AIAA 1st Ice Prediction Workshop July 26-29, 2021

Boeing LEWICE2D and LEWICE3D summaries

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Summary

LEWICE2D and LEWICE3D both yielded good comparisons to test data in several areas:

	Cp	Beta	Ice mass	Horn angle	Ice height
LEWICE2D	√	√ to fair	√	√	√
LEWICE3D	√	√ to fair	√	√	fair

Beta here is water collection efficiency, not side-slip angle.

The LEWICE3D ice height results may be improved if a method for determining the analysis ice density can be found.

The amount of variation in measured ice shape parameters between test and analysis was similar to that found in NASA/CR-1999-208690, “Validation Results for LEWICE 2.0”.

It is not clear if the differences in ice shape would have a measurable effect on aerodynamic performance effects such as lift and drag.

LEWICE2D calculations

The NASA code LEWICE2D (version 3.2.2) was used for the calculations herein.

LEWICE2D uses a multi-step approach to calculating the ice shape, with typically 8 to 16 sub-steps to reach a final ice shape. The automatic time step selection was used for all cases.

The default flow solver (potential flow) was used for all cases.

LEWICE2D does not have a convenient way to include tunnel walls, so the walls were not included.

The nominal AOA was used for all cases (no corrections for tunnel walls or 3D effects)

The default ice density (917 kg/m^3) was used for all cases.

Beta here is water collection efficiency, not side-slip angle.

LEWICE2D calculations sweep corrections

As LEWICE2D is a 2D code, it was necessary to apply corrections for the effects of sweep.
The sweep corrections used are summarized below.

To perform analysis with LEWICE2D, the following process was used:

- Use the 2D cut normal to the airfoil leading edge
- Use the nominal AOA
- Use the nominal test section airspeed and T_static values
- Use LWC_analysis = LWC *cos(sweep)

To report analysis values, all values are reported without corrections, except for:

- Beta_3D = Beta_2D * cos(sweep)
- Cp_3D = Cp_2D * (cos(sweep))**2

Beta here is water collection efficiency, not side-slip angle.

LEWICE3D calculations

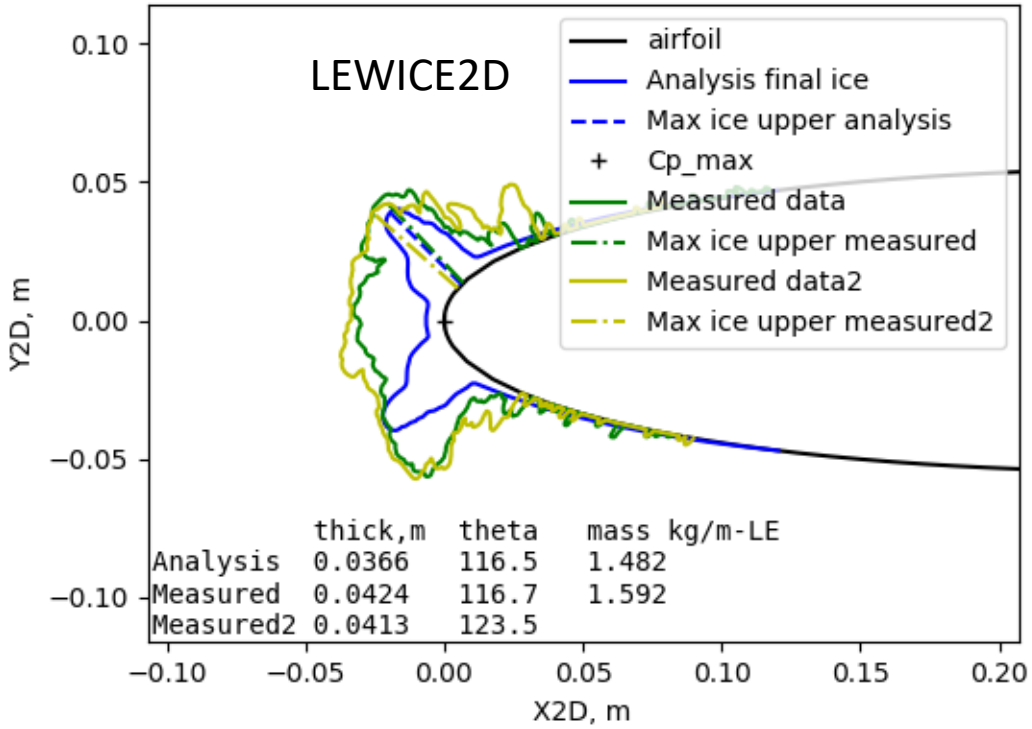
The NASA code LEWICE3D (LEWICE3D MPI 2.2.01, trajmc3d.40jclh225gb.f) was used for the calculations herein.
CFD++ version 17.1, was used for the flow field analysis.
LEWICE3D uses a single time step approach to calculating an ice shape.

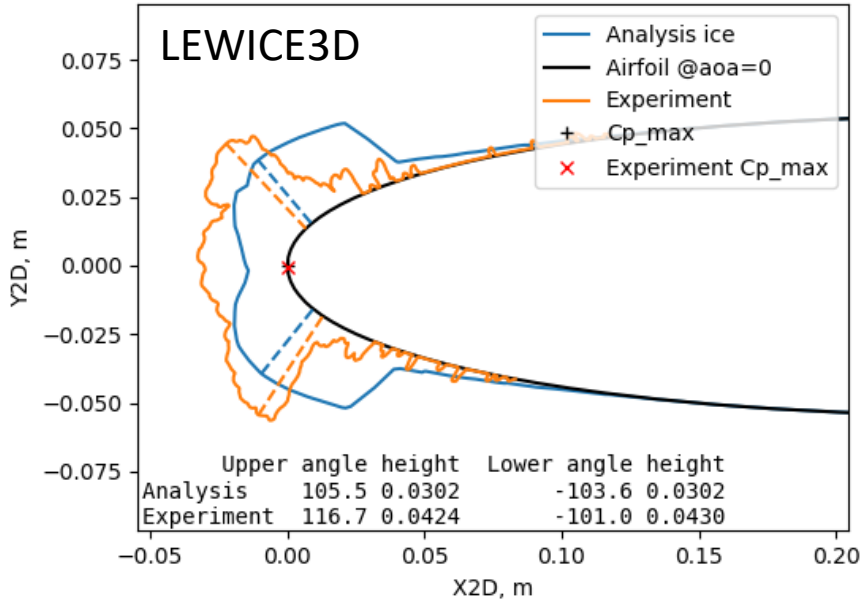
The CFD grids supplied on the IPW web page were used, except for cases 121, 241, and 242.
For those conditions, the supplied grids yielded errors in LEWICE3D.
So, the geometry was constructed in free air for those conditions.

