

Roughness Parameter Optimization of the McClain Model in GlennICE

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Abstract

Aircraft icing remains a significant threat to aviation safety. Software that predicts the impingement and ice accretion on full aircraft geometries and aircraft components are in demand and NASA Glenn is committed to produce software that meets this need. One of the key parameters affecting an accurate prediction of iced geometry is the effect of ice roughness on the heat transfer coefficient. While many efforts have been made to implement the roughness in the flow solver, this report takes a correlation for roughness height distribution that is based on experimental measurements and demonstrates how to relate those measurements to an augmentation to the heat transfer coefficient provided by the flow solution. The outcome of this effort was the calibration of defaults for user supplied parameters to this correlation through comparison with 95 large glaze conditions from experiment by adjusting user-supplied parameters in the roughness augmentation equation.

Introduction

Surface roughness has long been an important consideration in icing. Early works focused on the measurement of roughness and its effect on heat transfer [1–5]. The initial attempts to incorporate roughness effects into icing simulation used an integral boundary layer method described by Schlichting [6] and incorporated roughness to determine transition [7] as well as the augmentation to heat transfer [8]. These criteria were used in LEWICE [9] and LEWICE3D [10] to predict transition and turbulent heat transfer with roughness effects. This technique was extended for 3D boundary layers by Blanchard et. al. [11]. Other researchers built roughness effects through turbulence models such as that developed by Aupoix [12] and Menter [13]. Examples include the efforts of Beaugendre [14], Knopp [15], Bernardini [16] Tagawa [17], and Min [18]. Neither the boundary layer approach nor the turbulence model approach is always applicable in GlennICE [19]. GlennICE is a computational tool that is being developed by NASA to predict ice shapes on multi-dimensional geometries of higher complexities based on a computational flow solution that a user provides. GlennICE does not calculate the flow solution, rather it reads in a solution from other sources. These flow solvers may or may not have a turbulence model that includes roughness effects on heat transfer. Heat transfer coefficient is a critical parameter for predicting the ice shape and will increase as ice begins to accrete and the surface becomes rough. A methodology is needed to incorporate this effect other than through the use of turbulence models. The current implementation within GlennICE incorporates a roughness model that was designed by McClain [20] which incorporates measurements of ice roughness distributions over a wide variety of conditions and geometries to produce the correlation

provided. The roughness measurements have been reported in several papers [21–27]. The final correlation is based on parameters that are obtained from the flow field such as pressure coefficient (C_p), specified values for the icing conditions such as liquid water content (LWC), and the rate of mass impinging the surface. This implementation also includes the introduction of two user-defined parameters (UDPs): the ideal rime limit and turbulent heat transfer augmentation. The ideal rime limit is a dimensional value in meters and determines the point at which the growth of ice stops being considered roughness and subsequently becomes an ice shape. The turbulent heat transfer coefficient (htc) augmentation is a factor that scales the heat transfer coefficient augmentation to the roughness values provided by the correlation. This value had previously been set within GlennICE to a default value of 3 based on the best prediction of case 242 from the Ice Prediction Workshop [28].

Since the roughness augmentation model implemented within GlennICE requires these two UDPs to be defined, it is desired that suggested values be obtained that show the best agreement with experimental ice shapes over a variety of pressure gradient profiles, temperature differences, and freestream conditions. In order to accomplish this, six different airfoils have been chosen that have documented ice shapes and freestream conditions. Previous experimental testing within the NASA Icing Research Tunnel (IRT) provides a matrix of 95 different conditions to be analyzed [29]. The airfoils being investigated are the NACA-0012, NACA-0015, NACA-23012, NLF-0414, GLC-305, and LTHS geometries [30].

Methodology

This section is intended to describe the workflow of an initial GlennICE run to aid the user in becoming familiar with the GlennICE software. The complete workflow for the GlennICE software is illustrated in Figure 1. The white boxes in the process are external to GlennICE and accomplished with third party software. The green, blue, red, and orange boxes denote work accomplished by the GlennICE software.

This flow chart illustrates a multi-shot simulation strategy where the user is responsible for remeshing the new iced geometry and rerunning the Computational Fluid Dynamics (CFD) solver. This multi-shot capability is optional, and currently only single shot computations have been performed.

GlennICE uses a discretized flow field generated from a Computation Fluid Dynamics (CFD) solver. To maintain flexibility with a wide variety of commercial and in-house CFD solvers, the coupling between GlennICE and the CFD software is currently all one-way

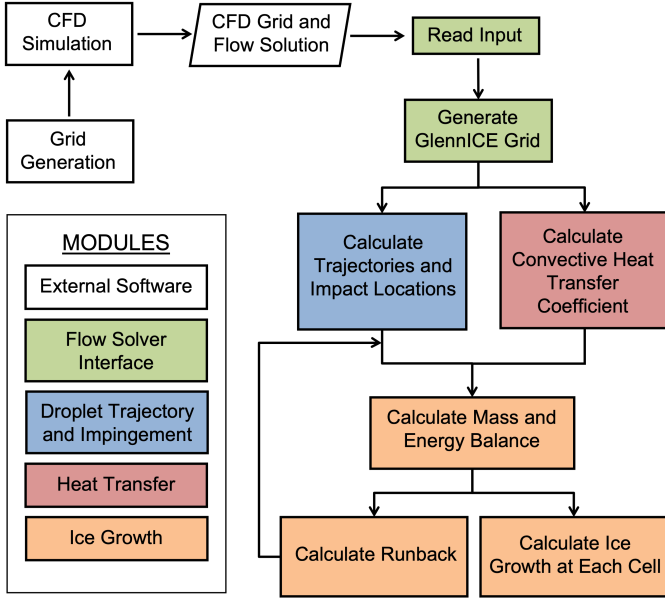


Figure 1: Flow chart of the GlennICE process.

coupling. As such GlennICE can be classified as a CFD post-processor. Currently this level of coupling has been sufficient for external icing problems. Because of the one-way coupling, GlennICE can theoretically accept solutions from a wide variety of CFD solvers. It does this by supporting a handful of widely used CFD file formats that a majority of CFD solvers utilize. However, it should be noted that there are many storage variants. GlennICE requires pressure, density, u, v, w -velocity components, and the three components of the surface wall shear. It also requires the estimated wall distance to the surface which was used by the turbulence model for the adaptive refinement scheme published previously [31]. Finally, GlennICE requires either the heat transfer coefficient or two solutions with the wall heat flux and different wall temperatures from which it can calculate the heat transfer coefficient. Currently GlennICE will read solutions in Fieldview [32] unstructured format or Tecplot [33] 'szplt' binary format.

GlennICE integrates particle trajectories using a method developed by Dormand and Prince [34]. It is a 4th order Runge-Kutta scheme that is designed to minimize error of the 5th order term. This means that it computes both the 5th order result and the 4th order result and returns the difference as the error. Particles are released from a user-supplied bounding box and subsequently refined based on the distance of the trajectory to the surface or based on whether it hits. Details of this method were presented previously [31]. Due to the large number of cases studied, the MVD drop size was used for all runs. A droplet distribution was not expected to change the results for the straight wing cases studied.

Heat transfer coefficients can be specified using either a single CFD solution or two solutions. The single solution methodology assumes the CFD solver provided a value of heat transfer coefficient. Alternatively, the user can provide GlennICE with two CFD solutions differing only by the wall thermal boundary condition. GlennICE uses this information to calculate heat transfer coefficient and adiabatic wall temperature. It is assumed that the heat transfer coefficient, h_{tc} , and adiabatic wall temperature, T_{aw} , are independent of wall thermal condition. Therefore, at every location, given (T_1, q_1) and (T_2, q_2) two simultaneous equations are solved for h_{tc} and T_{aw} . This technique relies on the definition of h_{tc} shown in Eq 1.

$$q = h_{tc} * (T_{wall} - T_{aw}) \quad (1)$$

The user can specify these two files if they consist of identical meshes, however, the two CFD solutions differ in their specification of the temperature of the surface. These options do not necessarily account for the roughness effects, however. Many solvers contain a turbulence model that accounts for sand-grain roughness such as those proposed in references [14–18]. In lieu of this, the heat transfer coefficient computed by this process was augmented using an empirical roughness model that was developed by McClain [35] to predict roughness variation on a surface. The equations programmed into GlennICE are shown in Eqns. 2-4. These equations use two user-defined values that can be adjusted. The first user-defined value is the ideal rime limit (IRL), $t_{r,max}$ and the second empirical constant is the augmentation constant, A . The McClain paper only provides Eq. 2 and does not define $t_{r,max}$ or the heat transfer augmentation. The best values for these parameters are the subject of ongoing research. The values selected for this paper were chosen to provide the best fit to the experimental data. Since this equation depends on freezing fraction, which depends on the heat transfer coefficient chosen, an iterative approach was used to find final values. The initial heat transfer coefficient was used to find a freezing fraction at each face. Then that freezing fraction was used to find the roughness and augmented heat transfer coefficient for each face as shown below. The second iteration would then use the updated heat transfer coefficient and the process would continue until values no longer change. Typically, six iterations have proven sufficient to converge to the final heat transfer coefficient. While this parameter introduces a third UDP to the model, the parameter is a convergence metric and not an input that is used to change heat transfer augmentation.

$$R_q = t_r * 0.7 * (1 - C_p) * \eta * (0.34 + \Delta T_{os}^{\frac{2}{3}}) * e^{\frac{-\Delta T_{os}}{2.25}} \quad (2)$$

Where:

$$t_r = \min\left[\frac{LWC * V_{\infty} * time * \beta}{\rho_{ice}}, t_{r,max}\right] \quad (3)$$

The augmented heat transfer is:

$$h_{tcA} = h_{tc} * (1 + \frac{A * R_q}{0.001}) \quad (4)$$

The parameters A and $t_{r,max}$ are the user-defined parameters described above by Eq. 3 and Eq. 4. A linear expression relating roughness to heat transfer coefficient was chosen for simplicity and is not intended to imply that the augmentation is necessarily linear to the roughness. Other forms of augmentation could be used in the future. The icing rime limit is used to denote the difference between what is considered "roughness" and what is considered the ice shape.

The mass and energy balance at the surface uses the same terms as employed in LEWICE. However, LEWICE required a marching algorithm starting at a stagnation point to compute the runback ice mass. To avoid this, GlennICE uses the surface shear stress from the CFD solver. There are four ways that water flow can enter or exit a triangular surface face. The details of this methods were reported in a previous paper and will not be replicated here [19].

A fully three-dimensional ice growth was produced using a prismatoid method with node-based smoothing. The process is based on computing the node centered normal vectors and solving a cubic equation at each location to find the appropriate distance from the surface that maintains the computed ice volume. This surface redefinition process was described in a previous paper [28] and will not be replicated here.

