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

\[
\begin{align*}
\frac{\partial m_{\text{air}}}{\partial x} & \quad \frac{\partial m_p}{\partial x} \\
\frac{\partial T_{\text{air}}}{\partial x} & \quad \frac{\partial T_p}{\partial x} \text{ or } \frac{\partial \eta_p}{\partial x} \\
\frac{\partial v_{\text{air}}}{\partial x} & \quad \frac{\partial v_p}{\partial x}
\end{align*}
\]
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 psia)
- \( \pm 0.5 \text{ °C} \) (1 °F)
- \( \pm 1\% \) 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

\[ \text{RH}_s = 76\% \quad U = 3 \text{ m/s} \]
\[ \text{RH}_s = 127\% \quad U = 135 \text{ m/s} \]
Condensation Cloud Experiments

Cond# 101      Spray Off  RH$_{0,i}$ = 54%  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/cm³ (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**

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

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

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

<table>
<thead>
<tr>
<th>Cond #</th>
<th>Spray</th>
<th>On/Off</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>
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</thead>
<tbody>
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<td>Off</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>
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<tr>
<td>103</td>
<td>Off</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>
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<tr>
<td>105</td>
<td>On</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>

[Images of Cond #102, Cond #103, Cond #105]
Experiment Configurations

- Temp + Humidity
- Melt Fraction
- Airfoil Icing

- Particle Size
- Particle Size
- Total Water Content
Tomography – Icing Cloud Spread

\[ U_e = 85 \text{ m/s} \]
\[ MVD_i = 50 \mu \text{m} \]
\[ RH_{0,i} = 10\% \]
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
  – $T_{0,i} = 7.2\ ^\circ C$
  – $P_{0,i} = 44.6\ kPa$
  – $TWC_i = 7.0\ g/m^3$

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

- $U_e = 85$ 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 - $\Delta T_{air}$

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

- For $U_e = 85$ m/s and $MVD_i = 15$ $\mu$m:
  - Simulated data (red squares) compared to experimental data (black circles).

- For $U_e = 135$ m/s and $MVD_i = 15$ $\mu$m:
  - Similar data pattern as above.

- For $U_e = 85$ m/s and $MVD_i = 50$ $\mu$m:
  - No significant change in wet-bulb temperature change.

- For $U_e = 135$ m/s and $MVD_i = 50$ $\mu$m:
  - Similar to previous case, with no clear trend.
Plenum RH Sweeps – Melt Fraction

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

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

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

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

- $U_e = 85 \text{ m/s} \quad MVD_i = 15 \mu\text{m}$
  - Sim: □
  - Exp: ●

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

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

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

- For $U_e = 85 \text{ m/s}$ and $MVD_i = 15 \mu m$:
  - Simulations (red squares)
  - Experimental results:
    - CDP (black circles)
    - PDI (green triangles)

- For $U_e = 85 \text{ m/s}$ and $MVD_i = 50 \mu m$:
  - Simulations (red squares)
  - Experimental results:
    - CDP+CIP (black circles)
    - PDI (green triangles)
    - HSI (blue pluses)

- For $U_e = 135 \text{ m/s}$ and $MVD_i = 15 \mu m$:
  - Simulations (red squares)
  - Experimental results:
    - CDP (black circles)
    - PDI (green triangles)

- For $U_e = 135 \text{ m/s}$ and $MVD_i = 50 \mu m$:
  - Simulations (red squares)
  - Experimental results:
    - CDP+CIP (black circles)
    - HSI (blue pluses)
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**

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**Aerosol Parameters**

\# Density = 22,000/cm³  \quad \text{Initial Size} = 0.04 \, \mu\text{m}