Ice shapes Case-372
A “good” comparison

For Case-272 (sweep=45), the agreement between test and analysis ice shapes is good for both LEWICE2D and LEWICE3D, as measured by the upper ice “horn” angle and thickness.

However, the more subjective ice “shapes” appear to be different.



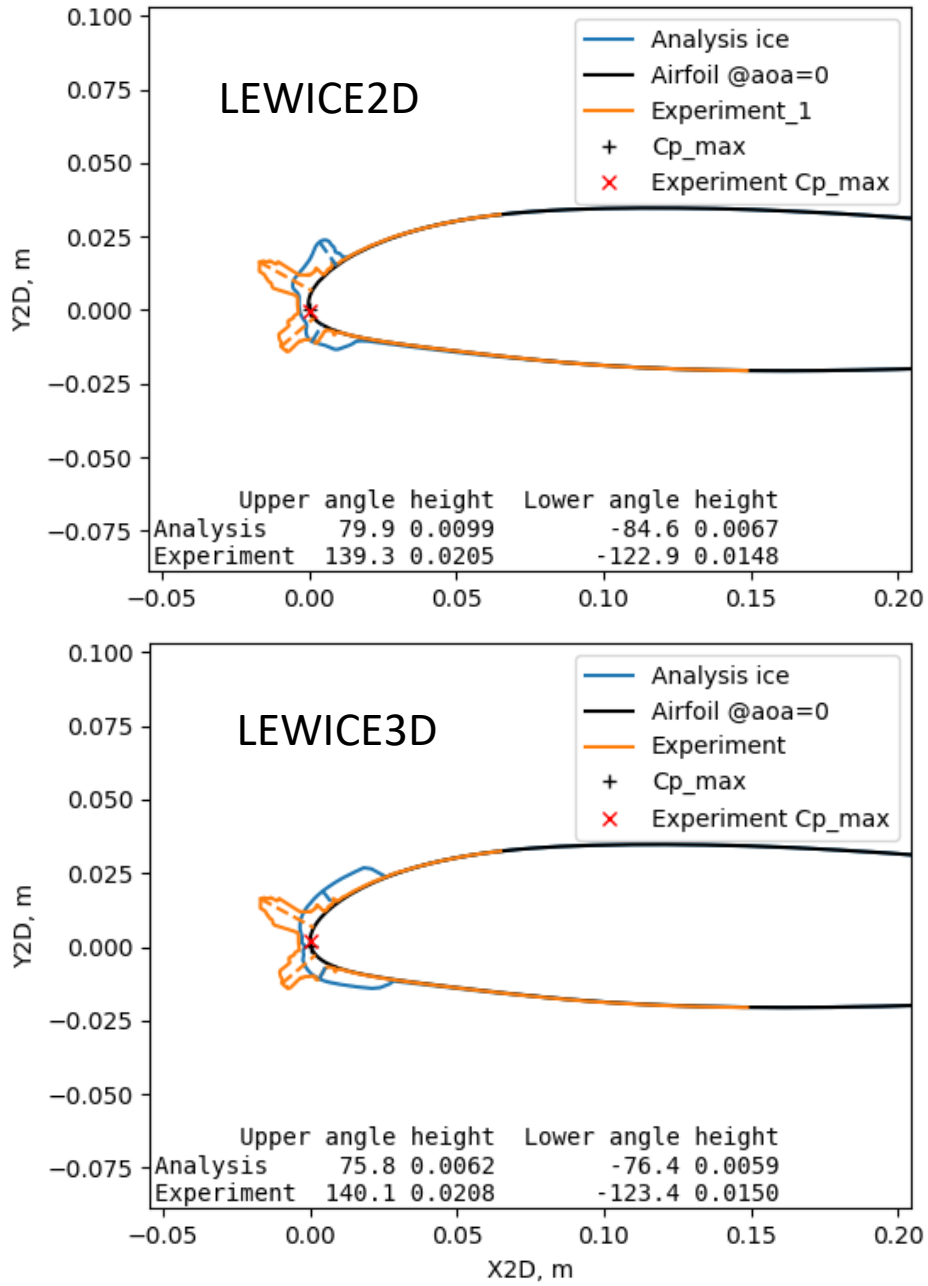


Ice shapes Case-242
A not so good comparison

For Case-242 (sweep=0), the agreement between test and analysis ice shapes is not good.

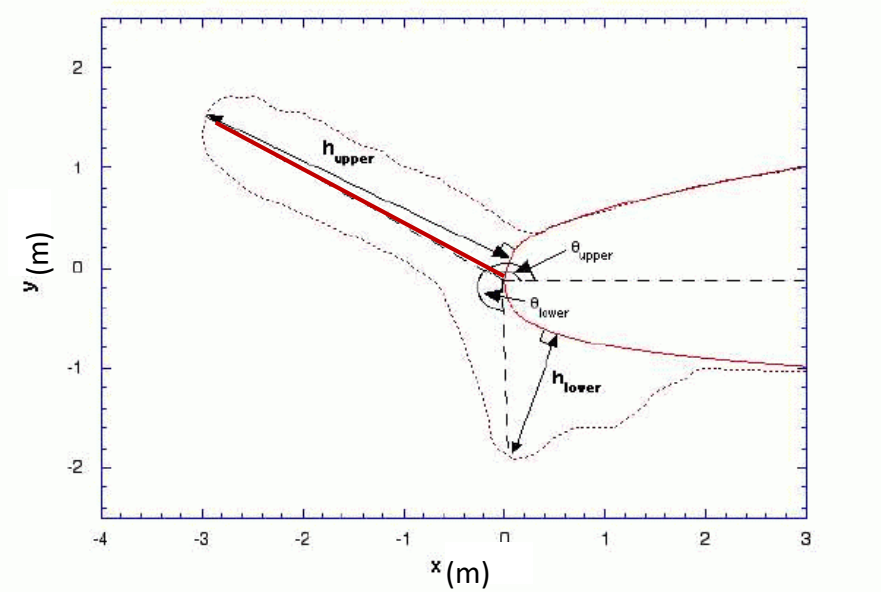
At the IPW planning committee meetings, the NASA specialist that was involved with the icing runnel test noted that the reported test conditions may be in error.

As so, Case-242 will not be included in the following summary ice shape comparisons.

