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Icing Branch Current Research Activities in Icing Physics

Mario Vargas

Airframe Icing Workshop
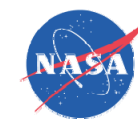NASA Glenn Research Center

Cleveland, Ohio   *June 9, 2009*
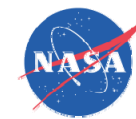
Outline

- Swept Wing Icing

- Scaling

- Droplet Break-up –NASA/INTA

- Icing Physics Flow Laboratory

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SWEPT WING ICING PHYSICS

Critical Distance Database

Technical Lead: Mario Vargas

Main Characteristics of Ice Accretions on Swept Wings

V=150 mph, T_{total}=25°F, LWC=0.75g/m^3, MVD=20μm

No-scallop

Incomplete Scallops

Complete Scallop
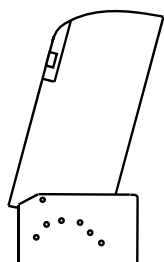
Airfoil at 15°
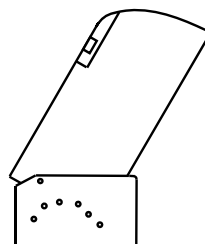
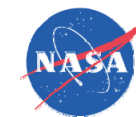**Airfoil at 30°**
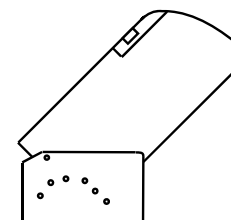
Airfoil at 45°
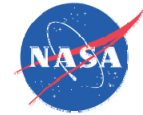
How Ice Accretions Develop on a Swept Wing
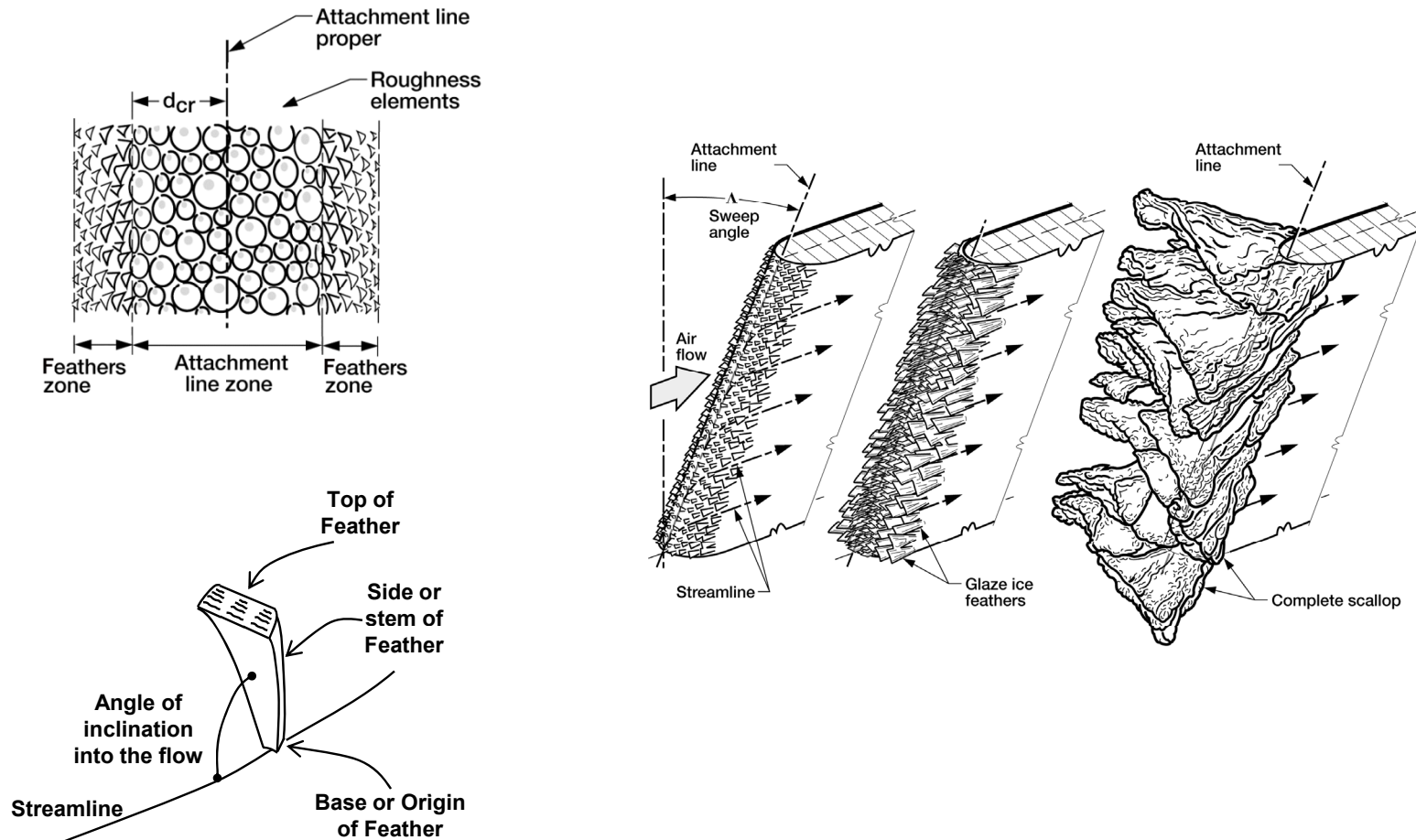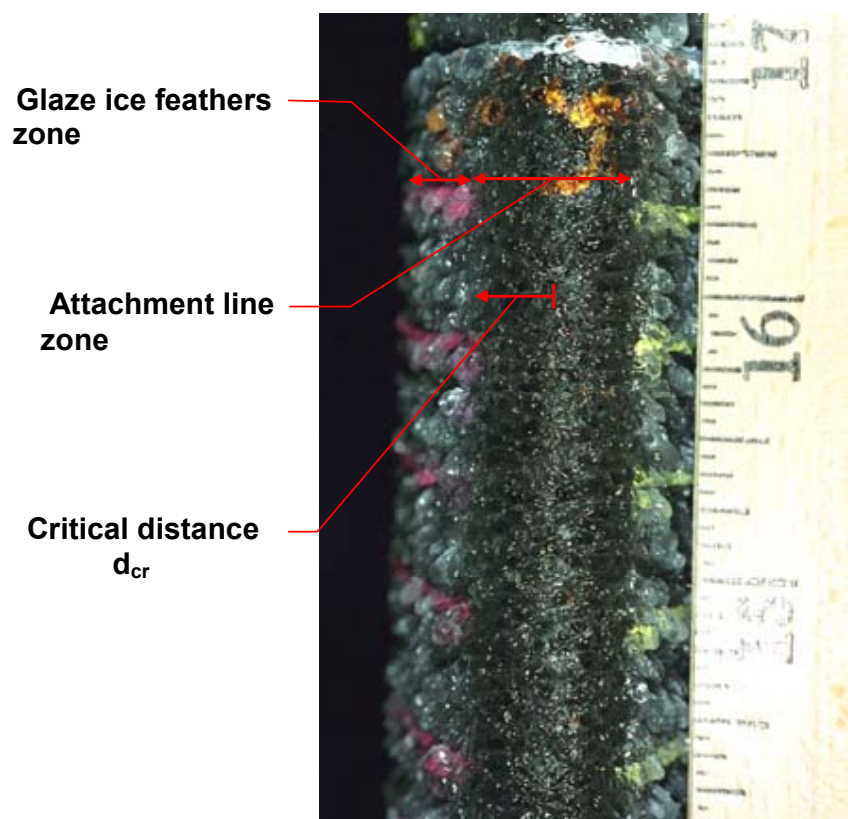
Critical Distance, d_{cr}

