Ice Accretion Measurements on an Airfoil and Wedge in Mixed-phase Conditions

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Outline

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• Introduction
• Experimental description
• Test conditions
• Imaging & analysis method
• Results
  – NACA 0012
  – Wedge
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• Acknowledgements
Background / Introduction

• Ingestion of atmospheric ice crystals by aircraft engines can cause ice to accrete on internal components leading to rollback, flameout, mechanical damage, etc.

• Experiments underway to understand fundamentals of mixed-phase and ice crystal icing in jet engines
  – NASA & NRC collaborations have had 3 test entries:
    • Nov 2010
    • Mar 2011
    • Mar & Apr 2012

• Traditional methods of recording ice shapes (e.g. tracings and castings) were not easily adaptable to this experiment
  – Rely primarily on video imagery
    • First two test methods only captured 1D ice growth along leading edge
    • 2012 test entry produced first analyzable 2D shapes

• This paper presents the ice accretion shape and surface temperature measurements from the 2012 test entry
  – The measurements are intended to help develop models of the ice-crystal icing phenomenon associated with engine ice-crystal icing
  – However, the primary test objectives of the 2012 entry were to characterize facility and prove out imaging concepts so only limited test runs were dedicated for accretion
Experiment Overview

NRC’s Research Altitude Test Facility (RATFac)

Test Procedure:
1. Set dry (cloud off) conditions
2. Turn on cloud for ~3-5 min for accretion test
3. Inserted SEA multiwire for LWC / TWC measurements
Test Articles

NACA 0012 Airfoil

Wedge Airfoil

Thermocouples (x 15)

Edge Heaters

1/8” recessed aluminum edges

Thermocouples (x 6)

Heated

Heated / Cooled Surface (described later)
Side view could not be analyzed from NACA 0012 cases due to obscurations
Optical View Port Tests

View though window
Analysis

Clean

Iced

Flow Direction

1 cm

Leading Edge and Flow Direction

Midspan

1 cm
Test Conditions – NACA 0012

- $P_0 = 6.5$ or $4.0$ psia ($\sim 45 \& 28$ kPa)
- $U = 85$ or $135$ m/s
- $T_0 = \sim 6$ to $19$ °C (cloud off)
  - Decreased with cloud on
- Wet bulb: $-5$°C $< T_{wb} < 4$
  - Injected steam set with cloud off
  - Measured humidity set cloud off & on
- $IWC_i = 7$ g/m$^3$ (no supplemental water)

$TWC_t = CF_{ice}IWC_i + CF_{noz}LWC_i - (GW_{on} - GW_{off})$

**Water source** | **Velocity (m/s)** | **CF**
--- | --- | ---
LWC (nozzles) | all | $CF_{noz} = 1.0$
IWC (grinder) | $85$ | $CF_{ice} = 1.0$
 | $135$ | $CF_{ice} = \frac{1.2 @ IWC = 15 \text{ g/m}^3}{1.5 @ IWC = 3 \text{ g/m}^3}$

$MR = \max(LWC_{m,083}, LWC_{m,021}) / TWC_t$

<table>
<thead>
<tr>
<th>Test</th>
<th>$P_0$ (psia)</th>
<th>$U$ (m/s)</th>
<th>$T_{0,\text{off}}$ (°C)</th>
<th>$T_{0,\text{on}}$ (°C)</th>
<th>$T_{wb,\text{off}}$ (°C)</th>
<th>$T_{wb,\text{on}}$ (°C)</th>
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<tbody>
<tr>
<td>796</td>
<td>6.5</td>
<td>86.2</td>
<td>13.2</td>
<td>7.2</td>
<td>-0.3</td>
<td>-0.1</td>
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<td>867</td>
<td>4.0</td>
<td>134.4</td>
<td>18.0</td>
<td>9.1</td>
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</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>$LWC_{m,083}$ (g/m$^3$)</th>
<th>$LWC_{m,021}$ (g/m$^3$)</th>
<th>$TWC_{m,HP}$ (g/m$^3$)</th>
<th>$GW_{off}$ (g/m$^3$)</th>
<th>$GW_{on}$ (g/m$^3$)</th>
<th>$TWC_t$ (g/m$^3$)</th>
<th>MR (%)</th>
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<tbody>
<tr>
<td>796</td>
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<td>4.85</td>
<td>3.35</td>
<td>4.01</td>
<td>9.13</td>
<td>14</td>
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</table>
NACA 0012 Result – Test 796