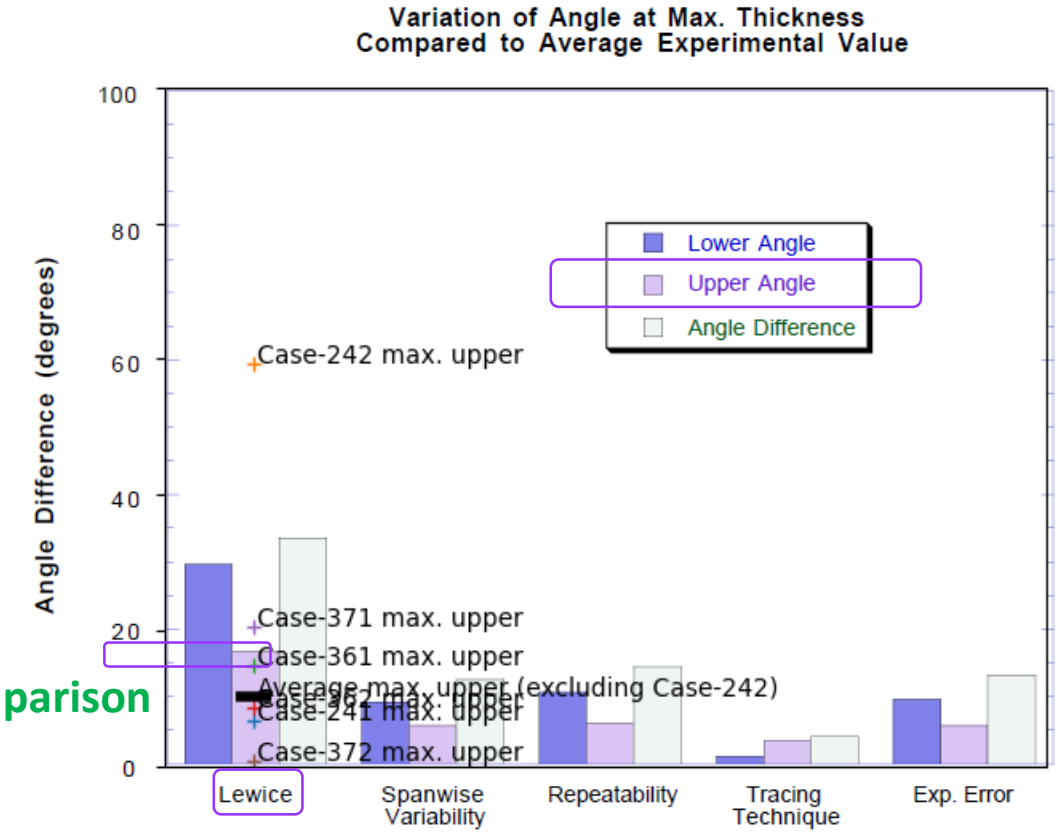


Results summary: LEWICE2D maximum ice thickness location

The LEWICE2D validation report NASA/CR-1999-208690 characterized the maximum ice thickness locations differences by maximum thickness angle “theta” differences.



The average for the cases herein, which include 3D cases, is better than the average of the LEWICE2D validation cases.

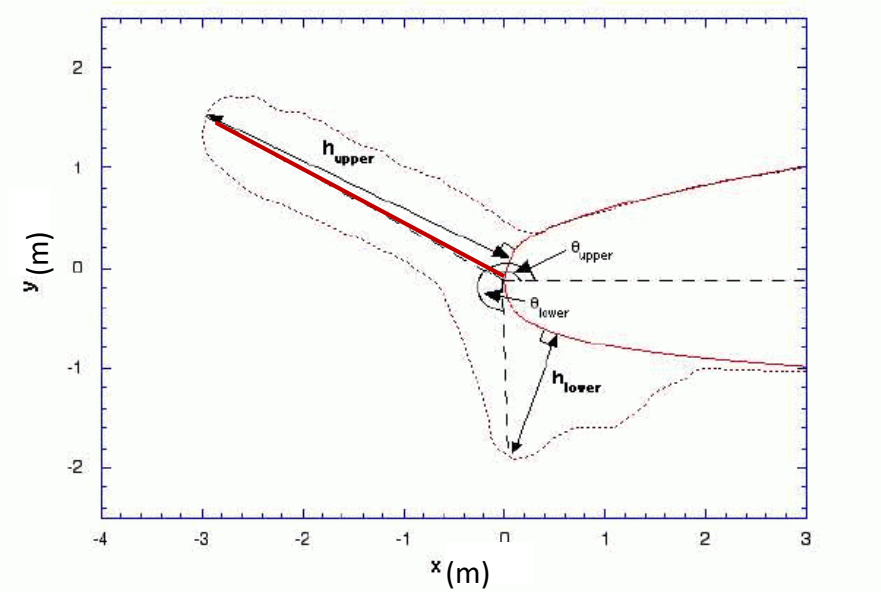


Good comparison

FIGURE 21. Variation of Angle at Max. Thickness Compared to Average Experimental Value

Results summary: LEWICE3D maximum ice thickness location

The LEWICE2D validation report NASA/CR-1999-208690 characterized the maximum ice thickness locations differences by maximum thickness angle “theta” differences.



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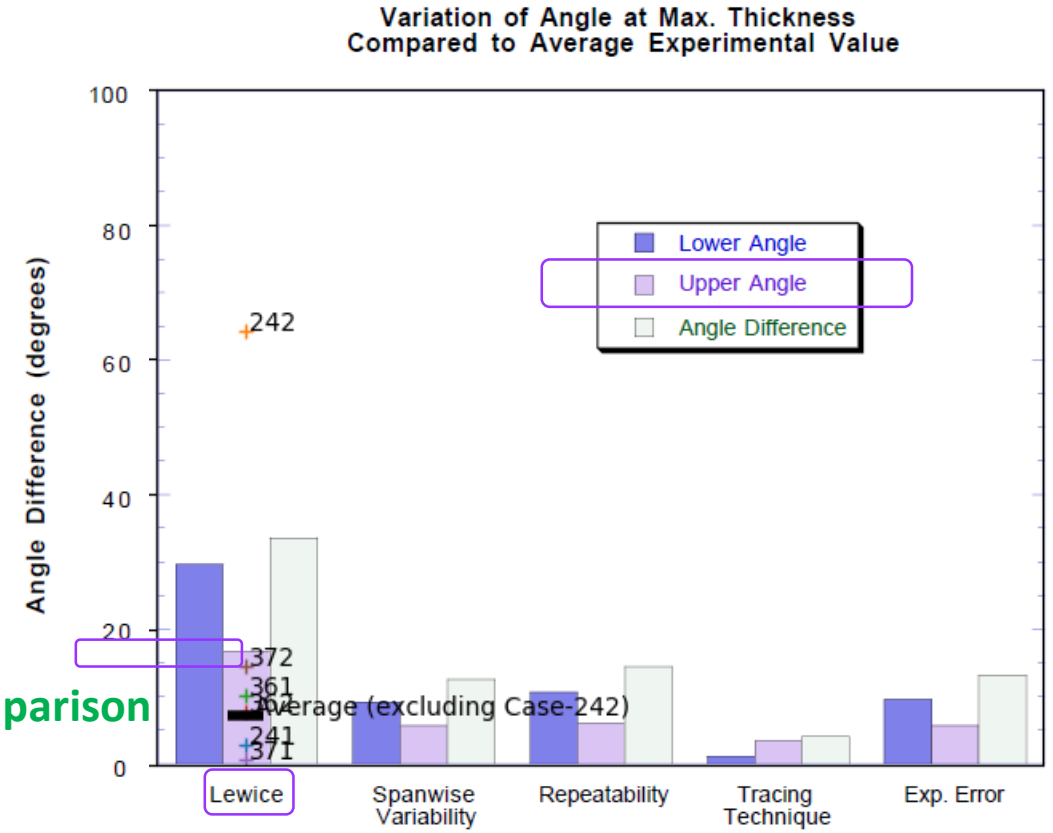


Good comparison

FIGURE 21. Variation of Angle at Max. Thickness Compared to Average Experimental Value

Results summary: LEWICE2D ice thickness

The average for the cases with revised density is larger than the average of the LEWICE2D validation cases.