For a given geometry, determines what type of ice accretion will develop

$\Lambda=30^O$,   V=150 mph,   T=25 ^{O}F,   LWC=0.75 g/m^3,   MVD=20 μm, τ=2 minutes

Glaze ice feathers zone

Attachment line zone

Critical distance d_{cr}
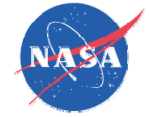
Reasons to Develop a Database of d_{cr} Measurements

- Prediction of the critical distance for a given geometry will allow us to determine in advance what type of ice accretion will form: complete scallop, incomplete scallop or no-scallop

- A database of critical distance measurements against icing conditions will be used to develop and validate a model of where the feathers develop with respect to the attachment line. The model will be implemented in LEWICE 3D
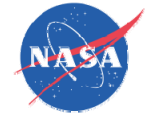
Current Research Work

- Initiated Development of Database of Critical Distance Measurements against Appendix C Icing Conditions

- Three Experiments were conducted

  - Two at the Goodrich Icing Wind Tunnel (IWT), February and April 2009

  - One at the Icing Research Tunnel (IRT), May 2009

- Data is being analyzed and the results will be presented at the 2009 AIAA 1st ASE conference in San Antonio, TX

- Work is funded under the NASA Integrated Resilient Aircraft Controls (IRAC) Project of the Aviation Safety Program and is listed as a milestone for the project
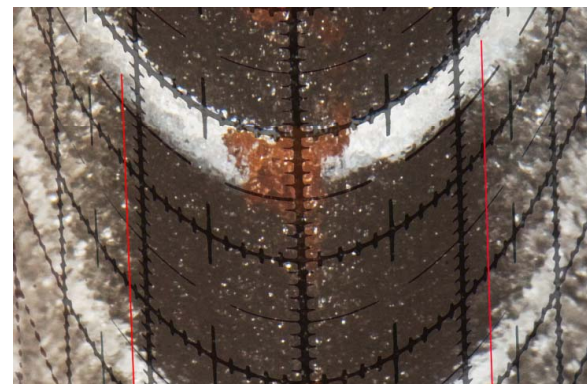
Critical Distance Measurement Experiment

Goodrich IWT Test Setup

Measurement Technique

- Time Sequence Imaging Technique (TSIT)

- Three cameras used

- One image every 2 seconds

- Grid image and ice accretion image combined to obtain measurement of d_{cr}

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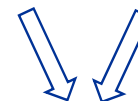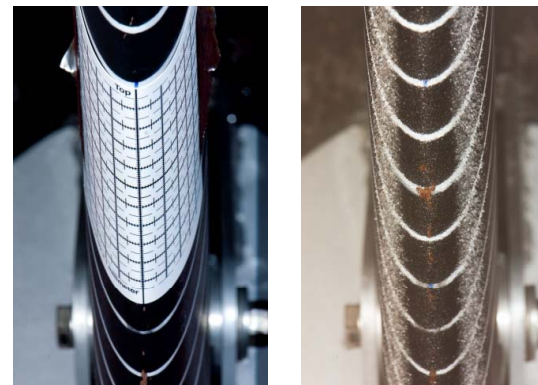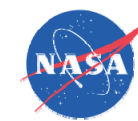
Extension and Validation of Scaling Methods

Technical Leads: Jen-Ching (Paul) Tsao and Eric Kreeger
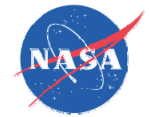
Develop Scaling Methods in SLD

- Develop scaling methods for SLD conditions

  - Evaluate the film Weber number scaling proposed by Dr. Alex Feo of INTA for glaze icing in SLD

  - Apply the Olsen method to scale LWC and T_{st} in SLD & App. C

  - A 3-day test entry (Sep. 08) in the IRT

  - The result will be presented in the 2009 AIAA 1st ASE conference in San Antonio, TX

