OPTIMIZED PARAMETERS FOR MCCLAIN CORRELATION IN GLENNICE

William Wright, HX5 LLC
Thomas Ozorowski, NASA Glenn
David Rigby, HX5 LLC

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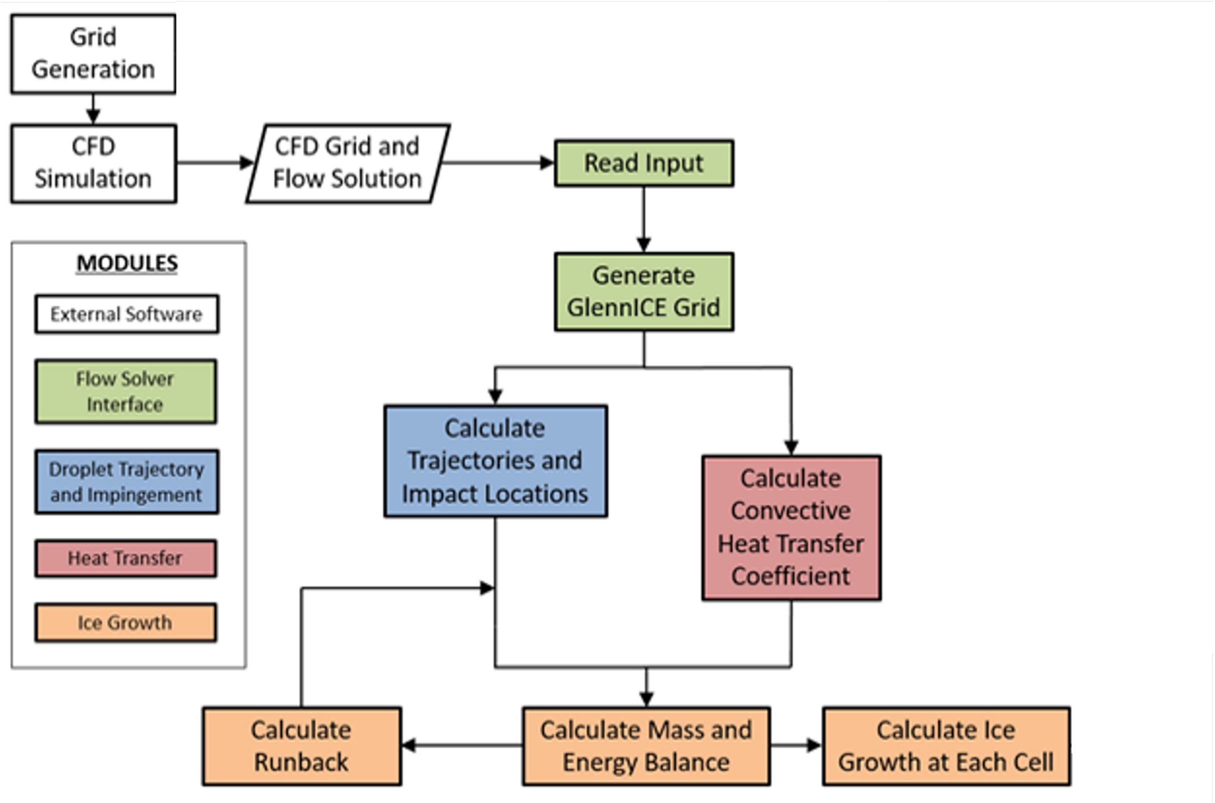
Presentation Overview

- Roughness effects on heat transfer
- GlennICE overview
- Heat transfer augmentation in GlennICE due to roughness
- Empirical case study process
- Results
- Conclusions

Prior Efforts to Augment Heat Transfer with Roughness

- **LEWICE/LEWICE3D**
  - Reads in CFD flow solution
  - CFD solution only used for trajectory calculation
  - Heat transfer coefficient calculated via integral boundary layer with sand-grain roughness (Schlichting)
- **RANS Models that incorporate roughness effects**
  - Wilcox
  - Aupoix
  - Menter
- **GlennICE**
  - Reads in CFD flow solution
  - Uses heat transfer coefficient from CFD
    - CFD may or may not have included roughness effects
    - Need to account for cases where CFD did not incorporate roughness (such as Spalart-Allmaras)

