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, Twater)
  • 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 $\rho_{\text{air}}$, $v_{\text{air}}$, $T_{\text{air}}$, $P$
- 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 °C (1 °F)
- ± 1% RH
Model Formulation – Experiment Configurations

2 Configurations – May 2015

Multi-element Probe

Cloud Droplet Probe

0.24 m (9.6 in)
# Model Formulation – *Differential Expressions*

## Gas

\[
\frac{\partial m_{\text{air}}}{\partial x} \quad \frac{\partial v_{\text{air}}}{\partial x} \quad \frac{\partial T_{\text{air}}}{\partial x} \quad \frac{\partial \rho_{\text{air}}}{\partial x} \quad \frac{\partial P}{\partial x}
\]

## Cloud

\[
\frac{\partial m_{p}}{\partial x} \quad \frac{\partial v_{p}}{\partial x} \quad \frac{\partial T_{p}}{\partial x} \quad \frac{\partial \eta_{p}}{\partial x}
\]

## Geometry

\[
\frac{\partial A}{\partial x} = \text{known}
\]

![Diagram showing flow direction and change in variables]

- Flow Direction:
  - \( v_{\text{air}} \rightarrow v_{\text{air}} + \partial v_{\text{air}} \)
  - \( T_{\text{air}} \rightarrow T_{\text{air}} + \partial T_{\text{air}} \)
  - \( \rho_{\text{air}} \rightarrow \rho_{\text{air}} + \partial \rho_{\text{air}} \)
  - \( P + \partial P \)
  - \( A + \partial A \)
  - \( m_{\text{air}} + m_{\text{wv}} \)

- \( v_{\text{wv}} \)
- \( T_{\text{wv}} \)
- \( m_{\text{wv}} \)
Model Formulation – Differential Expressions

\[
\begin{align*}
\frac{\partial m_{\text{air}}}{\partial x} & = \frac{\partial m_p}{\partial x} \\
\frac{\partial n_{\text{air}}}{\partial x} & = \frac{\partial n_p}{\partial x} \\
\frac{\partial T_{\text{air}}}{\partial x} & = \frac{\partial T_p}{\partial x} \quad \text{or} \quad \frac{\partial \eta_p}{\partial x} \\
\frac{\partial \rho_{\text{air}}}{\partial x} & \\
\frac{\partial P}{\partial x} & = \frac{kP n_{\text{air}}(\rho_{\text{air}}A n_{\text{air}} + m_{\text{wv}})}{(kPA - n_{\text{air}}(\rho_{\text{air}}A n_{\text{air}} + m_{\text{wv}}))} \left( \frac{1}{A} \frac{\partial A}{\partial x} - \frac{1}{v_{\text{ref}}} \frac{\dot{m}_{\text{wv}}}{m_{\text{air}}} \right)
\end{align*}
\]

\[\frac{\partial A}{\partial x} = \text{known}\]
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 ($C_p$, $L_{\text{heat}}$, etc.)
Sample Simulation

**Test Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$ (K)</td>
<td>277.3</td>
</tr>
<tr>
<td>RH$_0$ (%)</td>
<td>10.8</td>
</tr>
<tr>
<td>$P_0$ (kPa)</td>
<td>87.5</td>
</tr>
<tr>
<td>$v_e$ (m/s)</td>
<td>85</td>
</tr>
<tr>
<td>$TW_{C_{bulk}}$ (g/m$^3$)</td>
<td>2.3</td>
</tr>
<tr>
<td>$T_{water}$ (K)</td>
<td>280.4</td>
</tr>
<tr>
<td>MVD ($\mu$m)</td>
<td>42</td>
</tr>
<tr>
<td>$Tw_{b0}$ (K)</td>
<td>269.3</td>
</tr>
</tbody>
</table>

**Model Results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res. Time (s)</td>
<td>1.26</td>
</tr>
<tr>
<td>$\Delta T_{0,e}$ (K)</td>
<td>-2.7</td>
</tr>
<tr>
<td>$\Delta \omega_e$ (g/kg)</td>
<td>1.2</td>
</tr>
<tr>
<td>$\eta_e$ (melt ratio)</td>
<td>0.20</td>
</tr>
<tr>
<td>$TW_{C_e}$ (g/m$^3$)</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Delta TW_{b0,e}$ (K)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Model/Experiment Comparison – $TWC_{bulk}$ Sweep

**Target Conditions**

<table>
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<tr>
<td>$v_e$ (m/s)</td>
<td>85</td>
</tr>
<tr>
<td>$P_0$ (kPa)</td>
<td>87.3</td>
</tr>
<tr>
<td>$T_0$ (°C)</td>
<td>4.2</td>
</tr>
<tr>
<td>$RH_0$ (%)</td>
<td>10</td>
</tr>
<tr>
<td>$MVD$ (µm)</td>
<td>40</td>
</tr>
<tr>
<td>$T_{water}$ (°C)</td>
<td>7</td>
</tr>
</tbody>
</table>

**Takeaways:**

- Bulk vs Point
- $\Delta \omega_{%diff} \sim 30\%$
- $\Delta T_{%diff} \sim 30\%$
- $\Delta Twb_{0,e} =$ slight increase
Model/Experiment Comparison – RH Sweep

Target Conditions

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</thead>
<tbody>
<tr>
<td>$v_e$ (m/s)</td>
<td>85</td>
</tr>
<tr>
<td>$P_0$ (kPa)</td>
<td>87.2</td>
</tr>
<tr>
<td>$T_0$ (°C)</td>
<td>6.6</td>
</tr>
<tr>
<td>$TWC_{bulk}$ (g/m³)</td>
<td>1.0</td>
</tr>
<tr>
<td>$MVD$ (µm)</td>
<td>15</td>
</tr>
<tr>
<td>$T_{water}$ (°C)</td>
<td>7</td>
</tr>
</tbody>
</table>

Wet Bulb Temps

<table>
<thead>
<tr>
<th>RH₀ (%)</th>
<th>$Twb₀$ (°C)</th>
<th>$Twb₅$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-2.2</td>
<td>-4.4</td>
</tr>
<tr>
<td>35</td>
<td>0.6</td>
<td>-1.7</td>
</tr>
<tr>
<td>50</td>
<td>1.7</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

Takeaways:
- $Twb₀$ important
- Small RH window

\[
\Delta \text{Humidity, g/vap/kg dry air}
\]

\[
\Delta \text{Temperature, °C}
\]

\[
\Delta T_{wb}, ^\circ\text{C}
\]
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

**Takeaway:** Good $MVD_e$ agreement for $MVD_i = 15 \, \mu m$
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 $T_{\text{water}}$ tests
- Good agreement with particle size measurements
- $T_{\text{wb0}}$ slight increase, important to determine cloud phase
- Model guided development of test matrix for Fundamental Physics of ICI 2016 tests
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