Develop Scaling Methods in SLD

Evaluate Feo's film Weber number in glaze icing

c = 91.49 cm, 09-26-08 Run 2

c = 35.6 cm, 09-30-08 Run 4 (We_f + Olsen)
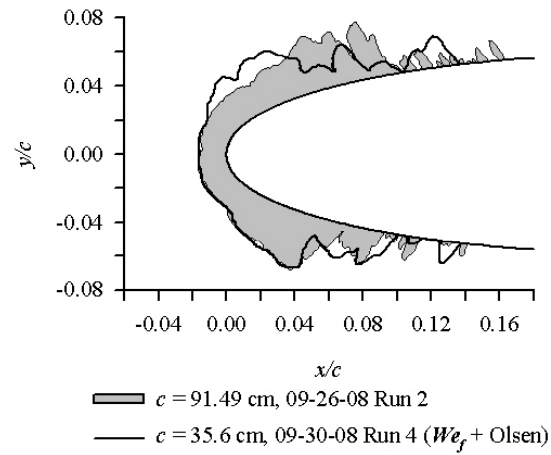
Date/Run	c, cm	α, ^{0}	t_{st}, °C	t_{tot}, °C	V, kt	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	$\beta_0 A_c$	n_0	We_L, 10^6
09-26-08/2	91.4	0	-11.0	-10.2	76	147	1.68	10.0	94	1.48	1.39	0.32	0.68
09-30-08/4	35.6	0	-8.1	-5.5	142	66	1.17	4.0	94	1.98	1.87	0.29	0.92

Extend Scaling Methods to Swept Wing Icing

- Extend current scaling methods to swept wing icing applications by modifying the expressions for the heat transfer coefficient, the collection efficiency and the freezing fraction at stagnation

  - For the heat transfer coefficient use Reshotko's expression for a clean airfoil:

  $$h_{o, \Lambda} = h_{o, \Lambda=0} * (\cos \Lambda)^{0.5}$$

  - For the collection efficiency the proposed expression is:

  $$\beta_{o, \Lambda} = \beta_{o, \Lambda=0} * \cos \Lambda$$

- Experimental validation of the analytical expression for $\beta_{o, \Lambda}$ on a swept NACA 0012 wing section

  - A total of 5-day entry (May & Sep. 08) in the IRT

  - The result will be presented in the 2009 AIAA 1st ASE conference in San Antonio, TX

National Aeronautics and Space Administration
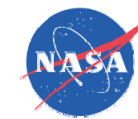
Extend Scaling Methods to Swept Wing Icing
Stagnation Collection Efficiency from Experiment, $\beta_{0,\Lambda}$

Proposed β_0 for NACA 0012 at sweep Λ

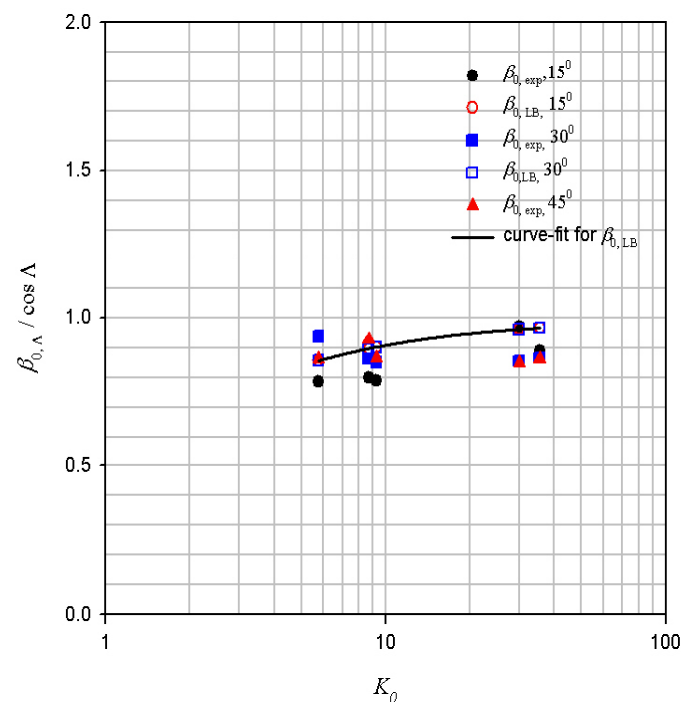$$\beta_{o,\Lambda} = \beta_{o,\Lambda=0} * \cos \Lambda$$

Experimental Validation
$$\beta_{o,\Lambda} = \Delta / (d * n_o * A_c)$$

$d/2$

Δ
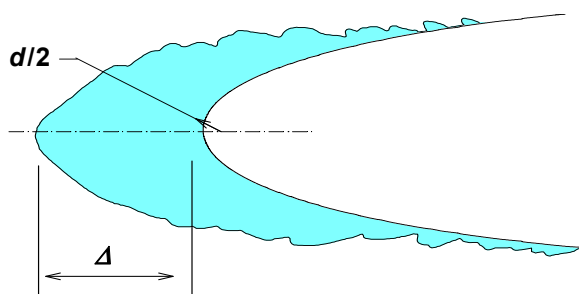
Δ **Stagnation Ice Thickness**

D **2x Airfoil L.E. Radius**

$(\beta_{0,\Lambda} / \cos \Lambda)$ vs K_0

Extend Scaling Methods to Rotorcraft Icing

- Extend current scaling methods to rotorcraft icing applications

    - Evaluate existing scaling methods for NACA 0012 airfoils at non-zero angle of attack (AoA)

    - A total 7-day entry (Sep. 08 & Feb. 09) in the IRT

    - The result was just presented in the AHS International 65th Annual Forum & Technology Display in Grapevine, TX

- All current scaling work is supported by the NASA Subsonic Rotary Wing (SRW) Project of the Fundamental Aeronautics Program.