GlennICE Overview



Heat Transfer Augmentation in GlennICE

- **Heat transfer coefficients are supplied to GlennICE via two modes**
  - ➢ Reading surface heat transfer coefficient (HTC) directly
  - ➢ Reading surface heat fluxes and computing HTC
    - – Requires two flow solutions with different wall temperature boundary conditions
    - – These flow solutions are user-supplied as GlennICE does not directly interact with the CFD solver
- **Roughness can be incorporated via turbulence model or by adjustment in GlennICE**
  - ➢ Adjustment via turbulence model could require modifications to flow solvers
    - – Adjustments we can't make since we do not develop CFD solvers
- **Heat transfer in GlennICE can be augmented by a constant or by using an augmentation based on roughness height**
  - ➢ Roughness height calculated by McClain correlation

McClain Roughness Correlation

- **Experiments conducted over several years in IRT to measure roughness**
  - ➢ Uses scanned ice shapes (short time sprays) for a variety of conditions
  - ➢ Tests performed on multiple geometries
- **An experimentally-derived correlation was produced that provides roughness distribution on a given geometry**
  - ➢ Utilizes both surface and freestream variables
- **Roughness height correlation may not be applicable to ice crystals or geometries other than wings.**
- **The purpose of this effort is to empirically relate roughness height distribution to HTC augmentation**

McClain Correlation for Roughness Distribution

$$R_q = \min\left[IRL, \frac{\dot{m}_{imp} * t}{A_{face} * \rho_{ice}}\right] 0.7\left(1 - C_p\right)\eta_f [0.34 + \frac{2}{3}\Delta\mathrm{T}_{stag} \exp\left[-\frac{\Delta\mathrm{T}_{stag}}{2.25}\right]]$$

IRL = ideal rime limit (user input)

$\dot{m}_{imp}$**= impinging water mass rate (kg/s)**

t = time (s)

A_{face} **= area of surface face (m^2)**

ρ_{ice} **= ice density (kg/m^3)**

C_p **= pressure coefficient (dimensionless)**

η_f **= freezing fraction (dimensionless)**

$\Delta T_{stag} = T_{melt} - T_{tot}$ **(K)**

- **Roughness distribution will set location where maximum roughness occurs.**
- **This will fix the horn angle for glaze cases (location of maximum augmentation).**

Heat Transfer Augmentation in GlennICE

$HTC_{Augmented}$ = (1+ Aug*R_q/0.001)*HTC_{input}

Aug = augmentation factor (user input)

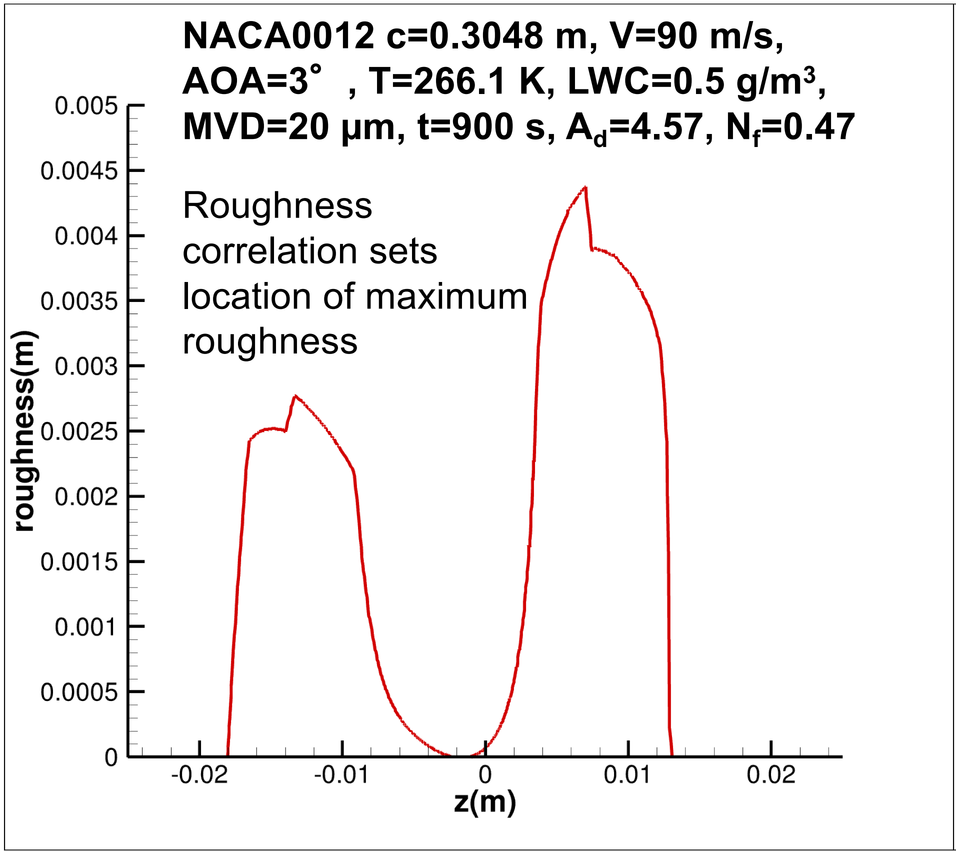
Rq = roughness height (mm)