Experimental Overview

Experimental data for the comparisons were taken from tests in the Icing Research Tunnel over the course of several years [30, 36–45]. All of the geometries were straight wing (extruded airfoils) that went from floor to ceiling in the IRT. The wing sections were mounted on a turntable so that angle of attack could be varied. Aerodynamic and meteorological conditions chosen in the test were based on the objectives of the specific test. Ice shapes were documented by cutting out a small section with a heated piece of metal, then inserting a cardboard template into the slot. The shapes were traced with a pencil and later digitized. The conditions chosen for this study were large glaze ice shapes as these shapes are typically the most difficult to predict. Conditions with large ice shapes was based on the Accumulation Parameter as defined by Eq. 5:

$$A_c = \frac{LWC * V_\infty * time}{\rho_{ice} * D_{LE}} \quad (5)$$

Ice shapes with an Accumulation Parameter greater than three were considered large. Glaze conditions were defined by conditions with a stagnation point freezing fraction less than 0.6. Stagnation point freezing fraction can be calculated from the leading edge diameter of the airfoil, the flow and meteorological conditions using the scaling relationships [46]. After applying the two criteria above, 95 conditions remained from these tests for this study. The conditions are listed in the appendix. The range of conditions are shown in the table below.

Table 1: Range of Conditions for Test Cases

Variable	Low	High
Chord (m)	0.305	1.223
Mach	0.11	0.47
Re	1M	7.8M
MVD (μm)	15	175
AOA [deg]	0	6

Geometries

A 2-D representation of the previously mentioned airfoils is used and a subsequent mesh for each airfoil is generated. The profiles of the six different airfoils being investigated are shown in the Figure 2. Point distributions for NACA airfoils were produced from the equations that define those airfoils. Airfoil coordinates for the other three airfoils (NLF-414, GLC305, LTHS) were read into the software Rhino [47] where the profiles were smoothed before grids were generated.

Computational Domain

The domain is setup such that the boundary conditions induce a subsonic pressure driven flow utilizing the experimental conditions from the case matrix. A viscous wall boundary condition is imposed on the airfoils, two symmetry planes are setup on the minimum and maximum Y-locations, and freestream boundaries are located on the minimum and maximum Z-locations. The inflow and outflow boundaries along with the freestream boundaries are located +/- 10 chord lengths away from the origin which coincides with the leading edge of the airfoils. A representation of the computational domain can be seen in the Figure 3 where the domain boundaries are identified with the exclusion of a single symmetry plane. Each mesh that was generated is fully unstructured where the boundary layer is resolved such that initial wall spacing is obtained from the case which required the minimum wall spacing such that a value of $y^+ = 1$ is obtained. The mesh is then geometrically grown for a total of 40 times at a defined growth rate of $r = 1.2$ utilizing Pointwise and the T-Rex extrusion solver [48]. Each airfoil is then extruded along the spanwise direction for a total of 4 times such that a 'three-dimensional' geometry can be analyzed. This results in a subsequent mesh of approximately 300K cells for each airfoil. An example grid is shown in Figure 4. Since GlennICE acts as a post-processing tool, a volume

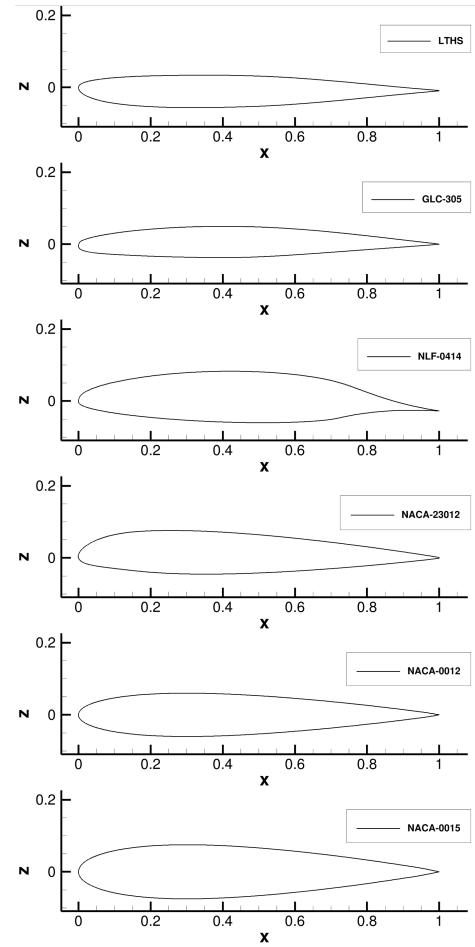


Figure 2: Airfoil geometries being used for the roughness optimization: LTHS, NACA-23012, GLC-305, NACA-0012, NLF-0414, and NACA-0015.

flow solution is required by GlennICE in order to grow a subsequent ice shape. The flow solver utilized is discussed in the following section.

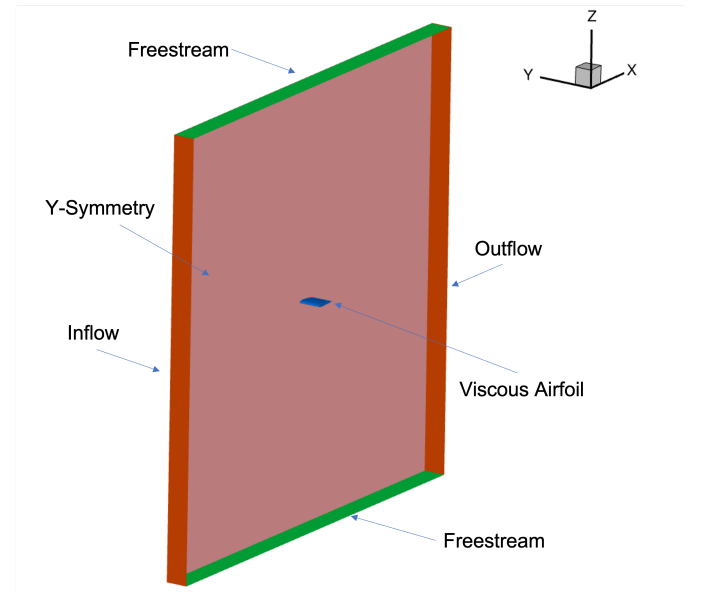


Figure 3: Computational domain setup for the roughness optimization.

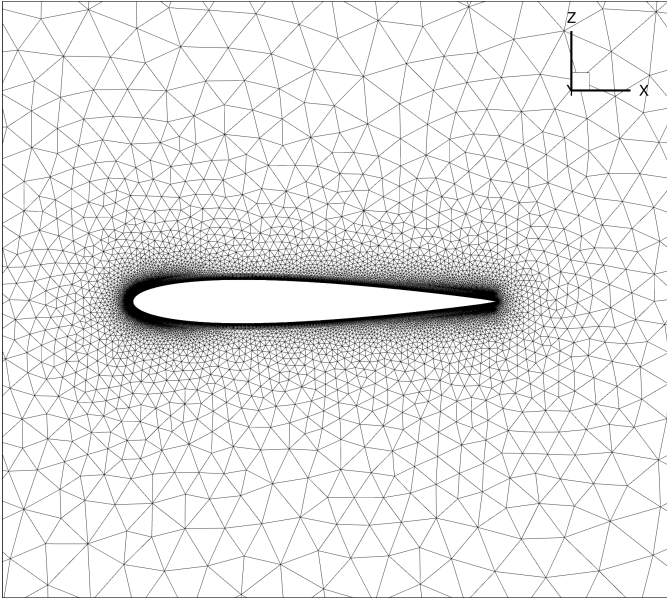


Figure 4: Unstructured grid used for NACA0012 airfoils

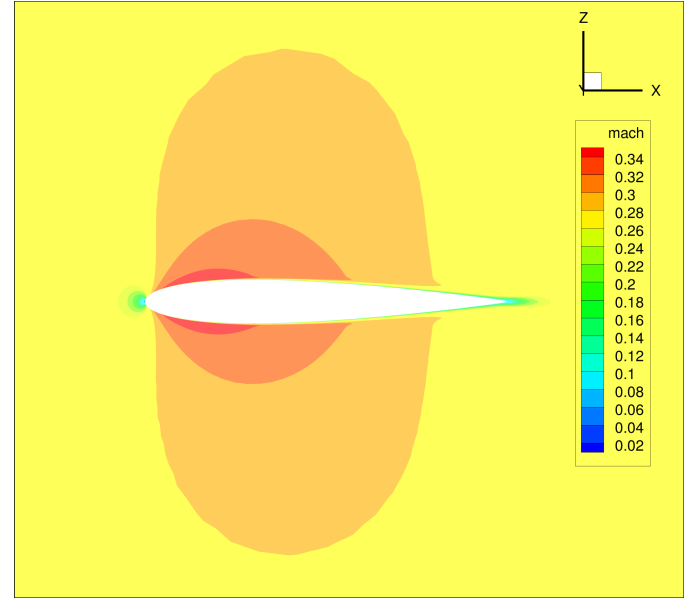


Figure 5: Mach Contours for Case AC1038436

Computational Solver

The NASA production CFD code FUN3D was used in order to generate the flow solutions and surface quantities necessary for ice accretion as described previously [49]. For the roughness cases, the HANIM CFL controller was utilized to limit the amount of monitoring needing and to decrease the computational cost of a single solution [50]. The cases were run compressibly while using the SA turbulence model with a roe flux differencing scheme and a consistent linearization scheme for the residual construction [51, 52]. No flux limiters were used for any of the roughness cases. This process was automated such that the matrix of conditions was read in, a single FUN3D case was generated that adjusted the unique conditions from the matrix for each case, and then submitted the job without the need for any user input. The NACA0012 and GLC305 geometries had cases with more than one chord length, all of the grids were generated using a unit chord (non-dimensional) and the various chord sizes were specified in the FUN3D input. Multiple grid resolutions and inviscid wall boundaries were also generated for each geometry to ensure a grid-independent solution. Since GlennICE requires two different wall temperature ratios, a wall temperature ratio of 1 and 1.04 were used such that the heat transfer coefficient can be solved for within GlennICE. The wall temperature ratio is simply the ratio of wall temperature to the freestream. This resulted in approximately 200 different cases being generated and run automatically with minimal input by the user while simultaneously reducing the risk of an error being introduced unknowingly within the case generation. The convergence criteria for each case was kept constant and required the RMS of the meanflow and turbulence residuals to be converged below $1E-14$ which typically corresponded to around a 10-order reduction in the residuals. The Mach contours and surface pressures for a sample case (AC1038436) from the selected test matrix are shown in Figure 5 and Figure 6.