- The scaling method development supported by SRW is also applicable to the IRAC goals

National Aeronautics and Space Administration
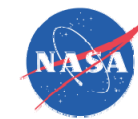
Droplet Break-up

NASA/INTA Space Act Agreement Research Work

Technical Lead: Mario Vargas

Overview

- Objective of the research effort:

    - *To study large droplet deformation and break-up near the leading edge of large transport airfoils*

- Collaborative effort between NASA and the Instituto Nacional de Técnica Aerospacial (INTA) through a Space Act Agreement.

- Technical lead at INTA is Dr. Alejandro Feo Palacios

- Work is funded under IRAC

Current Activities

- Icing Branch research participation

  - To develop a high-speed imaging technique in collaboration with the Glenn Imaging

    Technology Center (ITC) that allows:

    (1) to follow a single droplet time history to deformation and break-up

    (2) to measure diameter, velocity and acceleration of the droplet

  - Lead and participate in the experiments conducted at the INTA test cell

- Low-speed experiment (66 m/s) was conducted at the INTA test cell in Madrid in

  November of 2008

- High speed experiment (90 m/s) will be conducted in November of 2009 at the

  INTA test cell

Droplet Break-Up Experiment

Retardo 04.00ms
1mm

Retardo 04.60ms
1mm

Retardo 04.90ms
1mm

d

U_{dx}
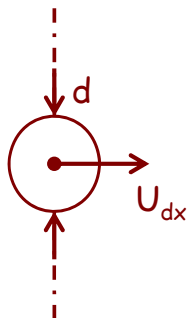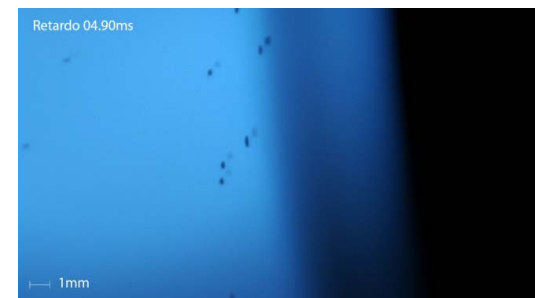
VARIABLES

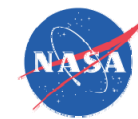ρ_a; U_{dx}; U_{ax}; d; μ_a; $\sigma_{w/a}$; $(\Delta U_{dx}/\Delta t)$

$U_{dx} \equiv$ **droplet velocity in body axis**

$U_{ax} \equiv$ **air velocity**
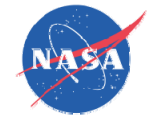
Icing Physics Flow Laboratory

Technical Lead: Andy Broeren

Icing Physics Flow Lab

- Two research facilities are located in the Icing Physics Flow Lab

Vertical Icing Studies Tunnel (VIST)

Droplet Imaging Flow Tunnel (DrIFT)

VIST Dimensions and Specifications
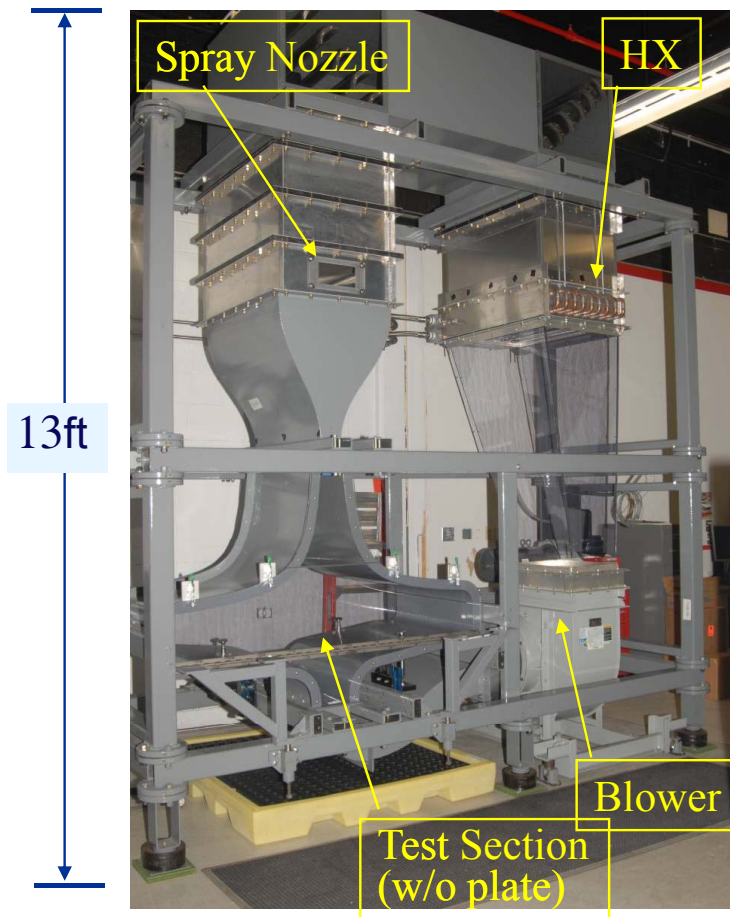
- **Tunnel Dimensions**

  - Plenum: 24-in x 36-in

  - Contraction: 4-in x 30-in
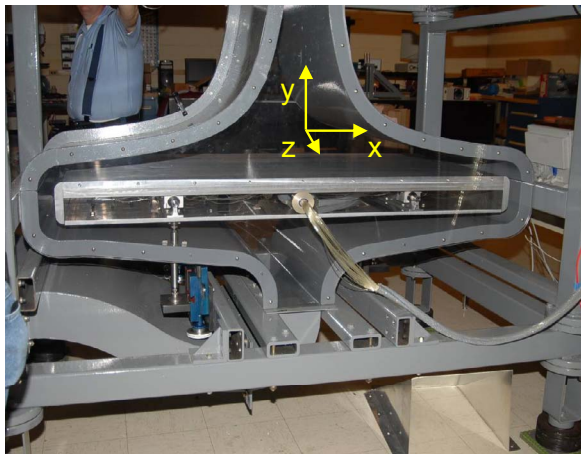
  - Test Section: 64-in x 30-in