The ice density determination is a potential area of improvement for the use of LEWICE3D.

Note that the thickness difference has a accretion rate t_{max} term.

$$difference = \frac{abs(Thick1 - Thick2)}{t_{max}}$$

$$t_{max} = \frac{(LWC)(V)(Time)}{\rho_{ice}} \qquad (7)$$

Where t_{max} is a maximum theoretical ice thickness with 100% freezing and 100% collection efficiency.

Good comparison

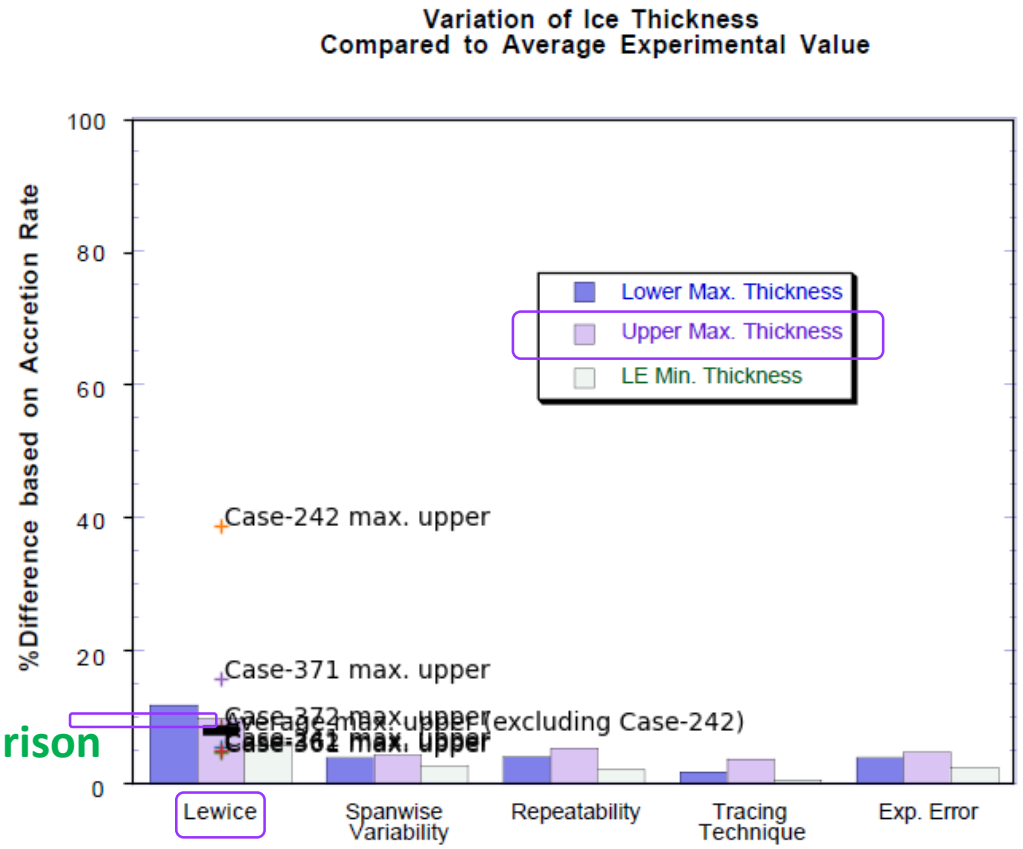


FIGURE 19. Variation of Ice Thickness Compared to Average Experimental Value

LEWICE3D ice density

The “Experimental Void Density” from Tables 1 and 2 of AIAA 2014-2200 were used for the swept NACA 0012 cases.

	Experimental Void Density, kg/m^3
Case-361	528
Case-362	355
Case-371	437
Case-372	402

Swept ice cases not in AIAA 2014-2200:

Case-241 (not swept) 917 kg/m^2

Case-242 (not swept) 917 kg/m^2

All other cases used ice density = 917 kg/m^2 (swept or not swept)

Results summary: LEWICE3D ice thickness

The average for the cases with revised density is larger than the average of the LEWICE2D validation cases.

The ice density determination is a potential area of improvement for the use of LEWICE3D.

Note that the thickness difference has a accretion rate t_{max} term.

$$difference = \frac{abs(Thick1 - Thick2)}{t_{max}}$$

$$t_{max} = \frac{(LWC)(V)(Time)}{\rho_{ice}} \qquad (7)$$

Where t_{max} is a maximum theoretical ice thickness with 100% freezing and 100% collection efficiency.

