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 \( \rho_{\text{air}}, v_{\text{air}}, T_{\text{air}}, P \)
  – Air and particle flow are steady and one dimensional
  – Temperature is uniform within the perfectly spherical particle
  – Full particle size distributions used

\[
\begin{align*}
\frac{\partial m_{\text{air}}}{\partial x} & \quad \frac{\partial m_p}{\partial x} \\
\frac{\partial T_{\text{air}}}{\partial x} & \quad \frac{\partial T_p}{\partial x} \quad \text{or} \quad \frac{\partial \eta_p}{\partial x} \\
\frac{\partial v_{\text{air}}}{\partial x} & \quad \frac{\partial v_p}{\partial x}
\end{align*}
\]
PSL Geometry and Capabilities

Tunnel Capability
- Freeze out liquid cloud
- 12 parameters can be varied
  - $P$, $V$, $T_{\text{air}}$, $T_{\text{water}}$, RH, MVD, TWC, Water Type, Nozzle Pattern...

Tunnel Controllability
- $\pm 0.3 \text{ kPa (}.05 \text{ psia)}$
- $\pm 0.5 \text{ }^\circ\text{C (1 }^\circ\text{F)}$
- $\pm 1\% \text{ RH}$

![Diagram of tunnel configuration with specifications and annotations]
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

Cond# 101  Spray Off  $RH_{0,i} = 54\%$, $RH_{s,e,calc} = 90\%$

Cond# 102  Spray Off  $RH_{0,i} = 64\%$, $RH_{s,e,calc} = 107\%$

Cond# 103  Spray Off  $RH_{0,i} = 76\%$, $RH_{s,e,calc} = 127\%$

Cond# 105  Spray On   $RH_{0,i} = 77\%$, $RH_{s,e,calc} = 128\%$
Aerosol Particulates Background

- Organic and inorganic in composition
- Size distribution from 0.003 µm to 2.5 µm
- # density variations
  - 3,100/cm³ (Alps)
  - 100,00/cm³ (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 °C : Condense as liquid
  - Twb <= 0 °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 ($C_p$, $L_{\text{heat}}$, etc.)
**Test Conditions**

\[ T_{0,i} = 10.0 \, ^\circ C \quad U_e = 135 \, \text{m/s} \]

\[ P_{0,i} = 78.2 \, \text{kPa} \quad MVD_i = 15 \, \mu\text{m} \]

\[ RH_{0,i} = 77\% \quad TWC_i = 7.1 \, \text{g/m}^3 \]

- **Spray On**
  - \( RH_{0,i} = 77\% \quad RH_{s,e,calc} = 128\% \)
# Supersaturation Simulation Comparisons

(\(\omega = \text{mass mixing ratio}\))

| Cond # | Spray On/Off | \(T_{0,i} \) \( ^\circ \text{C} \) | \(T_{s,e,calc} \) \( ^\circ \text{C} \) | \(RH_{0,i} \) % | \(RH_{s,e,calc} \) % | \(\omega_{100\%RH} \) g/kg | \(\omega_{i,exp} \) g/kg | \(\omega_{e,exp} \) g/kg | \(\omega_{e,sim,\text{none}} \) 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            |

**Notes:**

- Cond: Experimental condition number.
- Spray: On/Off status of the spray system.
- \(T_{0,i} \) and \(T_{s,e,calc} \): Temperature values.
- \(RH_{0,i} \) and \(RH_{s,e,calc} \): Relative humidity values.
- \(\omega_{100\%RH} \) and \(\omega_{i,exp} \): Mass mixing ratios at 100% RH and experimental conditions, respectively.
- \(\omega_{e,exp} \) and \(\omega_{e,sim,\text{none/aero}} \): Mass mixing ratios from experimental and simulation results.
Experiment Configurations

- **Temp + Humidity**
  - Humidity & Temperature Traversing Probe
- **Melt Fraction**
  - Multiwire Probe
  - Temp and Humidity
  - NACA 0012 Airfoil
- **Airfoil Icing**
  - Humidity
  - Temp
- **Particle Size**
  - CDP
  - Humidity
  - Temp
- **Particle Size**
  - CIP
  - Humidity
  - Temp
- **Total Water Content**
  - IKP2
  - Humidity
  - Temp
Tomography – Icing Cloud Spread

\[ \phi_{eq} = 0.339 \, m \]

