# Icing Analysis of a Swept NACA 0012 Wing Using LEWICE3D Version 3.48

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# Outline

- **Experimental Method**

- **Analytical Method**

  - ANSYS CFX

  - LEWICE3D Version 3.48

- **Configuration**

  - Experiment

  - CFD

- **Analysis**

- **Conclusions**

# IRT NACA 0012 Swept Wing Model



45° Sweep



30° Sweep

# Wax Casting Process



ice shape tracings



leading edge removed



dipping ice shape in wax bath



final wax mold

# Ice Density Calculation



ice shape length
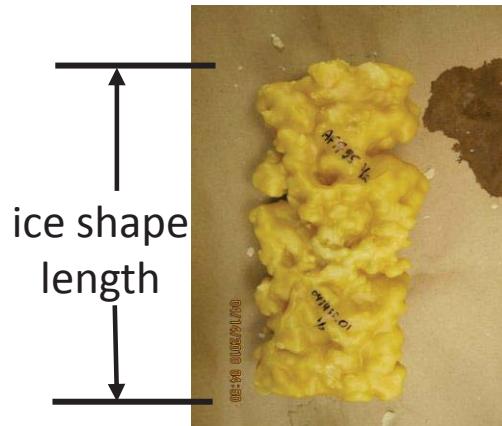
wax mold



Ice shape with feathers



ice area
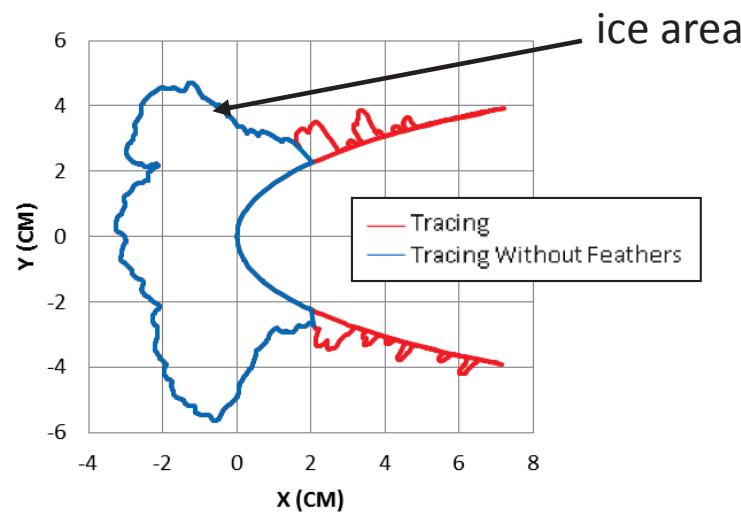
removal of feathers from ice shape
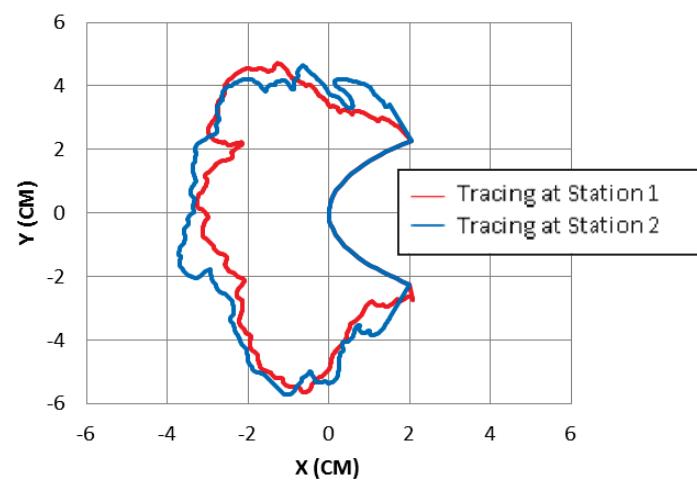


comparison of tracings at station 1 and 2

# ANSYS CFX

- The unstructured ANSYS 13 meshing methods include patch conforming and patch independent tetrahedral, sweep, multi-zone, hex dominant, automatic and cut cell.

- The automatic meshing method which combines the sweep method and the tetrahedral patch conforming methods was used to generate the mixed element grids used in this study.

- The ANSYS 13 CFX flow solver is a 3D compressible, unstructured, Reynolds Averaged Navier-Stokes based method.

- The finite volume based CFX solver generates flow solutions on mixed element, vertex based grids.

- The parallel solver, which can solve steady or unsteady cases, employs local time stepping to aid in convergence.

# LEWICE3D Version 3.48

- ## Version 3.48

  - 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 packet based collection efficiency algorithm was developed which calculates particle trajectories from inflow block boundaries to outflow block boundaries. This method is used for calculating and passing collection efficiency and particle property data between blade rows for turbo-machinery calculations.
  - 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.
  - The NASA Glenn Ice Crystal Phase Change Model was incorporated which tracks temperature and phase of water based particles through the flow-field
  - 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 Void Ice Density Model

Particle Trajectory

Void Region

Roughness Element

ds

$\theta$

Surface

$K_r$

$R_c$



- Impact Angle, 90; XKR, .001
- Impact Angle, 90; XKR, .05
- Impact Angle, 90; XKR, 1.
- Impact Angle, 50; XKR, .001
- Impact Angle, 50; XKR, .05
- Impact Angle, 50; XKR, 1.
- Impact Angle, 25; XKR, .001
- Impact Angle, 25; XKR, .05
- Impact Angle, 25; XKR, 1.
- Impact Angle, 10; XKR, .001
- Impact Angle, 10; XKR, .05
- Impact Angle, 10; XKR, 1.

