



GlennICE: Verification and Validation v5.1.0

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Contents

Contents	i
List of Abbreviations	iv
List of Symbols	v
Abstract	1
About This Document	2
Acknowledgment	3
Introduction	4
Validation	5
Verification	5
Documentation and Release Cycle	5
1 Twin Otter Tail Section Impingement Test Case	6
1.1 Experimental Data	6
1.2 Simulation Details	6
1.2.1 Geometry and Mesh	6
1.2.2 Simulated Dry Air	10
1.2.3 Simulated Cloud	10
1.3 Results and Comparison Methodology	12
1.3.1 Comparison Approach	12
1.4 Validation	15
1.5 Verification	17
1.5.1 GlennICE Version 5.1.0	17
Conclusion	20
Bibliography	21

List of Figures

1.1	Twin Otter Airfoil Model Installed in the IRT	7
1.2	Twin Otter Airfoil Coordinates	7
1.3	Twin Otter Mesh	8
1.4	Twin Otter Two Dimensional Mesh Slice	8
1.5	Twin Otter Surface Geometry	9
1.6	Close Up View of the Twin Otter Leading Edge Surface Mesh	9
1.7	Residuals of the Reynolds Averaged Navier Stokes Simulation Using a Spalart-Allmaras Tur- bulence Model	10
1.8	Y-Plus on the Viscous Twin Otter Airfoil Section	11
1.9	Coefficient of Pressure vs X	11
1.10	Twin Otter Validation.	16
1.11	Twin Otter Verification (1)	18
1.12	Twin Otter Verification (2)	19

List of Tables

1.1	Twin Otter CFD Run Conditions	10
1.2	Twin Otter Icing Conditions	10
1.3	MVD = 21 μm - 27 Bin Droplet Distribution	11

List of Abbreviations

AATT	Advanced Air Transport Technology
AAVP	Advanced Air Vehicle Program
ARMD	Aeronautics Research Mission Directorate
CFD	Computational Fluid Dynamics
CGNS	CFD General Notation System
FAA	Federal Aviation Administration
FUN3D	Fully Unstructured Navier-Stokes 3D
GlennICE	Glenn Icing Computational Environment
IRT	Icing Research Tunnel
MCCS	Maximum Combined Cross Section
MVD	Median Volume Diameter
MPI	Message Passing Interface
STL	Stereolithography
SZL	Tecplot Subzone Data
TACP	Transformative Aeronautics Concepts Program
TRL	Technology Readiness Level
TTT	Transformational Tools and Technologies
TWC	Total Water Content

List of Symbols

ρ	Density
ρ_{ice}	Ice Density
p	Pressure
p_0	Stagnation Pressure
u	x-Component of Velocity
v	y-Component of Velocity
w	z-Component of Velocity
x	x-Coordinate
y	y-Coordinate
z	z-Coordinate
T_{Wall}	Wall Temperature
Q_{Wall}	Wall Heat Flux
$x_{Wall\ Shear}$	x-Component of Wall Shear Stress
$y_{Wall\ Shear}$	y-Component of Wall Shear Stress
$z_{Wall\ Shear}$	z-Component of Wall Shear Stress
htc	Heat Transfer Coefficient
T_{AW}	Adiabatic Wall Temperature
T_0	Stagnation Temperature
V_∞	Freestream Velocity
AOA	Angle of Attack

Abstract

GlennICE (Glenn Icing Computational Environment) is a specialized computational tool designed to predict ice growth on complex three-dimensional geometries using input from user-supplied computational fluid dynamics (CFD) solutions. Historically, its validation has relied on individual technical studies addressing aspects such as surface redefinition, collection efficiencies, and roughness models. While these studies provide valuable insights, they do not establish a systematic approach for assessing the tools accuracy across multiple software releases. This report presents a standardized framework for verifying and validating GlennICE by rerunning established test cases, comparing predictions with experimental data, and archiving results. By implementing this structured methodology, the tools performance can be consistently evaluated over time.

About This Document

This document benchmarks the current verification and validation efforts of the software, GlennICE. It is not intended to detail the algorithms of the software, nor does it describe how users can interact with and configure these algorithms to produce desired simulation results. As the capabilities of GlennICE evolve, NASA intends to update this document, resources permitting, to further benchmark its V&V efforts.

For software suggestions, improvements, error reports, or difficulties with the contents of this document, please contact the GlennICE team at GlennICE-support@lists.nasa.gov. For detailed instructions on how to interact with the software to achieve the desired simulation results, please refer to the GlennICE manual.

Acknowledgment

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Introduction

GlennICE (Glenn Icing Computational Environment) is a computational tool designed to calculate ice growth on complex three-dimensional geometries using input from a user-supplied computational fluid dynamics (CFD) solution for the geometry of interest. The NASA John H. Glenn Research Center at Lewis Field is developing this tool to aid those evaluating, designing, and certifying aircraft, engines, and aircraft components for flight in icing conditions. This domestically available software is being developed to enable the introduction of new icing physics into a computational environment in a manner that is open for evaluation and eventual use by industry, academia, and other government organizations.

For those readers familiar with NASA's other computational icing tools, LEWICE [1] and LEWICE3D [2], they should note that GlennICE is being designed to address a generalized three-dimensional icing problem. This differs from LEWICE and LEWICE3D, both of which relied on assumptions that are well suited for performing analysis on special cases, such as cantilevered wings, but not necessarily the optimal approach for the general case. To date, GlennICE has been applied to several cases of interest, such as the CRM, the Ice Prediction Workshop, as well as aiding in the design of wind-tunnel models. Some of these applications included comparisons to LEWICE3D, in which the results compared qualitatively favorably to the legacy tool. However, these comparisons are largely unpublished. It is appreciated that LEWICE3D has significant usage and acceptance as a computational icing tool for design and certification. Due to the lack of usage and validation of GlennICE, the Technology Readiness Level (TRL) [3] is considered low. However, with future usage and feedback, the TRL is expected to grow with improvements in functionality and capability. The authors encourage the usage of GlennICE but note that care should be taken when being used as a design and certification tool.

For those readers not familiar with NASA's other computational icing tools, it may be useful to appreciate that history. In the 1980s, NASA began developing a computational tool for ice accretion modeling, which eventually became the LEWICE software. LEWICE is a two-dimensional ice accretion code based on a potential flow solution, a Lagrangian droplet trajectory calculation, and the Messinger model [4] for ice growth. This software has been validated through comparisons to a large database of experimental ice shapes and collection efficiency measurements [5]. LEWICE runs quickly and efficiently on a standard laptop computer, and version 3.2.3 is currently available in the NASA software repository [6].

The next step in the development of ice accretion software at NASA was the LEWICE3D software. This software performs ice growth calculations along user-specified two-dimensional cuts or along surface streamlines using a computational approach for the ice growth calculation derived from the two-dimensional LEWICE software. LEWICE3D takes a three-dimensional solution from a user-supplied CFD solution and performs a three-dimensional Lagrangian droplet trajectory calculation to determine the water impingement at all locations on the geometry of interest. The aforementioned ice growth calculation method is then performed to obtain ice shape profiles at discrete locations on the surface. LEWICE3D has also been validated through comparison to a more limited database of three-dimensional ice shapes [7]. Version 3.6.3 is currently available in the NASA software repository [8].

