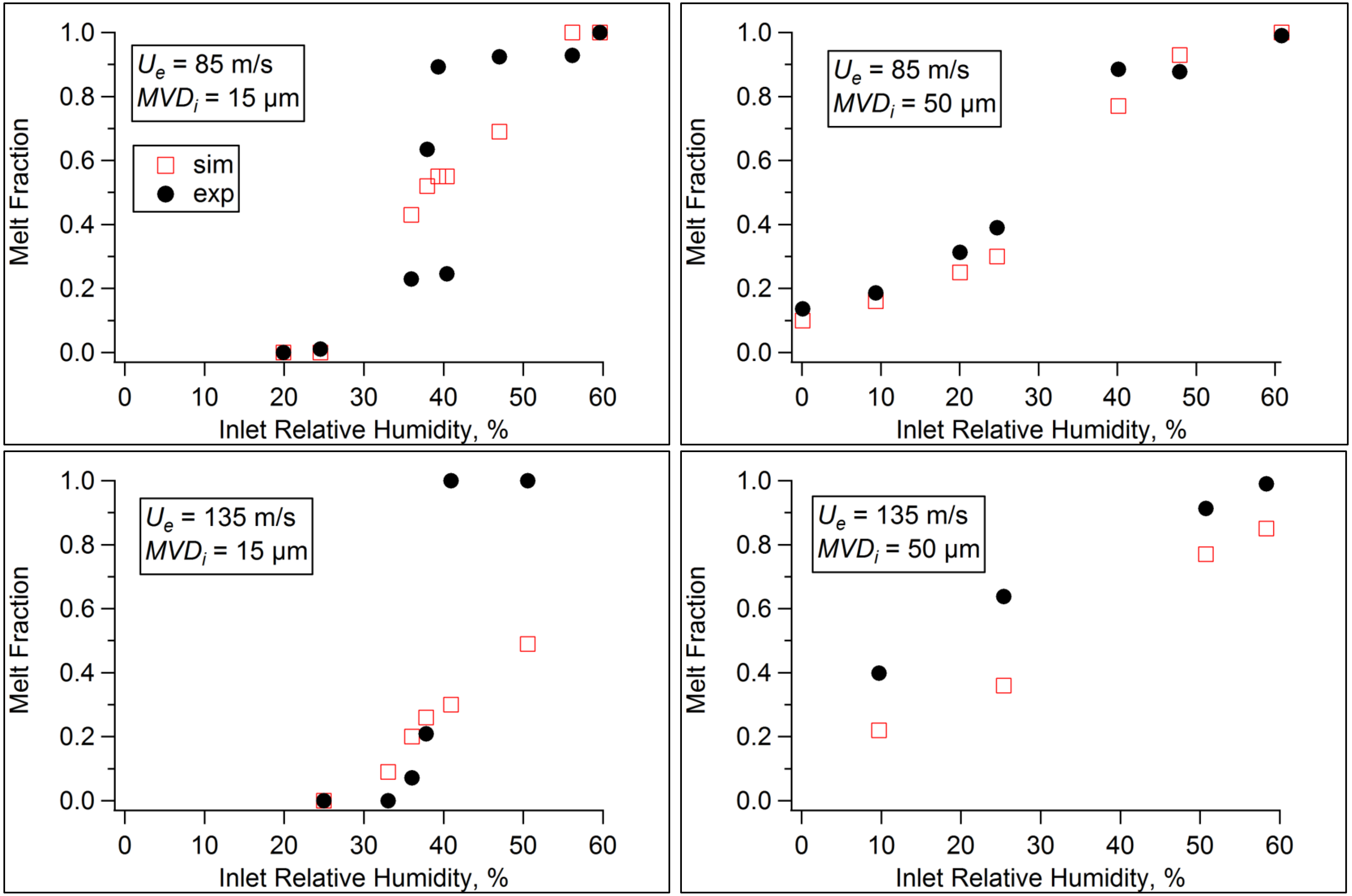
Plenum RH Sweeps - ΔT_{air}



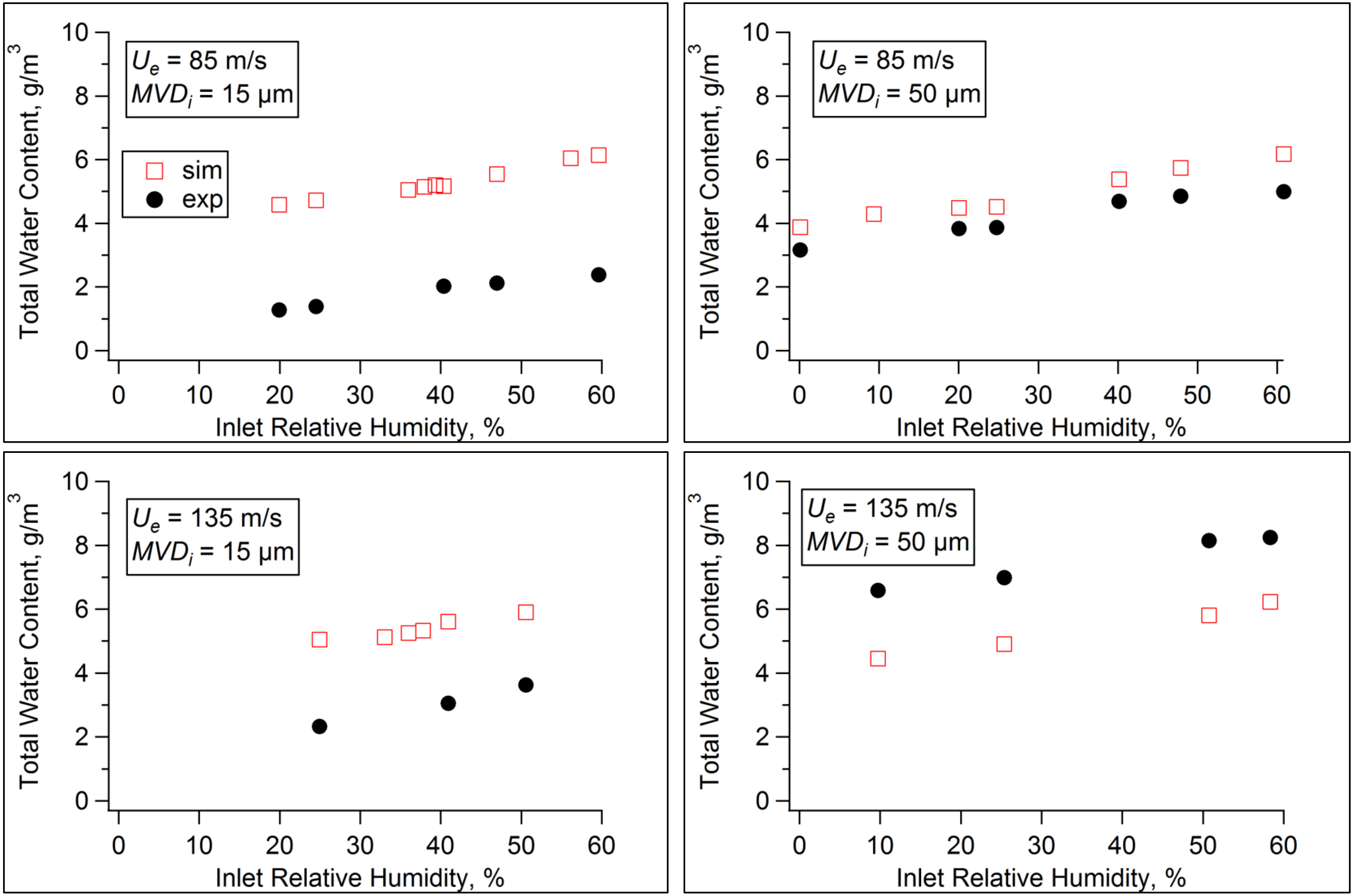
Plenum RH Sweeps - ΔTwb



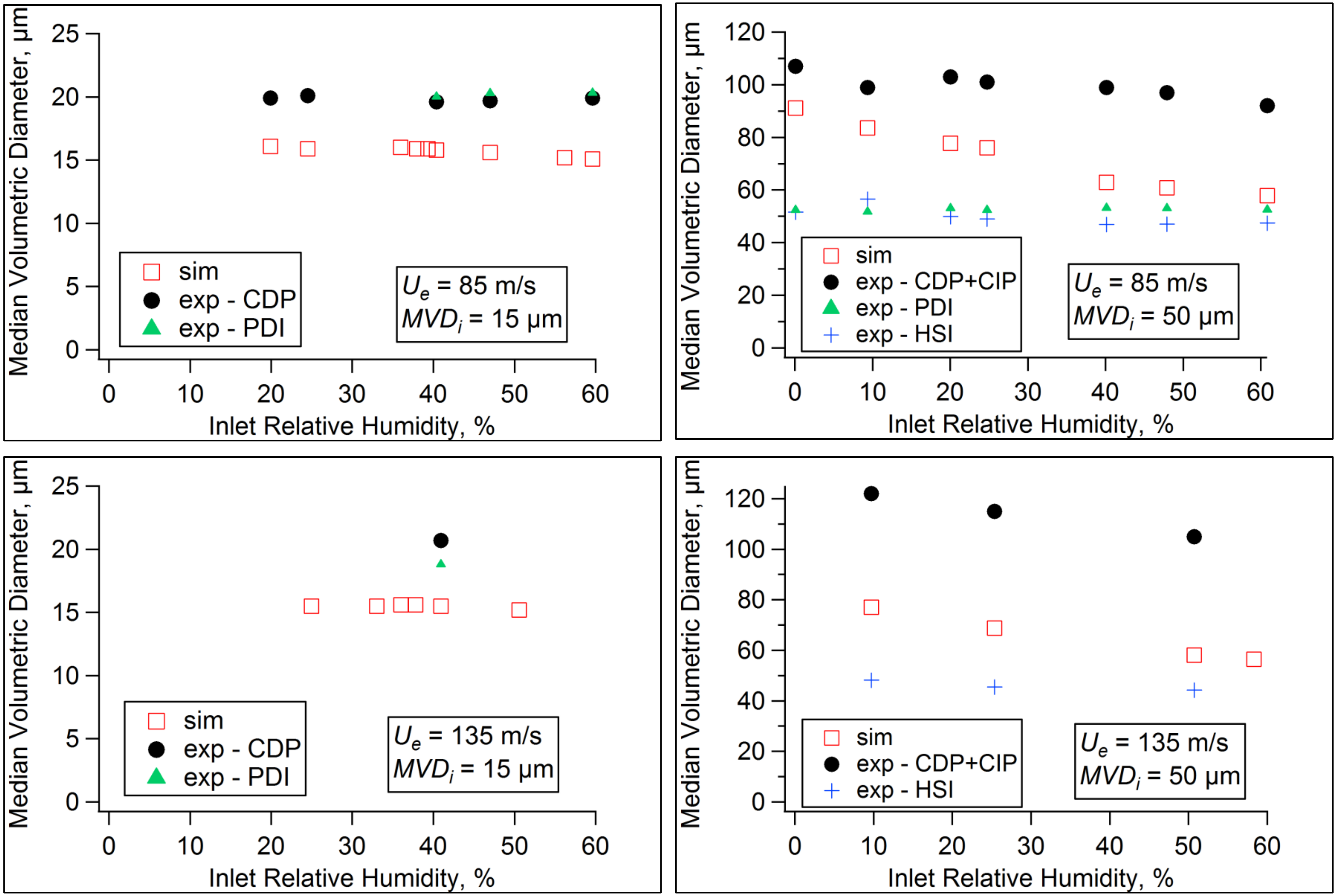
Plenum RH Sweeps – Melt Fraction



Plenum RH Sweeps - TWC



Plenum RH Sweeps - MVD



Summary

- Model written to understand Air - Cloud interactions in PSL
- Aerosol Condensation implemented for better accuracy
- Model over-predicts amount of evaporation (ΔT_{air}, Δ Hum)
  - Correct trend for varying RH
- Smaller Twb changes, important to determine cloud phase
- Good agreement for melt ratio
- TWC and MVD comparisons suggest 2D effects
- 1D model will not capture 2D cloud movement
- Provides useful predictions even as 1D
  - Model guided development of test matrix for fundamental ICI tests

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- I would like to thank my Icing Branch colleagues at NASA GRC for technical guidance.

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Simulation Results – Aerosol Parametric Analysis

Test Conditions

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