- **Tunnel Specifications**

  - Planar stagnation point flow

  - Max Airspeed at contraction 25 m/s

  - Design point V_o = 17 m/s

  - Air Temperature Min = -15°C

  - Planned   LWC: 0.1 – 1.5 g/m3

  - Planned   MVD: 20 – 2000 µm

VIST Research Activities

VIST Test Section

Plate Design

- **60" x 30" in Six Layers:**
- **Highly polished AL surface w/ 38 pres. taps**
- **Imbedded heat flux gauges w/ TCs**
- **Heaters to control surface temp**

- **Objective**
    - **To understand ice accretion physics in the stagnation region**

- **Approach**
    - **Create a thick, low-speed planar stagnation boundary layer to allow visualization and measurement of the air-water-ice interface**

- **The design point**
    - **Re_δ = 630 (δ_{99} = 2 mm, V_{edge} = 17 m/s)**
    - **Dynamically similar to the stagnation point flow on a large transport wing at $Re_c = 10^7$ by matching Re_δ of the first 2% chord**

- **Current Research Activities**
    - **Validation and calibration of the facility**
    - **Measuring flow quality**

- **Facility not yet operational, additional resources needed to have it research-ready in FY10**
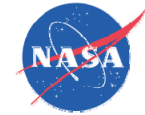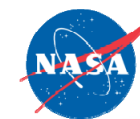
DrIFT Research Activities

Droplet Imaging Flow Tunnel (DrIFT)

- **Objective**
  - **To develop visualization methods for investigating droplet splashing around an iced airfoil**

- **Approach**
  - **Introduce a stream of mono-dispersed large droplets to impinge on a pre-defined region of an artificial ice shape mounted on an airfoil**
  - **Record with a high-speed imaging and laser-sheet illumination trajectories and deformation**

- **Capabilities**
  - **6" x 6" Test Section**
  - **175 mph (empty tunnel)**
  - **Phantom High Speed Camera**
  - **Sheet Laser and Intensified Camera**
  - **Phase Doppler Particle Analyzer (PDPA)**

- **Current Research Activities**
  - **Development of high speed imaging techniques to measure diameter, velocities, acceleration and deformation of large droplets near a leading edge (NASA/INTA work) funded under IRAC**

Icing Simulation

Colin Bidwell
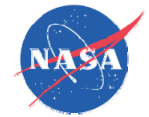
NASA Glenn Research Center

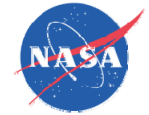Glenn Research Center

June 9, 2009

www.nasa.gov

Outline

- LEWICE
    - Version 3.2.2 Status
    - Current Development
- LEWICE3D
    - Version 2 Status
    - Current Development

LEWICE Major Applications

- General application is the determination of amount and location of ice accretion on an aircraft.

- Used to determine water loading on aircraft surfaces so that the size and location of the ice protection system can be determined.

- Used to design and analyze hot air and electro-thermal ice protection systems.

- Used to determine ice shapes for FAA failed ice protection system test. These ice shapes are built and attached to aircraft by manufacturers for flight tests to insure that the aircraft can still fly with ice resulting from a failed ice protection system.

LEWICE 3.2.2 Methodology

- **Flow Solver**
  - Uses Hess-Smith 2D potential panel code or 2D Navier-Stokes flow solver to determine flow field about surface

- **Droplet Trajectories**
  - Calculate water droplet trajectories from some upstream location until impact on the surface or until body is bypassed using 4th order predictor-corrector method

- **Water Collection**
  - Determine water droplet impact location pattern between impingement limits

- **Heat Transfer**
  - Perform quasi-steady analysis of control volume mass and energy balance in time stepping routine using integral boundary layer method with roughness effects

- **Ice Growth**
  - Ice growth calculated using scheme based on Messinger Model. Density correlations used to convert ice growth mass into volume