GlennICE is the next step in the development of ice accretion software at NASA. In order to enable users to utilize the CFD tool they have the most experience with and the greatest confidence in, GlennICE has been developed to be extensible to use various common CFD solution file formats as input.

The software then proceeds to calculate the ice shape for the geometry used in the CFD analysis. GlennICE calculates the full three-dimensional droplet trajectory using the Lagrangian method and then performs the mass and energy balance on all discrete surface elements that have had water input, whether through direct impact or through runback from adjacent elements. The water runback along the surface is determined by the shear stress imparted to the water from the surrounding airflow. The ice growth at each element is then used to create a new three-dimensional ice surface. The new surface is output in a format suitable for use by the grid generation tool employed by the user to perform the next time step in the ice growth process.

To ensure GlennICE produces reliable and accurate simulations of real-world icing conditions, it is important to go through a thorough validation and verification process. These steps help confirm that the software is not only based on sound theoretical models but also performs correctly in practice.

In the past, GlennICE has been validated primarily through technical publications [9, 10, 11]. While these

studies have been valuable in demonstrating the software’s capabilities, they mostly provide snapshots of its performance at specific points in time. What has been missing is a consistent way to track and document how GlennICE evolves and improves over different versions. This document aims to fill that gap.

Validation

Validation, in this context, means checking whether the software accurately models real-world physical problems. Since experimental data often comes with uncertainties, some comparisons will be quantitative, while others will rely on qualitative assessments.

The validation process starts by selecting a test case with available experimental data. A numerical simulation is then run using GlennICE, and the results are compared to the experimental data. When possible, this comparison is made using numerical values; otherwise, a qualitative assessment is done to judge how well the results align. If the agreement is reasonable, the validation is considered successful, and the next step is verification.

Verification

Verification ensures that GlennICE’s algorithms are working correctly and that the software behaves as expected. This is done through testing.

The verification process begins by running simulations using highly conservative settings, which help establish a reliable reference result, often called the "golden" result. The same simulations are then repeated with default settings, and the difference between the two results is evaluated. If the differences are within an acceptable range, the test is considered successful. More details on the golden results will be provided in later sections.

Documentation and Release Cycle

Each new version of GlennICE is not just about adding new features—it also includes extensive testing and validation. Whenever a new version is released, if applicable, a new experimental test case will be introduced. These test cases help push the software’s capabilities by testing different geometries and important variables like impingement limits, surface roughness, and ice shape.

Each release will come with detailed documentation summarizing the latest validation and verification results, as well as any improvements made since the last version. Additionally, past results will be archived, creating a clear record of GlennICE’s performance across multiple versions. This process ensures that the development of GlennICE is transparent and that users can track how the software has improved over time.

From a verification and validation standpoint, GlennICE follows the standard models and simulations framework outlined in [NASA STD-7009](#). The case with experimental data introduced in version 5.1.0 is:

- Twin Otter, **Chapter 1 - Twin Otter Tail Section Impingement Test Case**

1 Twin Otter Tail Section Impingement Test Case

The geometry simulated in this chapter is the horizontal tail section of De Havilland DHC-6 Twin Otter Icing Research Aircraft.

1.1 Experimental Data

The experimental data used for comparison was obtained from several tests conducted over the years in the Icing Research Tunnel [12, 13, 14]. These tests utilize a dye-tracer technique, which involves spraying water mixed with a known concentration of blue dye onto the model which is covered with a strip of blotter paper. The amount of dye captured on the blotter strip is then measured and related to the local collection efficiency. The experimental database contains collection efficiency measurements for several different airfoils, both clean and iced.

The database conditions are outlined in Table 1 of the LEWICE 3.0 Validation report [5]. This document however, specifically analyzes the Twin-Otter Tail Section, $AoA = 0^\circ$, $21\text{-}\mu\text{m}$ run. The ice shape conditions used in the reference were selected from within the Appendix C envelope, representing a severe glaze condition that could be used for FAA compliance as a 45-minute hold on an unprotected surface case. The drop size distributions were measured during the experiment.

The estimated experimental uncertainty analysis, as presented in the reports, indicated that variations in spray time, dye concentration, spray pressures, tunnel velocity, and cloud unsteadiness due to turbulence contributed to a 14% variation in maximum collection efficiency values. In the following comparisons with predicted results, this 14% uncertainty was used as a representative experimental error for all parameters.

1.2 Simulation Details

1.2.1 Geometry and Mesh

The Twin Otter airfoil section as installed in the IRT can be seen in Figure 1.1. The two dimensional airfoil coordinates of the Twin-Otter tail airfoil section are detailed in Table C4.1 of Ref. [15]. The airfoil coordinate locations from this reference are depicted as black dots in Figure 1.2. The airfoil coordinates utilized for the simulations in this report are depicted as red dots in that same figure. There are two things to note from Figure 1.2. Firstly, examining the left subplot it can be seen that the leading edge coordinates utilized in the computational analysis in this report are unchanged from those specified in Ref. [15]. Secondly, the coordinate locations used in the aft portion of the airfoil were modified such that the truncated trailing edge was appropriately resolved.

Pointwise [16] was utilized to generate a single block mixed element unstructured mesh. The surface mesh of the airfoil was generated from a diagonalized structured mesh such that the nodes of the surface mesh were consistent with the desired airfoil coordinate locations along the entire span. Pointwise's T-Rex meshing capability was utilized to grow a volume mesh with an appropriate near wall prism layer for capturing the boundary layer. No near wall prism layer was generated on the tunnel walls, as these surfaces are being modeled as inviscid. An image of mesh of the boundaries of the volume can be seen in Figure 1.3 to give the reader a sense of the volume mesh. A two dimensional slice of the mesh can be seen in Figure 1.4 showing the blending of the T-Rex generated near wall prism layer with the unstructured volume mesh. The first cell height of the prism layer was specified as two microns with a prism layer growth rate of 1.2.



