Numerical Analysis of Mixed-Phase Icing Cloud Simulations in the NASA Propulsion Systems Laboratory

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Outline

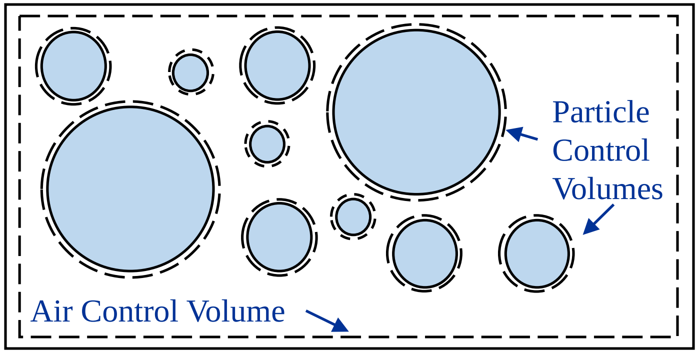
- Introduction
- Model Formulation
- Sample Simulation
- Model/Experiment Comparisons
  - Preliminary Tests to Fundamental ICI – Run May 2015 PSL
  - 3 Sweeps (TWC, RH, T_{water})
  - Particle size comparison
- Summary

Introduction

- Many engine power-loss events reported since the 1990’s
- Mason et al. hypothesized how power-loss events can result from ice crystals entering the engine core
- Ingestion of ice into engine is 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
- Model previously written to simulate NRC RATFac
- Objective: Understand the air - cloud interactions in PSL tunnel

Model Formulation – *General Description*

- Simulates PSL icing tunnel
- Model couples air and cloud particle conservation eqs
  - Mass, energy fully coupled
  - Air is treated as ideal compressible gas
  - Isentropic equations used to solve ρ_{air}, v_{air}, T_{air}, P
- Full particle size distributions used
- “air” = humid air = air + vapor