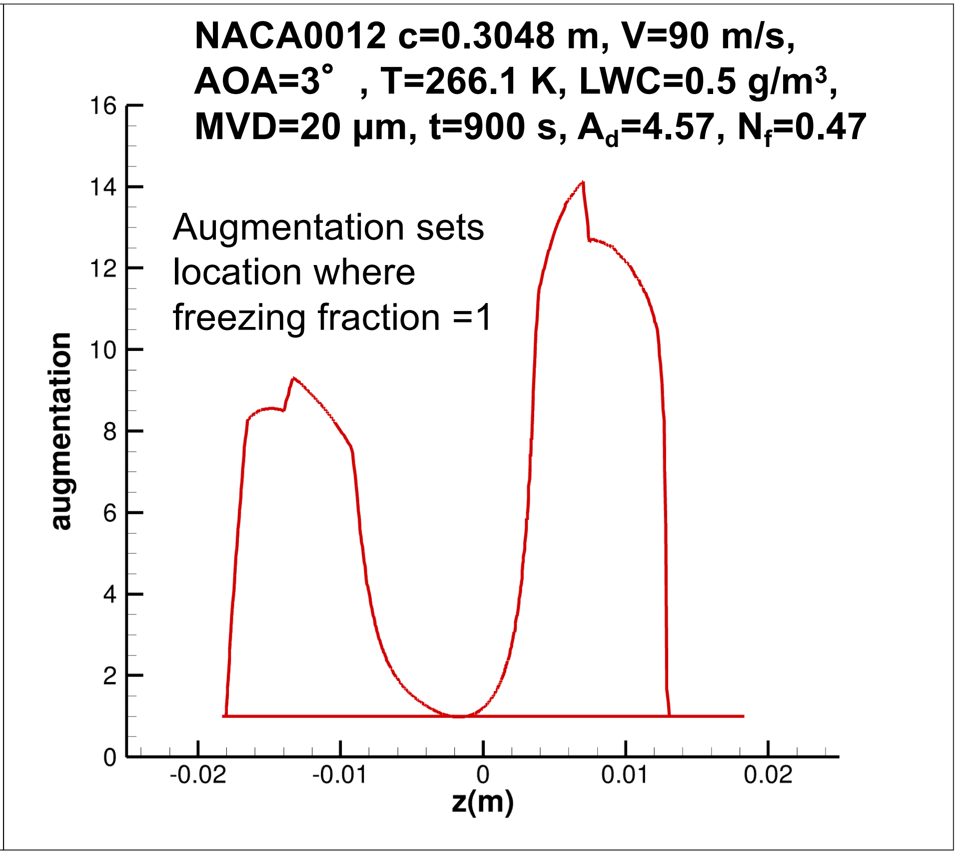
- Roughness distribution defined on previous slide

HTC_{input}=input heat transfer coefficient

Augmentation value will determine where local freezing fraction =1 and stops water runback

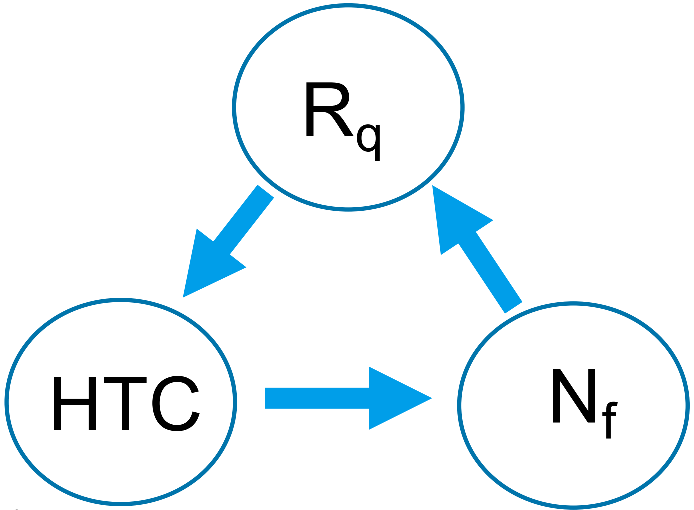
Sample Roughness Augmentation Distribution