Figure 1.1: Twin Otter Airfoil Model Installed in the IRT

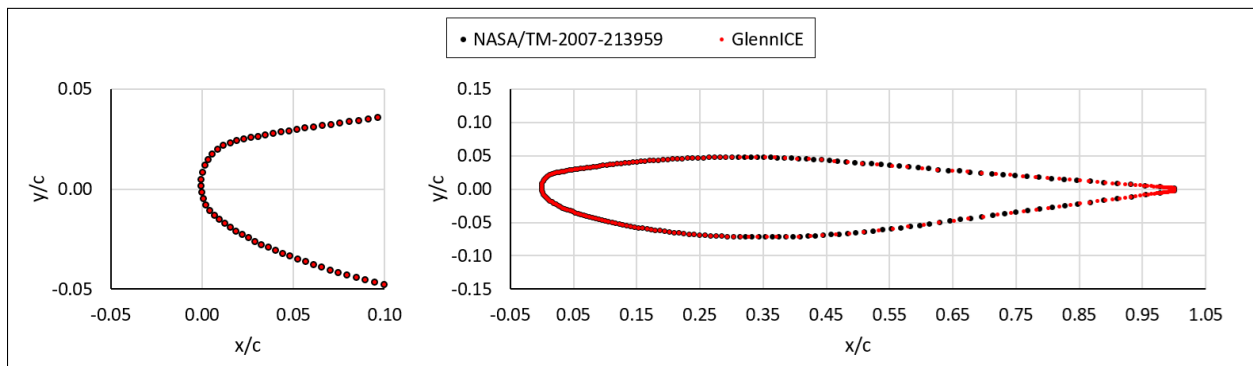


Figure 1.2: Twin Otter Airfoil Coordinates

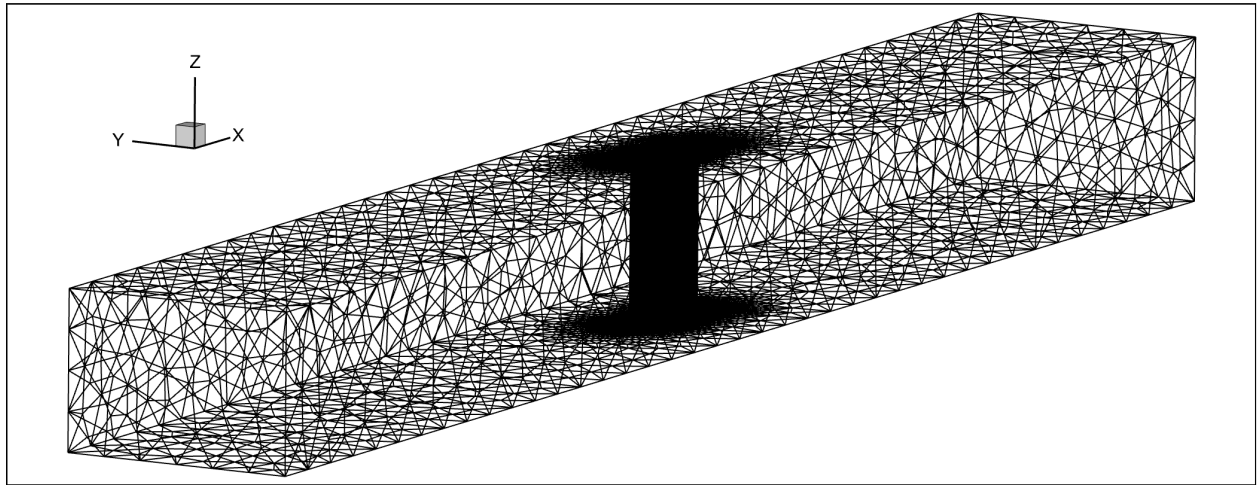


Figure 1.3: Twin Otter Mesh

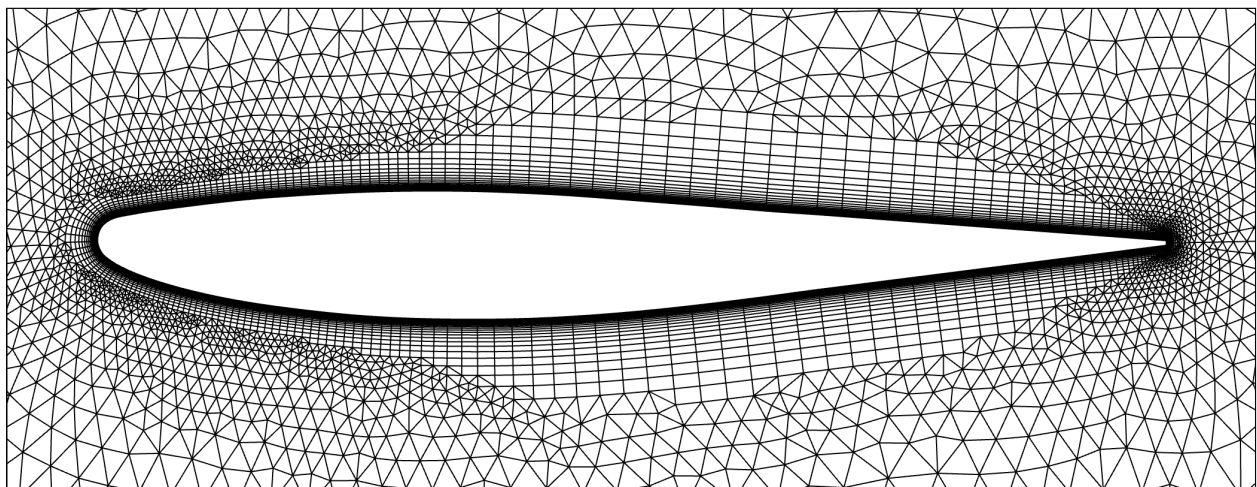


Figure 1.4: Twin Otter Two Dimensional Mesh Slice

Unique decisions were made when constructing the computational surfaces of the Twin Otter airfoil section. The airfoil section was composed of two surfaces and can be seen in Figure 1.5. One surface accounts for most of the airfoil section geometry and is depicted with a grey color in Figure 1.5. The second surface is of a similar size, shape and position to the blotter strip that was used to collect the experimental impingement data detailed in Ref. [15]. This second surface is depicted with a light blue color. This unique configuration was constructed to limit the computational cost of associated with evaluating the impingement on the Twin Otter airfoil section. GlennICE has a feature finding capability that allows it to target surfaces of interest, and by constructing the mesh in such a fashion, the simulation will only spend time evaluating the region of the airfoil section that is of interest, the blotter strip region of the mesh. Figure 1.6 shows a close up view of this blotter strip region along with the diagonalized structured surface mesh.

