Altitude Effects on Thermal Ice Protection System Performance; a Study of an Alternative Simulation Approach

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Presentation will include:

- Need for Study
- Initial test results
- Study Plan
- Development of alternate scaling method
- Flight scenarios
- Reference & Scaled test conditions
- Test Description & Results
- Summary
Need for Study

Aircraft efficiency $\uparrow$

- Onboard power available $\downarrow$
- Thermal IPS power $\downarrow$
- Running wet vs. evaporative
- Develop and test thermal IPS at ground level icing facility
- Method to account for altitude effects
- Validation data for Computational tools

Example IPS power graph:
- Evaporative
- Running Wet

Power Required, W/in²

Descent | Warm Hold

Example IPS power
Initial Study & 2012 Test

• Objectives:
  – Study physics
  – Test altitude scaling method (Re)

• Outcomes
  – Heat transfer scaled well
  – Mass transfer did not
  – Water drops blown off surface?

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Study Plan

- Define scaling method (alt/grd)
- Altitude Icing Wind Tunnel (AIWT)
- NACA airfoil with Heated Air IPS
- Various icing scenarios
- IPS operated in running wet mode
- Compare results: ice accreted, surface temps, heat rejection
- Assess scaling method, insight on processes

\[ \text{[Icing Conditions]}_{\text{altitude}} = \text{[Icing Conditions]}_{\text{ground level}} \]
Thermal IPS Scaling Method

Parameters matched:

• Reynolds number \( \text{Re} = \frac{\rho \cdot V \cdot d}{\mu} \), \( d = 2 \times \text{LE radius} \)

• Water loading \( M_w = LWC \cdot V \cdot \beta \)

• Impingement \( K_0 = f(\text{Re}_{\text{droplet}}) \)

• Recovery temperature \( T_r = T_s(1+r((\gamma-1)/2)M^2) \)

Also matched: RHF, \( H_c, H_g, \text{Nu, Sh, St, St}_m \)

Not matched: \( \dot{\eta}, \text{We} \)
Alternate Thermal IPS Scaling Method

Parameters matched:

• Weber number \( \text{We} = \frac{\rho_w \cdot V^2 \cdot d}{\sigma} \), \( d = 2 \times \text{LE radius} \)
• Water loading \( M_w = \text{LWC} \cdot V \cdot \beta \)
• Impingement \( K_0 = f(\text{Re}_{\text{droplet}}) \)
• Recovery temperature \( T_r = T_s (1 + r((\gamma - 1)/2)M^2) \)
• Model leading edge surface temperatures*

Not matched: \( \text{Re}, \dot{\eta}, \text{RHF}, H_c, H_g, \text{Nu}, \text{Sh}, \text{St}, \text{St}_m \)

*Requires two steps: Re match run (dry) followed by We match
Flight Scenarios for study

- Descent
- Cold Hold
- Warm Hold

Reference Conditions

<table>
<thead>
<tr>
<th>Flight phase</th>
<th>Alt., m</th>
<th>V, kt</th>
<th>AOA, deg</th>
<th>$T_s$, °C</th>
<th>LWC, g/m³</th>
<th>MVD, μm</th>
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<tr>
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<td>0.35</td>
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<tr>
<td>Warm Hold</td>
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<td>0</td>
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</table>
# Altitude Thermal Scaling Study

Reference and corresponding scale conditions

<table>
<thead>
<tr>
<th>Flight phase</th>
<th>Alt. m</th>
<th>V kt</th>
<th>T_s °C</th>
<th>LWC g/m³</th>
<th>MVD μm</th>
<th>Re-2xr x10⁶</th>
<th>We-2xr x10⁶</th>
<th>M_w g/m²-s</th>
<th>K₀</th>
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</table>
Facility

• NRC Canada Altitude Icing Wind Tunnel (AIWT)

  • Test Section: 57 cm x 57 cm (22.5 in. x 22.5 in.)
  • Airspeeds: 10 – 194 kts
  • Air Temp: -35°C to +40°C
  • LWC: 0.1 to 3 g/m³
  • MVD: 8 to 100 μm
  • Altitude simulation: ground level to 9100 m
Model

- Simple design to study fundamentals
- Aluminum skin on aluminum spar and rib frame

NACA 0018, 45.7 cm (18 in.) chord

Heated Air IPS

- 2D flow
- Piccolo tube, single row of holes
## Runback Ice - Descent

<table>
<thead>
<tr>
<th></th>
<th>Alt (m)</th>
<th>$P_{alt}$ (kPa)</th>
<th>V (kt)</th>
<th>$T_s$ (°C)</th>
<th>LWC (g/m³)</th>
<th>MVD (μm)</th>
<th>Tau (s)</th>
<th>Ice (g)</th>
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<td>21.5</td>
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Diagram with data points for NACA 0018, QD2251 - Ref, QD2252 - Re Sc, and QD2253 - We Sc. Dimensions in mm.
Runback Ice - Descent