Fair comparison

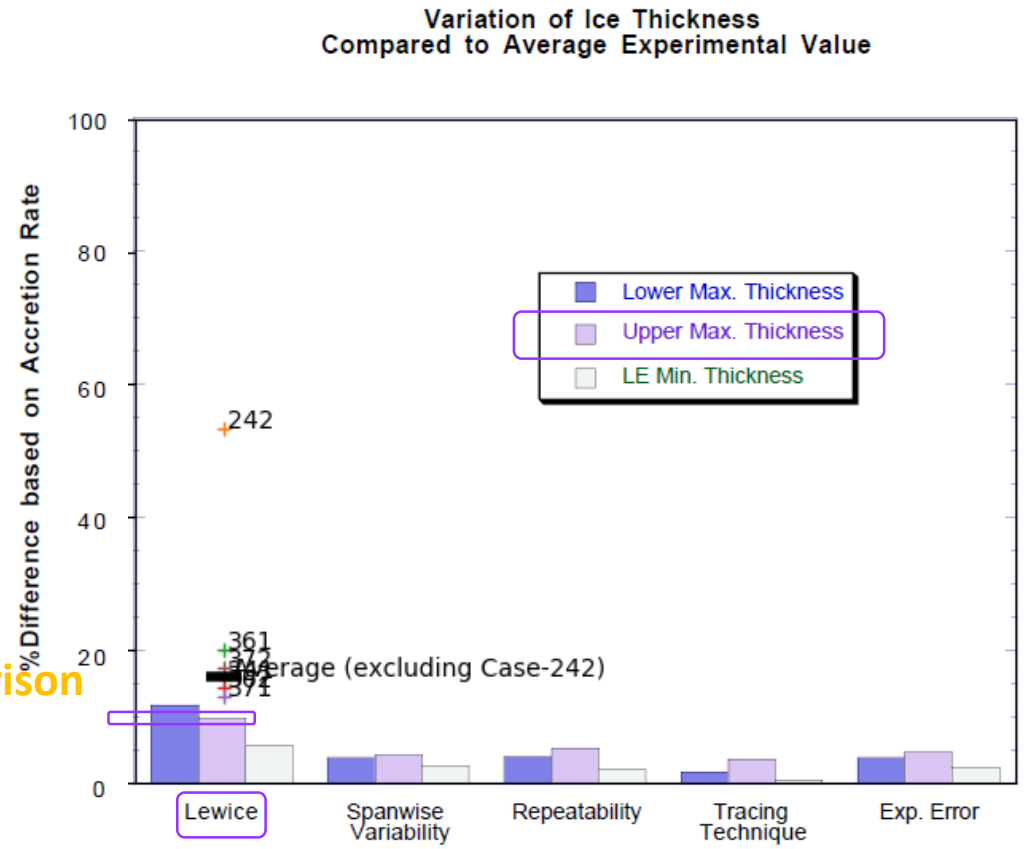


FIGURE 19. Variation of Ice Thickness Compared to Average Experimental Value

Final Notes

Good results were achieved with LEWICE2D analysis, despite these apparent limitations:

- Potential flow analysis (no boundary layer or turbulence)
- No tunnel walls included
- Use of nominal AOA (no correction for walls, measured stagnation location, or 3D effects)
- Fixed ice density
- Simple sweep corrections (no 3D effects)

Good results were also achieved with LEWICE3D (except for ice thickness)

The LEWICE3D results may be improved if a method for determining the analysis ice density can be found.

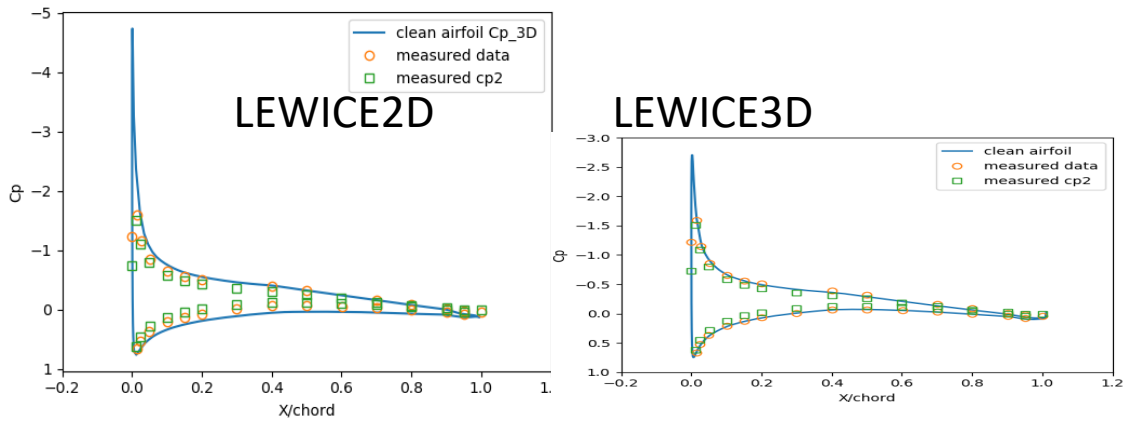
Appendix

Results summary: Cp data cases

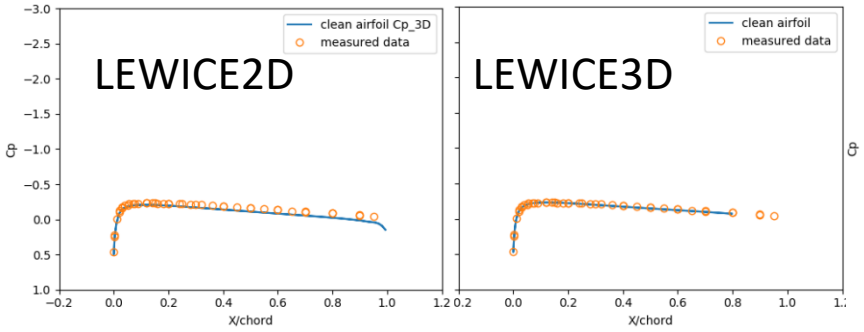
Good comparison

The agreement between analysis and test was “good”, for both LEWICE2D and LEWICE3D.