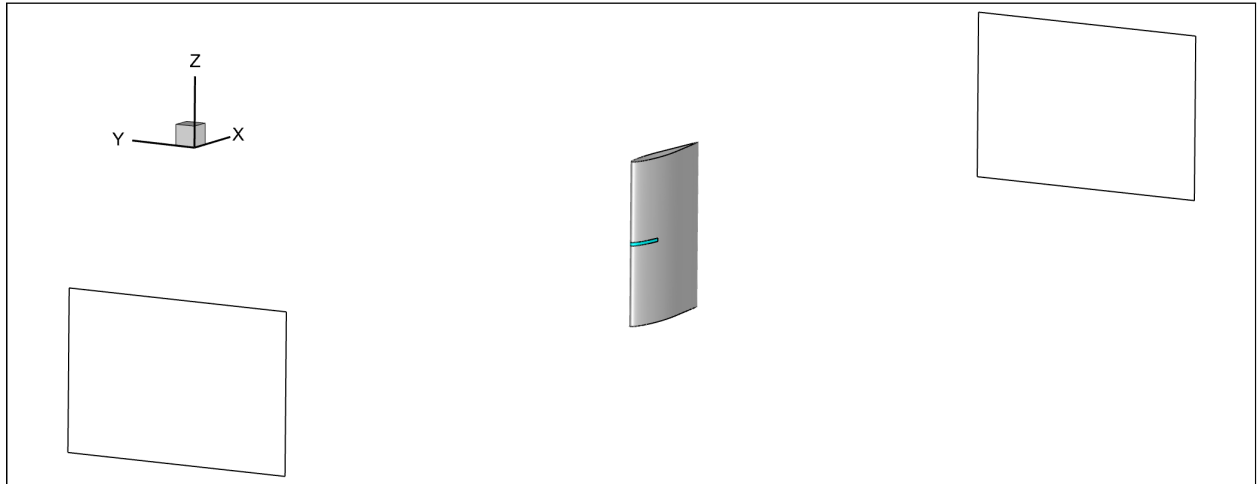


Figure 1.5: Twin Otter Surface Geometry

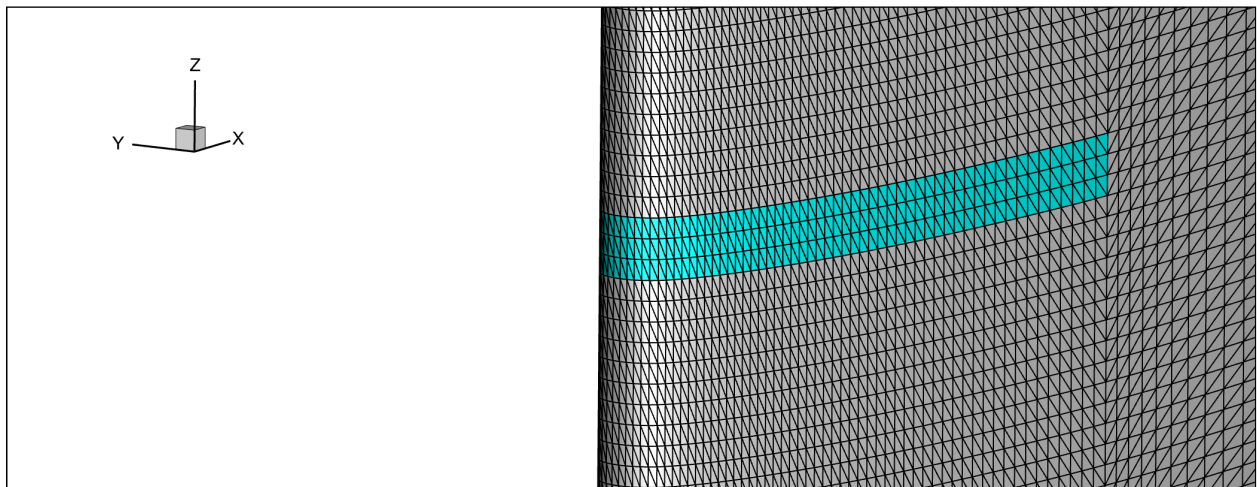


Figure 1.6: Close Up View of the Twin Otter Leading Edge Surface Mesh

1.2.2 Simulated Dry Air

The dry air flow solutions were simulated with NASA's FUN3D CFD software [17] using the Hierarchical Adaptive Nonlinear Iteration Method (HANIM) to control convergence. Roe's flux difference splitting was used in conjunction with a Spalart-Allmaras model for turbulence closure. The operating conditions simulated in this study are given in Table 1.1.

Table 1.1: Twin Otter CFD Run Conditions

AOA (deg)	Chord (m)	U_∞ (m/s)	M_∞	$T_{s,\infty}$ (K)	ρ_∞ (kg/m ³)	$Re/L^* \times 10^6$
0	1.4478	334.94	0.23357	279.1	1.2049	5.399855

Five thousand iterations were performed which resulted in the continuity and momentum residuals (R1-4) settling to a value less than $1e-18$, and the energy residual (R5) settling to a value less than $1e-16$. The turbulence residual (R6) did not settle by five thousand iterations, but was below a value of $1e-15$ and the flow solution was deemed sufficiently converged for this study. A graphical depiction of the residual history can be seen in Figure 1.7. Additionally, a contour of y^+ values across the airfoil section are plotted in Figure 1.8. It can be noted from this figure that the first cell height spacing of two microns was sufficient to achieve a y^+ less than one across the entire airfoil section, as desired.

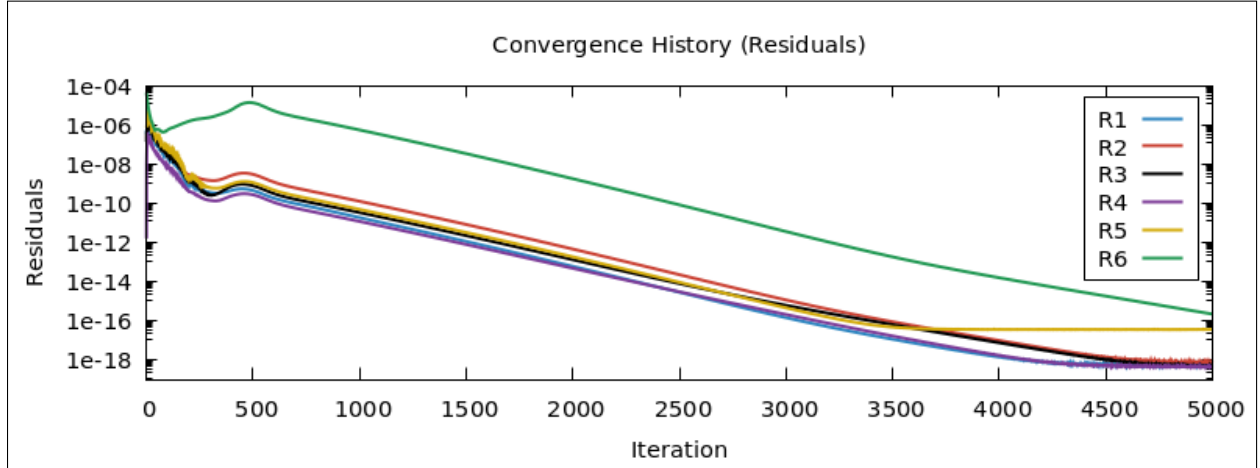


Figure 1.7: Residuals of the Reynolds Averaged Navier Stokes Simulation Using a Spalart-Allmaras Turbulence Model

Coefficient of pressure was extracted at the centerline of the tunnel and compared with available experimental data. This comparison is depicted in Figure 1.9. The experimental data plotted in that figure corresponds to the data labeled "2001 Experiment" in Figure 77 of Ref. [15].

1.2.3 Simulated Cloud

A multi bin ice accretion case will be conducted to generate an ice shape at the conditions shown in Table 1.2. The values for the droplet diameters and mass fractions have been computed and provided within Table 1.3.