\[ U = 85 \text{ m/s}, \ P_0 = 6.5 \text{ psia}, \ T_{wb0} = -0.1 \^\circ \text{C}, \ IWC_i \approx 7 \text{ g/m}^3 \]
**Variation of growth rate with MR**

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>U</td>
<td>85 m/s</td>
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<tr>
<td>$P_0$</td>
<td>6.5 psia</td>
</tr>
<tr>
<td>$IWC_i$</td>
<td>7 g/m$^3$</td>
</tr>
<tr>
<td>$T_{WB}$</td>
<td>0 to -1 °C</td>
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</tbody>
</table>

Scans 824, 802, 834, 796

\[ \dot{r} \text{ increases then decreases with } \text{MR} \]
NACA 0012 Result – Test 867

\[ U = 134 \text{ m/s}, \quad P_0 = 4.0 \text{ psia}, \quad T_{wb0} = 1.7 \, ^\circ\text{C}, \quad IWC_i \approx 7 \text{ g/m}^3, \quad MR = 14\% \]

Only case with substantial ice growth at 135 m/s from available data
Test Conditions – Wedge

- $P_0 = 6.5$ or $10.0$ psia ($\sim 45$ & $69$ kPa)
- $U = 85$ m/s
- $T_0 = \sim 8$ to $21$ °C (cloud off)
  - Decreased with cloud on
- Wet bulb: $1^\circ$C $< T_{wb} < 5$
  - Adjusted incoming stream and measured humidity
- $IWC_i = \sim 7$, $8.5$, or $17$ g/m$^3$
  - One case with supplemental water (1003)
Wedge Result – Test 901

$U = 87 \text{ m/s, } P_0 = 6.5 \text{ psia, } T_{wb0} = 2.5 \text{ °C, } IWC_i \approx 16.7 \text{ g/m}^3, \text{ MR}=13\%$

Similar test (883) with $IWC_i \approx 7 \text{ g/m}^3$ (MR = 16%) did not show ice accretion
Wedge Heating-Cooling System

- Heating/cooling achieved by spraying heated/cooled water/antifreeze on back of 1/8” thick Ti 6Al-4V icing surface through ~ 100 1/32” holes
Cooled Wedge Result – Test 982

\[ U = 86 \text{ m/s}, \quad P_0 = 10 \text{ psia}, \quad T_{wb0} = 1.2 \, ^\circ \text{C}, \quad IWC_i \cong 16.7 \, \text{g/m}^3 \]

Growth rate is 2.9% reference growth rate assuming all ice sticks
Cooled Wedge Result – Test 982 (Side Profile Measurements)

Flow (\(\alpha = -6^\circ\))

- Time: t = 89.5 sec
- Time: t = 228 sec
- Time: t = 427 sec

Ice Thickness

- Time: t = 89.5 sec
- Time: t = 228 sec
- Time: t = 427 sec

24X playback
Summary (1 of 2)

• This paper presents measurements of ice accretion shape from ice-crystal icing experiments conducted at the NRC RATFac
  – Data provided for development of ice-crystal accretion models
  – Select surf. temperature measurements available in paper

• Used two different models: NACA 0012 and wedge
  – Several wedge tests included actively cooled surface

• Tested at different U, T, and P
  – Only a limited set of permutations
  – NACA 0012 tests used only injected ice particles which naturally melted in the warm airflow (no supplemental LWC)
Summary (2 of 2)

• The ice accretion measurements included:
  – leading-edge thickness (both models)
  – 2D cross-section profile (wedge & 1 NACA 0012 case)

