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

\[
\frac{\partial m_{\text{air}}}{\partial x} \quad \frac{\partial m_p}{\partial x}
\]

\[
\frac{\partial T_{\text{air}}}{\partial x} \quad \frac{\partial T_p}{\partial x} \text{ or } \frac{\partial \eta_p}{\partial x}
\]

\[
\frac{\partial v_{\text{air}}}{\partial x} \quad \frac{\partial v_p}{\partial x}
\]
PSL Geometry and Capabilities

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

**Tunnel Controllability**
- $\pm 0.3 \text{ kPa} (0.05 \text{ psia})$
- $\pm 0.5 ^\circ \text{C} (1 ^\circ \text{F})$
- $\pm 1\% \text{ RH}$
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

\[ \text{RH}_s = 76\% \quad U = 3 \text{ m/s} \]

\[ \text{RH}_s = 127\% \quad U = 135 \text{ m/s} \]
Condensation Cloud Experiments

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

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

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

Cond# 105      Spray On
\( RH_{0,i} = 77\% \quad RH_{s,e,calc} = 128\% \)
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.)
Supersaturation Simulation Profiles

**Test Conditions**

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

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

<table>
<thead>
<tr>
<th>Cond #</th>
<th>Spray</th>
<th>$T_{0,i}$</th>
<th>$T_{s,e,calc}$</th>
<th>$RH_{0,i}$</th>
<th>$RH_{s,e,calc}$</th>
<th>$\omega_{100%RH}$</th>
<th>$\omega_{i,exp}$</th>
<th>$\omega_{e,exp}$</th>
<th>$\omega_{e,sim,none}$</th>
<th>$\omega_{e,sim,aero}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>Off</td>
<td>10.9</td>
<td>1.8</td>
<td>64</td>
<td>107</td>
<td>5.61</td>
<td>6.01</td>
<td>5.99</td>
<td>6.01</td>
<td>6.00</td>
</tr>
<tr>
<td>103</td>
<td>Off</td>
<td>10.1</td>
<td>1.1</td>
<td>76</td>
<td>127</td>
<td>5.34</td>
<td>6.87</td>
<td>6.35</td>
<td>6.87</td>
<td>6.79</td>
</tr>
<tr>
<td>105</td>
<td>On</td>
<td>10.0</td>
<td>1.0</td>
<td>77</td>
<td>128</td>
<td>5.30</td>
<td>6.81</td>
<td>6.42</td>
<td>7.15</td>
<td>6.94</td>
</tr>
</tbody>
</table>

![Cond # 102](image1.png) ![Cond # 103](image2.png) ![Cond # 105](image3.png)
## Experiment Configurations

<table>
<thead>
<tr>
<th>Temp + Humidity</th>
<th>Melt Fraction</th>
<th>Airfoil Icing</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Temp + Humidity" /></td>
<td><img src="image2" alt="Melt Fraction" /></td>
<td><img src="image3" alt="Airfoil Icing" /></td>
</tr>
</tbody>
</table>

- **Temp + Humidity**
  - Humidity & Temperature Traversing Probe

- **Melt Fraction**
  - Temp
  - Multiwire
  - Humidity

- **Airfoil Icing**
  - NACA 0012 Airfoil
  - Humidity
  - Temp

- **Particle Size**
  - Humidity
  - CDP

- **Particle Size**
  - Humidity
  - CIP

- **Total Water Content**
  - Humidity
  - IKP2
  - Temp
Tomography – Icing Cloud Spread

$U_e = 85 \text{ m/s}$
$MVD_i = 50 \text{ \mu m}$
$RH_{0,i} = 10\%$

$\phi_{eq} = 0.339 \text{ m}$

$\phi = 0.610 \text{ m}$
$\phi = 0.762 \text{ m}$
$\phi = 0.914 \text{ m}$
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**
  - $T_{0,i} = 7.2\, ^0C$
  - $P_{0,i} = 44.6\, kPa$
  - $TWC_i = 7.0\, g/m^3$

- **Twb Ranges**
  - $Twb_{0,i} = -6.9\, ^0C$ (0% RH)
  - $Twb_{0,i} = +2.4\, ^0C$ (60% RH)
Plenum RH Sweeps - $\Delta$Humidity

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

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

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

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

- For $U_e = 85 \text{ m/s}$ and $MVD_i = 15 \mu\text{m}$:
  - The air temperature change shows a trend with changes in inlet relative humidity.
  - The graph indicates a decrease in temperature with increasing humidity.

- For $U_e = 85 \text{ m/s}$ and $MVD_i = 50 \mu\text{m}$:
  - Similarly, the air temperature change is observed to decrease with humidity.

- For $U_e = 135 \text{ m/s}$ and $MVD_i = 15 \mu\text{m}$:
  - The trend is consistent with lower temperature changes at higher relative humidities.

- For $U_e = 135 \text{ m/s}$ and $MVD_i = 50 \mu\text{m}$:
  - The graph shows a less pronounced trend compared to the previous cases.

The data points are color-coded to distinguish between simulation (sim) and experiment (exp) results.
Plenum RH Sweeps - $\Delta Twb$

- $U_e = 85 \text{ m/s}$, $MVD_i = 15 \mu\text{m}$
- $U_e = 135 \text{ m/s}$, $MVD_i = 15 \mu\text{m}$
- $U_e = 85 \text{ m/s}$, $MVD_i = 50 \mu\text{m}$
- $U_e = 135 \text{ m/s}$, $MVD_i = 50 \mu\text{m}$
Plenum RH Sweeps – Melt Fraction

- $U_e = 85 \text{ m/s}$
  - $MVD_i = 15 \mu\text{m}$
  - Melt Fraction vs. Inlet Relative Humidity, %

- $U_e = 85 \text{ m/s}$
  - $MVD_i = 50 \mu\text{m}$
  - Melt Fraction vs. Inlet Relative Humidity, %

- $U_e = 135 \text{ m/s}$
  - $MVD_i = 15 \mu\text{m}$
  - Melt Fraction vs. Inlet Relative Humidity, %

- $U_e = 135 \text{ m/s}$
  - $MVD_i = 50 \mu\text{m}$
  - Melt Fraction vs. Inlet Relative Humidity, %
Plenum RH Sweeps - TWC

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

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

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

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

- Median Volumetric Diameter, µm
- Inlet Relative Humidity, %

For $U_e = 85$ m/s:
- $MVD_i = 15$ µm

For $U_e = 135$ m/s:
- $MVD_i = 15$ µm

Legend:
- sim
- exp - CDP
- exp - PDI
- exp - CDP+CIP
- exp - PDI
- exp - HSI
Summary

- Model written to understand Air - Cloud interactions in PSL
- Aerosol Condensation implemented for better accuracy
- Model over-predicts amount of evaporation ($\Delta T_{\text{air}}$, $\Delta \text{Hum}$)
  - 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
Acknowledgments

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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**

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

**Aerosol Parameters**

- Density = 22,000/cm³
- Initial Size = 0.04 µm

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![Graph A](image1)

**Graph A**

Final Relative Humidity, %

- Aerosol Number Density, #/cm³

![Graph B](image2)

**Graph B**

Final Relative Humidity, %

- Initial Aerosol Diameter, nm

Values:

- B: 132.4, 132.3, 132.2, 131.5