Table 1.2: Twin Otter Icing Conditions

MVD (μm)	LWC (g/m^3)	Spray Time (s)	Icing Temp. (K)
21	0.2	10	279.15

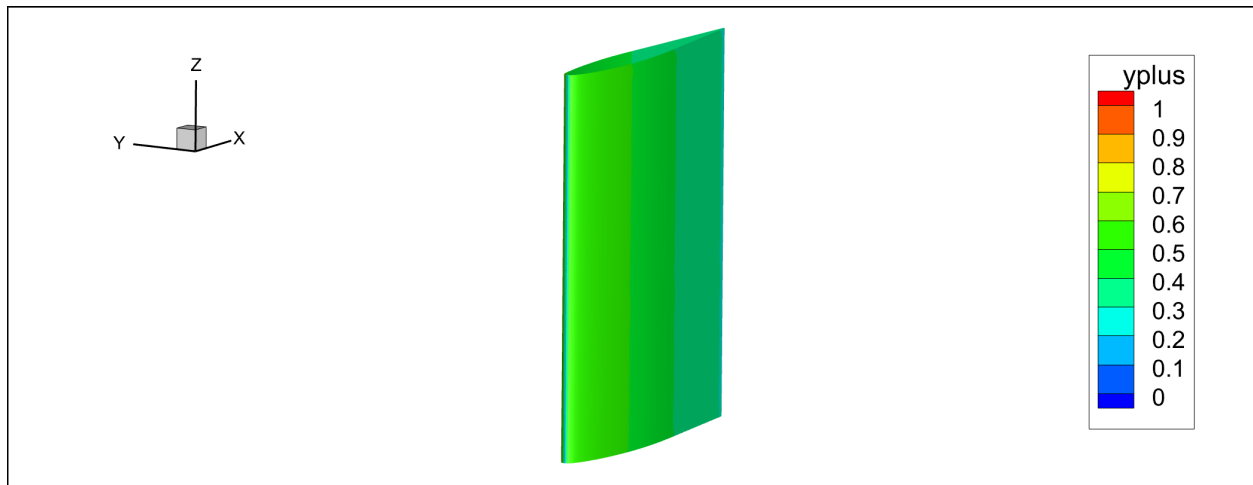


Figure 1.8: Y-Plus on the Viscous Twin Otter Airfoil Section

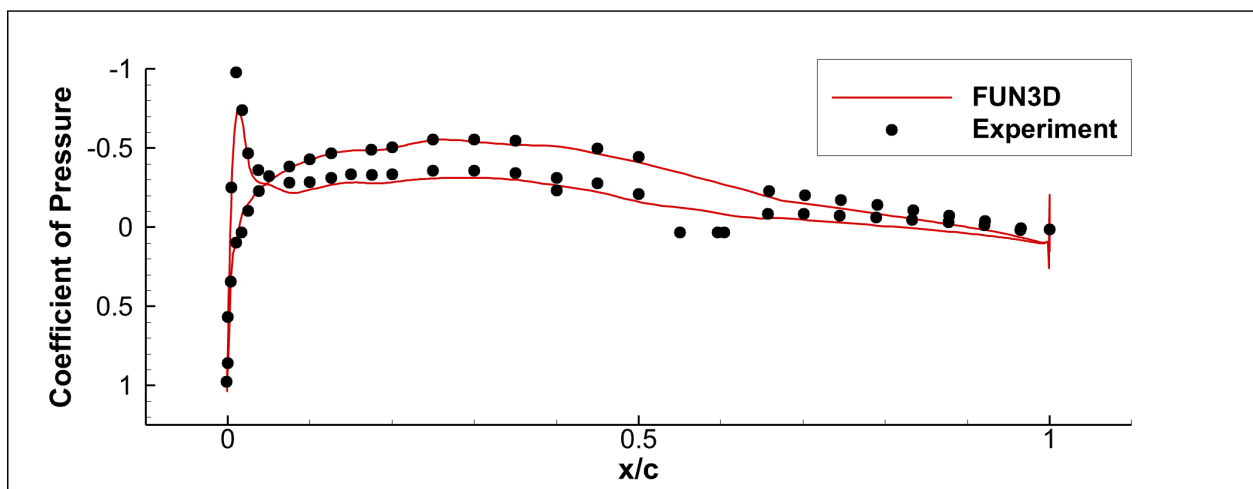


Figure 1.9: Coefficient of Pressure vs X

Table 1.3: MVD = 21 μm - 27 Bin Droplet Distribution

Diameter (μm)	4.00077	8.759436	10.27464	11.76303	13.22518	14.65941	16.06485	17.3624	18.53165
Mass Fraction	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475
Diameter (μm)	19.68089	20.8358	21.99513	23.18513	24.42356	25.71301	27.13809	28.7678	30.76125
Mass Fraction	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475	0.0475
Diameter (μm)	34.40258	47.86874	61.85915	68.70525	76.91782	84.84912	92.38594	103.4067	163.963
Mass Fraction	0.0475	0.0475	0.01	0.01	0.01	0.005	0.005	0.005	0.005

1.3 Results and Comparison Methodology

A 27-bin drop size distribution was used to accurately model impinging water in the LEWICE simulation. The number of bins was chosen because it matches the total number of bins from the FSSP and OAP instrumentation, eliminating the need for interpolation of the drop size distribution.

The comparison process for collection efficiencies differs from the approach used in previous reports for ice shape comparisons [5]. Previously, the analysis focused on maximum collection efficiency, total collection efficiency (water catch rate), upper & lower impingement limits, and the locations on the upper & lower surfaces where collection efficiency reached 10%. In this report the collection efficiency is only studied. Since this simulation involves a multi-bin ice accretion case, both the total and bin-wise collection efficiencies are analyzed.

1.3.1 Comparison Approach

When comparing to experiments, four different models were considered:

1. **LEWICE (NS)**: LEWICE simulation using a Navier-Stokes flow solver, without considering splashing and breakup effects.
2. **LEWICE (S)**: LEWICE simulation incorporating splashing and breakup effects.
3. **GlennICE**: A GlennICE simulation using the default input settings (namelist shown below).
4. **Golden**: A GlennICE simulation with more stringent inputs to minimize errors and maximize accuracy.