Ice Shape and UDP Impact

Collection efficiencies and ice shapes were calculated using GlennICE for each of the 95 cases listed in the appendix. GlennICE calculates collection efficiency by running a set number of iterations and reporting the convergence achieved. Show in Figures 7-11 are an example of the results for a sample case. Restart runs can then be made until the GlennICE process achieved convergence as defined within [19]. All 95 cases were run with a single set of UDPs for the heat transfer augmentation. Variation of the augmentation parameters

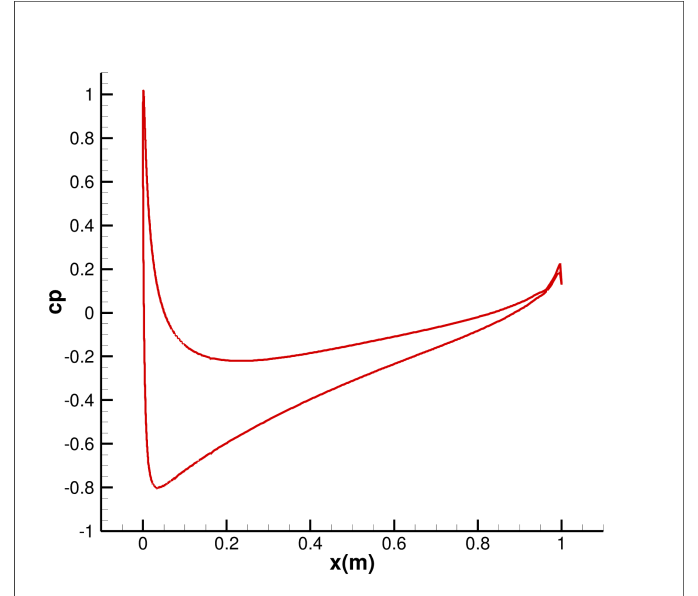


Figure 6: Pressure Distribution for Case AC1038436

could then be performed quickly using the surface restart capability in GlennICE. A surface restart run was executed for each of the 95 cases for a new combination of UDP's. A total of 2280 cases were performed for the analysis to measure the impact the UDPs had on the final ice shape.

To illustrate how the user-defined parameters (UDP's) change the resultant ice shape, by adjusting only the 'ideal rime limit' or the 'turbulent heat transfer coefficient augmentation' initial trends and variations are shown in Figure 12. First, the ideal rime limit, $t_{r,max}$, is kept constant at 0.007 m, while the augmented turbulent heat transfer coefficient is changed from 1, 3, 5, and 7 using the results from a NACA 23012 case. The result of these adjustments are seen in the Figure 12(a) where the NACA 23012 airfoil is seen in black, and the resultant ice shapes formed from the incremental A values are plotted concurrently. It is seen that for this case, while holding the ideal rime limit constant, a decreasing value for the A augmentation results in a more blunt ice shape. This change also results in the horn angle on both the upper and lower surfaces to change and increase in

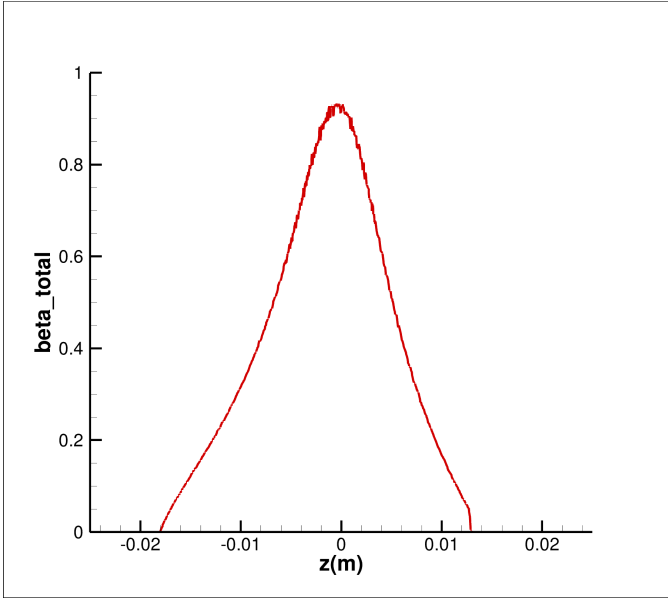


Figure 7: Collection Efficiency for Case AC1038436

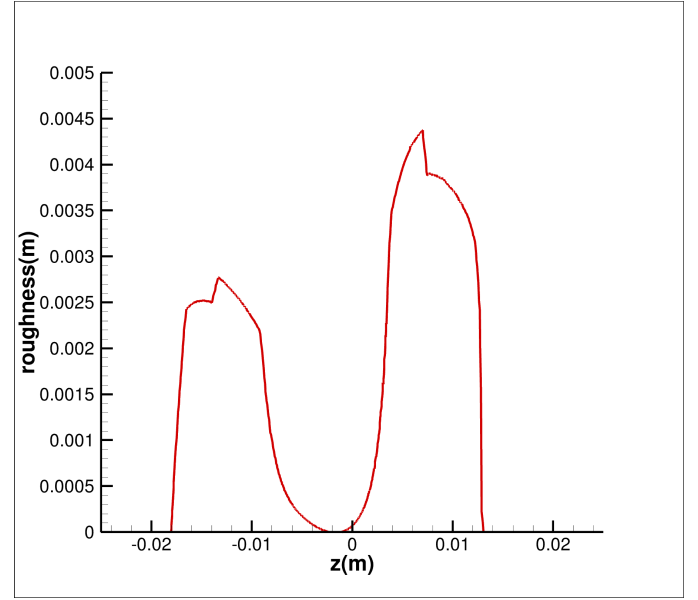


Figure 9: Roughness Distribution for Case AC1038436

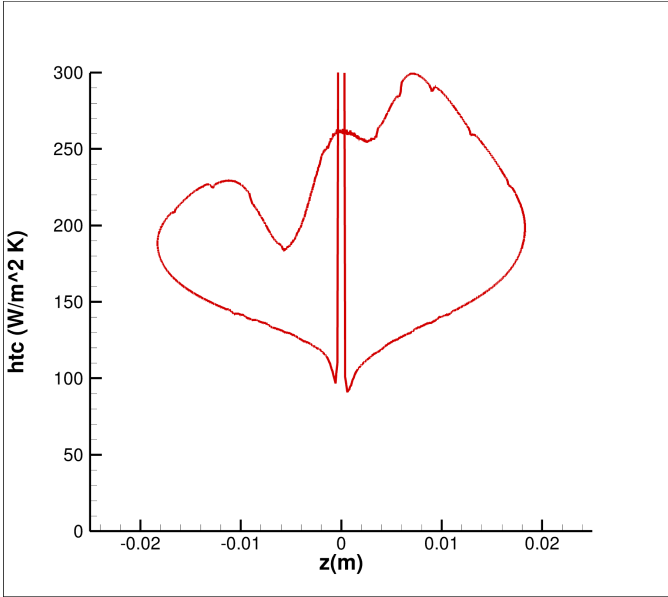


Figure 8: Non-Augmented Heat Transfer Coefficient for Case AC1038436

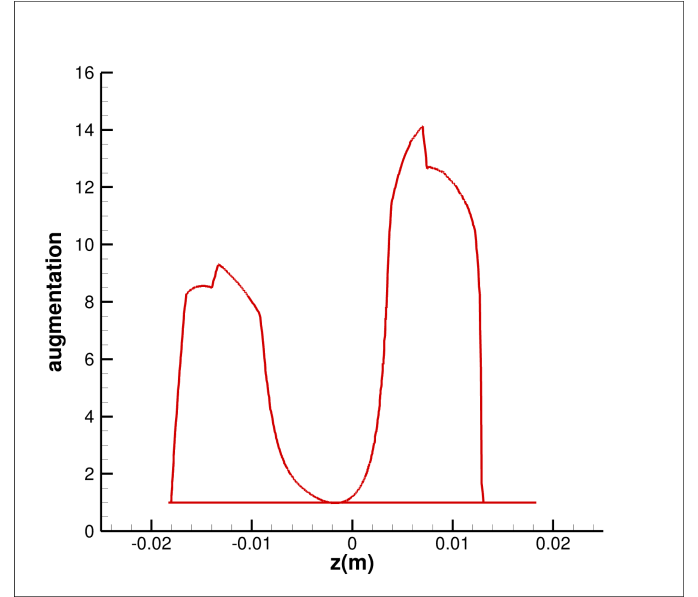


Figure 10: Heat Transfer Augmentation for Case AC1038436

size as the A augmentation increases. Now, keeping the A augmentation constant at 5, the ideal rime limit is adjusted from 0.001 m to 0.015 m at an increment of 0.002 m on the same NACA 23012 airfoil case and is shown in Figure 12(b). It is seen then, that as the ideal rime limit defined increases, the upper and lower horns of the ice shape move forward again. It can be concluded from this brief analysis that there are significant changes to the resultant ice shape that exist depending on the parameters defined by the user. By subjecting a similar analysis over a wider range of both ideal rime limit $t_{r,max}$ and turbulent A values on an expanded list of conditions, an assessment of the agreement between the experimental and computational results can be quantified.