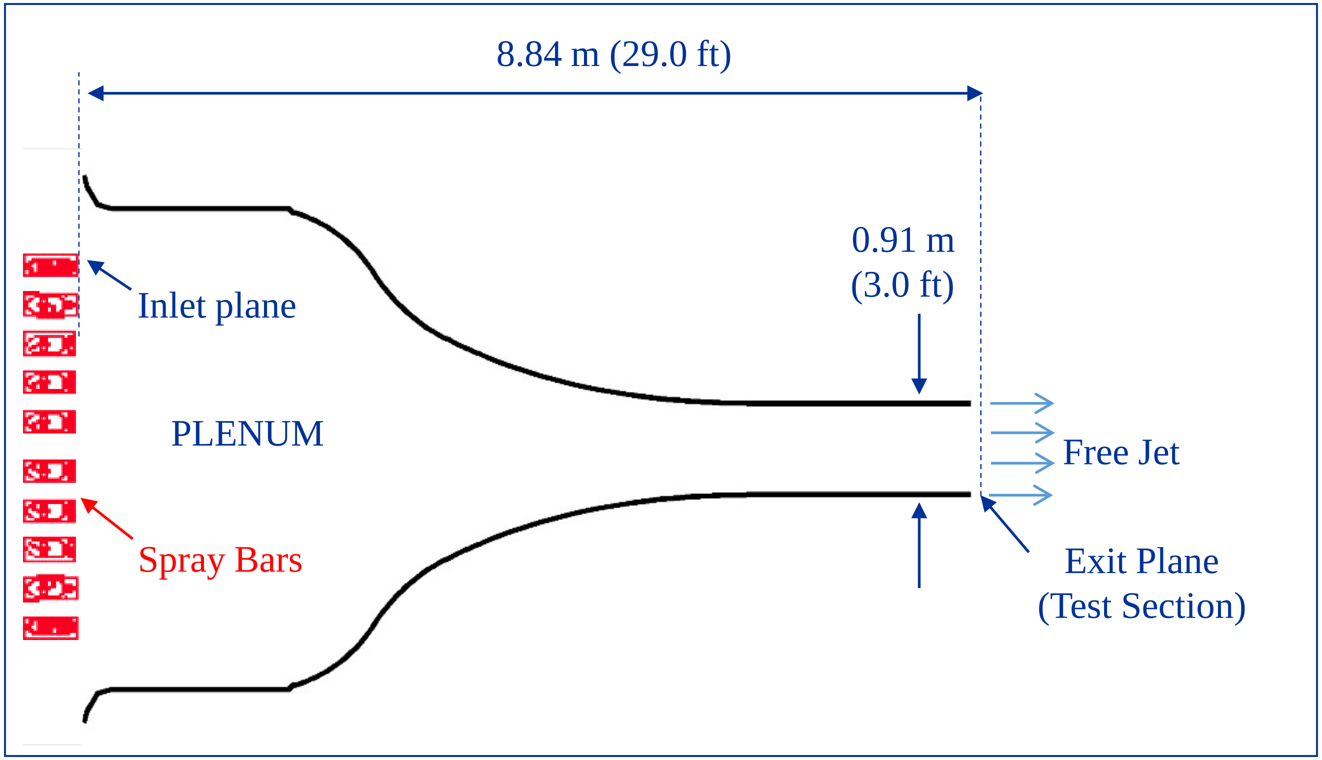
Model Formulation - *Assumptions*

- **Air and particle flow are steady and one dimensional**
- Dry air and water vapor are ideal gases
- **Air (air + vapor) is well mixed**
- Tunnel is adiabatic and mass is conserved
- Particle size distribution is characterized by a discrete set of diameters
- Particles are evenly spaced
- **All particles are perfectly spherical**
- Particle aggregation and breakup through collision are negligible
- **Particles are injected in the direction of the flow and remain entrained**
- **Temperature is uniform within the particle**
- Mixed phase particles are spatially homogeneous in water/ice content
- Evaporation, condensation occur at the particle surface at particle temperature
- The flow of particles and gas is a continuous stream

Model Formulation – *PSL Description*

Tunnel Controllability

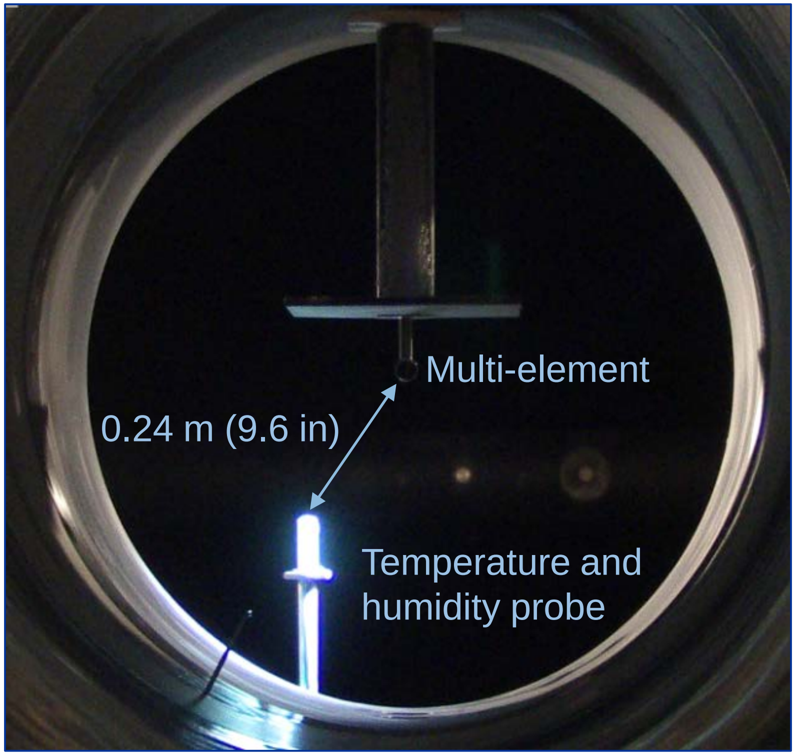
- ±0.3 kPa (.05 psia)
- ± 0.5 ^{O}C (1 ^{O}F)
- ± 1% RH



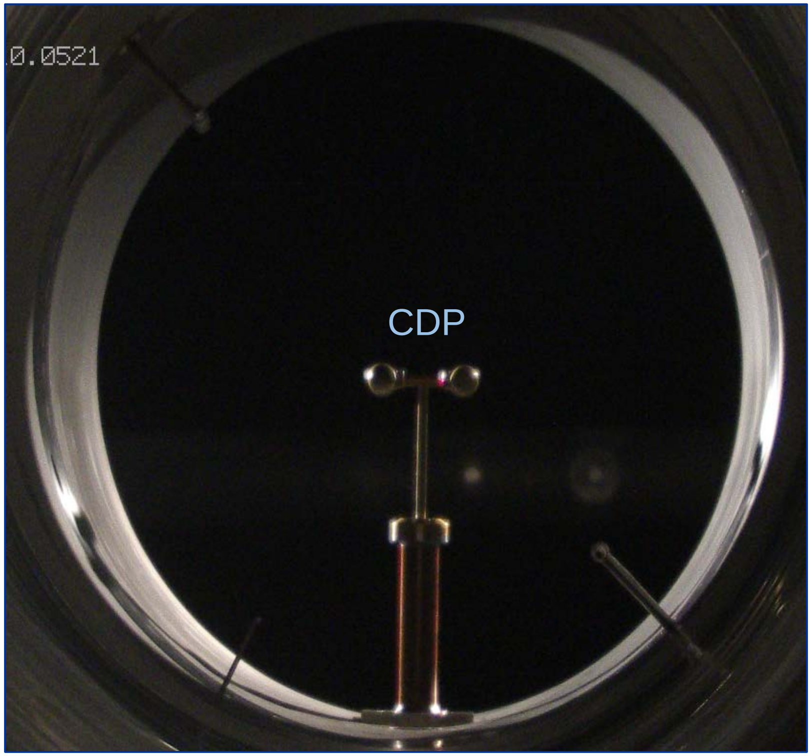
Model Formulation – *Experiment Configurations*