Iterative Process for Heat Transfer Augmentation

- **Roughness depends on freezing fraction**
- **Freezing fraction depends on htc**
- **HTC depends on roughness**
- **Iteration process**
  - ➢ Use initial htc to find freezing fraction
  - ➢ Use freezing fraction to find roughness
  - ➢ Use roughness to find new HTC
  - ➢ Process iterates to convergence
  - ➢ Number of roughness iterations is also a user input



Empirical Case Study Process

- **Three user inputs need to be defined**
  - ➢ Augmentation multiplier
  - ➢ Ideal rime limit
  - ➢ Number of roughness iterations (fixed at 6 iterations in this study)
- **Selected 95 cases from LEWICE validation database**
  - ➢ All cases were large (accumulation parameter based on diameter over 3)
  - ➢ All cases were glaze (stagnation freezing fraction less than 0.5)
  - ➢ Data consists of 2D tracings on straight wing airfoil cross-sections
    - – Six airfoils represented

Process to Determine Correlation Coefficients

- **Create grids in Pointwise**
  - Rhino used to create smooth airfoil geometries
- **Run FUN3D on all 95 conditions**
  - Grid sensitivity study performed
  - No variation in turbulence model (SA-neg used for all cases)
- **Run GlennICE on all 95 conditions for using one combination of correlation parameters**
- **Obtain ice shape measurements using THICK utility**
  - Horn angles and horn thicknesses
  - THICK utility introduces its own errors
- **Repeat GlennICE runs for another combination of correlation parameters**

Virtual Test Matrix

Augmentation factor varied from 1 to 7 (1,3,5,7)

Ideal rime limit varied from 1 to 15 (1,3,5,7,9,11,13,15)