Ice Void IDensity, kg/m³

Freezing Fraction

# IRT Icing Tests for NACA 0012 Wing

- The icing tests for the NACA 0012 swept wing tip were conducted during two entries in the IRT.

- The February 2010 tests generated 13 icing test points for the 45$^o$ swept configuration.

- The February 2014 tests generated 18 icing test points for the 30$^o$ swept configuration.

- Tunnel spray conditions, videos, photographs and ice shape tracings were taken for all of the test points.

- Pressure distributions, ice shape scans and wax molds were taken for select test points.

- The tests involved temperature sweeps at large and small inertia parameter settings for the 45$^o$ and 30$^o$ sweep configurations to test the range of the void density model which depends upon particle impact angle and freezing fraction.

# Ice Shape Calculations for NACA 0012 Swept Wing

- The ANSYS 13 CFX software was used to generate the grids and viscous, compressible flow solutions for the swept models.

- The isolated wing models employed a plane of symmetry at the wing root and a normal wall spacing of $3.8 \times 10^{-6}$ m which corresponds to a y+=1 spacing at a Reynolds number of 7.2 million and a reference length of 1 m.

- The volume grid for the 45° swept model contained 5,640,314 volume elements and 1,520,916 nodes. The volume grid for the 30° swept model contained 6,093,024 volume elements and 1,653,950 nodes.

- All cases were run at 0° angle-of-attack using a 7 bin IRT based distribution.

- The small inertia parameter (K=0.036) icing condition employed a tunnel speed of 45 m/s, median volume diameter of 15 microns and an LWC of 1.5 g/m$^3$.

- The large inertia parameter (K=0.378) icing condition employed a tunnel speed of 103 m/s, median volume diameter of 32 microns and an LWC of .45-.47 g/m$^3$.