2 Configurations – May 2015

Multi-element Probe



Cloud Droplet Probe



Model Formulation – *Differential Expressions*

Gas

$$\frac{\partial m_{air}}{\partial x} \longleftrightarrow \frac{\partial m_p}{\partial x}$$

$$\frac{\partial v_{air}}{\partial x} \longrightarrow \frac{\partial v_p}{\partial x}$$

$$\frac{\partial T_{air}}{\partial x} \longleftrightarrow \frac{\partial T_p}{\partial x} \text{ or } \frac{\partial \eta_p}{\partial x}$$

$$\frac{\partial \rho_{air}}{\partial x}$$

$$\frac{\partial P}{\partial x}$$

Cloud

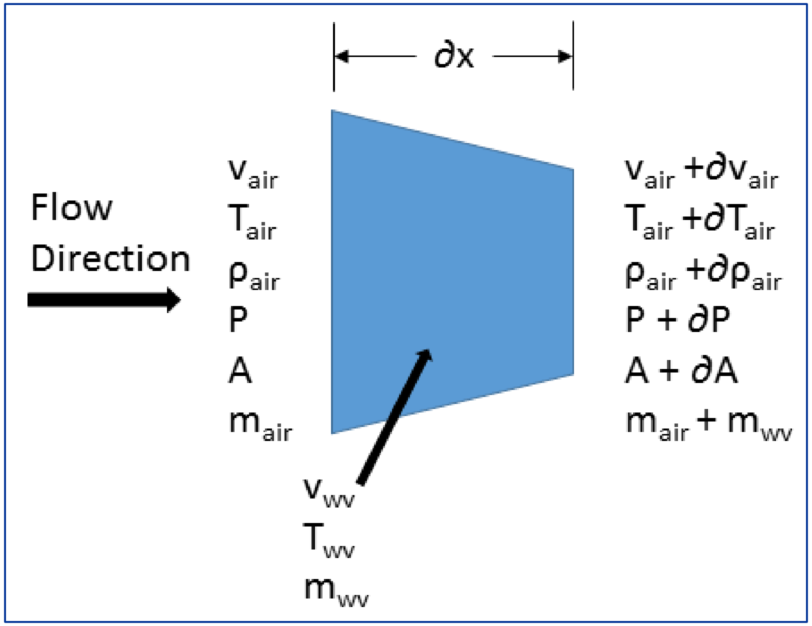
$$\frac{\partial m_p}{\partial x}$$

$$\frac{\partial v_p}{\partial x}$$

$$\frac{\partial T_p}{\partial x} \text{ or } \frac{\partial \eta_p}{\partial x}$$

Geometry

$$\frac{\partial A}{\partial x} = \text{known}$$

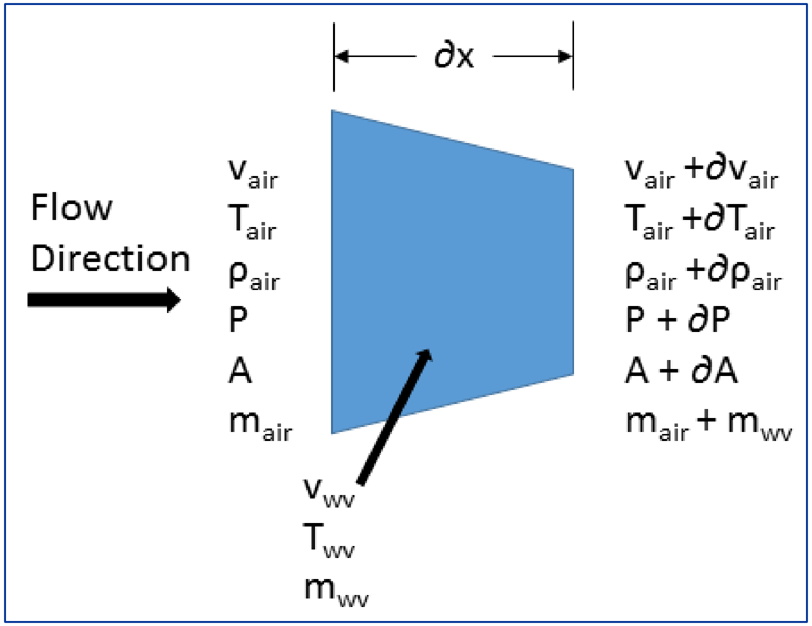


Model Formulation – *Differential Expressions*

Gas		Cloud
$\frac{\partial m_{air}}{\partial x}$	$\leftrightarrow$	$\frac{\partial m_p}{\partial x}$
$\frac{\partial v_{air}}{\partial x}$	$\rightarrow$	$\frac{\partial v_p}{\partial x}$
$\frac{\partial T_{air}}{\partial x}$	$\leftrightarrow$	$\frac{\partial T_p}{\partial x}$ or $\frac{\partial \eta_p}{\partial x}$
$\frac{\partial \rho_{air}}{\partial x}$		