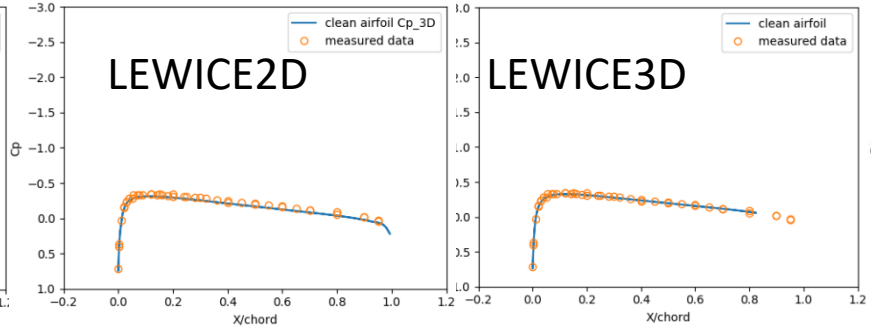
Case-111 Swept Tail



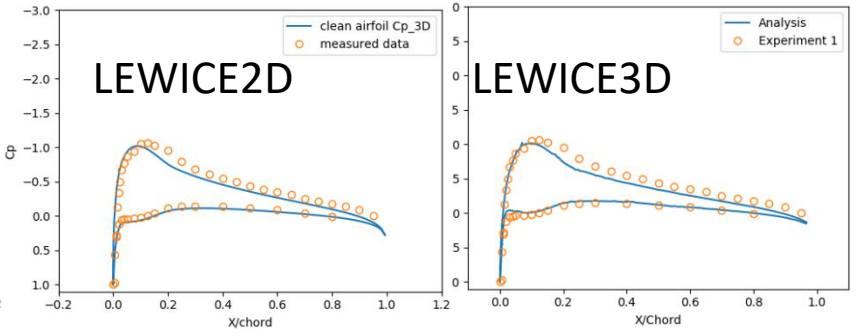
Case-371 NACA 0012 45 sweep



Case-361 NACA 0012 30 sweep



Case-241 NACA 23012

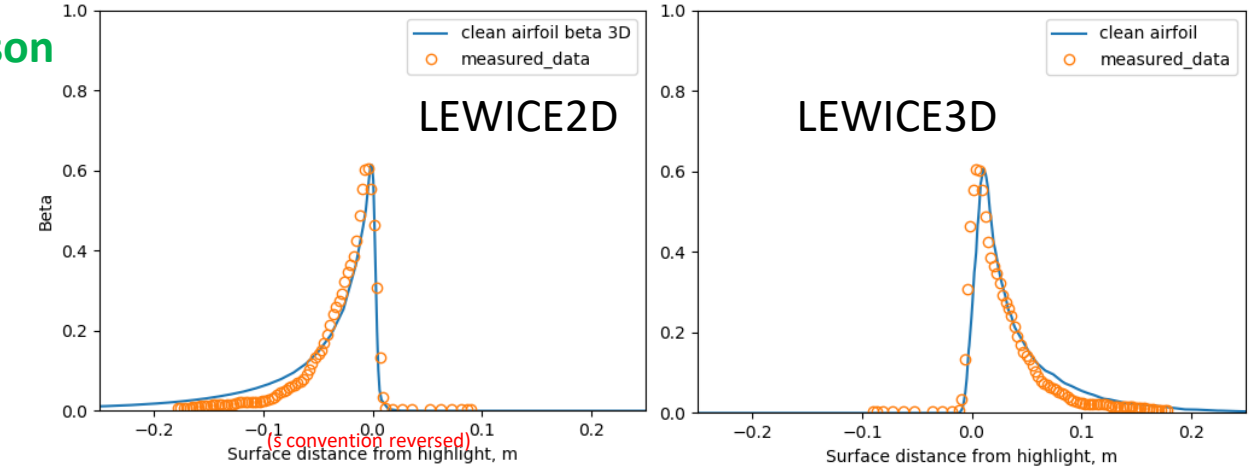


Results summary: Impingement data cases

Case-111 Swept tail

Good comparison

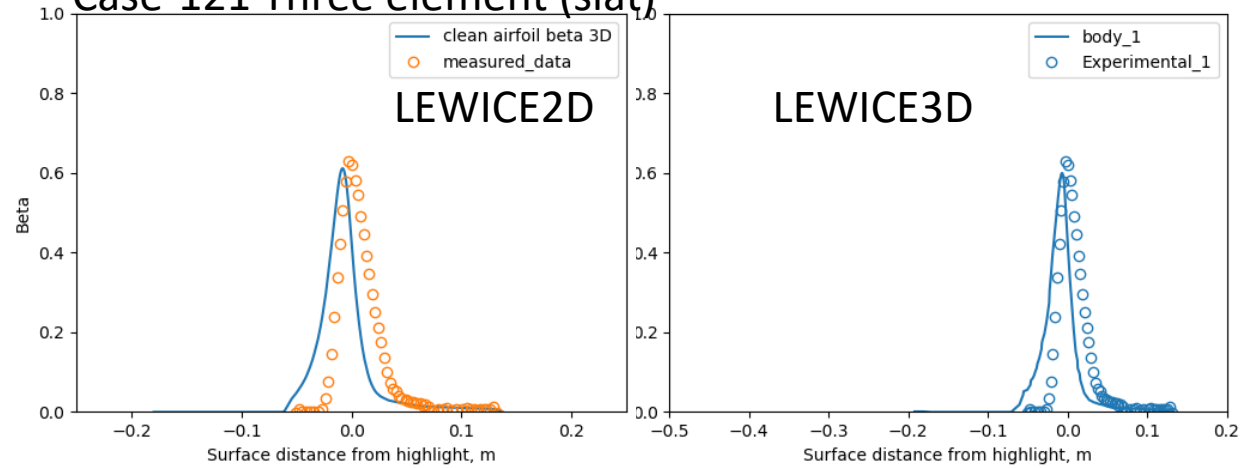
For the single element airfoil swept tail case, the agreement between the calculated and measured impingement “beta” rates was “good”.



Case-121 Three element (slat)

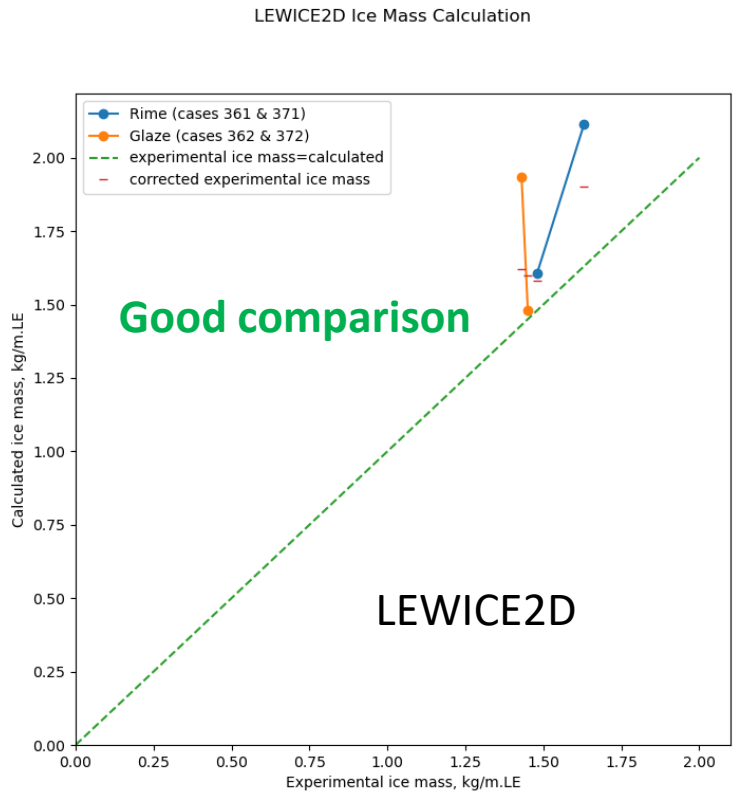
Fair comparison

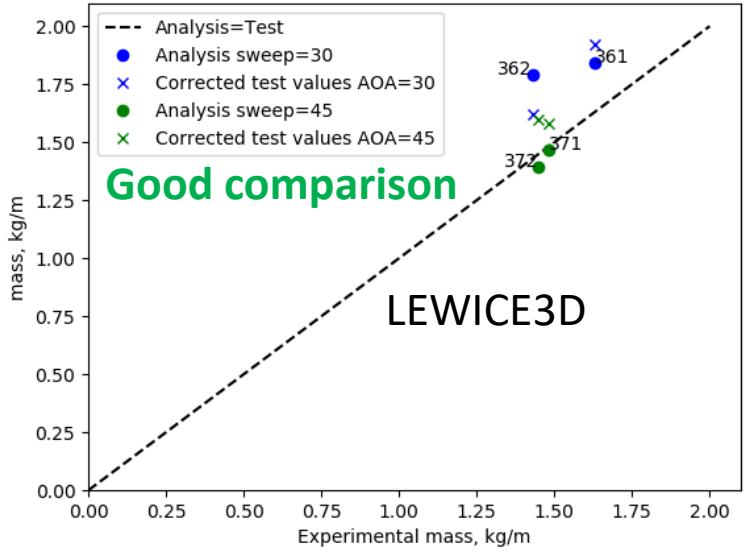
For the three element airfoil case, the agreement between the calculated and measured impingement rates was “fair”.