# Ice Shape As a Function of Temperature
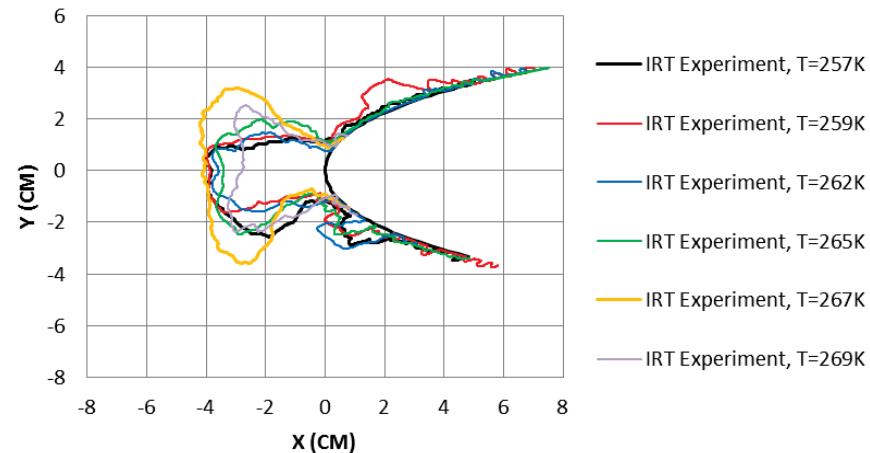


45° sweep, small K
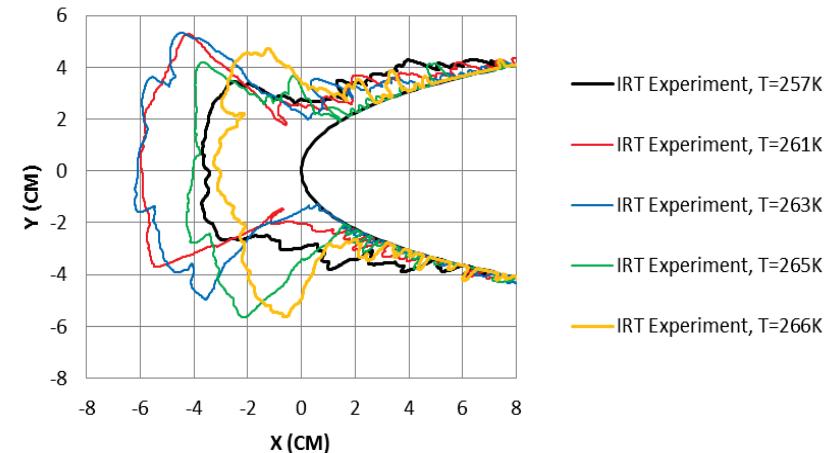


45° sweep, large K
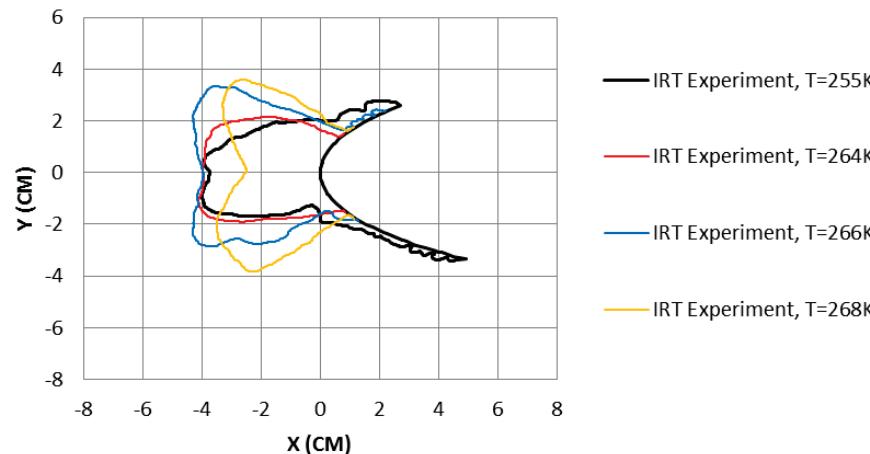


30° sweep, small K
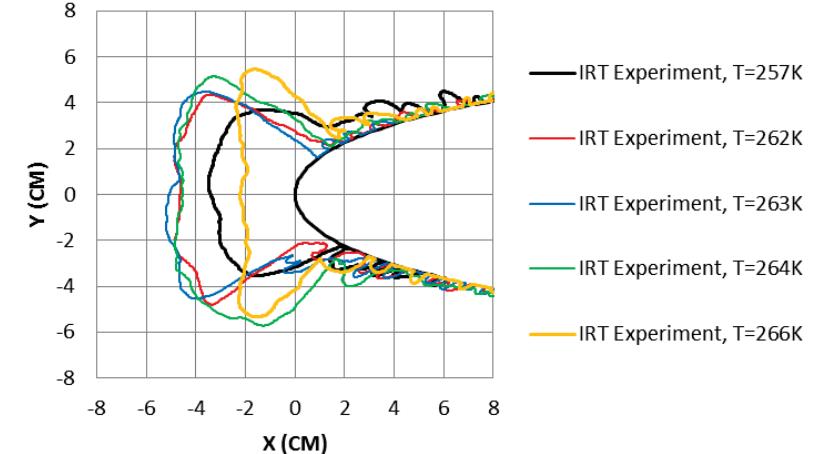


30° sweep, large K

# Ice Shape As a Function of Temperature
## 30° sweep, Small K
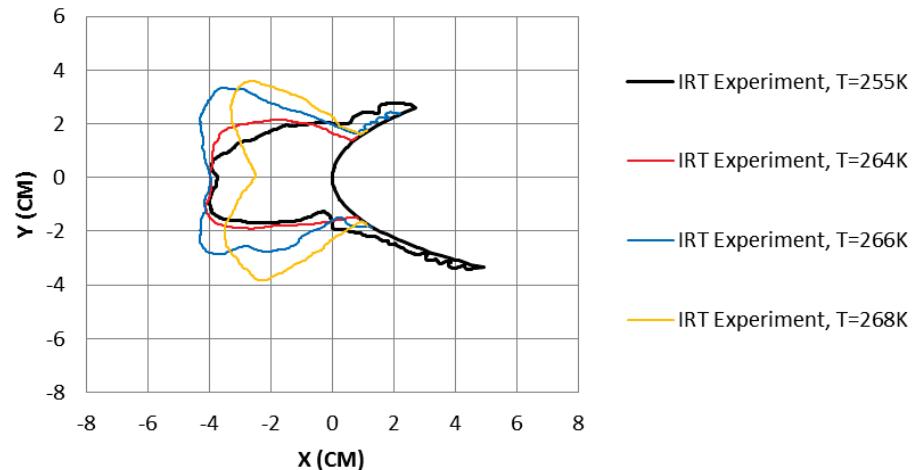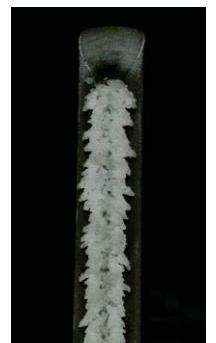