Geometry

$$\frac{\partial A}{\partial x} = \text{known}$$



$$\frac{\partial P}{\partial x} = \frac{kPv_{air}(\rho_{air}Av_{air} + \dot{m}_{wv})}{(kPA - v_{air}(\rho_{air}Av_{air} + \dot{m}_{wv}))}\left(\frac{1}{A}\frac{\partial A}{\partial x} - \frac{1}{v_{ref}}\frac{\dot{m}_{wv}}{m_{air}}\right)$$

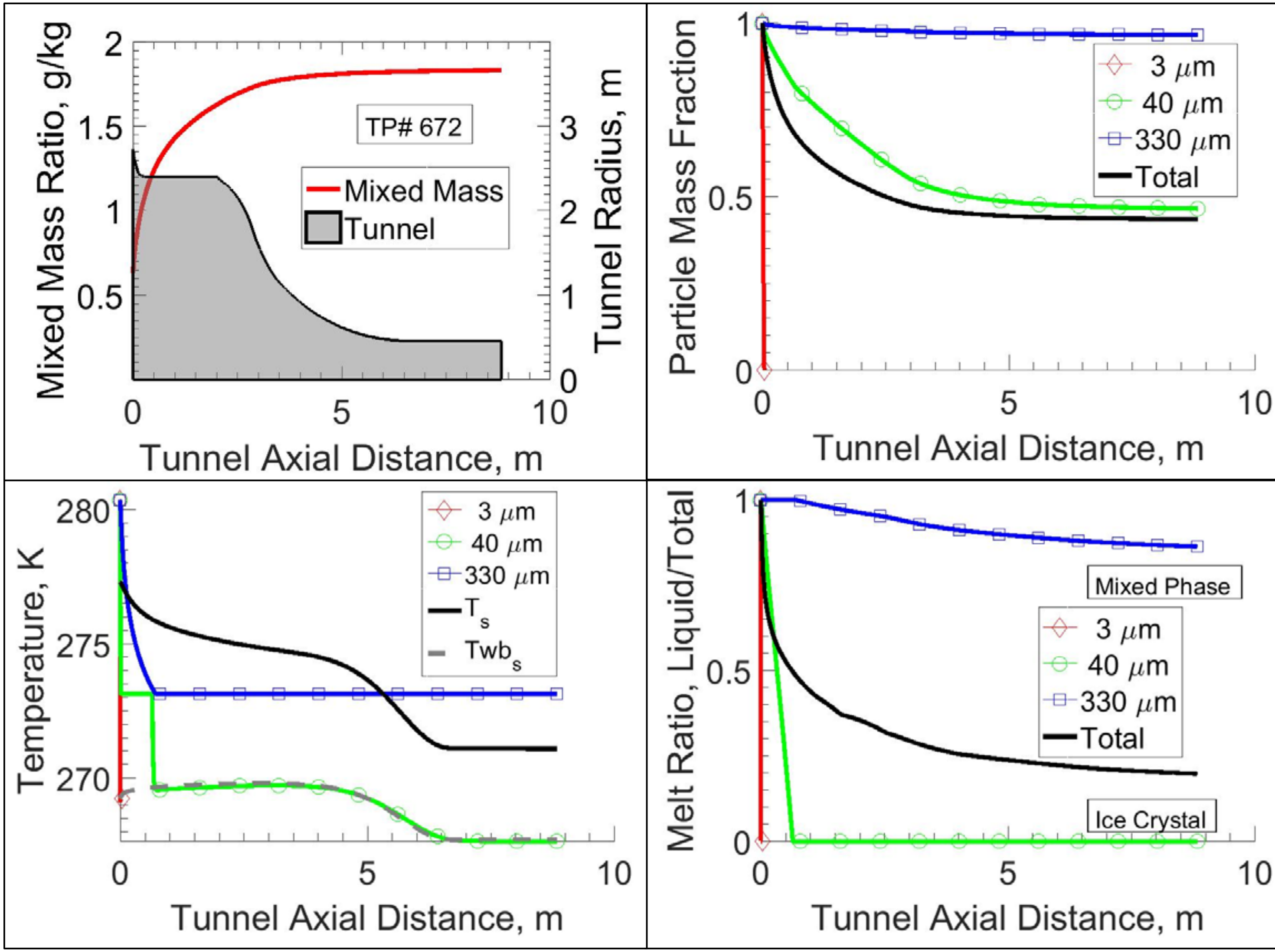
Model Formulation - *Algorithm*

- Written in MATLAB version R2015b
- 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.)