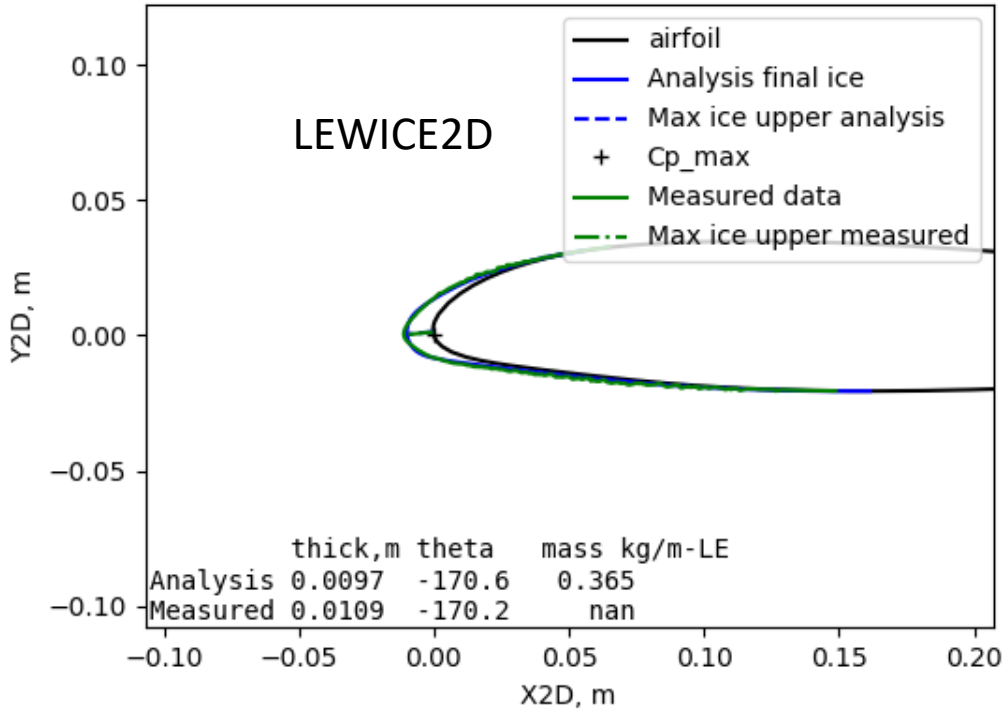
Beta here is water collection efficiency, not side-slip angle.