T = 255K          T = 264K          T = 266K          T = 268K

# Ice Shape As a Function of Temperature

## 45° sweep, Large K
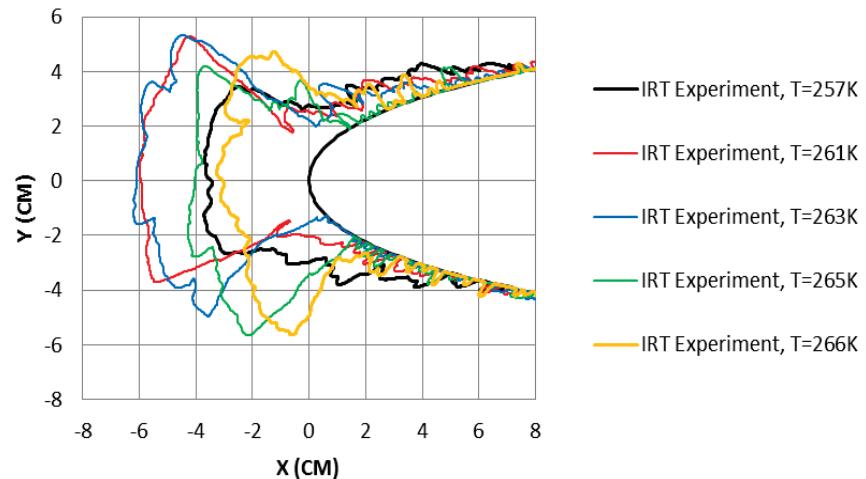


T = 257K   T = 261K   T = 263K   T = 265K   T = 266K

# Ice Shape As a Function of Icing Time
## $30^{o}$ sweep, large K, static temperature, 263K
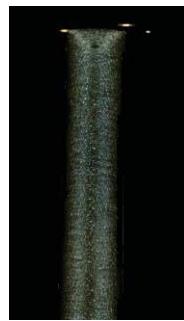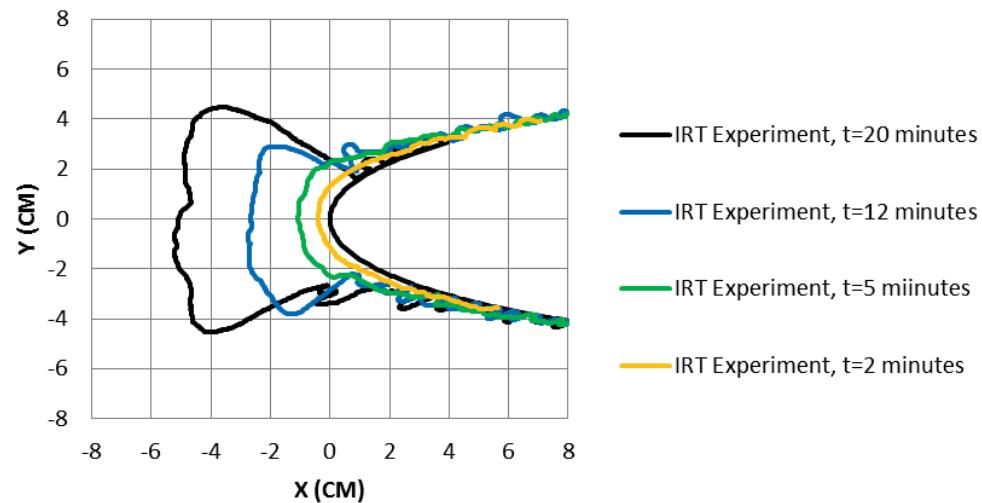


2 minutes  5 minutes  12 minutes  20 minutes

# Ice Shape As a Function of Icing Time
## $30^o$ sweep, large K, static temperature, 257K
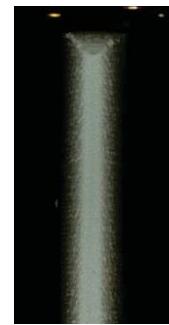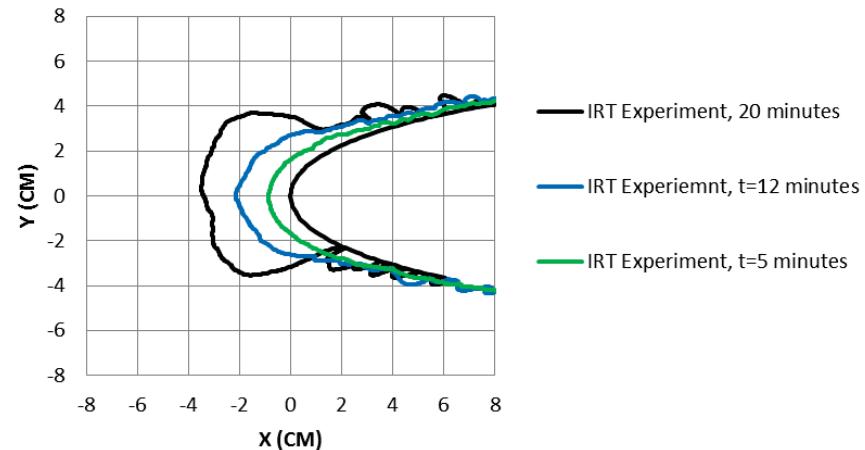


5 minutes
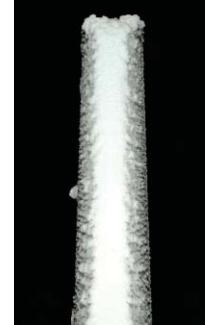
12 minutes
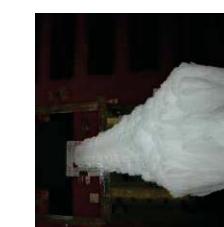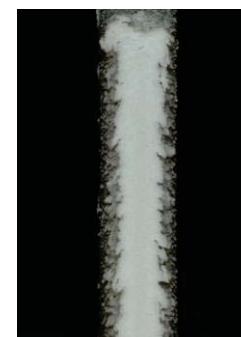
20 minutes

