SUPERCOOLED LARGE DROPLET
DEFORMATION AND BREAKUP NEAR
THE LEADING EDGE OF LARGE
TRANSPORT AIRFOILS

Mario Vargas

NASA Glenn Research Center, Cleveland, OH
OUTLINE

• Space Act Agreement with INTA

• Current Research Work on Droplet Break-up
  – Objectives, Approach, Experimental Setup, Data Analysis, Results

• Summary of Droplet Break-up Research completed as of January 2011

• Current Work being done in preparation for 2011 Experiment

• Future Work
History of Space Act Agreement with INFA

• Agreement started in October of 2004

• Initial Research Work 2004-2007
  – Developed experimental methods to generate water spray representative of the range of conditions identified in FAA Appendix C
  – Evaluated rivulet break-up length and rivulet spacing versus water-film thickness for varying tunnel conditions
  – Film Weber number scaling developed for glaze icing in SLD

• Current Research Work 2007-Present
  – DROPLET BREAKUP
Current Research Work on Droplet Breakup

Objectives

• Study and measure large droplet deformation and breakup near the leading edge of airfoils

• Gain understanding of the physical mechanisms and non-dimensional parameters, and develop an empirical model to predict droplet breakup

• Scale the results to predict droplet breakup near the leading edge of large transport airfoils

• Provide a database of measurements that can be used for validation of computational studies
Approach

• Experimental Approach
  – Rotating arm with test airfoil attached at the end
  – Droplets falling perpendicularly at one location along the airfoil path

• Use state of the art high speed imaging for observation and measurement of droplet deformation and breakup as they approach the leading edge of the airfoil (as seen in a frame of reference fixed on the airfoil)

• Measure horizontal and vertical displacement of droplets and calculate main non-dimensional parameters: velocity, acceleration, Weber, Reynolds and Bond numbers

• Analyze data to understand physical mechanisms, develop empirical model to predict droplet breakup and scale results to large airfoils
Approach

Conceptual View of Experiment
Experimental Set-Up
Rotating Arm
Experimental Set-Up
Rotating Arm
Experimental Set-Up
Rotating Arm
Experimental Set-Up
Test Matrix for High Speed Experiment

- 5 days of testing - 80 test points
- Airfoil velocities of 50, 60, 70, 80 and 90 m/sec
- For each velocity, runs were conducted for theoretical droplet sizes of 523, 415, 333, 191, 138 and 114 μm
- Two magnifications were used
Experimental Set-Up
Imaging Resolution and Field of View

Two magnifications and the corresponding field of views were used.

For the case of 75,000 fps the resolution is 192Hx312V.

14.3 pixels per mm

312 pixels
21.8 mm

192 pixels 13.4 mm

69.0 pixels per mm

312 pixels
4.5 mm

192 pixels 2.8 mm
Data Analysis

- *Spotlight 8* software package used for data analysis
- Frame by frame study of the movies
- Zooming-in and out on single frames
- Tracking a single droplet in x-y directions
  - Measurement of horizontal and vertical displacement against time
Data Analysis

Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
Frame Number = 101; Camera Time = 14,480 μsec

Droplet #2
Data Analysis

Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
Frame Number = 174; Camera Time = 15,667 μsec
Data Analysis

Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
Frame Number = 190; Camera Time = 15,667 μsec

Droplet #2
Data Analysis

Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
Frame Number = 207; Camera Time = 15,893 µsec

Airfoil

Droplet #2
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 μm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V; Tracking begins at frame 174
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 µm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 \( \mu m \); Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V; Tracking begins at frame 174
Results
Change of Frame of Reference

Frame of Reference at rest with respect to the LE of the Airfoil

Distance from the LE of the Airfoil
millimeters
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 μm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V; Tracking begins at frame 174

Distance from the LE of the Airfoil
millimeters
-45 -40 -35 -30 -25 -20 -15 -10 -5 0

V_{droplet}
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 μm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V; Tracking begins at frame 174

Distance from the LE of the Airfoil millimeters

Droplet Acceleration m/sec^2

-130000 -120000 -110000 -100000 -90000 -80000 -70000 -60000 -50000 -40000 -30000 -20000 -10000 0
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 µm; Airfoil Velocity = 90 m/sec  
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
Weber Number

Inertia Forces = \( ma \propto \rho L^3 \frac{dv}{ds} \frac{ds}{dt} \propto \rho L^3 V \frac{V}{L} \propto \rho V^2 L^2 \)

Surface Tension Forces \( \propto L\sigma \)

\[
We = \frac{\rho_{air} |V_{air} - V_{droplet}|^2 D}{\sigma_{water/air}}
\]

\( \iff \) Forces trying to pull the drop apart

\( \iff \) Forces trying to hold the drop together
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 μm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

\[ We = \frac{\rho_{\text{air}} |V_{\text{air}} - V_{\text{droplet}}|^2 D}{\sigma_{\text{water}}} \]
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 µm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

\[
Re = \frac{\rho_{\text{air}} |V_{\text{air}} - V_{\text{droplet}}| D}{\mu_{\text{air}}}
\]

Distance from the LE of the Airfoil millimeters
Results

Droplet #2, 01252010.19C; Drop Diameter = 490 μm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

\[ C_d = \frac{4}{3} \frac{\rho_{\text{water}}}{\rho_{\text{air}}} \frac{D}{|V_{\text{air}} - V_{\text{droplet}}|^2} \frac{dV_{\text{droplet}}}{dt} \]
Results