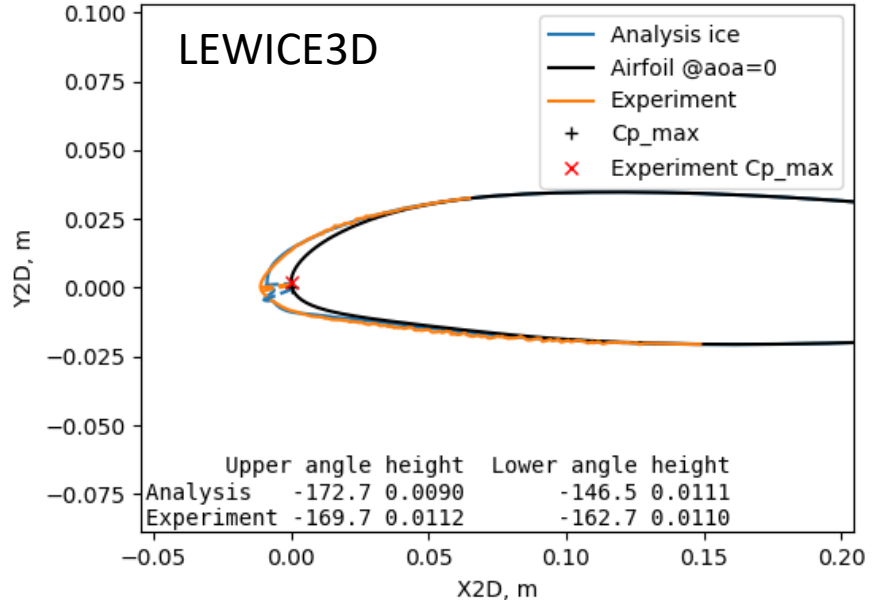
Results summary: Ice mass cases



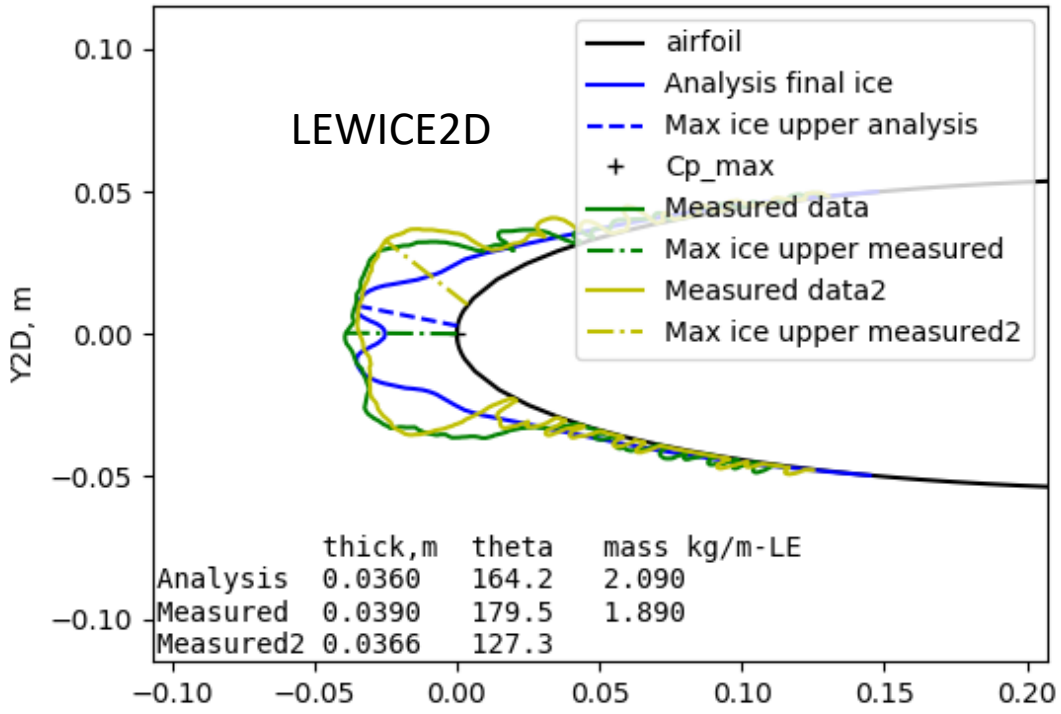


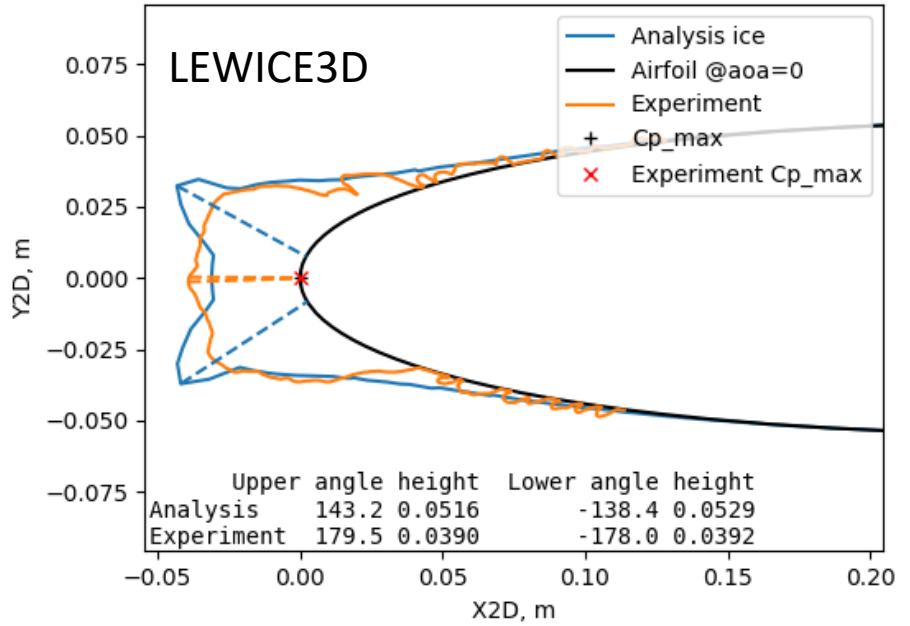
Ice shapes Case-241



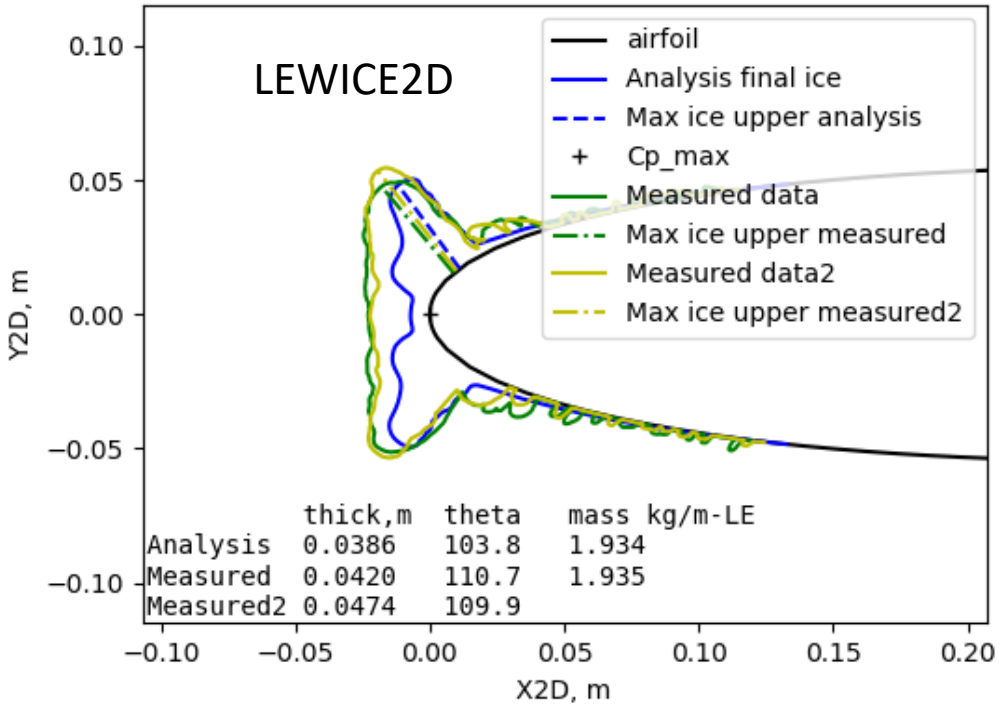


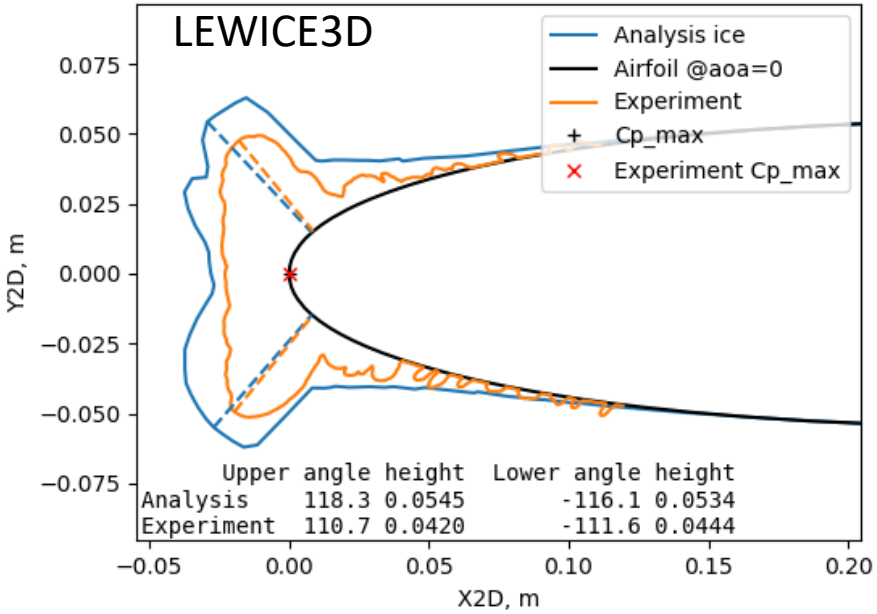
Ice shapes Case-361





Ice shapes Case-362





Ice shapes Case-371