# Ice Shape Comparisons
## 30° sweep, large K, static temperature, 264K
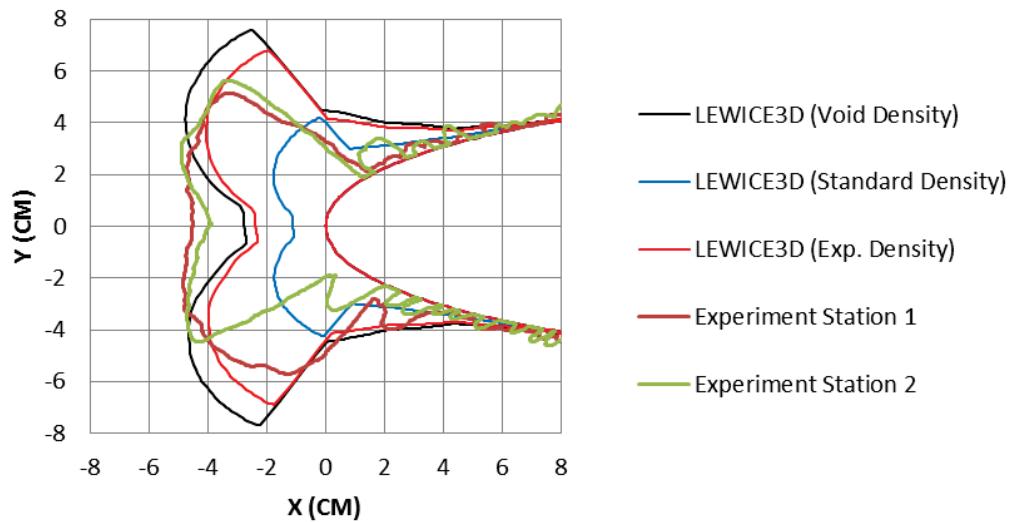
# Ice Shape Comparisons
## $45^o$ sweep, small K, static temperature, 257K
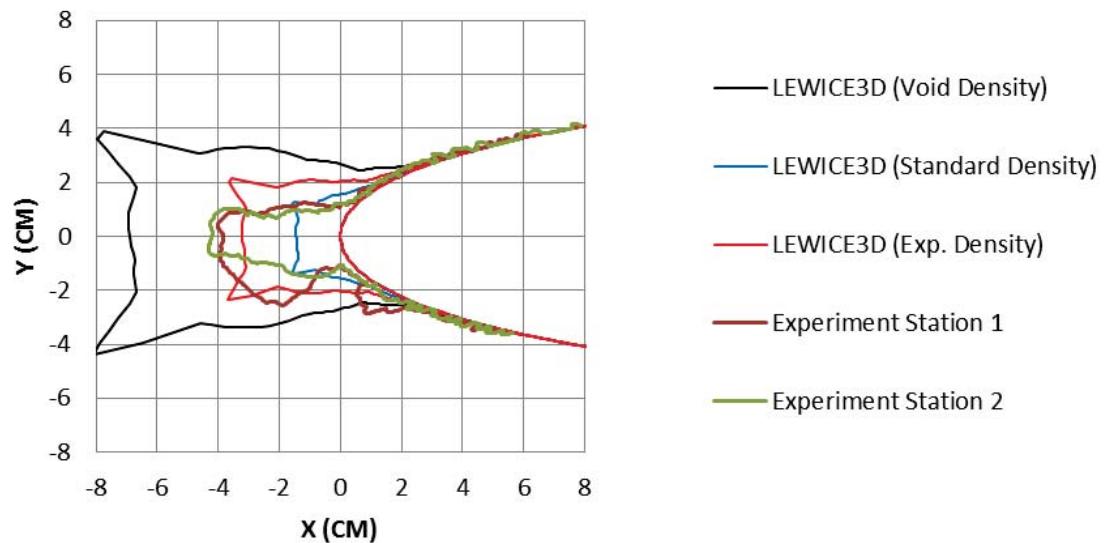