Sample Simulation

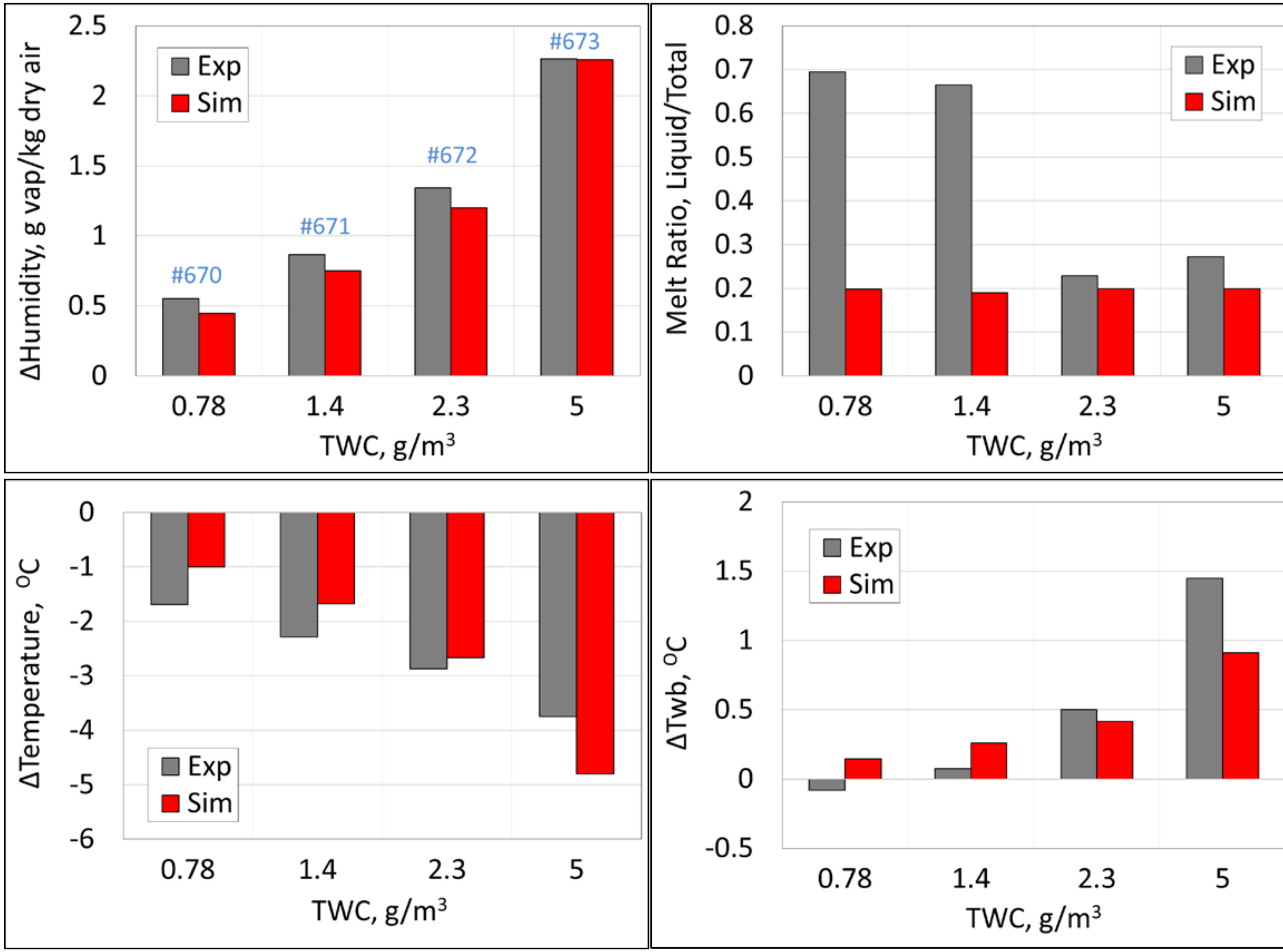
Test Conditions	
T_0 (K)	277.3
RH_0 (%)	10.8
P_0 (kPa)	87.5
v_e (m/s)	85
TWC_{bulk} (g/m^3)	2.3
T_{water} (K)	280.4
MVD (μm)	42
Twb_0 (K)	269.3

Model Results	
Res. Time (s)	1.26
$\Delta T_{0,e}$ (K)	-2.7
$\Delta \omega_e$ (g/kg)	1.2
η_e (melt ratio)	0.20
TWC$_e$ (g/m^3)	1.0
$\Delta Twb_{0,e}$ (K)	0.5