Leading Edge Inner Surface Temperatures
Descent Case

Heated Air Temperatures

Heated Air Energy Input
## Runback Ice – Warm Hold

<table>
<thead>
<tr>
<th></th>
<th>Alt (m)</th>
<th>$P_{\text{alt}}$ (kPa)</th>
<th>$V$ (kt)</th>
<th>$T_s$ ($^\circ$C)</th>
<th>LWC (g/m$^3$)</th>
<th>MVD (μm)</th>
<th>Tau (s)</th>
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<td>19.8</td>
<td>420</td>
<td>28.6</td>
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- No tracings
Runback Ice - Warm Hold

**Heated Air Temperatures**

- **Ref**
- **Re - Sc**
- **We - Sc**

**Heated Air Energy Input**

- **Ref**
- **Re Sc**
- **We Sc**

Leading Edge Inner Surface Temperatures

- **Warm Hold**

- **Dry**
- **Wet**

*squ - Ref QD2212*

*cir - Re sc QD2215*

*tri - We sc QD2267*

**Temperature, Celcius**

![Graph showing temperature changes across different conditions](graph.png)

**s/c**
# Runback Ice – Cold Hold

<table>
<thead>
<tr>
<th></th>
<th>Alt m</th>
<th>$P_{alt}$ kPa</th>
<th>V kt</th>
<th>$T_s$ °C</th>
<th>LWC g/m³</th>
<th>MVD μm</th>
<th>Tau s</th>
<th>Ice g</th>
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<td>19.5</td>
<td>600</td>
<td>15.5*</td>
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*Ice remaining after partial ice shed*
Runback Ice – Cold Hold

Leading Edge Inner Surface Temperatures
Cold Hold

squ - Ref QD2240
cir - Re scale QD2263
tri - We Scale QD2264
grad - We scale QD2271

Heated Air Temperatures

Heated Air Energy Input - Cld Hld
Runback Ice Mass

- More ice accreted for Re-scaled conditions
- Mass of ice accreted for We-scaled conditions more similar to that accreted at reference (altitude) conditions

* Some ice shed
Summary

• Surface temperatures and heat rejection rates matched well between reference and Re-scaled conditions

• Re-scaled conditions resulted in greater mass of ice accreted

• We-scaled conditions combined with $T_{surf}$ matching resulted in ice accretions more similar in mass and location of ice

• Greater convective cooling with We-scaling does affect freezing of runback water

• Results indicate that surface water is being re-entrained in airstream

• The two-step, Re & We scaling method produced ice accretions more similar to those at the reference altitude conditions, but differences in convective cooling warrant further investigation

• Model of water shedding being investigated

• Joint report being written
Backup Slides
Test Procedure

1. Set Ref press & temp
2. Tunnel and model to SS w/IPS ON
3. Spray ON & IPS adjusted to desired RB ice
4. IPS settings determined; tunnel OFF & model cleaned
5. Run test
6. Ice documented: Photos, tracings, thickness, mass
7. Repeat at Re Sc conditions
8. Ice documented: Photos, tracings, thickness, mass
9. Airspeed & Temp Set for We Sc; IPS adjusted to Ref/Re LE Temperatures
10. Spray ON at We Sc conditions
11. Ice documented: Photos, tracings, thickness, mass
Nomenclature

c = model chord (18 in./45.7 cm)
d = twice the model leading edge radius
H_c = convective heat transfer coefficient
H_g = convective mass transfer coefficient
IPS = ice protection system
K = inertia parameter
K_0 = modified inertia parameter
LWC = liquid water content
M = Mach number
MVD = median volumetric diameter
M_w = water loading
Nu = Nusselt number
qdot = power density
r = recovery factor
Re = Reynolds number
Re_{(droplet)} = Reynolds number based on droplet diameter
Re sc = Reynolds number scaled conditions
Ref = Reference conditions
RHF = Relative Heat Factor
s = surface distance
Sh = Sherwood number

St = Stanton number
St_m = Stanton number for mass transfer
T_r = recovery temperature
T_s = static temperature
V = true air speed
We = Weber number
We sc = Weber number scaled conditions

β = collection efficiency at stagnation
γ = ratio of specific heats for air
H = freezing fraction
μ = air viscosity
ρ = air density
ρ_w = water density
σ = surface tension, water-air