- **Iterate**
 - With new ice shape, iterate entire routine

National Aeronautics and Space Administration

LEWICE Version 3.2.2

- Version 3.2.2 released September 2005
- Version 3.2.2 features
  - Analysis of Hot air and electro-thermal ice protection systems
  - SLD droplet splashing model
  - Droplet breakup model
- Approximations
  - Multi-time step
  - Flow calculated using 2D panel code or 2D Navier-Stokes flow solver
  - Messinger quasi-steady control volume icing model
  - Heat transfer calculated using integral boundary layer algorithm with roughness effects.
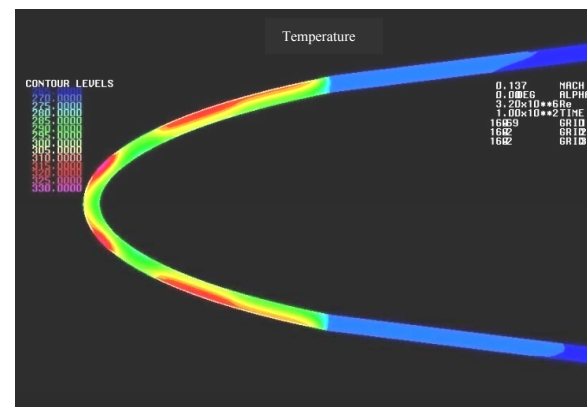 - Surface water loading generated from trajectories calculated from free-stream to surface.
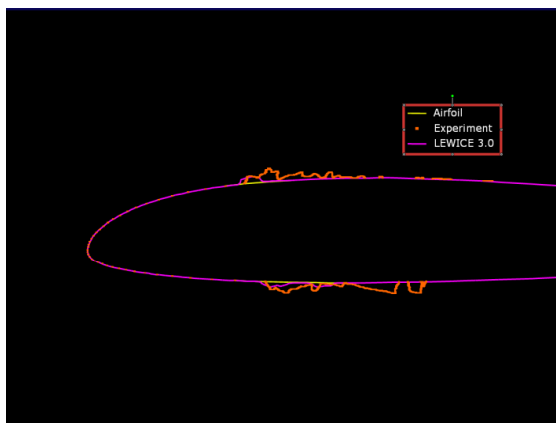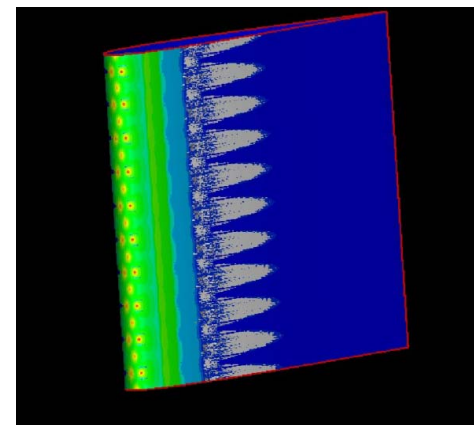
LEWICE – 2D Icing Tool
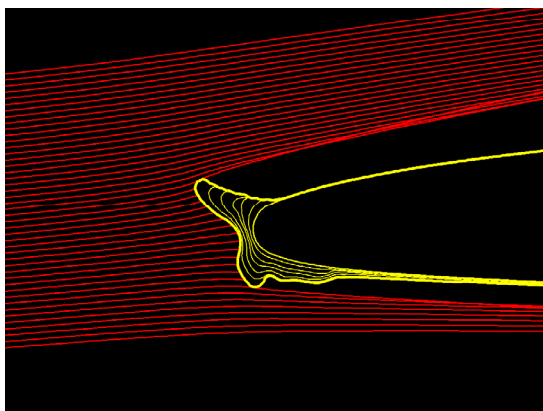
Droplet Trajectory and Ice Shape Prediction

Electro-Thermal System Performance

Residual Ice Prediction


Bleed Air System Performance

Current LEWICE Development

- Mixed phase capability

    – Surface energy balance with ice instead of super-cooled water

- Particle energy balance

    – Evaporation (super-cooled drops)

    – Sublimation (ice particles)

- Automated multi-time step ice accretion using unstructured Navier-Stokes (FUN2D)

LEWICE3D Major Applications

- General application is the determination of amount and location of ice accretion on an aircraft.

- Used to determine water loading on aircraft surfaces so that the size and location of the ice protection system can be determined.

- Used to determine ice shapes for FAA failed ice protection system test. These ice shapes are built and attached to aircraft by manufacturers for flight tests to insure that the aircraft can still fly with ice resulting from a failed ice protection system.

- Used to determine location of icing sensors (don't want to put a sensor in a position where there is no ice).

- Used to determine corrections for cloud measurement instruments (e.g. droplet size probes, liquid water content probes) on an aircraft (the aircraft causes a flow disturbance the result of which is that an instrument mounted on the aircraft will not read the correct free stream cloud properties).
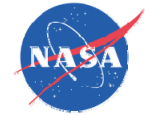
LEWICE3D Methodology

- **Flow Solver**
    - User supplies grid based flow solution. LEWICE3D can handle multi-block structured grids, "VSAERO" type structured grids, adaptive cartesian grids (ICEGRID/PATCHGRID), and unstructured grids

- **Droplet Trajectories**
    - Trajectories are calculated using 4th order Adams-type predictor-corrector method developed by Hillyer Norment.

- **Water Collection**
    - Collection efficiencies for simple 2D or 3D regions can be calculated using a modified LEWICE2D scheme.
    - Collection efficiencies for complex regions are calculated using a quadtree area based collection efficiency method.

- **Heat Transfer**
    - Perform quasi-steady analysis of control volume mass and energy using integral boundary layer method with roughness effects using 3D strip approach.

- **Ice Growth**
    - Ice growth calculated using modified LEWICE2D scheme based on Messinger Model. Ice Density model with additions for "scalloped" ice shapes.
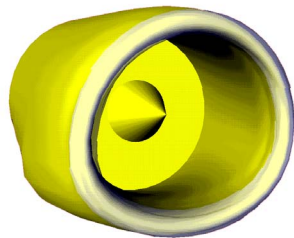
LEWICE 3D Version 2

- ## Version 2 Released March 2007

- ## Version 2 Features
  - Automated most users inputs
  - Roughness model incorporated
  - Ice density model for scallop ice shapes
  - Variable area collection efficiency method installed which reduces calculation times and insures convergence
  - Dynamic memory allocation and OpenMP and MPI parallelization has been incorporated to optimize memory and speed on modern computers.