Model/Experiment Comparison – TWC_{bulk} Sweep

Target Conditions	
v_e (m/s)	85
P_0 (kPa)	87.3
T_0 (°C)	4.2
RH_0 (%)	10
MVD (μm)	40
T_{water} (°C)	7

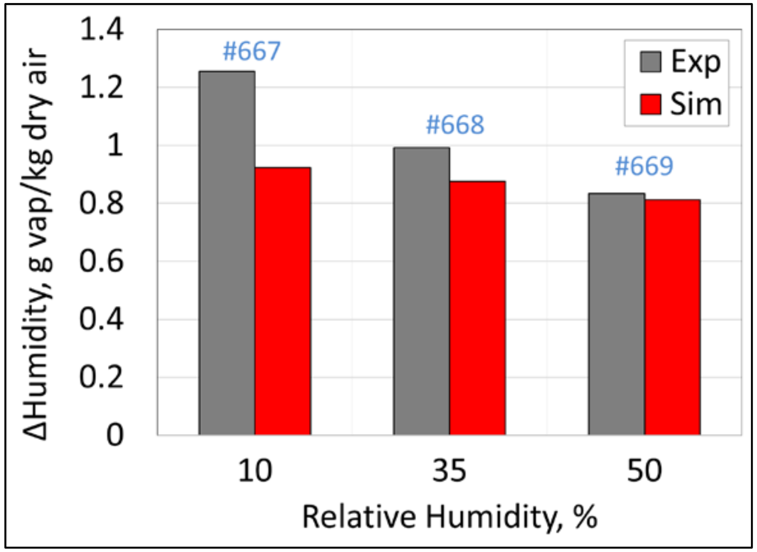


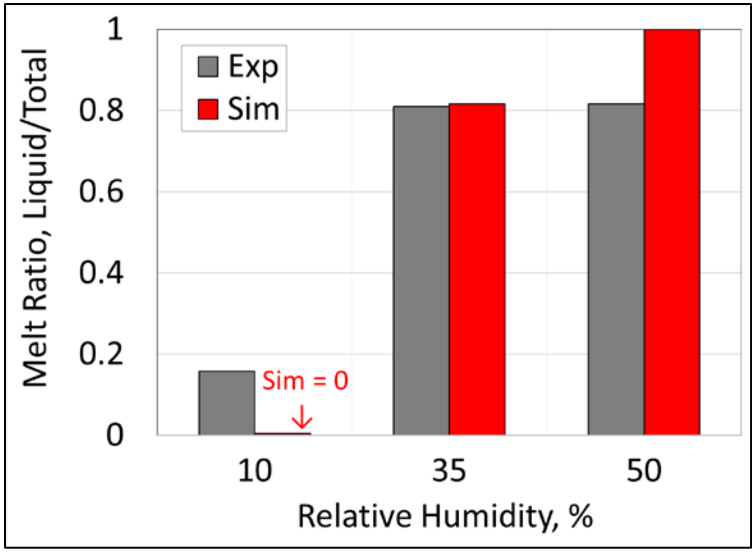
Takeaways:

- Bulk vs Point
- $\Delta\omega_{\%diff}$ ~ 30%
- $\Delta T_{\%diff}$ ~ 30%
- $\Delta Twb_{0,e}$ = slight increase

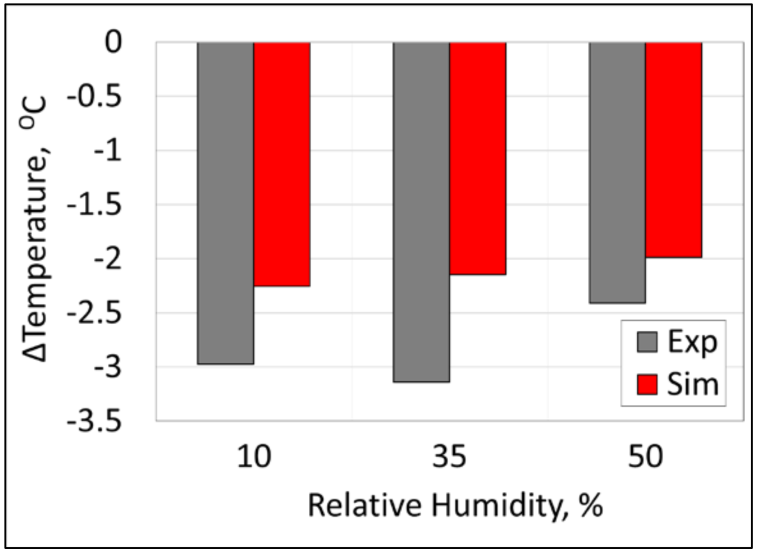
Model/Experiment Comparison – *RH* Sweep