# Ice Density Comparisons
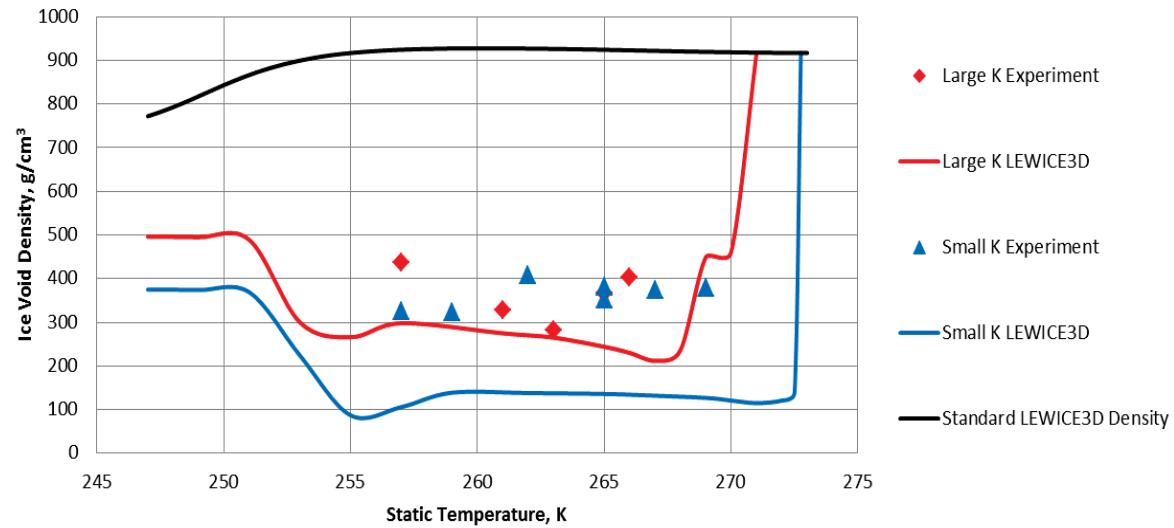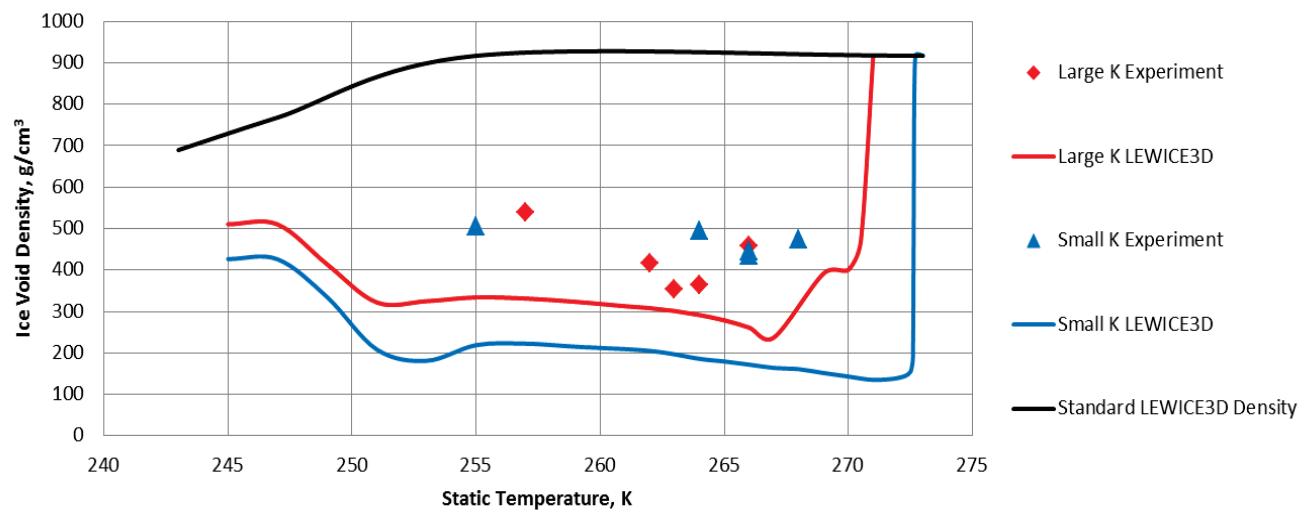
# Ice Shape As a Function of Icing Temperature
## 45$^o$ sweep, large K