Ice Shape Parameters

Once all of the ice shape predictions were generated, measurements of horn angle and ice thickness were extracted using the LEWICE utility THICK [9]. THICK determines the x, z location where the maximum ice thickness occurs and calculates the angle between that location

and the airfoil leading edge. Ice thickness is measured from this location to to the nearest point on the airfoil using a unit normal calculated from the airfoil coordinates. Upper horn angle, lower horn angle, upper horn ice thickness and lower horn ice thickness were obtained for each GlennICE case produced. Measurements were also taken for the ice shape tracings from the experiment as well as the LEWICE multi-shot ice shape prediction. The measurements for the experimental shapes and LEWICE shapes were provided by a previous LEWICE validation effort [53]. That effort used ice shapes from over 3000 experiments so that comparisons from simulations could be made based on the variability of ice shape tracing taken for repeat runs and various spanwise locations. Because of the process used by THICK to find horn angle, small perturbations in the experimental ice shape could result in larger differences in horn angle. This is shown in Figure 13. If ice shape tracings from two different experiments showed a peak location on either side of the upper horn shown, that could result in THICK reporting a horn angle difference of 31° . Despite this, the measurements recorded by THICK are still useful since the results from LEWICE and GlennICE will have the same issues and the important parameters are the relative difference

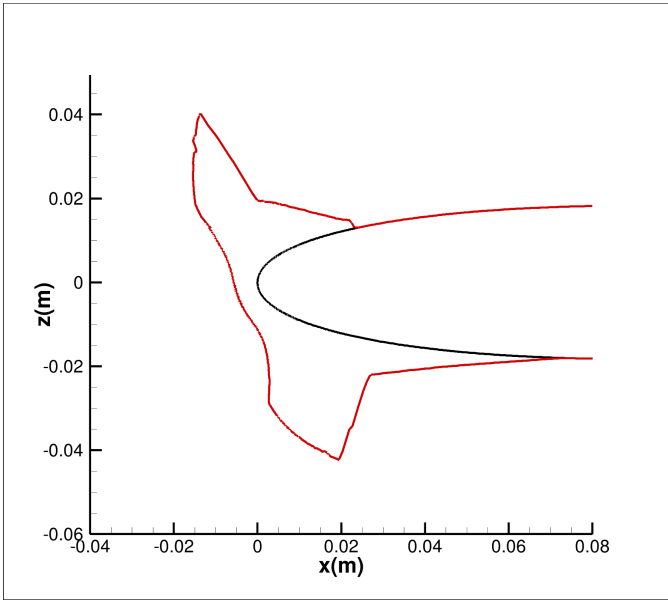
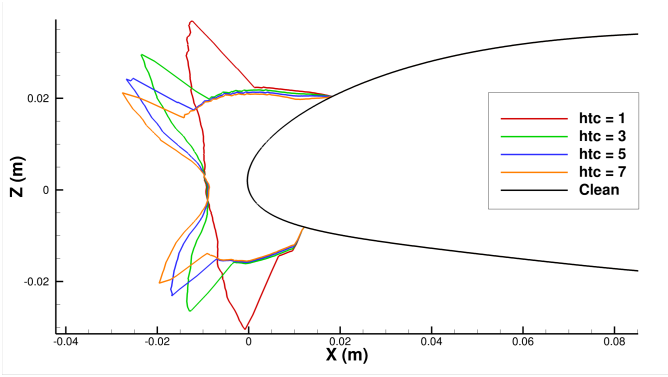
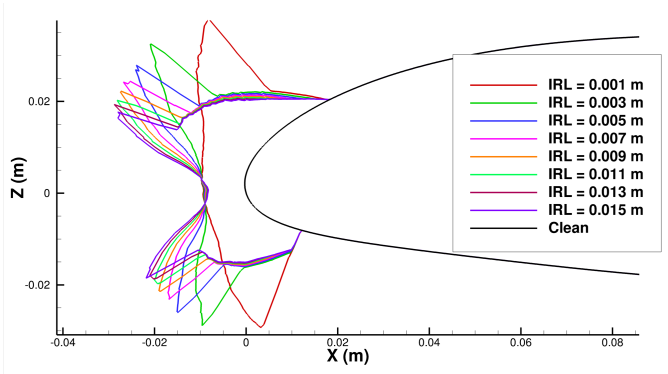


Figure 11: Ice Shape for Case AC1038436



(a) Ideal Rime Limit = 0.007 m



(b) htc = 5

Figure 12: Resultant ice shapes when holding either ideal rime limit constant or htc constant and adjusting the alternate.

between GlennICE and experiment versus the experimental variability. The results shown in the next section will be based on the differences measured by THICK.

Results

Once all of the GlennICE ice shapes were obtained for each combination of the UDPs given, measurements of horn angle and horn

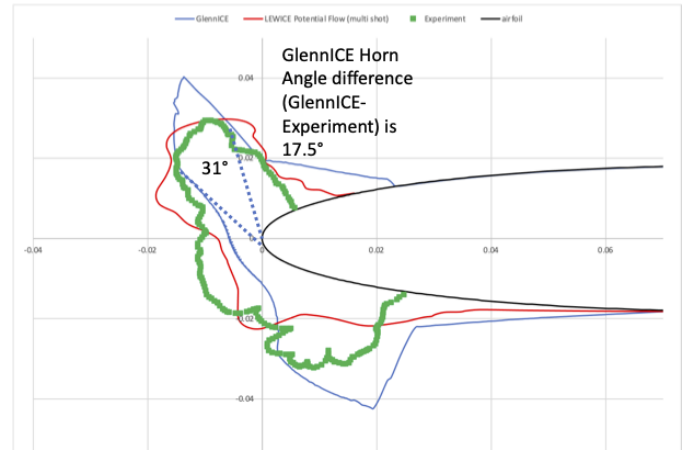


Figure 13: Variability in Horn Angle Measurement produced by THICK

thickness were obtained for the experimental ice shapes and for each GlennICE case as described in the previous section. The absolute difference between the GlennICE result and the experimental ice shape for each measurement was calculated for each of the 95 conditions for a given combination of ideal rime limit and heat transfer augmentation. Those 95 measurement results were then averaged to obtain an average difference for the user-defined parameters chosen. Those results could be plotted as a function of the parameter to illustrate which choice of parameter led to the most accurate ice shapes over the entire range of conditions. This is shown in Figures 14-21.

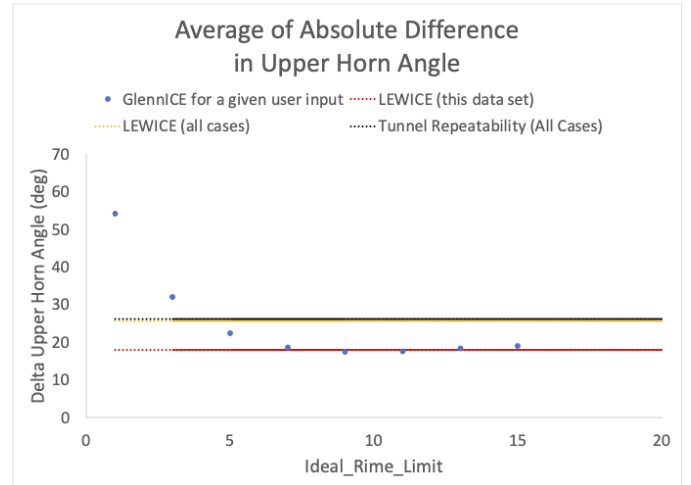


Figure 14: Average Difference in GlennICE Upper Horn Angle versus Ideal Rime Limit

The plots shown in Figures 14-21 show a similar trend between them in that there is a large variation for lower values of the individual UDP where the resultant values plateau as the parameters increase. The results also show that the changes are similar for each parameter, showing that the two UDPs are not independent from each other. That is, the combination of ideal rime limit = 1 mm and augmentation = 7 produces the same ice shape as that obtained using an ideal rime limit = 7 mm and an augmentation of 1. To illustrate this, the results were plotted as a function of the product of icing rime limit times the augmentation. This is shown in Figures 22-25. These results show that not only do the results fall on the same curve the results continue to plateau as shown previously. The results also show that the difference between GlennICE and the experiment is on par with or even below the run-to-run variation of tunnel repeatability. Physically, this plateau effect occurs because the roughness equation defines the horn location. Once all of the water runback from the leading edge

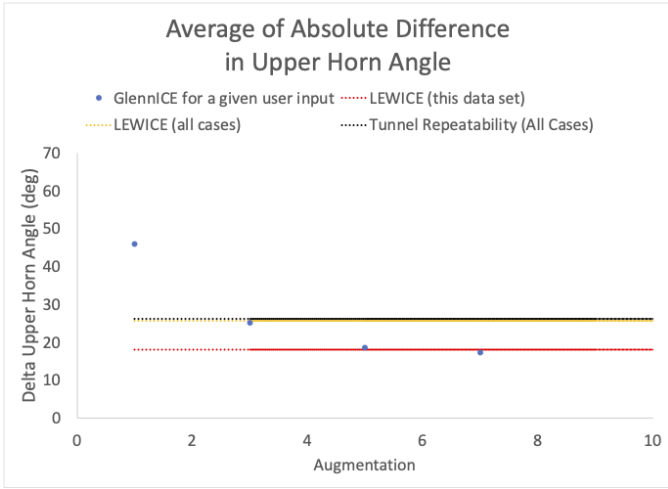


Figure 15: Average Difference in GlennICE Upper Horn Angle versus Heat Transfer Augmentation

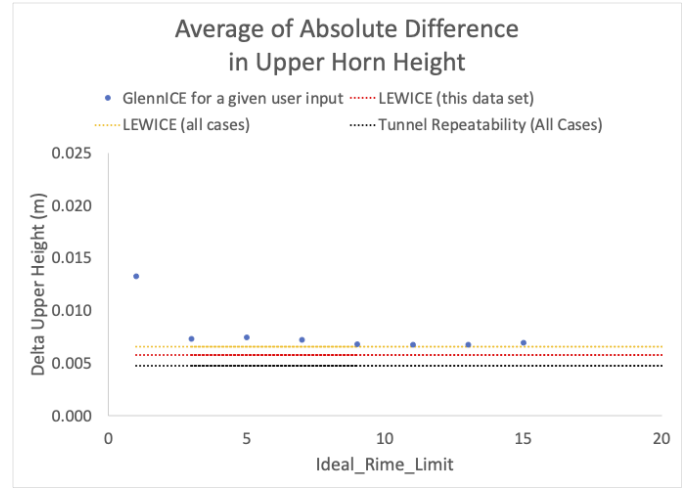


Figure 18: Average Difference in GlennICE Upper Horn Height versus Ideal Rime Limit

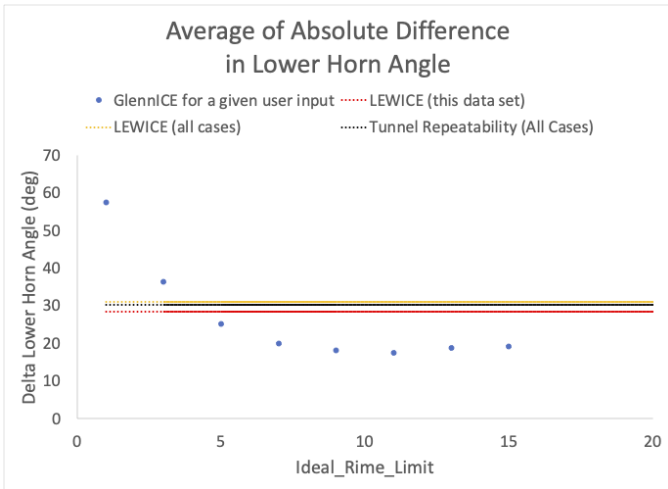


Figure 16: Average Difference in GlennICE Lower Horn Angle versus Ideal Rime Limit