Velocity Effect

Drop Diameter = 490 μm; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

![Graph showing drop velocity as a function of distance from the LE of the airfoil. The graph includes lines for different drop velocities: 50 m/sec, 60 m/sec, 70 m/sec, 80 m/sec, and 90 m/sec. The x-axis represents distance from the LE of the airfoil in millimeters, and the y-axis represents drop velocity in m/sec.]
Results

Velocity Effect

Drop Diameter = 490 μm; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

Distance From the Leading Edge of the Airfoil
millimeters

Droplet Acceleration
m/sec^2
50 m/sec
60 m/sec
70 m/sec
80 m/sec
90 m/sec

Distance From the Leading Edge of the Airfoil
millimeters

-80000 -70000 -60000 -50000 -40000 -30000 -20000 -10000 0

50 m/sec
60 m/sec
70 m/sec
80 m/sec
90 m/sec
Results

Velocity Effect

Drop Diameter = 490 μm; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
Results

Velocity Effect

Drop Diameter = 490 μm; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V
# Results

## Droplet Deformation and Breakup

<table>
<thead>
<tr>
<th>Time</th>
<th>Distance</th>
<th>Weber No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 μsec</td>
<td>-81.4 mm</td>
<td>~0</td>
</tr>
<tr>
<td>13.3 μsec</td>
<td>-69.6 mm</td>
<td>7.3</td>
</tr>
<tr>
<td>80.0 μsec</td>
<td>-63.6 mm</td>
<td>8.2</td>
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<tr>
<td>146.7 μsec</td>
<td>-57.6 mm</td>
<td>9.3</td>
</tr>
<tr>
<td>213.3 μsec</td>
<td>-51.6 mm</td>
<td>10.6</td>
</tr>
<tr>
<td>280.0 μsec</td>
<td>-45.6 mm</td>
<td>12.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Distance</th>
<th>Weber No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>346.7 μsec</td>
<td>-39.6 mm</td>
<td>14.0</td>
</tr>
<tr>
<td>413.3 μsec</td>
<td>-33.6 mm</td>
<td>16.4</td>
</tr>
<tr>
<td>480.0 μsec</td>
<td>-27.6 mm</td>
<td>19.3</td>
</tr>
<tr>
<td>546.7 μsec</td>
<td>-21.6 mm</td>
<td>23.2</td>
</tr>
<tr>
<td>613.3 μsec</td>
<td>-15.6 mm</td>
<td>28.2</td>
</tr>
<tr>
<td>680.0 μsec</td>
<td>-9.6 mm</td>
<td>34.9</td>
</tr>
</tbody>
</table>

<table>
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<th>Time</th>
<th>Distance</th>
<th>Weber No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>706.7 μsec</td>
<td>-7.2 mm</td>
<td>38.2</td>
</tr>
<tr>
<td>733.3 μsec</td>
<td>-4.8 mm</td>
<td>42.0</td>
</tr>
<tr>
<td>760.0 μsec</td>
<td>-2.4 mm</td>
<td>46.2</td>
</tr>
<tr>
<td>786.7 μsec</td>
<td>0 mm</td>
<td>51.0</td>
</tr>
</tbody>
</table>
Main Results

• The pattern of deformation and breakup of the droplets follows the Bag type observed and reported by other researchers in past studies with other experimental configurations.

• All the observed droplet breakups occurred just before the droplet hit the airfoil. For velocities of 50 m/sec and 60 m/sec no droplet breakup was observed. A limited number of droplet breakups were observed at 70 m/sec. Nearly all the droplet breakups were observed at 80 and 90 m/sec.

• Values of the Weber number along the path of the droplet increase as the droplet approaches the airfoil.

• Measurements on droplets of 490μm in diameter at each airfoil velocity of 50, 60, 70, 80 and 90 m/sec showed that at a higher airfoil velocity, the droplet experiences higher Weber numbers for longer times.
Summary of Research Completed as of Jan 2011

- In 2007, NASA and INTA began an experimental research program to obtain droplet breakup data on an airfoil configuration.

- A droplet breakup rotating rig was designed and built at INTA.

- The first sets of experiments were conducted at low speeds (15-66 m/s) in November of 2008.

- A high speed experiment (50-90 m/s) was conducted in January of 2010.

- Results were presented at the 2010 AIAA Atmospheric and Space Environments Conference in Toronto, Canada.
Current Work

- Error analysis on the measurements from the high speed experiment
- Continue measurements and calculations with the data from the high speed experiment
  - The database consists of about 400 droplets
- Understand the meaning of the drag coefficient calculations
- Road Map of Future Work
- Preparations for experiment to be conducted in July 2011
- Submitted Paper for the 2011 SAE International Conference in Chicago
- Air flow field characterization in the facility using PIV system
AIR FLOW FIELD CHARACTERIZATION

Experimental setup – Vertical Plane
FUTURE WORK

• Observation and measurement of droplet deformation and breakup on three geometrically scaled versions of the DBKUP 002 airfoil

• One model scaled down to $\frac{1}{2}$ size of the DBKUP 002, another scaled up 1.5 times the size and another scaled up 2 times the size

• Experiment planned for July 2011

• This additional research will allow us to learn how to scale the droplet deformation, breakup and measurements to larger transport airfoils
End of Presentation