T=257K



T=263K
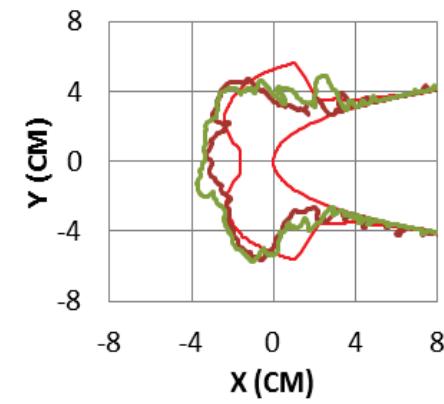


T=266K
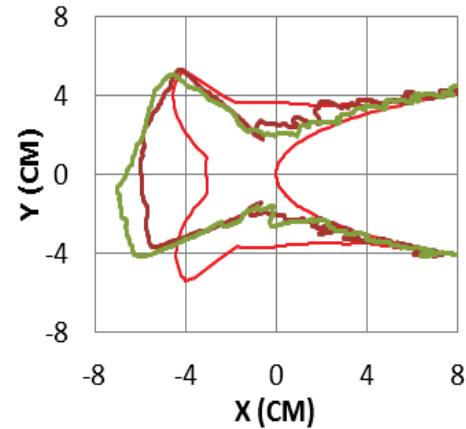


T=261K
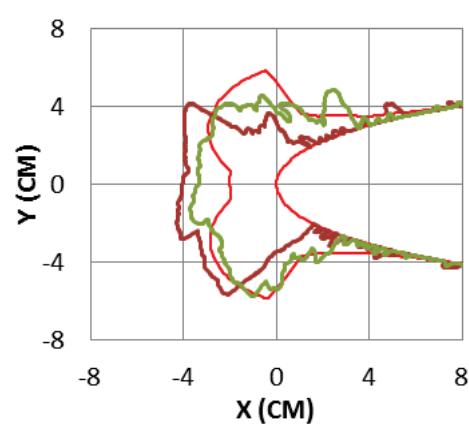


T=265K

— LEWICE3D (Exp. Density)
— Experiment Station 1
— Experiment Station 2

# Leading Edge Heat Transfer Enhancement
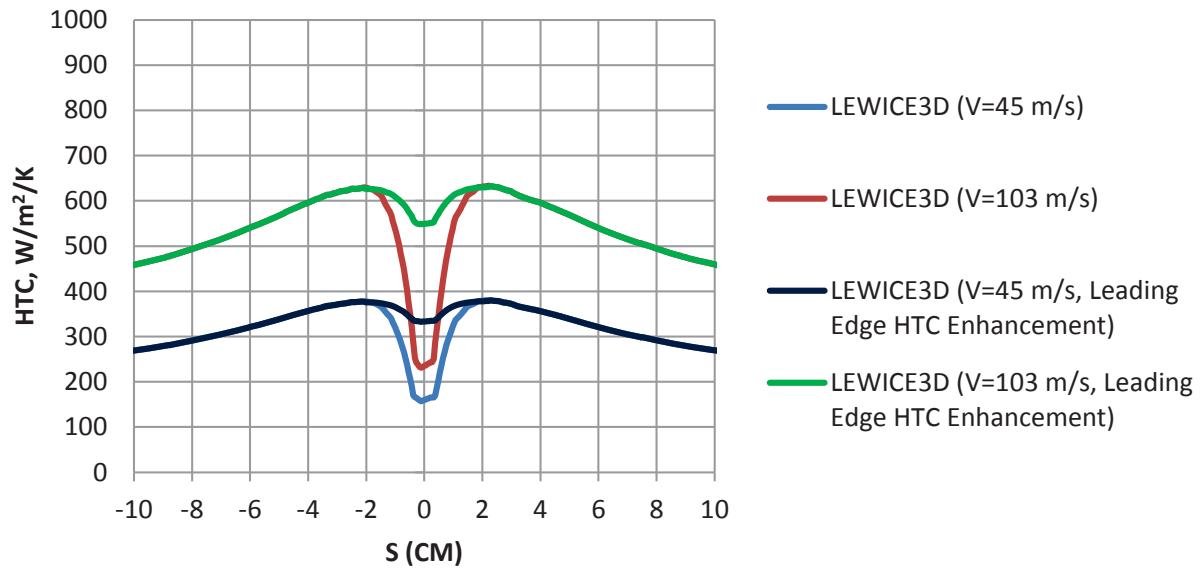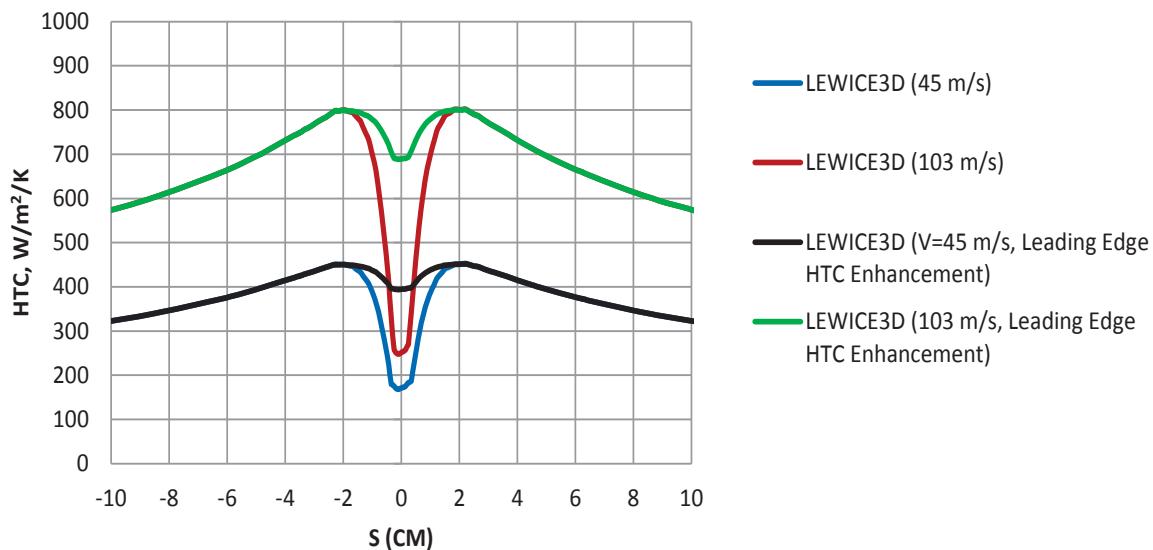
# Comparisons for Void Density Model Using Mass Averaged Impact Angle