- \( U_e = 85 \, m/s \)
- \( MVD_i = 50 \, \mu m \)
- \( RH_{0,i} = 10\% \)
Experimental Test Conditions for 4 RH Sweeps

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

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

• $T_{wb}$ Ranges
  – $T_{wb0,i} = -6.9\,^\circ C$ (0% RH)
  – $T_{wb0,i} = +2.4\,^\circ C$ (60% RH)
Plenum RH Sweeps - ΔHumidity

- $U_e = 85 \text{ m/s}$
  - $MVD_i = 15 \mu m$

- $U_e = 135 \text{ m/s}$
  - $MVD_i = 15 \mu m$

- $U_e = 85 \text{ m/s}$
  - $MVD_i = 50 \mu m$

- $U_e = 135 \text{ m/s}$
  - $MVD_i = 50 \mu m$
Plenum RH Sweeps - $\Delta T_{\text{air}}$

- $U_e = 85$ m/s, $MVD_i = 15$ μm
- $U_e = 135$ m/s, $MVD_i = 15$ μm
- $U_e = 85$ m/s, $MVD_i = 50$ μm
- $U_e = 135$ m/s, $MVD_i = 50$ μm
Plenum RH Sweeps - $\Delta T_{wb}$

- $U_e = 85$ m/s, $MVD_i = 15$ μm

- $U_e = 85$ m/s, $MVD_i = 50$ μm

- $U_e = 135$ m/s, $MVD_i = 15$ μm

- $U_e = 135$ m/s, $MVD_i = 50$ μm
Plenum RH Sweeps – Melt Fraction

For $U_e = 85$ m/s and $MVD_i = 15 \mu$m:

- Melt Fraction vs. Inlet Relative Humidity (%)
  - Black dots: experiment
  - Red squares: simulation

For $U_e = 85$ m/s and $MVD_i = 50 \mu$m:

- Melt Fraction vs. Inlet Relative Humidity (%)
  - Black dots: experiment
  - Red squares: simulation

For $U_e = 135$ m/s and $MVD_i = 15 \mu$m:

- Melt Fraction vs. Inlet Relative Humidity (%)
  - Black dots: experiment
  - Red squares: simulation

For $U_e = 135$ m/s and $MVD_i = 50 \mu$m:

- Melt Fraction vs. Inlet Relative Humidity (%)
  - Black dots: experiment
  - Red squares: simulation
Plenum RH Sweeps - TWC

- $U_e = 85 \text{ m/s}$
  - $MVD_i = 15 \text{ µm}$
  - $MVD_i = 50 \text{ µm}$

- $U_e = 135 \text{ m/s}$
  - $MVD_i = 15 \text{ µm}$
  - $MVD_i = 50 \text{ µm}$
Plenum RH Sweeps - MVD

Median Volumetric Diameter, μm

Inlet Relative Humidity, %

$U_e = 85 \text{ m/s}$

$MVD_i = 15 \mu$m

$U_e = 85 \text{ m/s}$

$MVD_i = 50 \mu$m

Median Volumetric Diameter, μm

Inlet Relative Humidity, %

$U_e = 135 \text{ m/s}$

$MVD_i = 15 \mu$m

$U_e = 135 \text{ m/s}$

$MVD_i = 50 \mu$m
Summary

- Model written to understand Air - Cloud interactions in PSL
- Aerosol Condensation implemented for better accuracy
- Model over-predicts amount of evaporation ($\Delta T_{air}$, $\Delta$ 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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Simulation Results – Aerosol Parametric Analysis

Test Conditions

\[ T_{0,i} = 10.0 \, ^{\circ}\text{C} \quad U_e = 135 \, \text{m/s} \]
\[ P_{0,i} = 78.2 \, \text{kPa} \quad MVD_i = 15 \, \mu\text{m} \]
\[ RH_{0,i} = 77\% \quad TWC_i = 7.1 \, \text{g/m}^3 \]

Aerosol Parameters

\# Density = 22,000/cm\(^3\) \quad \text{Initial Size} = 0.04 \, \mu\text{m}

Aerosol Number Density, #/cm\(^3\)

Final Relative Humidity, %

140 \quad 138 \quad 136 \quad 132 \quad 116

1.0E+03 1.0E+04 1.0E+05 1.0E+06

Initial Aerosol Diameter, nm

Final Relative Humidity, %

132.4 \quad 132.2 \quad 131.5

0 500 1000 1500