Note: The two LEWICE model results were not included in the reference [5] but are simulated here for qualitative comparison. The following GlennICE namelist file `glennice.nml` will be utilized for the Twin Otter validation case:

```
&files
  solution_in = "Otter_0AoA_57inch_part1_tec_volume.szplt"
  solution_surface_in = "Otter_0AoA_57inch_tec_boundary.szplt"
  volume_restart_file = "Otter_volume_restart.dat"
  tecplot_out = "Otter_output.szplt"
  stl_outer_mold_line_out = "Otter_IceShape.stl"
/
&release
  inlet_coverage="full"
/
&distribution
  diameter(1:5)   = 4.000770, 8.759436, 10.27464, 11.76303, 13.22518
  diameter(6:10)  = 14.65941, 16.06485, 17.36240, 18.53165, 19.68089
  diameter(11:15) = 20.83580, 21.99513, 23.18513, 24.42356, 25.71301
  diameter(16:20) = 27.13809, 28.76780, 30.76125, 34.40258, 47.86874
  diameter(21:25) = 61.85915, 68.70525, 76.91782, 84.84912, 92.38594
  diameter(26:27) = 103.4067, 163.9630

  mass_fraction(1:5)   = 0.0475, 0.0475, 0.0475, 0.0475, 0.0475
  mass_fraction(6:10)  = 0.0475, 0.0475, 0.0475, 0.0475, 0.0475
  mass_fraction(11:15) = 0.0475, 0.0475, 0.0475, 0.0475, 0.0475
  mass_fraction(16:20) = 0.0475, 0.0475, 0.0475, 0.0475, 0.0475
  mass_fraction(21:25) = 0.01, 0.01, 0.01, 0.005, 0.005
  mass_fraction(26:27) = 0.005, 0.005
/
&bin_count
  nbins = 27
/
&slice
  plane_normal=0.,0.,1.0
```

```

point_on_plane=0.,0.,0.9144
x_max=0.4
surface_index = 2
/
&surface_count
  number_of_surfaces=5
/
&surface_nml
  category = , "Icing", "Inlet"
/
&freestream
  twc = 1.0
/
&htc_augmentation
  augmentation_type = "McClain_roughness"
  turbulent_htc_augmentation = 3.0
  ideal_rime_limit = 0.004
/
&variable_properties
  ! Scaling density
  map_index = 4
  scale_factor = 1.2049
/
&variable_properties
  ! Scaling u-velocity
  map_index = 5
  scale_factor = 334.94
/
&variable_properties
  ! Scaling v-velocity
  map_index = 6
  scale_factor = 334.94
/
&variable_properties
  ! Scaling w-velocity
  map_index = 7
  scale_factor = 334.94
/
&variable_properties
  ! Scaling pressure
  map_index = 8
  scale_factor = 135171.840 !  $\rho_{\infty} * a_{\infty}^2$ 
/
&variable_properties
  ! Scaling temperature
  map_index = 9
  scale_factor = 279.1
/
&variable_properties
  ! Scaling heating
  map_index = 14
  spelling = 'heating'
  scale_factor = -6.79726894 !  $W/cm^2$  to  $W/m^2$  and a sign change
/
&variable_properties
  map_index = 11
  spelling = 'cf_x'
/
&variable_properties

```

```

    map_index = 12
    spelling = 'cf_y'
/
&variable_properties
    map_index = 13
    spelling = 'cf_z'
/

```

The main difference between the default and golden runs lies in three namelist inputs: `&mass_flux_solver`, `&trajectory_solver`, and `&adaptive_refinement`. The default solution is run with default settings:

```

&mass_flux_solver
/
&trajectory_solver
/
&adaptive_refinement
/

```

as such GlennICE will auto-populate these setting to:

```

&mass_flux_solver
    max_iterations = 23
/
&trajectory_solver
    abs_tol=1.e-8
    rel_tol=1.e-7
/
&adaptive_refinement
    max_face_count = 60
    fraction_contained_tol = 0.5
    hit_percent_limit=25.0
    use_nonuniform_tolerance = .true.
    pct_converged_limit=90
/

```

and the golden solution is run with the following settings:

```

&mass_flux_solver
    max_iterations = 23
/
&trajectory_solver
    abs_tol=1.e-12
    rel_tol=1.e-12
/
&adaptive_refinement
    max_face_count = 10000000
    fraction_contained_tol = 0.99
    hit_percent_limit=50.0
    use_nonuniform_tolerance = .false.
    pct_converged_limit=100.0
/

```

GlennICE then runs the simulations, parses and exports a subset of data, and then compares the exported data to the experimental results seen in the reference [15]. The slice of GlennICE data is generated by creating line segments between neighboring face centers, and then linearly interpolating the face centered solution data to the intersection location of the line segment with the slice plane.

1.4 Validation

The total collection efficiency β_{total} from these four models, along with experimental results, is plotted against the wrap distance s/c . A wrap distance of $s/c = 0$ represents the leading edge of the airfoil. Since this section focuses **only** on the qualitative analysis of results, the total collection efficiency is the primary metric for comparison. As shown in Figure 1.10a, the resulting β_{total} values qualitatively agree well with the experimental data. The GlennICE simulation also aligns closely with both LEWICE (S) and LEWICE (NS) models.

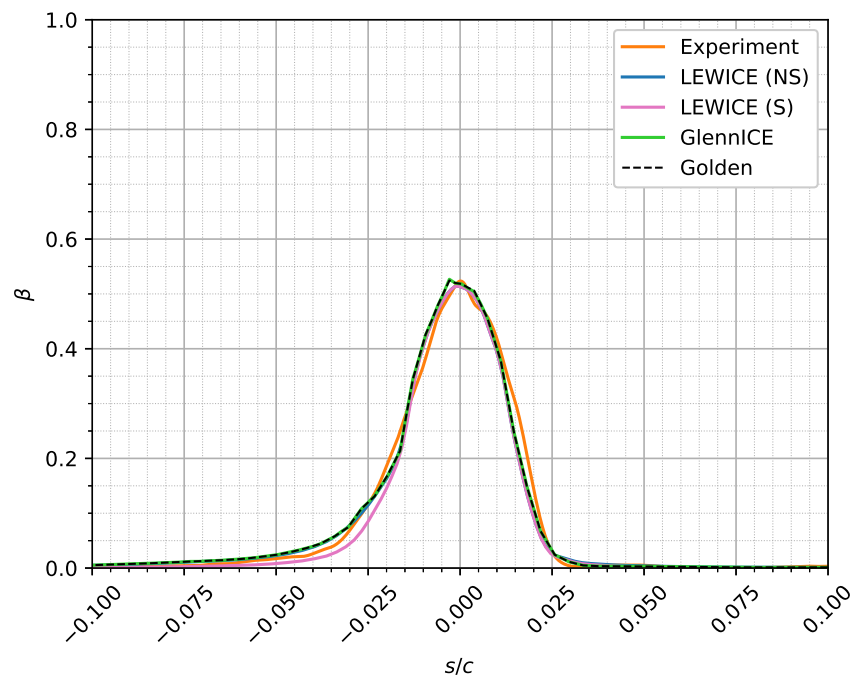
Before proceeding to the verification analysis of individual bins, it is valuable to quantitatively compare the "golden" GlennICE run to the default GlennICE run. The absolute difference is computed as:

$$\text{Absolute Difference} = |\beta_{\text{result}} - \beta_{\text{golden}}|$$

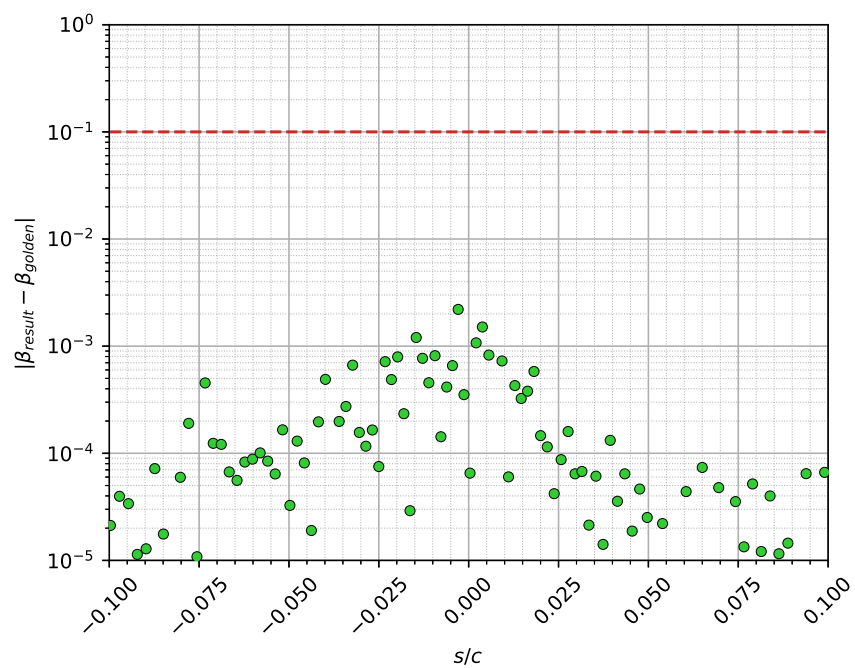
with a predefined tolerance:

$$\text{Tolerance} = 0.1$$

Overall, the results in Figure 1.10b indicate that the errors for the total collection efficiency remain within the expected tolerance level.



(a) β_{total} vs. Wrap Distance s/c



(b) β_{total} Error vs. Wrap Distance s/c

Figure 1.10: Twin Otter Validation.

1.5 Verification

Following the successful validation efforts described in the previous section, attention now turns to verifying the GlennICE software. To establish a baseline, GlennICE is first run with parameters specifically chosen to ensure algorithmic consistency and minimize errors. These outputs are designated as the “golden” results. The same simulation is then executed using default parameters, and the difference between these two runs is documented in each version-specific subsection below.

1.5.1 GlennICE Version 5.1.0

A similar namelist file described in **Section 1.4 - Validation** is used here. Figures 1.11 and 1.12 display the collection efficiencies for the golden solution versus the default 5.1.0 release of GlennICE. Each subfigure (a), (b), (c), and (d) contains two subplots:

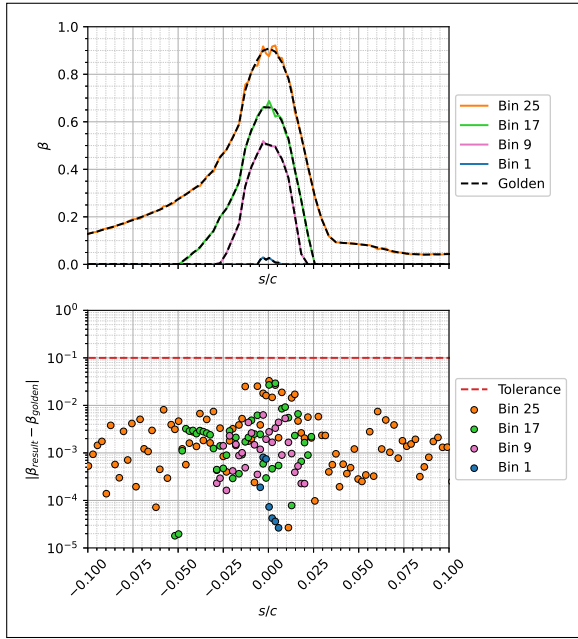
1. Top subplot analyzes the collection efficiency, β , versus the wrap distance (s/c) for multiple bins under both the default and golden solutions.
2. Bottom subplot analyzes the absolute difference versus the wrap distance (s/c). The absolute difference is computed as:

$$\text{Absolute Difference} = |\beta_{result} - \beta_{golden}|$$

with a predefined tolerance:

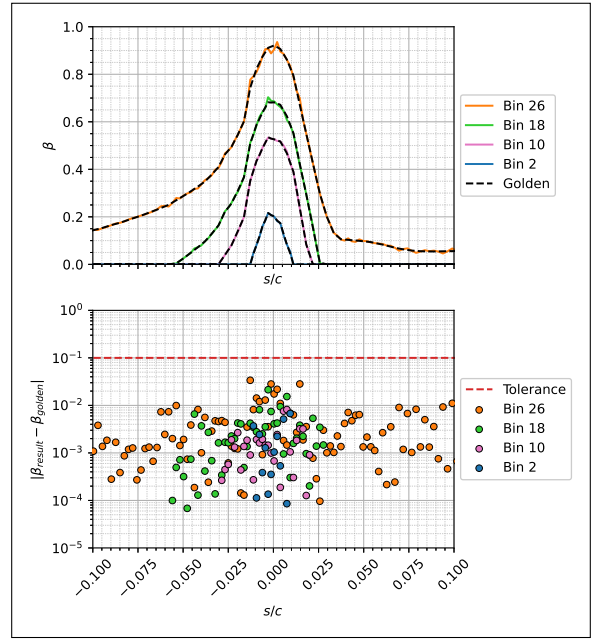
$$\text{Tolerance} = 0.1$$

Overall, the results indicate that the errors for all 27 bins remain within the expected tolerance level.