- ## Approximations
  - Single time step
  - Ice shapes calculated along 3D strips
  - Steady or time averaged flow solutions required
  - Grid based application requires user supplied 3D flow solutions on structured, or unstructured grids
  - Messinger quasi-steady control volume icing model
  - Heat transfer calculated using integral boundary layer algorithm with roughness effects
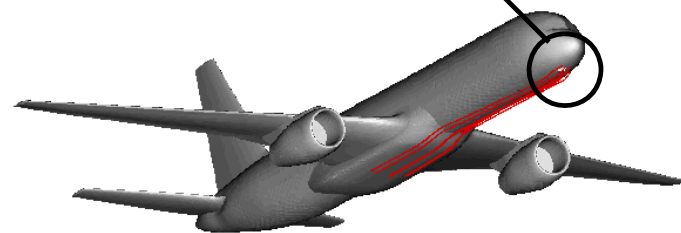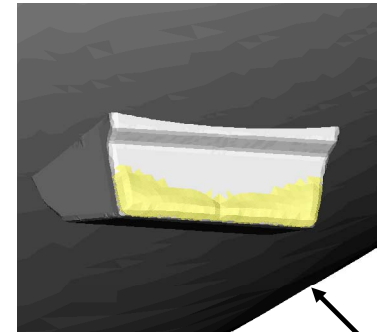 - Surface water loading generated from trajectories calculated from upstream to surface

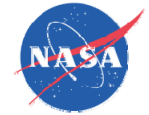# LEWICE3D - 3D Icing Tool

Version 2 of the LEWICE 3D ice accretion computational tool calculates water and ice accretion on complex aircraft surfaces

Boeing 737-300 Inlet

Boeing 757 with FLIR Pod

# Current LEWICE3D Development
## (LEWICE3D Version 3)

- A grid block transformation scheme which allows the input of grids in arbitrary reference frames, the use of mirror planes, and grids with relative velocities has been developed.

- A simple ice crystal and sand particle bouncing scheme has been included.

- Added an SLD splashing model based on that developed by William Wright for the LEWICE 3.2.2 software.

- A new area based collection efficiency algorithm will be incorporated which calculates trajectories from inflow block boundaries to outflow block boundaries. This method will be used for calculating and passing collection efficiency data between blade rows for turbo-machinery calculations.
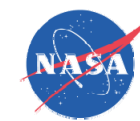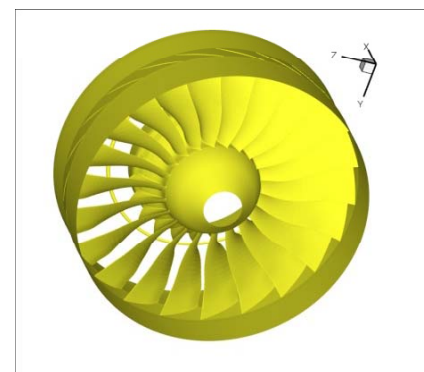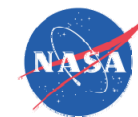
Grid Block Transformation and Mirroring Scheme
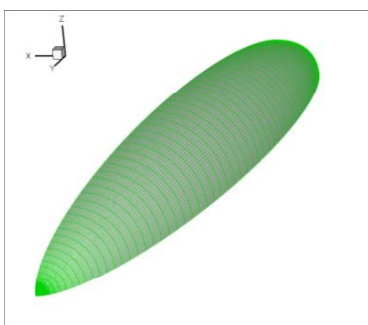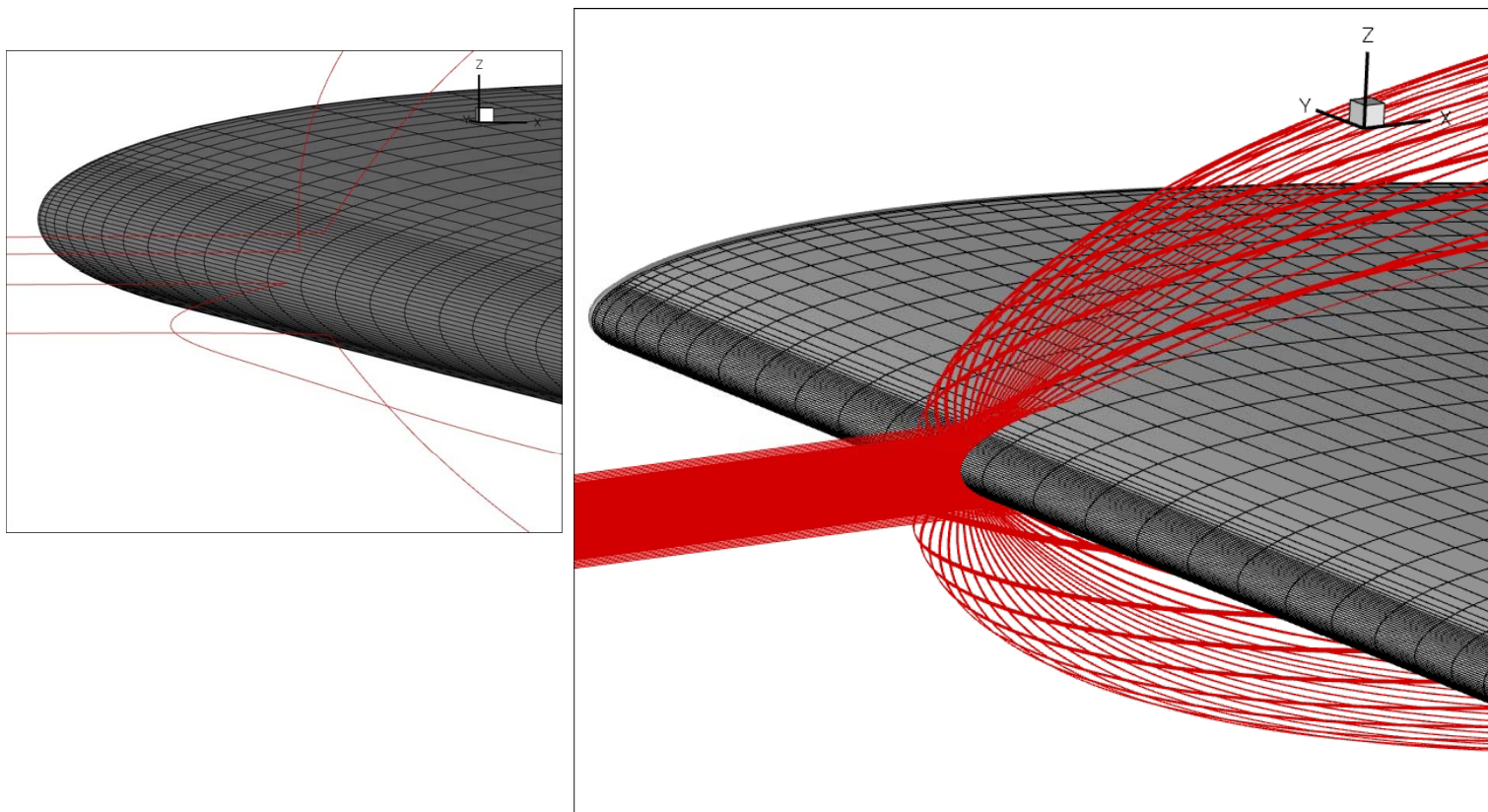