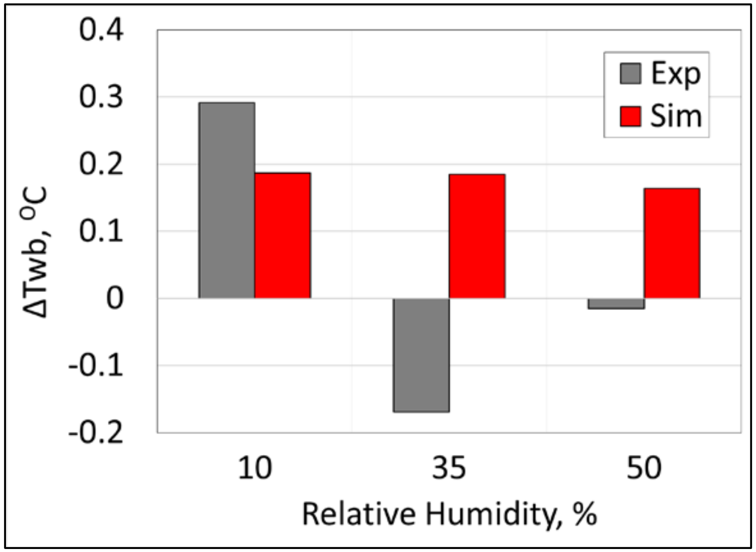
Target Conditions	
v_e (m/s)	85
P_0 (kPa)	87.2
T_0 (°C)	6.6
TWC_{bulk} (g/m^3)	1.0
MVD (μm)	15
T_{water} (°C)	7





Wet Bulb Temps		
RH_0 (%)	Twb_0 (°C)	Twb_s (°C)
10	-2.2	-4.4
35	0.6	-1.7
50	1.7	-0.6