45° sweep
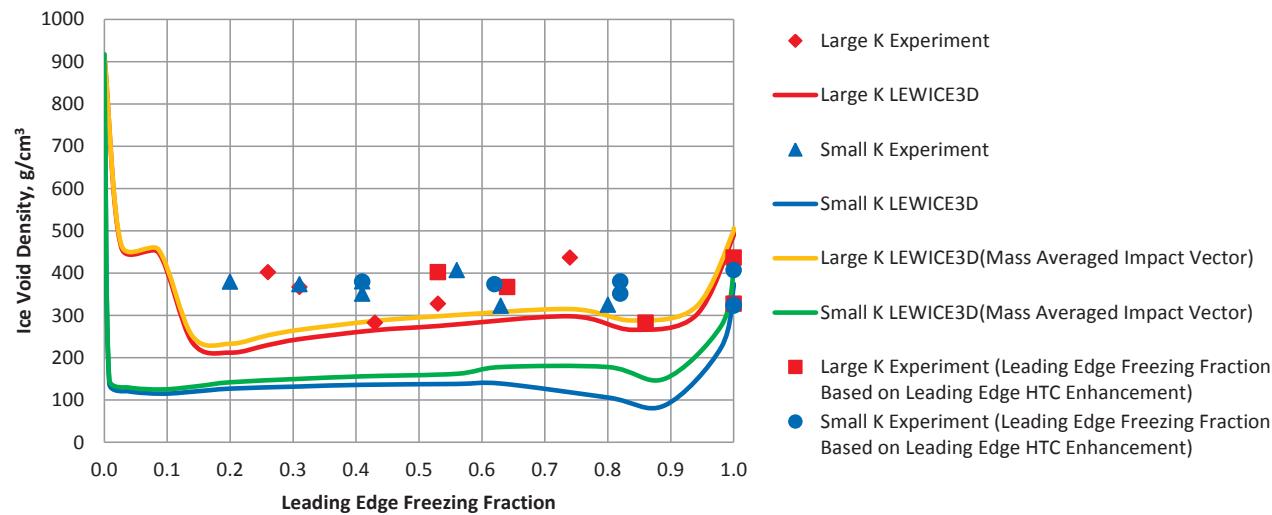
30° sweep
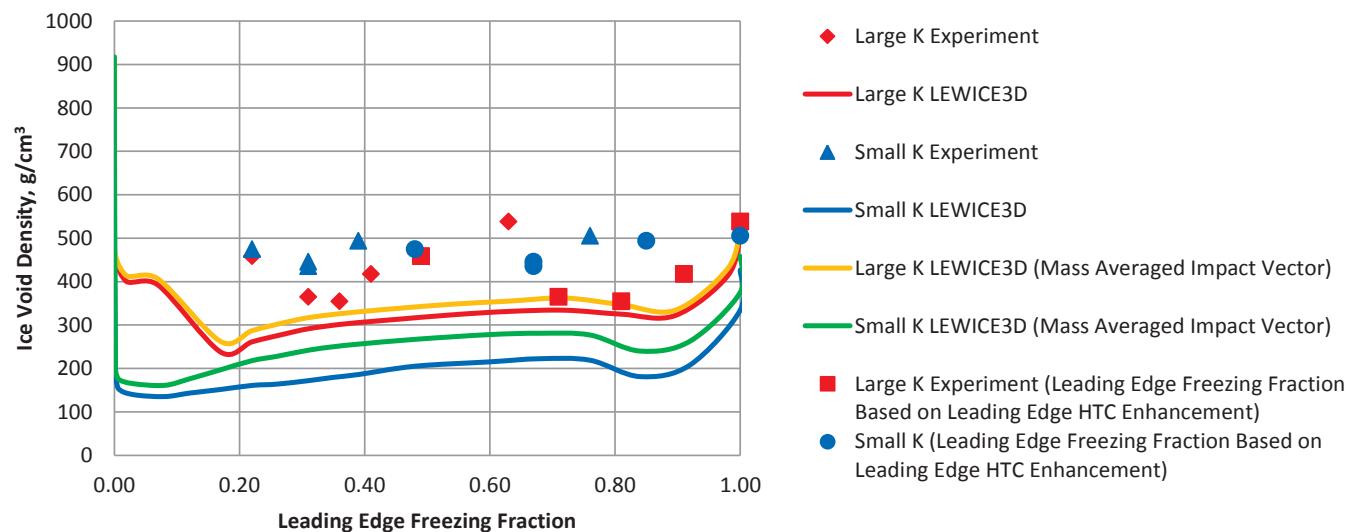
# Ice Shapes Using HTC and Ice Void Density Enhancements



Legend:
- LEWICE3D (Void Density)
- LEWICE3D (Standard Density)
- LEWICE3D (Exp. Density)
- LEWICE3D (Mass Averaged Impact Vector + Leading Edge HTC Enhancement)
- Experiment Station 1
- Experiment Station 2

$45^o$ sweep, small K

$45^o$ sweep, Large K

$30^o$ sweep, small K

$30^o$ sweep, Large K

# Conclusions

- Ice shape, ice density and iced area comparisons were made between experiment and prediction for a series of icing conditions for a swept NACA 0012 wing model to evaluate the LEWICE3D void density model which was developed to predict more accurate ice shapes for swept wings.

- The larger inertia parameter and sweep angles ice shapes showed a larger dispersion in leading edge ice thickness than the smaller inertia parameter and sweep angle cases. This was due to the increased void volume of the ice shapes for these cases.

- From the time series tested for the rime, glaze and scallop conditions it was deduced that the mass rate of accretion was linear and the iced area progression was linear except for the late stage scallop condition. For the late stage scallop condition (> 5 minutes) the mass rate of accretion was linear but the area percentage iced area increased with time due to the development of the scallop features with large void regions.

# Conclusions

- The LEWICE3D ice void density model under-predicted void density by an average of 30% for the large inertia parameter cases and by 63% for the small inertia parameter cases. This under-prediction in void density resulted in an over-prediction of ice area by an average of 115%.

- Major contributors to the overly conservative ice shape predictions were deficiencies in the leading edge heat transfer and the sensitivity of the void ice density model to the particle inertia parameter. The scallop features present on the ice shapes were thought to generate interstitial flow and horse shoe vortices which enhance the leading edge heat transfer.

- A set of changes to improve the leading edge heat transfer and the void density model were tested. The changes improved the ice shape predictions considerably.

- More work needs to be done to evaluate the performance of these modifications for a wider range of geometries and icing conditions