Rotation and Symmetry
Plane Mirroring
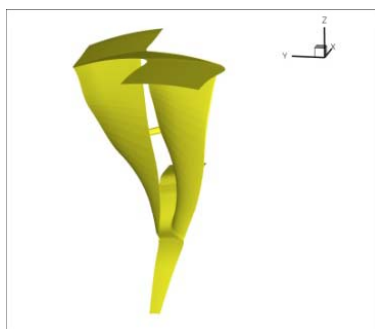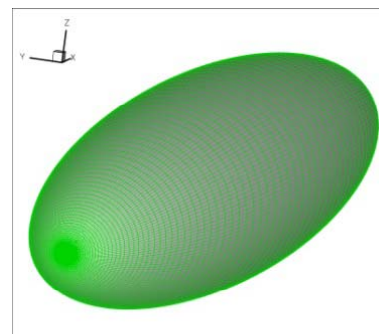
Radial Mirroring with
Relative Velocities

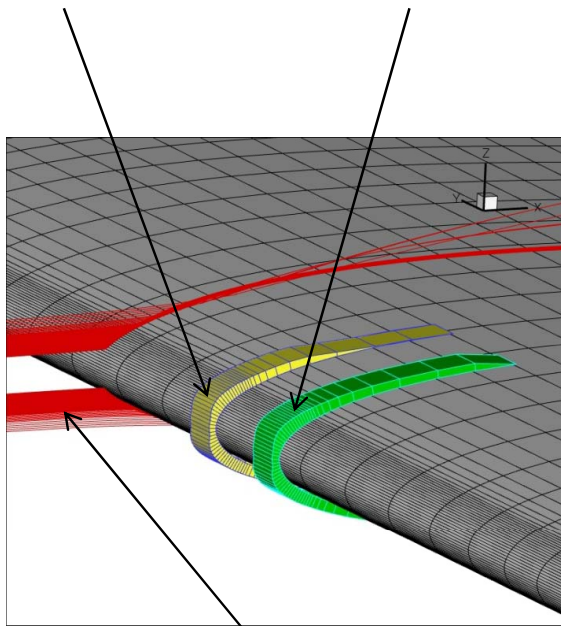# Particle Reflection Model For Bouncing Sand and Ice Crystals

SLD Splashing Model Based On Wrights LEWICE 3.2 Model

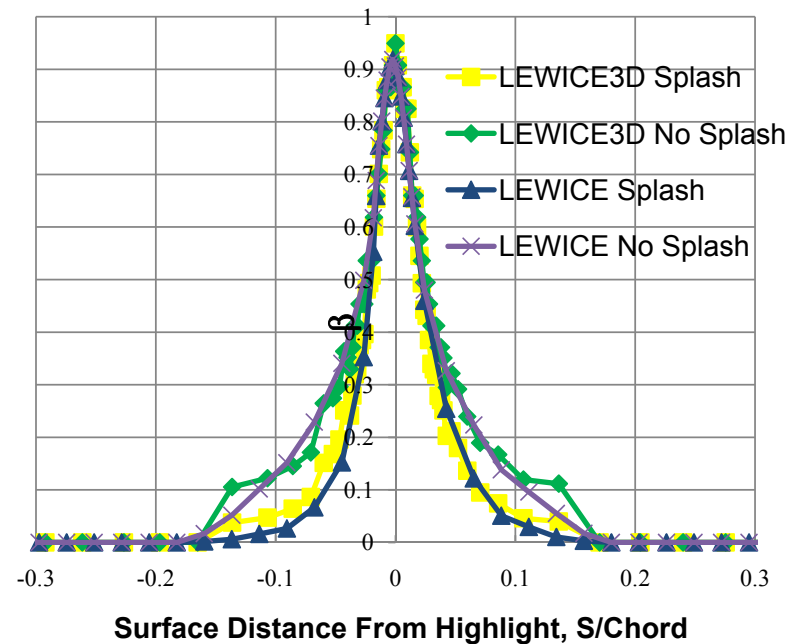### (NACA 0012; MVD=160 Microns; V=87 m/s)

Ice Shape
With Splashing

Ice Shape
No Splashing

Splashing Droplet Trajectories

LEWICE3D Splash
LEWICE3D No Splash
LEWICE Splash
LEWICE No Splash

β

Surface Distance From Highlight, S/Chord

Future LEWICE3D Validation Requirements

- Ice accretion data for 3-dimensional configurations needs to be generated to validate icing calculations (e.g., swept wings, radomes, inlets, etc.). The available data for validation is limited and most of it is proprietary.

- Ice crystal and sand rebound models need to be validated. Some data exists for sand but no data exists for ice crystals.

- A more sophisticated SLD splashing model and more detailed experimental splashing data needs to be generated to handle complex configurations such as multi-element wings with multiple impingement regions. The current model has been tuned to match data for simple configurations with single leading edge impingement regions. The current model approximates the splashed water from a droplet impact as a single drop which has limited accuracy for predicting the location of secondary impact zones.