Total GlennICE cases ran 2280

Roughness iterations set at 6

- Convergence of iteration confirmed

For these cases, augmentation factor and ideal rime limit are not independent

- Same ice shape produced by Aug=1, IRL=7 as with Aug=7, IRL=1

➢This occurs because the large glaze horns heights are > ideal rime limit

- Results plotted based on the product of these factors

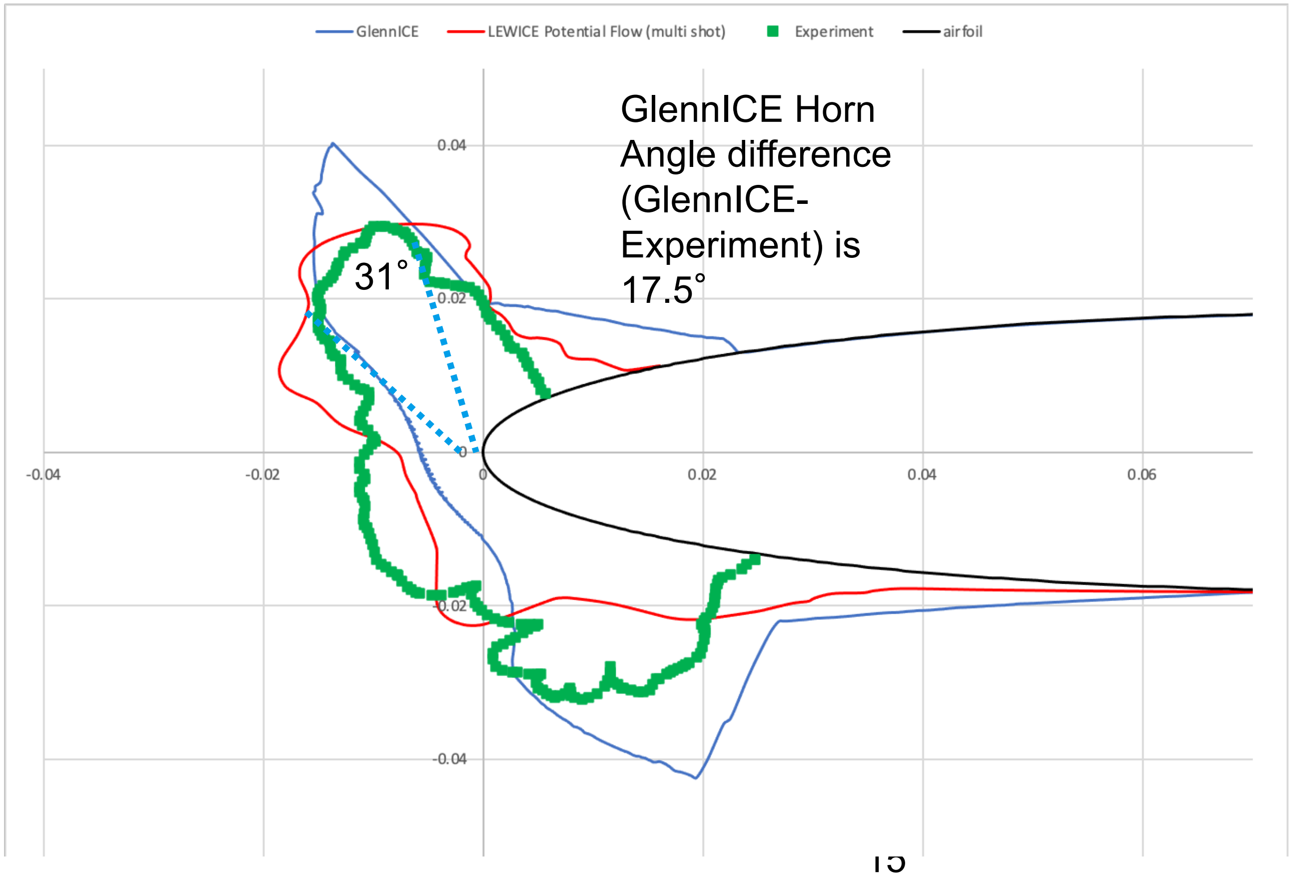
For a given combination of correlation parameters, results shown are based on THICK measurements for the 95 conditions (GlennICE – Experiment) and averaging the absolute difference

Errors Introduced by THICK Utility

- **Utility measures horn angle from the maximum ice thickness location**
- **Due to natural variation in this location, the reported horn angle can vary by 20° for ice shapes that are visibly very similar**