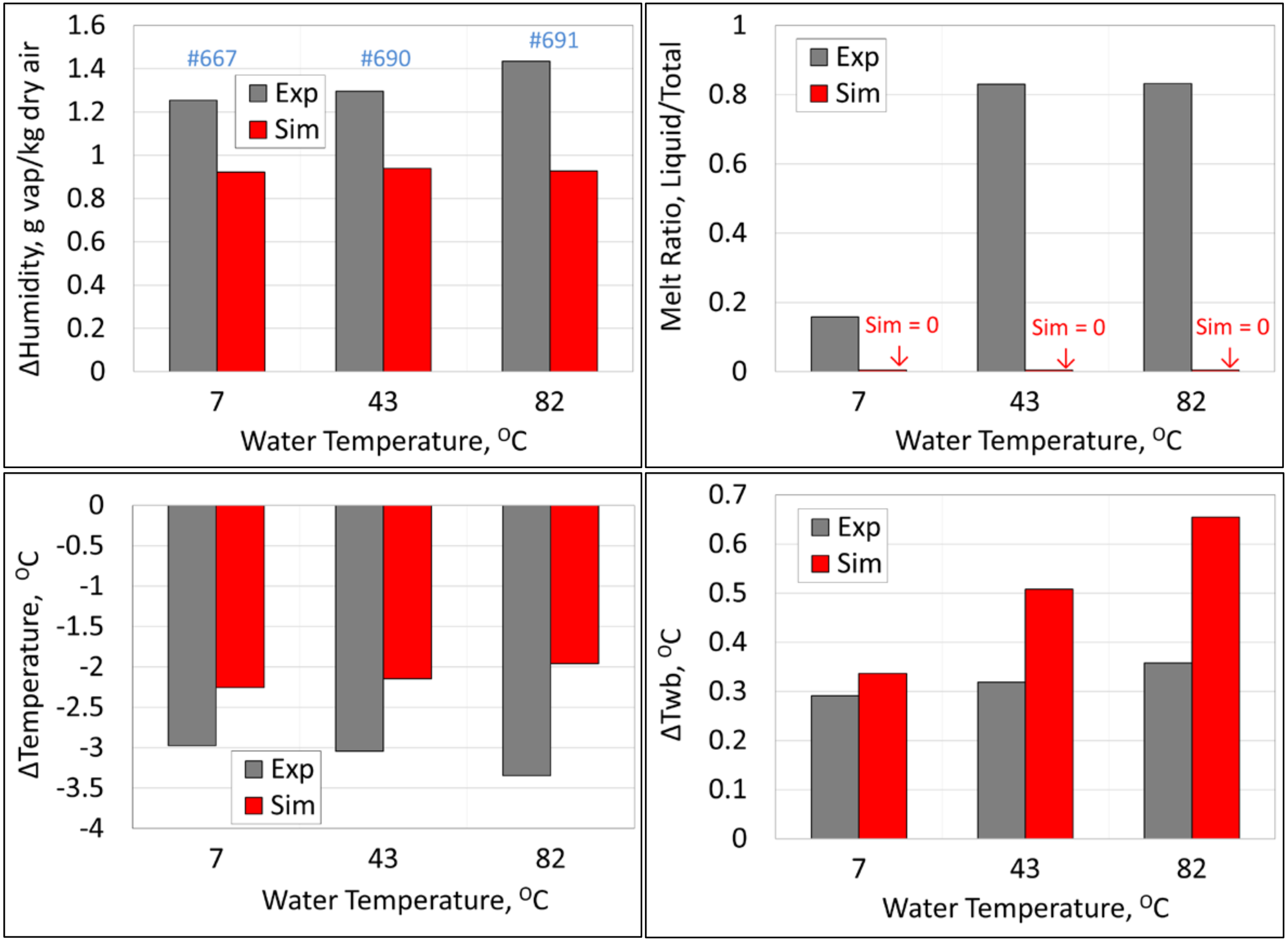


Takeaways:

- Twb_0 important
- Small RH window

Model/Experiment Comparison – T_{water} Sweep

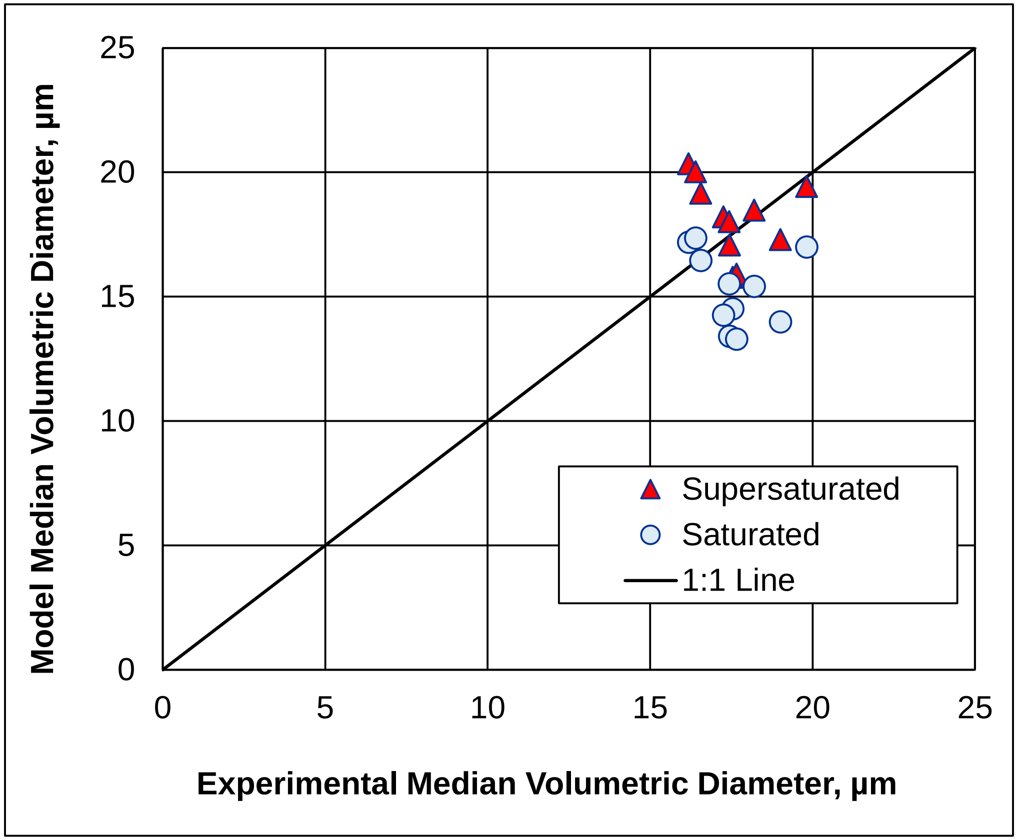
Target Conditions	
v_e (m/s)	85
P_0 (kPa)	87.2
T_0 (°C)	6.6
RH_0 (%)	10
TWC_{bulk} (g/m^3)	1.0
MVD (µm)	15



Takeaway:

- Poor melt agreement

Model/Experiment Comparison – *Particle Size*



	Min	Max
v_e (m/s)	68	192
P_s (kPa)	32.4	84.1
T_s (^{O}C)	-29	4
RH_0 (%)	40	50
T_{water} (^{O}C)	7	82
TWC_{bulk} (g/m^3)	0.5	1.3

Initial MVD = 15 μm

Takeaway: Good MVD_e agreement for MVD_i = 15 μm

Summary

- Model written to understand Air - Cloud interactions in PSL
- Model predicts to within 30% of measured changes in humidity and temperature
- Model predicted satisfactorily for melt ratio
  - Some disagreement for elevated T_{water} tests
- Good agreement with particle size measurements
- Twb_0 slight increase, important to determine cloud phase
- Model guided development of test matrix for Fundamental Physics of ICI 2016 tests

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