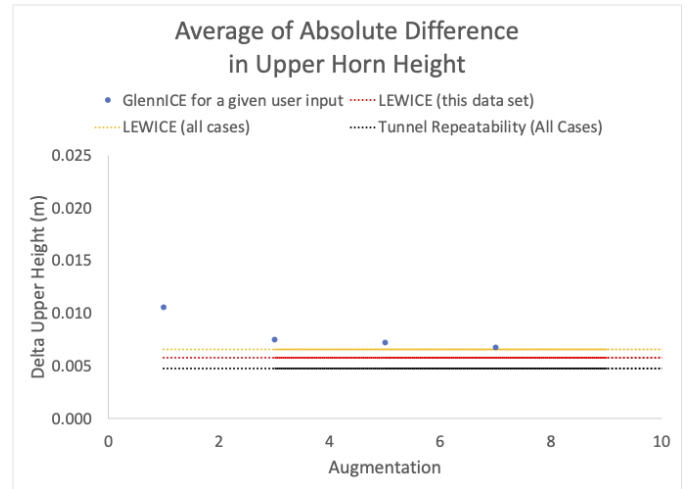


Figure 19: Average Difference in GlennICE Upper Horn Height versus Heat Transfer Augmentation

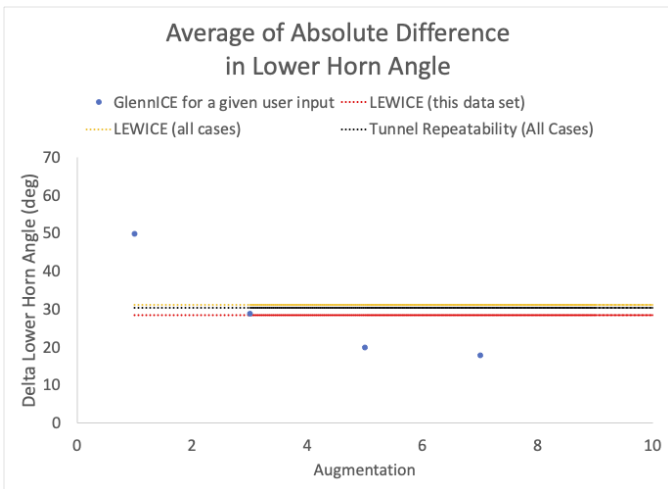


Figure 17: Average Difference in GlennICE Lower Horn Angle versus Heat Transfer Augmentation

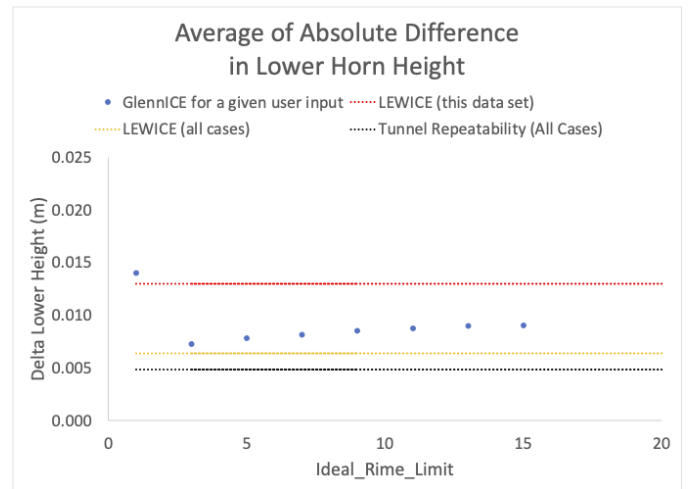


Figure 20: Average Difference in GlennICE Lower Horn Height versus Ideal Rime Limit

has frozen at this location, continued enhancement does not change the predicted results. This also implies that any multiplier beyond the minimum necessary to freeze water runback could be used.

The previous analysis demonstrated that, on average, the most accurate ice shapes were generated when the product of icing rime limit and augmentation was between 40 and 60. The default

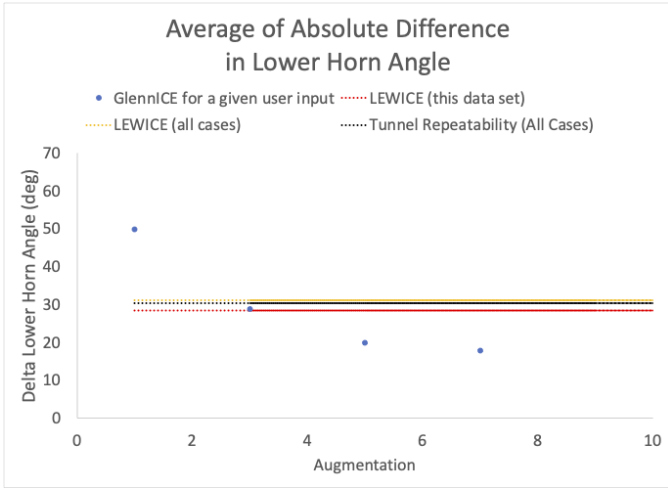


Figure 21: Average Difference in GlennICE Lower Horn Height versus Heat Transfer Augmentation

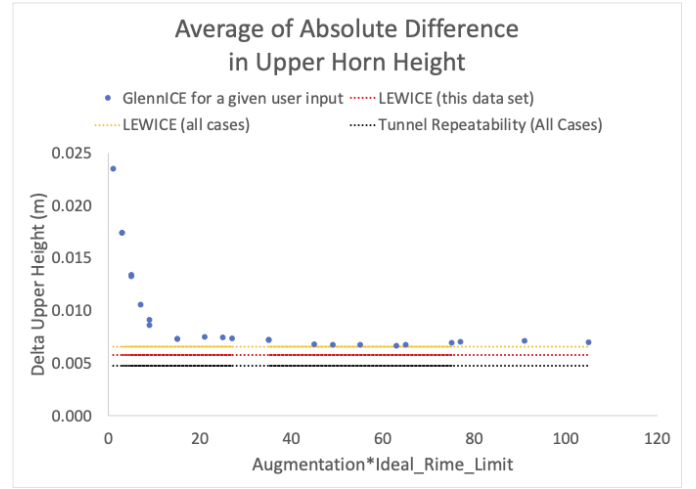


Figure 24: Average Difference in GlennICE Upper Horn Height versus Product of UDPs

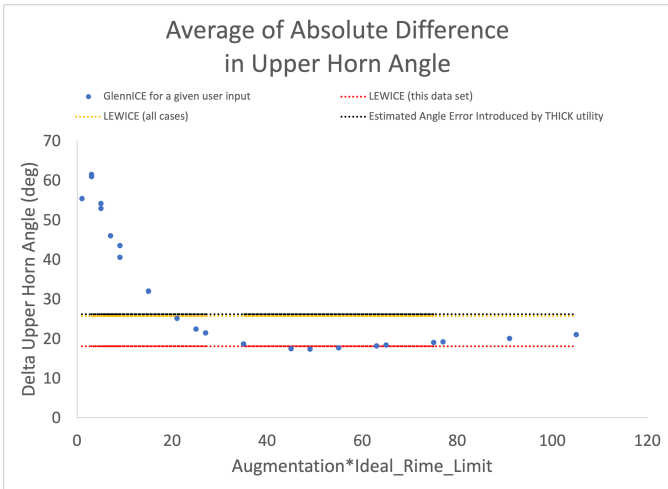


Figure 22: Average Difference in GlennICE Upper Horn Angle versus Product of UDPs

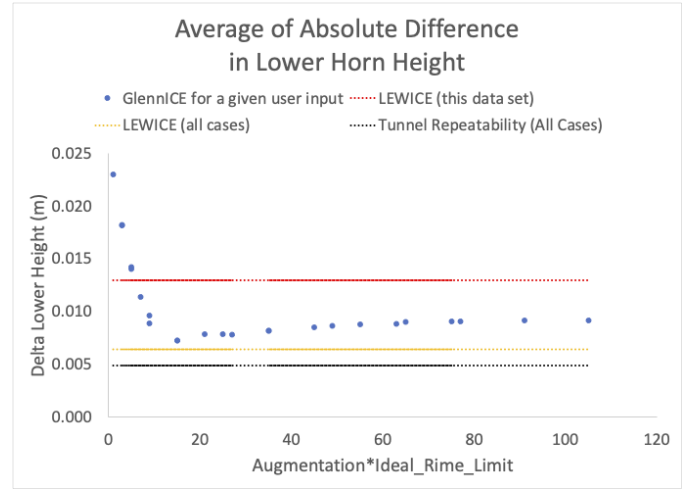


Figure 25: Average Difference in GlennICE Lower Horn Height versus Product of UDPs

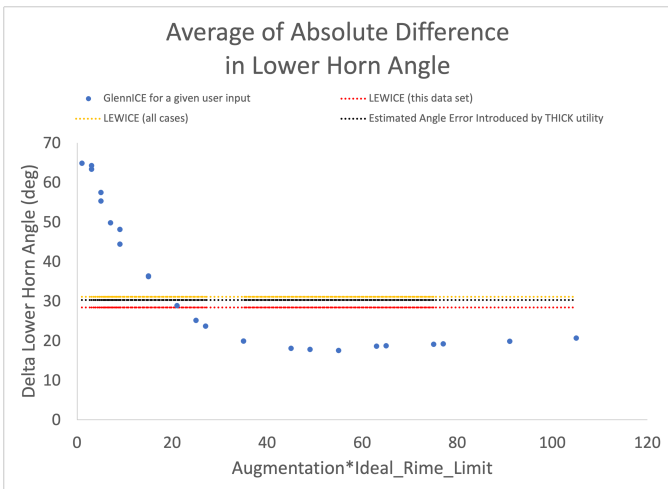


Figure 23: Average Difference in GlennICE Lower Horn Angle versus Product of UDPs

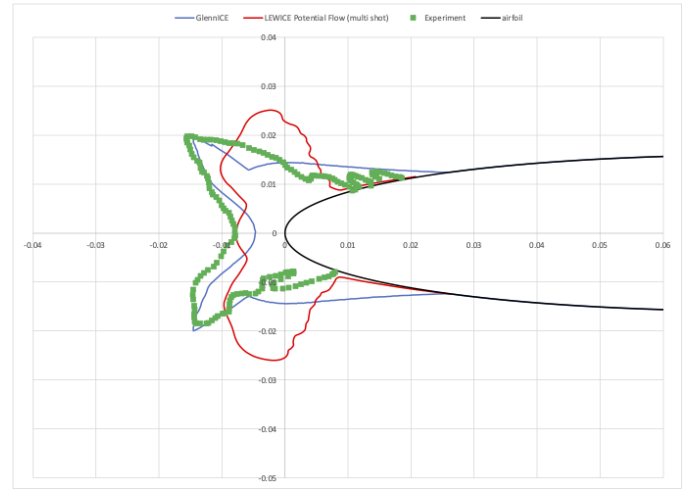


Figure 26: Ice Shape for Case AC1038436

Conclusion

parameters were set to an icing rime limit of 9 mm (0.009 m) and an augmentation multiplier of 5. The representative ice shapes using those parameters are shown in Figures 26-34.

