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

Tadas Bartkus, Jen-Ching Tsao
Ohio Aerospace Institute

Peter Struk
NASA Glenn Research Center

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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

\[
\begin{align*}
\frac{\partial m_{\text{air}}}{\partial x} & \quad \text{Air} \quad \frac{\partial m_p}{\partial x} \\
\frac{\partial T_{\text{air}}}{\partial x} & \quad \text{Cloud} \quad \frac{\partial T_p}{\partial x} \quad \text{or} \quad \frac{\partial \eta_p}{\partial x} \\
\frac{\partial v_{\text{air}}}{\partial x} & \quad \frac{\partial v_p}{\partial x}
\end{align*}
\]
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**
- $\pm 0.3 \text{ kPa } (.05 \text{ psia})$
- $\pm 0.5 \text{ °C } (1 \text{ °F})$
- $\pm 1\% \text{ RH}$

![Diagram of Tunnel Geometry and Capabilities](image-url)
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

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

\[ \text{RH}_s = 127\% \]
\[ U = 135 \text{ m/s} \]
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/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 °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**

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

Spray On  $RH_{0,i} = 77%$  $RH_{s,e,calc} = 128%$
## Supersaturation Simulation Comparisons

(\(\omega\) = 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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<tr>
<td>102</td>
<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>
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<td>6.87</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:**
- **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

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

$MVD_i = 50 \mu\text{m}$

$RH_{0,i} = 10\%$

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

$\varnothing 0.610 \text{ m}$

$\varnothing 0.762 \text{ m}$

$\varnothing 0.914 \text{ m}$
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
  – $T_{0,i} = 7.2 \ ^oC$
  – $P_{0,i} = 44.6 \ kPa$
  – $TWC_i = 7.0 \ g/m^3$

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

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

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

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

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

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

- $U_e = 85$ 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 – Melt Fraction

$U_e = 85$ 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

Inlet Relative Humidity, %
Plenum RH Sweeps - TWC

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

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

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

- $U_e = 135 \text{ m/s}$
- $MVD_i = 50 \text{ μm}$

Total Water Content, g/m³

Inlet Relative Humidity, %
Plenum RH Sweeps - MVD

- For $U_e = 85$ m/s, $MVD_i = 15$ µm
- For $U_e = 135$ m/s, $MVD_i = 15$ µm
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 $T_{wb}$ 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.
Simulation Results – Aerosol Parametric Analysis

**Test Conditions**

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

**Aerosol Parameters**

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

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Aerosol Number Density, #/cm³

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Initial Aerosol Diameter, nm