• NACA 0012
  – In some cases, initial growth rate, \( \dot{r} \), higher than at end of test
  – Results suggest that \( \dot{r} \) increases then decreases with MR
  – 135 m/s case showed less growth near midspan compared with root & tip

• Wedge
  – With adiabatic model, observed weakly adhered rapid accretions with shedding at \( T_{wb} \) above freezing
  – With active surface cooling, ice accretion without shedding occurred and the growth rate increased with \( MR \)
  – Accretions grew generally parallel to the icing surface
Acknowledgements

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  – National Research Council
  – Federal Aviation Administration
  – Transport Canada

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• Finally, the authors would like to thank Mr. Chris Lynch for his excellent imaging work during the experiments
Question
Ice Accretion Measurements on an Airfoil and Wedge in Mixed-phase Conditions
### Test Conditions – NACA 0012

<table>
<thead>
<tr>
<th>Test</th>
<th>Figure</th>
<th>$P_0$ (psia)</th>
<th>$U$ (m/s)</th>
<th>$V_{edge}$ (VAC)</th>
<th>$T_{0,\text{off}}$ (°C)</th>
<th>$T_{0,\text{on}}$ (°C)</th>
<th>$T_{wb,\text{off}}$ (°C)</th>
<th>$T_{wb,\text{on}}$ (°C)</th>
<th>$HR_{\text{off}}$ (g/kg)</th>
<th>$HR_{\text{on}}$ (g/kg)</th>
<th>$LWC_i$ (g/m$^3$)</th>
<th>$IWC_i$ (g/m$^3$)</th>
<th>$GWC_{\text{off}}$ (g/m$^3$)</th>
<th>$LWC_{m,083}$ (g/m$^3$)</th>
<th>$LWC_{m,021}$ (g/m$^3$)</th>
<th>$TWC_{\text{off}}$ (g/m$^3$)</th>
<th>$TWC_{\text{on}}$ (g/m$^3$)</th>
<th>MR (%)</th>
<th>$r_{120-180}$ (mm/s)</th>
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<td>6.5</td>
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<td>2.73</td>
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</table>

#### OPTICAL VIEW PORT TESTS

| Test | Figure | $P_0$ (psia) | $U$ (m/s) | $V_{edge}$ (VAC) | $T_{0,\text{off}}$ (°C) | $T_{0,\text{on}}$ (°C) | $T_{wb,\text{off}}$ (°C) | $T_{wb,\text{on}}$ (°C) | $HR_{\text{off}}$ (g/kg) | $HR_{\text{on}}$ (g/kg) | $LWC_i$ (g/m$^3$) | $IWC_i$ (g/m$^3$) | $GWC_{\text{off}}$ (g/m$^3$) | $LWC_{m,083}$ (g/m$^3$) | $LWC_{m,021}$ (g/m$^3$) | $TWC_{\text{off}}$ (g/m$^3$) | $TWC_{\text{on}}$ (g/m$^3$) | MR (%) | $r_{120-180}$ (mm/s) |
|------|--------|-------------|-----------|----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|---------------|----------------|----------------|----------------|----------------|--------|------------------|
| 834  | 9      | 6.5         | 85.7      | 0             | 13.6            | 7.3            | -0.1           | -0.1           | 3.5            | 5.9            | 0              | 6.94          | 1.80          | 0.51          | 0.39          | 2.75          | 3.02          | 5.72          | 9      | 0.14             | 0.018          |
| 843  | N/A    | 6.5         | 135.5     | 0             | 13.4            | 7.8            | -0.5           | -0.6           | 3.1            | 5.1            | 0              | 6.96          | 1.75          | 0.58          | 0.59          | 4.72          | 2.38          | 9.15          | 6      | 0                | 0              |
| 849  | 11     | 6.5         | 135.4     | 0             | 13.1            | 9.0            | 3.6            | 3.4            | 7.2            | 8.6            | 0              | 6.97          | 4.19          | 0.96          | 1.40          | 5.43          | 4.73          | 9.24          | 15     | 0.18             | N/A            |
| 855  | N/A    | 3.9         | 137.4     | 0             | 18.7            | 6.9            | -3.3           | -3.3           | 2.8            | 7.1            | 0              | 6.87          | 0.91          | 0.58          | 0.60          | 4.41          | 1.74          | 8.94          | 7      | 0                | 0              |
| 861  | N/A    | 4.0         | 133.8     | 0             | 17.4            | 7.6            | -1.4           | -1.4           | 5.5            | 9.1            | 0              | 7.05          | 1.90          | 0.64          | 0.68          | 4.32          | 2.59          | 9.10          | 7      | 0                | 0              |
| 867  | 10     | 4.0         | 134.4     | 0             | 18.0            | 9.1            | 2.1            | 1.7            | 9.6            | 12.8           | 0              | 7.02          | 3.35          | 0.92          | 1.29          | 4.85          | 4.01          | 9.13          | 14     | 0.17             | 0.0069         |
## Test Conditions - Wedge