GlennICE results were produced for a selection of 95 large glaze ice shapes. Ice shapes were compared with experiment through plots of

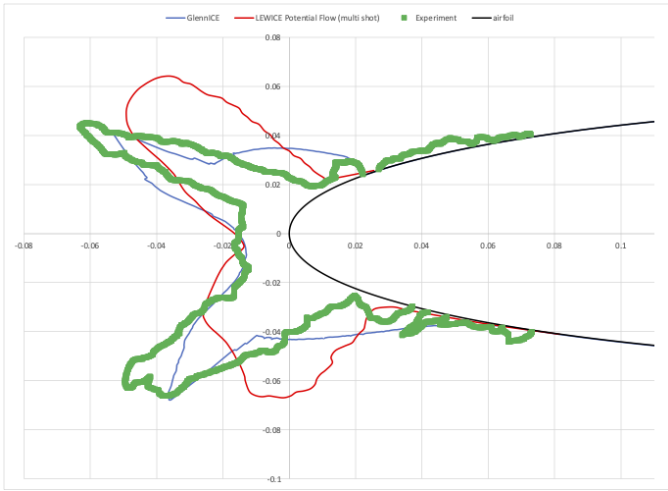


Figure 27: Ice Shape for Case AF080936

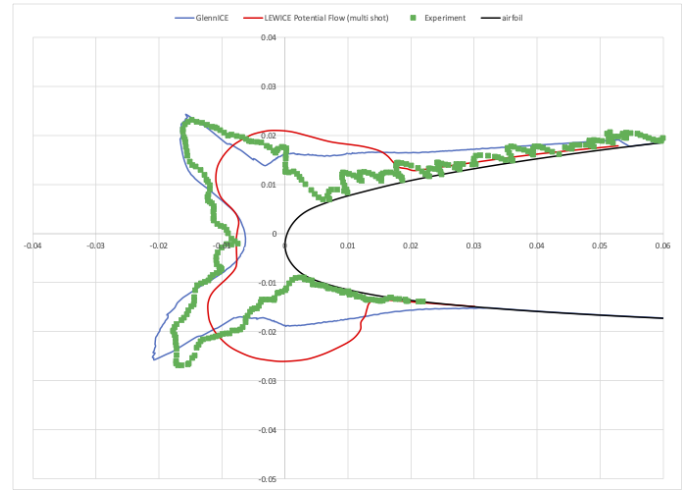


Figure 30: Ice Shape for Case HE1078236

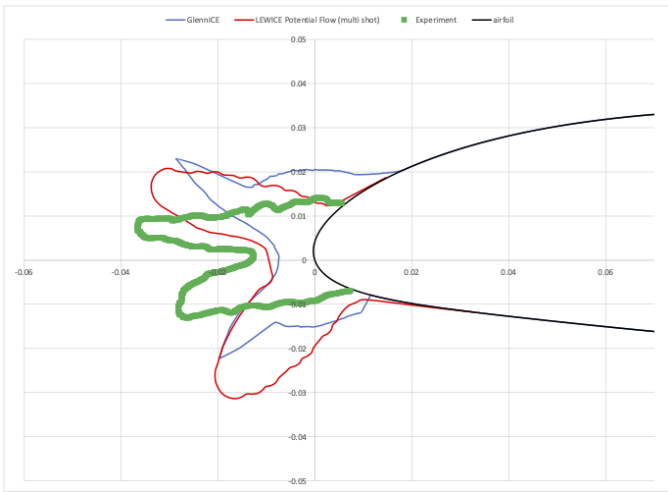


Figure 28: Ice Shape for Case ED071230

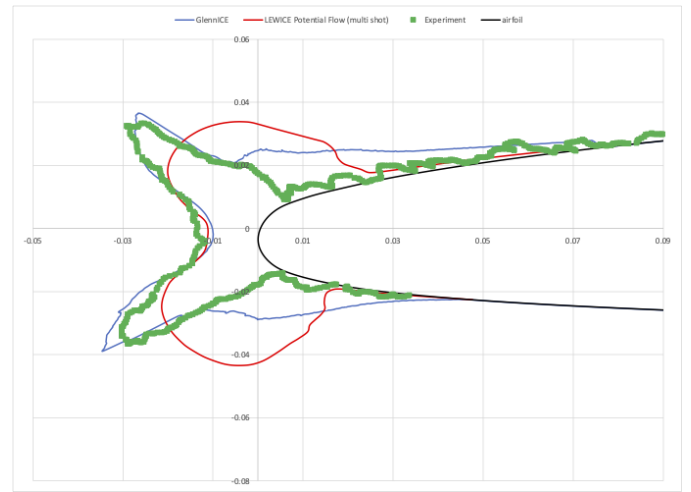


Figure 31: Ice Shape for Case HF1082436

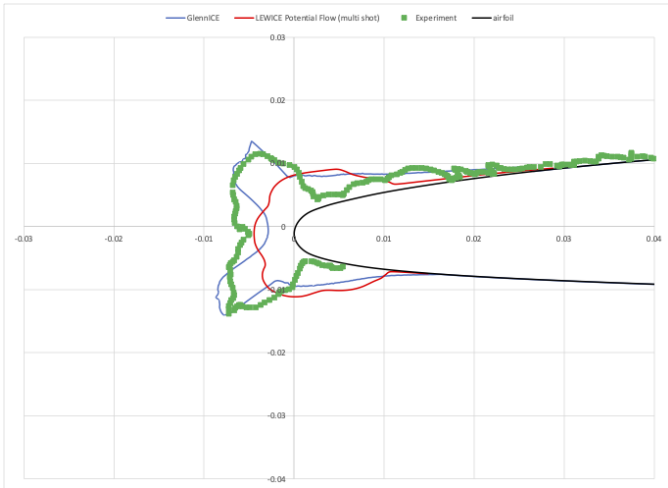


Figure 29: Ice Shape for Case HC1071536

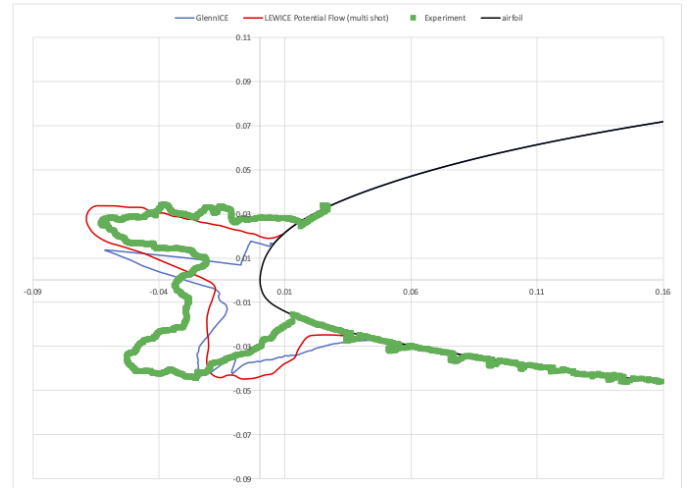


Figure 32: Ice Shape for Case IG1059742

the ice shapes but primarily through measurements of horn angle and horn thicknesses. Two user-defined parameters, the ideal rime limit and heat transfer augmentation were varied to find the closest fit over this wide range of conditions. The results showed that for ice shapes on straight wings in supercooled conditions, the values if ideal rime limit of 9 mm and augmentation of 5 produced the best

comparison to data. These values were set as the default values for other users of GlennICE. It is emphasized that these results are mainly applicable to straight wing geometries. A multi-shot analysis would also alter these parameters. Future validation efforts, especially on non-wing geometries, would be necessary to provide further confidence in the selection of the user-defined parameters for

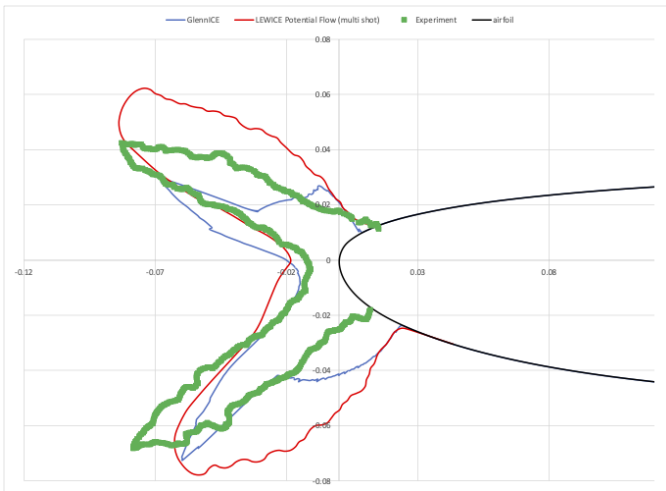


Figure 33: Ice Shape for Case JF1025636

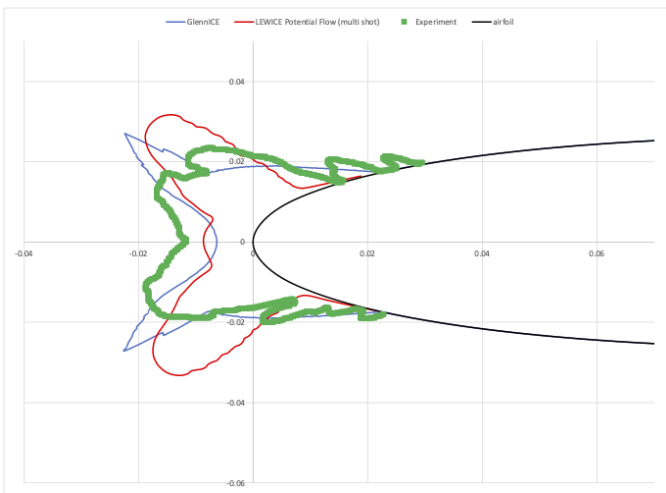


Figure 34: Ice Shape for Case OD1057536

GlennICE.

