Overview of Icing Research at NASA Glenn

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Outline

• The Icing Problem
• Types of Ice
• Icing Effects on Aircraft Performance
• Icing Research Facilities
• Icing Codes
Aircraft Icing

Ice build-up results in significant changes to the aerodynamics of the vehicle. This degrades the performance and controllability of the aircraft.
Aircraft Icing

During an in-flight encounter with icing conditions, ice can build up on all unprotected surfaces.
Recent Commercial Aircraft Accidents

- **ATR-72: Roselawn, IN; October 1994**
  - 68 fatalities, hull loss
  - NTSB findings: probable cause of accident was aileron hinge moment reversal due to an ice ridge that formed aft of the protected areas

- **EMB-120: Monroe, MI; January 1997**
  - 29 fatalities, hull loss
  - NTSB findings: probable cause of accident was loss-of-control due to ice contaminated wing stall

- **EMB-120: West Palm Beach, FL; March 2001**
  - 0 fatalities, no hull loss, significant damage to wing control surfaces
  - NTSB findings: probable cause was loss-of-control due to increased stall speeds while operating in icing conditions (8K feet altitude loss prior to recovery)

- **Bombardier DHC-8-400: Clarence Center, NY; February 2009**
  - 50 fatalities, hull loss
  - NTSB findings: probable cause was captain’s inappropriate response to icing condition
Where Does Icing Occur?
Where Does Icing Occur?
How Ice Forms

- In visible moisture (cloud & precip)
- Temperature range around -20° to +2°C
- Cloud contains supercooled liquid water, ice crystals

Ice Accretion Parameters:
- Velocity
- Drop Size (MVD)
- Liquid Water Content
- Temperature
- Accretion Time
How Ice Forms

Icing Certification Envelope “App C”

Freezing Drizzle

15 - 50 μm

Freezing Rain

500 μm

2000 μm
Types of Ice Accretions

- Clear Ice
- Rime Ice
- Mixed Ice

These images depict the three types of ice accretion.
Types of Ice Accretions

Glaze (Clear) Ice

- In general occurs at temperatures near 32°F and high LWCs
- Clear everywhere
- Horns may appear
- Drops do not freeze on impact
- Surface tends to be covered with roughness elements
- Physical mechanism of formation not well understood

V=225 mph
T_{total}=25 °F
LWC=0.75 g/m³
MVD=20 µm
\tau=5 minutes
Types of Ice Accretions

Rime Ice

- In general occurs at temperatures below -10° F
- White and opaque
- Horns do not appear
- Drops freeze on impact
- Surface tends to be smoother than for glaze ice
- Physical mechanism of formation well understood

From Bidwell
Types of Ice Accretions

Mixed Ice

- Ice accretion exhibits glaze ice around stagnation line and rime ice away from it
- Clear near the stagnation line, white and opaque away from it
- Horns may appear

V=150 mph
T_{total}= 5 ^\circ F
LWC=0.75 g/m^3
MVD=20 \mu m
\tau=2 minutes
Types of Ice Accretions

Swept Wing Icing

View from the side

View from behind

Λ = 15°

Λ = 30°

Λ = 45°
Types of Ice Accretions

Time Lapse
Icing Effects on Airplane Performance

- **Reduce maximum Lift**
  - Increase stall speed
  - Stall warn system may not compensate for ice
- **Increases Drag**
  - Reduces Climb rate
  - Reduces max speed
  - May reduce speed to the point of stall.
- **Increases Weight**
  - Usually not significant, fuel burn will offset
- **Thrust**
  - Increased thrust required, due to drag increase
  - GA aircraft are, typically, power limited
Icing Effects on Airplane Performance

Drag from unprotected surfaces
Icing Effects on Airplane Performance

Performance Data on Wing

*Airfoil in Icing Research Tunnel
Icing Effects on Airplane Performance

Comparison of iced-airfoil performance for $Re = 15.9 \times 10^6$, $M = 0.20$
Icing Effects on Airplane Performance

Iced Flight Dynamics Loss of Control (LOC)

- Multiple incidents and fatal accidents have occurred recently in which ice accretions were a causal factor
  - IPS usually operating, autopilot masked control changes

1994 - ATR-72, Roselawn, IN

- 68 fatalities
- Aileron hinge moment reversal with ridge of ice beyond the deicing boots
Ice Protection Systems

- Thermal (evaporative and running wet)
  - Heated air
  - Electrothermal
- Mechanical
  - Pneumatic
  - Ultrasonic
- Other
  - Freezing-point depressants
Engine Icing

- Ice crystal ingestion is a high priority area of research
- High ice water content occurs at high altitudes around large convective storms
- Over 200 power loss events since 1988

- Characterize the environment and develop capabilities to simulate and predict engine core ice accretion
Rotorcraft Icing

- Research objective is validated coupling of a rotor performance code with an ice accretion code

- Typically cannot fly fast enough (M > 0.6) to prevent icing by kinetic energy heating (except near the blade tips)
- Usually cannot gain enough altitude to fly above weather
- Helicopter operations often require remaining in an area for long periods of time
- Potential for severe vibration or damage due to ice shedding
- Smaller chord lengths
Icing Research Tunnel

Capabilities:
• Develop and test aircraft de-icing and anti-icing systems
• MVD: 15-50μ
• LWC: 0.2 to 3.0 g/m³
• 6’ x 9’ Test Section
• Temperatures: -25 C to 5 C
• Airspeeds: 50 to 350 kts
Propulsion Systems Lab

Capabilities:

- Altitude testing of mid-size engines
- Ice particle generation (MVD: 40-60 μ)
- IWC: 0.5 to 9.0 gm/m³
- Altitude simulation: 4000 to 40000 ft
- Temperatures: -60 F to 15 F
- Altitude simulation: 4000 to 40000 ft
- Airspeeds: M=0.15 to 0.8
Vertical Icing Studies Tunnel

Capabilities

- Planar stagnation point flow
- Test section 64-in x 30-in
- Airspeed at contraction:
  - Max = 25 m/s
  - Design point $V_0 = 17$ m/s
- Air Temperature: ambient to -15°C
- LWC: 0.1 – 1.5 g/m³ (design spec.)
- MVD: 20 – 2000 μm (design spec.)
Droplet Imaging Flow Tunnel

Capabilities

- 6” x 6” Test Section
- 175 mph (empty tunnel)
- Phantom High Speed Camera
- Sheet Laser and Intensified Camera
Ice Contamination Effects Flight Training Device: for familiarizing pilots with possible effects of ice contamination
Remote Sensing Ground Site: for developing and assessing remote icing condition detection algorithms

NASA Narrowbeam Multi-frequency Microwave Radiometer (NNMMR): for terminal area icing detection and warning
Benefits of Using Simulation

- Identify critical conditions for icing test campaigns
- Incorporate icing issues earlier into the design cycle
- Explore a larger portion of the icing envelope than can be examined by tunnel or flight testing
- Provide critical information for certification efforts along with tunnel and flight test information
- Provide a faster, cheaper and equally accurate assessment of icing effects for purposes of design and certification

<table>
<thead>
<tr>
<th>Icing Data Method</th>
<th>Data Points Obtained</th>
<th>Time Requirements</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Testing</td>
<td>10 - 50</td>
<td>2-3 months</td>
<td>Over $1 million</td>
</tr>
<tr>
<td>Icing Tunnel Testing</td>
<td>100 - 150</td>
<td>2-3 weeks</td>
<td>Approx. $500 thousand</td>
</tr>
<tr>
<td>LEWICE</td>
<td>Over 1000</td>
<td>1 day</td>
<td>One days salary</td>
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</tbody>
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LEWICE
Ice Accretion Prediction

LEWICE is a software package the predicts the size, shape, and location of ice growth on aircraft surfaces exposed to a wide range of icing conditions.

- Flow solution using potential flow or structured viscous solver
- Particle trajectory calculation, including impingement limit search for collection efficiency and multiple drop size distributions
- Integral boundary layer routine calculates heat transfer coefficient
- Quasi-steady analysis of control volume mass and energy balance in time stepping routine
- Geometry modification using density correlations to convert ice growth mass into volume allows multiple time-step solutions
- All physical effects modeled, including turbulence, bouyancy, droplet deformation, breakup and splashing
- Extensive validation against experimental data

LEWICE also models the behavior of thermal ice protection systems while exposed to the same range of icing conditions.
LEWICE: Ice Growth Simulation Software

**INPUT:**
- Flow Coordinates of a body surface
- Flight conditions (free stream velocity, temperature, angle of attack)
- Icing conditions (water droplet diameter, liquid water content of the cloud, water droplet size distribution)

**OUTPUT:**
- Ice shape geometry
- Collection efficiency on the surface
- Freezing fraction along ice surfaces
- Heat transfer values along the surface
- Temperatures along the surface
## LEWICE User Base

### US Aerospace Industry
- Learjet
- Gulfstream
- Raytheon
- Cessna
- Cox & Co.
- Goodrich
- P & W
- Bell
- Beech
- Nordham
- Northrop
- Ice Management Systems
- Many Others...

### Universities
- UIUC
- WSU
- MIT
- MSU
- CWRU
- Toledo
- Others...

### US Government
- NASA
- FAA
- CRREL
- NOAA
- NTSB
- AMCOM
- USAF
- NAVAIR

### Non-Aerospace
- Bridge cables
- Lake Erie wind turbine project

### International Distribution
- American Kestrel

**200+ Users of LEWICE**
LEWICE3D
Three-Dimensional Ice Accretion Software

LEWICE3D is a suite of codes used to determine the amount and location of ice accretion on an aircraft.

- Based on the Messinger model and Monte Carlo analysis
- Monte Carlo-based collection efficiency calculation using droplet impact counts
- Integral boundary layer technique used to generate heat transfer coefficients
- Ice growth calculated using a modified LEWICE scheme
- Supports both structured and unstructured grids
- Calculation off-body concentration factors
- Determination of shadow zones

Generation of a full ice accretion for 3D surfaces
SMAGGICE
Surface Modeling and Grid Generation for Iced Airfoils

The SMAGGICE software suite is an interactive toolkit used to prepare 2D cross-sections of iced airfoils for computational fluid dynamic analysis.

- geometry preparation
- block creation and grid generation
- grid quality checks
- flow solver interface
- convenience capabilities
- both single and multi-element airfoils
Summary

• NASA research provides tools, methods and databases for industry, academia, other government agencies
• NASA’s icing codes are the gold standard in the U.S. and the world
• NASA’s icing tunnel remains highly utilized and continues to expand its envelope of calibrated conditions
• NASA’s Propulsion Systems Lab will greatly expand the envelope for engine icing research with its new icing capability
• Few organizations conduct basic icing research in-house
• Pilot and dispatcher education and training, modifications to aircraft, improvements in detection, etc. have all contributed to saving lives
• Flight into known icing conditions will remain important as airspace capacity continues to grow