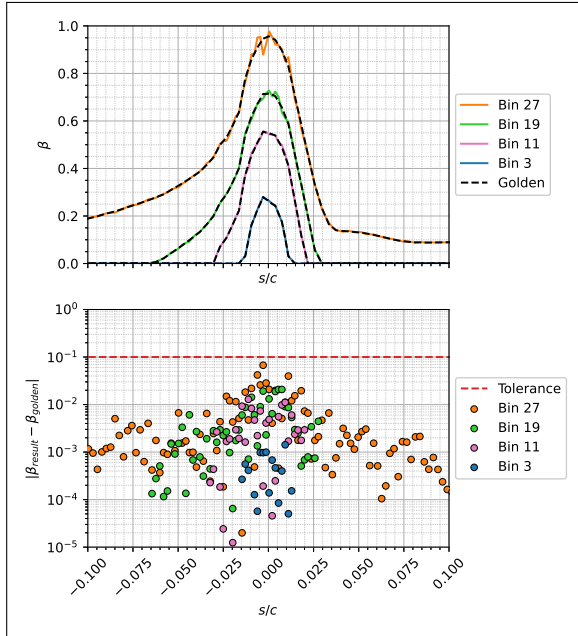
(a) Bins: 1, 9, 17, 25

Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c



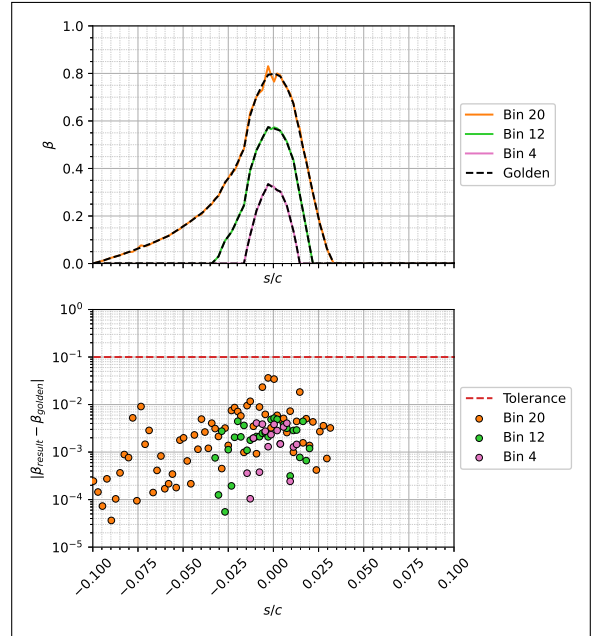
(b) Bins: 2, 10, 18, 26

Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c



(c) Bins: 3, 11, 19, 27

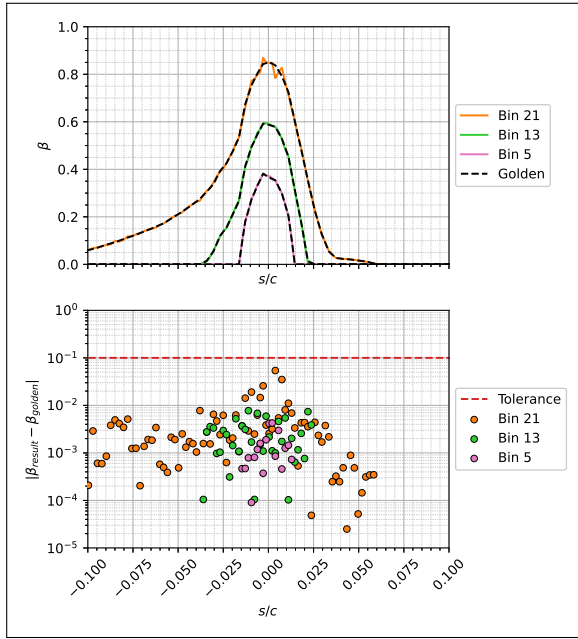
Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c



(d) Bins: 4, 12, 20

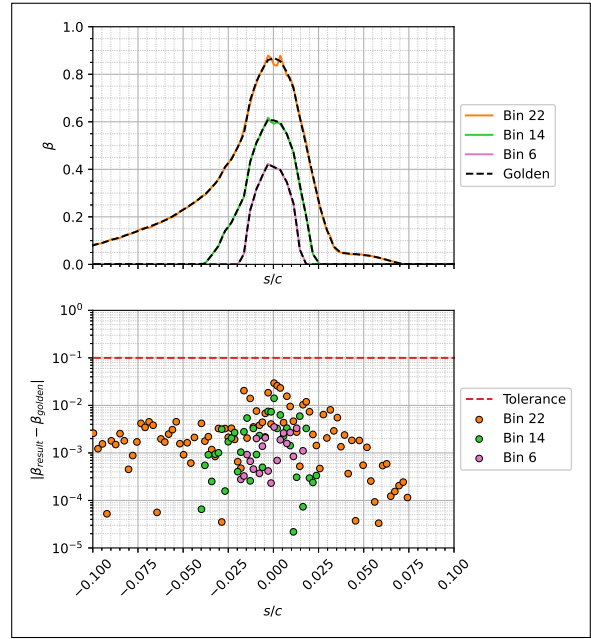
Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c

Figure 1.11: β and Absolute Difference vs. Wrap Distance s/c



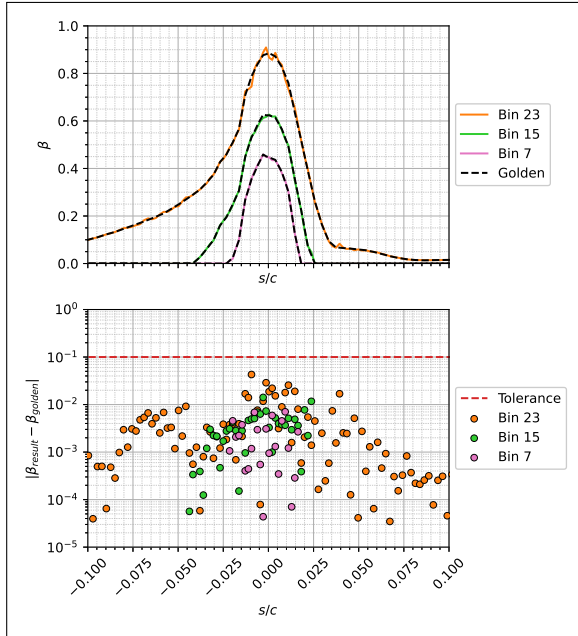
(a) Bins: 5, 13, 21

Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c



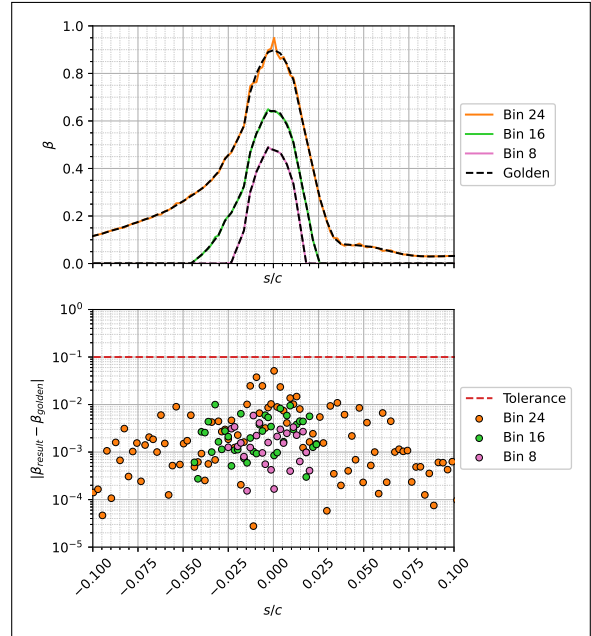
(b) Bins: 6, 14, 22

Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c



(c) Bins: 7, 15, 23

Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c



(d) Bins: 8, 16, 24

Top: β vs. Wrap Distance s/c
Bottom: Error vs. Wrap Distance s/c

Figure 1.12: β and Absolute Difference vs. Wrap Distance s/c

Conclusion

This document establishes a standardized framework for the verification and validation (V&V) efforts of GlennICE. By rigorously testing the software against a well-established test case and experimental data, this framework aims to not only confirm theoretical expectations but also validate GlennICE's practical applicability in real-world scenarios. The validation of the Twin Otter test case in **version 5.1.0** demonstrated strong alignment with experimental data and showed favorable comparisons to legacy tools like LEWICE and LEWICE3D. Additionally, verification tests confirmed that GlennICE's numerical outputs fall within expected tolerance levels. The structured validation and verification processes outlined in this document is crucial for establishing GlennICE as a reliable and authoritative tool in the aerospace industry. By adhering to these rigorous standards, GlennICE is positioned to significantly contribute to safer and more efficient aircraft operations under icing conditions.

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