References

1. E. Achenbach, "The effect of surface roughness on the heat transfer from a circular cylinder to the cross flow of air," *Int. J. Heat and Mass Transfer*, vol. 20, pp. 359–69, 1977.
2. L. Makkonen, "Heat transfer and icing of a rough cylinder," *Cold Regions Science and Technology*, vol. 10, pp. 105–116, 1985.
3. P. Poinsette, "Heat transfer measurements from a naca 0012 airfoil in flight and in the nasa lewis icing research tunnel," *NASA-CR-4278*, 1990.
4. J. Shin, "Characteristics of surface roughness associated with leading edge ice accretion," *NASA TM 106459 (AIAA-94-0799)*, 1994.
5. D. Anderson, D. Hentschel, and G. Ruff, "Measurement and correlation of ice accretion roughness," *NASA CR—2003-211823*, 1998.
6. H. Schlichting, *Boundary Layer Theory*. McGraw-Hill, 1979.
7. A. vonDoenhoff and E. Horton, "A low-speed experimental investigation of the effect of a sandpaper type of roughness on boundary-layer transition," *NASA TN 1349*, 1958.
8. P. Owen and W. Thomson, "Heat transfer across rough surfaces," *J. Fluid Mech.*, vol. 15, pp. 321–334, 1963.
9. NASA, "LEWICE 3.2.3 ice accretion software," 2008.
10. NASA, "LEWICE3D 3.6.3 ice accretion software," 2015.
11. G. Blanchard and et. al., "3d ice accretion modeling using an integral boundary layer method," *7th European Conference For Aeronautics And Aerospace Sciences (Eucass)*, 2017.
12. B. Aupoix and P. Spalart, "Extensions of the spalart–allmaras turbulence model to account for wall roughness," *International Journal of Heat and Fluid Flow*, vol. 24, p. 454–462, 2003.
13. F. Menter and R. Langtry, "Transition modelling for turbomachinery flows," *Low Reynolds Number Aerodynamics and Transition*, pp. 31–58, 2012.
14. H. Beaugendre, F. Morency, and W. Habashi, "Fensap-ice: Roughness effects on ice shape prediction," *Low Reynolds Number Aerodynamics and Transition*, pp. 31–58, 2012.
15. T. Knopp, B. Eisfeld, and J. Calvo, "A new extension for $k-\omega$ turbulence models to account for wall roughness," *International Journal of Heat and Fluid Flow*, vol. 30, pp. 54–69, 2009.
16. M. Bernardini, S. Pirozzoli, P. Orlandi, and S. Lele, "Parameterization of boundary-layer transition induced by isolated roughness elements," *AIAA Journal*, vol. 52, 2014.
17. G. Tagawa, F. Morency, and H. Beaugendre, "CFD study of airfoil lift reduction caused by ice roughness," *AIAA Applied Aerodynamics Conference AIAA-2018-3010*, 2018.
18. S. Min and K. Yee, "CFD study of airfoil lift reduction caused by ice roughness," *AIAA Journal*, vol. 59, 2021.
19. W. B. Wright, C. E. Porter, E. T. Galloway, and D. L. Rigby, "GlennICE 2.1 capabilities and results," *AIAA AVIATION 2022 Forum*, 2022.
20. S. T. McClain, M. Vargas, J.-C. Tsao, and A. P. Broeren, "A model for ice accretion roughness evolution and spatial variations," *AIAA AVIATION 2021 FORUM*, 2021.
21. S. T. McClain, D. Reed, M. Vargas, R. E. Kreeger, and J. C. Tsao, "Ice roughness in short duration SLD icing events," *6th AIAA Atmospheric and Space Environments Conference AIAA-2014-2330*, 2014.
22. S. T. McClain, M. Vargas, R. E. Kreeger, and J. C. Tsao, "A reevaluation of appendix c ice roughness using laser scanning," *SAE 2015 International Conference on Icing of Aircraft, Engines, and Structures SAE2015-01-2098*, 2015.
23. S. T. McClain, M. Vargas, and J. C. Tsao, "Characterization of ice roughness variations in scaled glaze icing conditions," *8th AIAA Atmospheric and Space Environments Conference AIAA-2016-3592*, 2016.
24. S. T. McClain, M. Vargas, and J. C. Tsao, "Ice roughness and thickness evolution on a swept naca 0012 airfoil," *9th AIAA Atmospheric and Space Environments Conference AIAA-2017-3592*, 2017.
25. S. T. McClain, M. Vargas, J. C. Tsao, and A. P. Broeren, "Ice roughness and thickness evolution on a business jet airfoil," *10th AIAA Atmospheric and Space Environments Conference AIAA-2018-3014*, 2017.
26. S. T. McClain, M. Vargas, J. C. Tsao, and A. P. Broeren, "Influence of freestream temperature on ice accretion roughness," *SAE Int. J. Adv. and Curr. Prac. in Mobility*, vol. 2, pp. 227–237, 2020.

27. S. T. McClain, M. Vargas, J. C. Tsao, and A. P. Broeren, "Influence of airfoil angle of attack on ice accretion roughness," *AIAA Aviation Forum AIAA-2020-2807*, 2020.
28. "Proceeds of the 1st aiaa ice prediction workshop," 2021.
29. W. Wright, "Validation results for LEWICE 3.0," *43rd AIAA Aerospace Sciences Meeting and Exhibit*, 2005.
30. H. E. Addy, "Ice accretions and icing effects for modern airfoils," *NASA TP-2000-210031*, 2000.
31. W. Wright, C. Porter, M. Potapczuk, E. Galloway, and D. Rigby, "An automated refinement process for particle trajectory methods in GlennICE," *AIAA 2021-2631*, 2021.
32. Fieldview, "Fieldview manual," 2021.
33. Tecplot, "Tecplot manual," 2021.
34. D. J. Prince, "A family of embedded runge-kutta formulae," *Journal of Computational and Applied Mathematics*, vol. 6, pp. 19–26, 1980.
35. S. T. McClain, M. Vargas, J. C. Tsao, and A. P. Broeren, "A model for ice accretion roughness evolution and spatial variations," *AIAA Aviation Forum AIAA-2021-22641*, 2021.
36. S. AC-9C, "Icing wind tunnel interfacility comparison tests," *SAE AIR 5666*, 2012.
37. D. Anderson and G. Ruff, "Scaling methods for simulating aircraft in-flight icing encounters," *NASA TM 107538*, 1997.
38. D. Anderson and T. Bond, "Effect of velocity in icing scaling tests," *AIAA-2000-0236*, 2003.
39. J. Shin and T. Bond, "Results of an icing test on a naca 0012 airfoil in the nasa lewis icing research tunnel," *AIAA-1992-647*, 1992.
40. J. Shin and T. Bond, "Repeatability of ice shapes in the nasa lewis icing research tunnel," *Journal of Aircraft*, vol. 31, pp. 1057–1063, 1994.
41. J. V. Zante, "A database of supercooled large droplet ice accretions," *NASA CR 2007-215020*, 2007.
42. D. Miller, M. Potapczuk, and T. Langhals, "Preliminary investigation of ice shape sensitivity to parameter variations," *AIAA-2005-73*, 2005.
43. D. Miller, M. Potapczuk, and T. Langhals, "Additional investigations of ice shape sensitivity to parameter variations," *AIAA-2006-469*, 2006.
44. S. Chen and T. Langhals, "Experimental validation on the modification techniques developed for the new scaling methods," *IRT Test Entry*, 1999.
45. A. Reehorst, J. Chung, M. Potapczuk, and Y. Choo, "The operational significance of an experimental and numerical study of icing effects on performance and controllability," *AIAA99-0374*, 1999.
46. D. Anderson, "Manual of scaling methods," *NASA/CR—2004-212875*, 2004.
47. Rhino3D, "Rhino manual," 2021.
48. Pointwise, "Pointwise manual," 2021.
49. R. T. Biedron, J.-R. Carlson, J. M. Derlaga, P. A. Gnoffo, D. P. Hammond, W. T. Jones, B. Kleb, E. M. Lee-Rausch, E. J. Nielsen, M. A. Park, C. L. Rumsey, J. L. Thomas, K. B. Thompson, A. C. Walden, L. Wang, and W. A. Wood, "Fun3d manual: 13.7," *NASA/TM—20205010139*, 2020.
50. L. Wang, B. Diskin, E. J. Nielsen, and Y. Liu, "Improvements in iterative convergence of fun3d solutions," *AIAA Scitech 2021 Forum*, 2021.
51. P. R. Spalart and S. Allmaras, "A one-equation turbulence model for aerodynamic flows," *30th Aerospace Sciences Meeting and Exhibit*, p. 439, 1992.
52. P. L. Roe, "Approximate riemann solvers, parameter vectors, and difference schemes," *Journal of Computational Physics*, vol. 43, no. 2, pp. 357–372, 1981.
53. W. Wright and M. Potapczuk, "Comparison of LEWICE and GlennICE in the SLD regime," *46th AIAA Aerospace Sciences Meeting and Exhibit AIAA-2008-0439*, 2008.

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Nomenclature/Abbreviations

A	augmentation to heat transfer
A_c	accumulation parameter
β	collection efficiency
C_p	pressure coefficient
D_{LE}	diameter of airfoil leading edge
htc	heat transfer coefficient
htc_A	augmented heat transfer coefficient
LWC	liquid water content
M	Mach number
MVD	median volume diameter
η	freezing fraction
P_{static}	static pressure
P_{total}	total pressure
ρ_{ice}	ice density
R_q	Surface roughness
Re	Reynolds number
T_{melt}	melt temperature
T_{static}	static temperature
T_{total}	total temperature
ΔT_{oS}	total temperature - melt temperature
$time$	time
t_r	ideal rime limit
$t_{r,max}$	maximum ideal rime limit
V	velocity
V_∞	freestream velocity
AOA	angle of attack
CFD	computational fluid dynamics
HANIM	hierarchical adaptive nonlinear iteration method
IRT	Icing Research Tunnel
LTHS	large transport horizontal stabilizer
LWC	liquid water content
MVD	mean value diameter
OML	outer-mold-line
RANS	Reynolds averaged Navier-Stokes
SA	Spallart-Allmaras
UDP	user defined parameter

APPENDIX A

Table 2: List of Conditions for Test Cases (Continues onto next page)