| Test | Figure | $P_0$ (psia) | $U$ (m/s) | $T_{\text{condant}}$ (°C) | $T_{0,\text{off}}$ (°C) | $T_{0,\text{on}}$ (°C) | $T_{\text{wb,off}}$ (°C) | $T_{\text{wb,on}}$ (°C) | $\text{HR}_{\text{off}}$ (g/kg) | $\text{HR}_{\text{on}}$ (g/kg) | $\text{LWC}_i$ (g/m$^3$) | $\text{IWC}_i$ (g/m$^3$) | $\text{GWC}_{\text{off}}$ (g/m$^3$) | $\text{LWC}_{\text{m,083}}$ (g/m$^3$) | $\text{LWC}_{\text{m,021}}$ (g/m$^3$) | $\text{TWC}_{\text{m,HP}}$ (g/m$^3$) | $\text{GWC}_{\text{on}}$ (g/m$^3$) | $\text{TWC}_i$ (g/m$^3$) | $\text{MR}$ (%) | $\dot{\text{r}}_{\text{initial}}$ (mm/s) | $\dot{\text{r}}_{360-420}$ (mm/s) |
|------|--------|-------------|-----------|--------------------------|-------------------------|-------------------------|------------------------|------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|
| 883  | N/A    | 6.5         | 87.1      | Adia                     | 19.9                    | 10.6                    | 3.5                    | 2.5                    | 4.2              | 6.9             | 0               | 6.84            | 2.14            | 0.88            | 0.80            | 3.18            | 3.42            | 5.56            | 16              | Trace           | Trace           |
| 889  | N/A    | 6.5         | 87.4      | Adia                     | 20.8                    | 12.7                    | 5.2                    | 4.4                    | 5.9              | 8.3             | 0               | 6.81            | 2.95            | 1.12            | 1.21            | 3.22            | 4.14            | 5.62            | 21              | 0               | 0               |
| 901  | 15     | 6.5         | 86.9      | Adia                     | 20.5                    | 8.3                     | 3.5                    | 2.5                    | 4.0              | 7.9             | 0               | 16.68           | 2.04            | 1.85            | 2.15            | 5.71            | 3.87            | 14.84           | 13              | 0.123           | 0.202           |
| 982  | 16     | 10.1        | 85.7      | -7                       | 8.5                     | 5.6                     | 1.1                    | 1.2                    | 2.9              | 4.2             | 0               | 8.43            | 2.40            | 0.76            | 0.52            | 3.30            | 3.43            | 7.40            | 10              | 0.017           | 0.015           |
| 996  | 17     | 10.0        | 83.9      | -5                       | 8.2                     | 4.3                     | 3.2                    | 2.1                    | 4.9              | 5.6             | 0               | 8.61            | 3.88            | 1.28            | 1.03            | 3.62            | 4.32            | 8.17            | 16              | 0.048           | 0.021           |
| 1003 | 18     | 10.0        | 84.1      | -5                       | 8.2                     | 3.8                     | 1.9                    | 1.4                    | 3.8              | 5.2             | 1.87            | 8.60            | 3.01            | 1.98            | 1.74            | 4.92            | 4.24            | 9.24            | 21              | 0.049           | 0.032           |