Case	Airfoil	chord <i>m</i>	Air Speed <i>kts</i>	AOA <i>deg</i>	Static Temp <i>K</i>	LWC <i>g/m³</i>	MVD <i>microns</i>	time <i>s</i>	Mach	Re
AC048336	NACA0012	0.3048	175.0	3	266.12	0.50	20.0	900	0.275	1.79E+06
AC048436	NACA0012	0.3048	175.0	3	266.12	1.00	20.0	600	0.275	1.79E+06
AC048636	NACA0012	0.3048	132.0	3	266.08	1.00	20.0	900	0.208	1.35E+06
AC048736	NACA0012	0.3048	132.0	3	266.08	1.00	40.0	900	0.208	1.35E+06
AC1033636	NACA0012	0.2667	115.1	0	265.83	1.04	36.7	538	0.181	1.03E+06
AC1036636	NACA0012	0.2667	183.7	0	265.72	0.89	21.8	395	0.289	1.64E+06
AC1036836	NACA0012	0.2667	167.6	0	266.04	0.75	22.9	514	0.264	1.50E+06
AC1038136	NACA0012	0.2667	124.6	0	265.77	1.22	35.0	423	0.196	1.12E+06
AC1038436	NACA0012	0.2667	184.8	0	263.40	0.88	21.8	400	0.292	1.67E+06
AC1038936	NACA0012	0.2667	184.7	0	263.14	0.75	19.0	468	0.292	1.67E+06
AC1040136	NACA0012	0.2667	115.6	0	263.30	1.06	36.6	526	0.183	1.05E+06
AC1049336	NACA0012	0.2667	167.4	0	263.43	0.78	22.9	496	0.265	1.52E+06
AC1049536	NACA0012	0.2667	124.7	0	263.44	1.20	35.0	428	0.197	1.13E+06
AD1109236	NACA0012	0.3556	200.0	0	260.93	0.61	175.0	828	0.318	2.44E+06
AD1109436	NACA0012	0.3556	150.0	0	260.93	0.99	175.0	678	0.238	1.83E+06
AD1109836	NACA0012	0.3556	100.0	0	260.93	1.68	175.0	600	0.159	1.22E+06
AE1005836	NACA0012	0.5334	200.0	4	262.33	1.60	30.0	360	0.317	3.64E+06
AE1005936	NACA0012	0.5334	200.0	4	262.33	1.80	30.0	360	0.317	3.64E+06
AE1111236	NACA0012	0.5334	200.0	0	265.26	0.92	20.0	714	0.315	3.59E+06
AE1111436	NACA0012	0.5334	201.0	0	259.48	0.92	20.0	714	0.320	3.71E+06
AE1169736	NACA0012	0.5334	200.0	0	261.21	0.70	20.0	900	0.318	3.66E+06
AE1169836	NACA0012	0.5334	200.0	0	261.21	1.00	20.0	900	0.318	3.66E+06
AE1170136	NACA0012	0.5334	70.0	0	265.84	1.70	20.0	900	0.110	1.25E+06
AE1171136	NACA0012	0.5334	200.0	0	261.21	0.80	20.0	618	0.318	3.66E+06
AE1171436	NACA0012	0.5334	70.0	0	265.84	1.60	20.0	900	0.110	1.25E+06
AE1171936	NACA0012	0.5334	200.0	0	261.21	0.80	20.0	900	0.318	3.66E+06
AE1172336	NACA0012	0.5334	130.0	0	264.26	1.06	20.0	900	0.205	2.34E+06
AF080936	NACA0012	0.9144	200.0	2	262.88	0.83	29.0	1200	0.317	6.22E+06
AF081536	NACA0012	0.9144	200.0	3	262.88	0.99	38.9	900	0.317	6.22E+06
AF081636	NACA0012	0.9144	200.0	3	262.88	0.96	36.7	900	0.317	6.22E+06
AF084236	NACA0012	0.9144	200.0	3	262.88	0.98	25.9	900	0.317	6.22E+06
AF1160636	NACA0012	0.9144	99.6	0	263.83	1.14	20.0	1687	0.157	3.09E+06
AF1161336	NACA0012	0.9144	149.5	0	265.11	1.15	20.0	1018	0.236	4.60E+06
AF1181736	NACA0012	0.9144	100.0	0	264.67	1.10	15.0	1912	0.158	3.08E+06
AF1181836	NACA0012	0.9144	149.9	0	261.84	1.00	15.0	1223	0.238	4.69E+06
AF1193936	NACA0012	0.9144	100.0	0	268.59	0.50	15.0	4185	0.157	3.03E+06
AF1194336	NACA0012	0.9144	100.0	0	265.28	1.00	15.0	2089	0.158	3.08E+06
AF1195136	NACA0012	0.9144	100.0	0	268.25	1.00	15.0	2092	0.157	3.03E+06
ED071136	NACA23012	0.4572	250.0	2	258.25	0.67	15.4	600	0.399	3.98E+06
ED071230	NACA23012	0.4572	250.0	2	260.47	0.67	15.4	600	0.398	3.94E+06
HC1070636	GLC305	0.3048	270.9	0	261.71	1.13	19.0	138	0.430	2.83E+06
HC1071036	GLC305	0.3048	289.6	0	260.77	1.15	20.0	126	0.460	3.04E+06
HC1071536	GLC305	0.3048	170.2	0	263.35	1.62	23.3	138	0.269	1.76E+06
HC1071636	GLC305	0.3048	169.9	0	263.29	1.80	23.0	138	0.269	1.76E+06
HC1072436	GLC305	0.3048	271.0	0	255.53	1.12	19.0	138	0.435	2.92E+06
HC1072836	GLC305	0.3048	292.3	0	254.34	1.12	19.0	126	0.470	3.17E+06
HC1073236	GLC305	0.3048	169.9	0	256.29	1.80	23.0	138	0.272	1.82E+06
HD1074836	GLC305	0.4572	220.2	0	261.37	1.50	26.0	185	0.350	3.45E+06
HD1075236	GLC305	0.4572	205.6	0	261.97	1.49	27.0	200	0.326	3.21E+06
HD1075636	GLC305	0.4572	171.9	0	263.20	1.47	29.0	241	0.272	2.67E+06
HD1076036	GLC305	0.4572	216.8	0	254.46	1.42	27.0	198	0.349	3.52E+06
HD1076436	GLC305	0.4572	207.4	0	254.82	1.42	27.0	206	0.333	3.36E+06
HD1076736	GLC305	0.4572	171.9	0	256.20	1.47	29.0	242	0.276	2.77E+06
HE1077536	GLC305	0.6096	155.1	0	265.71	0.81	30.7	606	0.244	3.17E+06
HE1078236	GLC305	0.6096	174.1	0	263.21	1.20	36.2	366	0.275	3.61E+06
HE1078536	GLC305	0.6096	173.7	0	263.18	1.30	35.0	360	0.275	3.60E+06
HE1079136	GLC305	0.6096	173.7	0	256.18	1.30	35.0	360	0.278	3.73E+06
HE1079736	GLC305	0.6096	159.0	0	259.93	0.93	36.0	550	0.253	3.35E+06
HE1079936	GLC305	0.6096	191.2	0	251.83	1.87	34.0	227	0.309	4.19E+06
HE1080036	GLC305	0.6096	186.9	0	258.72	0.92	34.0	471	0.298	3.96E+06
HE1080136	GLC305	0.6096	159.1	0	252.82	1.96	36.0	261	0.257	3.47E+06
HE1080236	GLC305	0.6096	171.2	0	259.40	0.93	35.0	513	0.273	3.61E+06
HE1080336	GLC305	0.6096	176.5	0	252.27	1.91	35.0	242	0.285	3.86E+06
HE1080536	GLC305	0.6096	173.7	0	256.18	1.27	43.0	360	0.278	3.73E+06
HE1080636	GLC305	0.6096	173.9	0	256.29	1.20	36.2	366	0.279	3.73E+06
HE1080836	GLC305	0.6096	173.3	0	256.38	1.30	20.1	366	0.278	3.71E+06

Case	Airfoil	chord <i>m</i>	Air Speed <i>kts</i>	AOA <i>deg</i>	Static Temp <i>K</i>	LWC <i>g/m³</i>	MVD <i>microns</i>	time <i>s</i>	Mach	Re
HF1009536	GLC305	0.9144	175.0	6	268.32	0.54	20.0	1350	0.274	5.30E+06
HF1009636	GLC305	0.9144	175.0	6	268.32	0.54	20.0	2700	0.274	5.30E+06
HF1009936	GLC305	0.9144	175.0	6	267.40	0.41	20.0	1998	0.275	5.33E+06
HF1010436	GLC305	0.9144	175.0	6	263.24	0.60	15.0	1350	0.277	5.44E+06
HF1010536	GLC305	0.9144	175.0	6	263.12	0.60	15.0	2700	0.277	5.44E+06
HF1012936	GLC305	0.9144	175.0	4	268.32	0.54	20.0	1350	0.274	5.30E+06
HF1013136	GLC305	0.9144	212.0	4	263.31	0.43	20.0	1350	0.335	6.58E+06
HF1013236	GLC305	0.9144	175.0	4	268.54	0.54	20.0	1350	0.274	5.30E+06
HF1013636	GLC305	0.9144	175.0	6	264.77	1.60	20.0	504	0.276	5.40E+06
HF1013936	GLC305	0.9144	175.0	6	258.17	1.60	20.0	504	0.280	5.58E+06
HF1014236	GLC305	0.9144	175.0	4	258.17	0.83	160.0	1200	0.280	5.58E+06
HF1014336	GLC305	0.9144	175.0	6	268.32	0.83	160.0	1200	0.274	5.30E+06
HF1026936	GLC305	0.9144	175.0	6	268.34	0.54	20.0	1350	0.274	5.30E+06
HF1081736	GLC305	0.9144	128.2	0	264.43	1.15	50.0	830	0.202	3.96E+06
HF1082036	GLC305	0.9144	137.2	0	264.39	1.10	50.0	812	0.217	4.24E+06
HF1082436	GLC305	0.9144	176.3	0	263.06	1.11	45.0	625	0.279	5.48E+06
HF1082836	GLC305	0.9144	129.0	0	257.68	1.17	50.0	807	0.206	4.12E+06
HF1083136	GLC305	0.9144	135.7	0	257.45	1.16	50.0	776	0.217	4.34E+06
HF1083436	GLC305	0.9144	176.3	0	256.06	1.10	45.0	627	0.283	5.68E+06
IG1059742	NLF0414	1.2294	135.5	1	266.29	0.70	20.0	2700	0.213	5.57E+06
JF1024136	LTHS	0.9144	250.0	0	264.92	0.41	20.0	1350	0.394	7.70E+06
JF1025436	LTHS	0.9144	253.0	-1	263.33	0.56	21.0	1110	0.400	7.86E+06
JF1025636	LTHS	0.9144	253.0	0	263.33	0.56	21.0	2214	0.400	7.86E+06
JF1025736	LTHS	0.9144	253.0	0	263.33	0.56	21.0	1476	0.400	7.86E+06
JF1025830	LTHS	0.9144	253.0	0	263.33	0.56	21.0	1110	0.400	7.86E+06
OD1057336	NACA0015	0.3531	185.1	0	268.14	0.75	19.0	600	0.290	2.17E+06
OD1057436	NACA0015	0.3531	166.0	0	268.35	0.68	23.4	732	0.260	1.94E+06
OD1057536	NACA0015	0.3531	185.1	0	263.14	0.75	19.0	600	0.293	2.22E+06
OD1057836	NACA0015	0.3531	166.0	0	263.35	0.77	23.4	648	0.263	1.99E+06