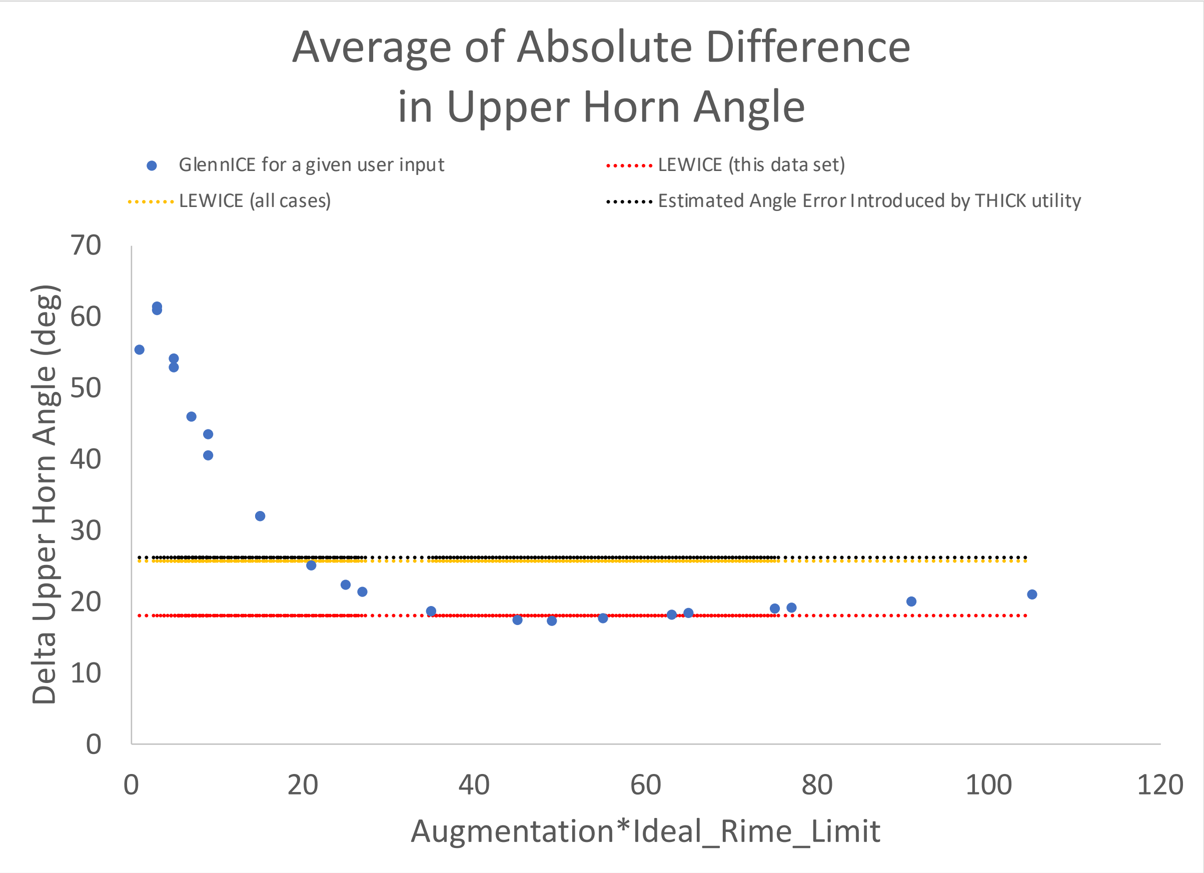
THICK Utility Error

Example of Horn Angle Errors introduced by THICK Utility

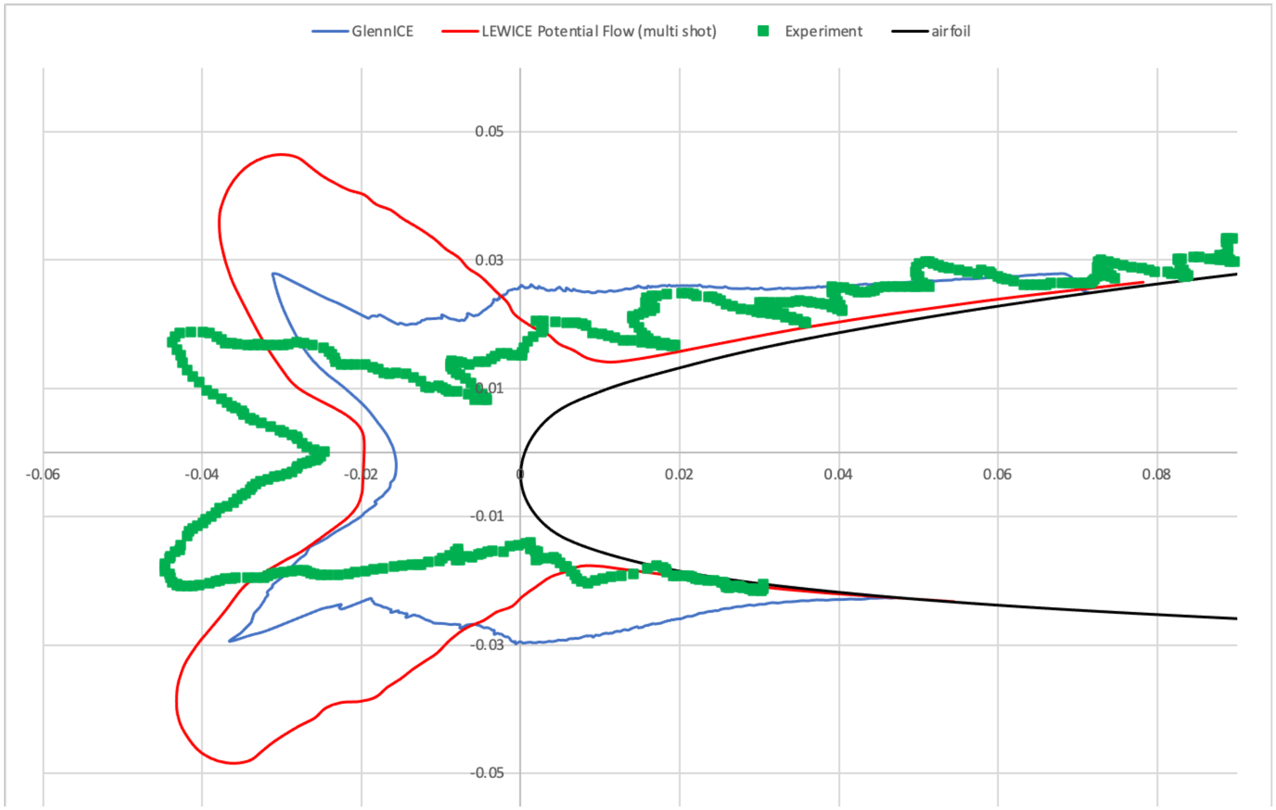


Results – Difference in Upper Horn Angle

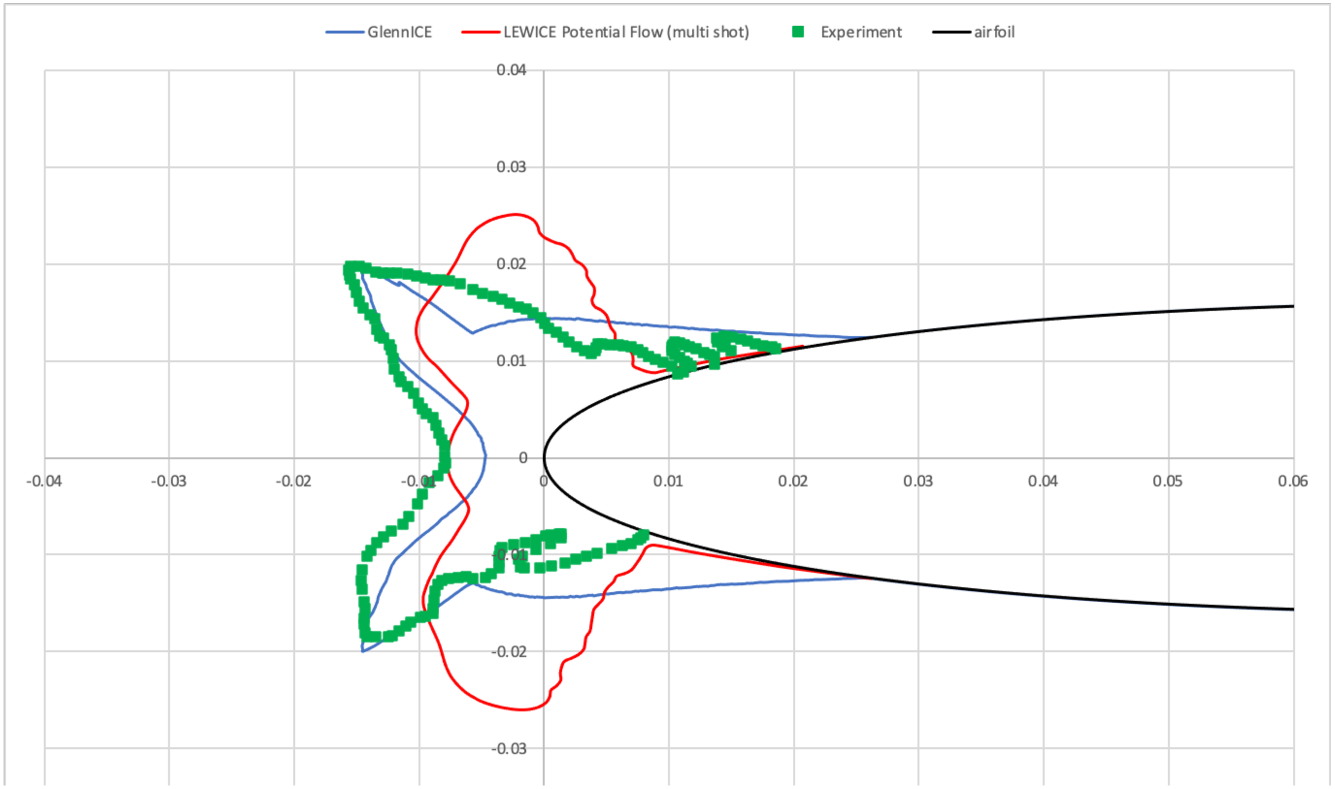
- Each blue dot represents the average difference for 95 GlennICE runs
- GlennICE prediction is within tunnel repeatability.
- Best prediction between 40-60



Example Case where Horn Angle Difference is Similar to Average Horn Angle Difference

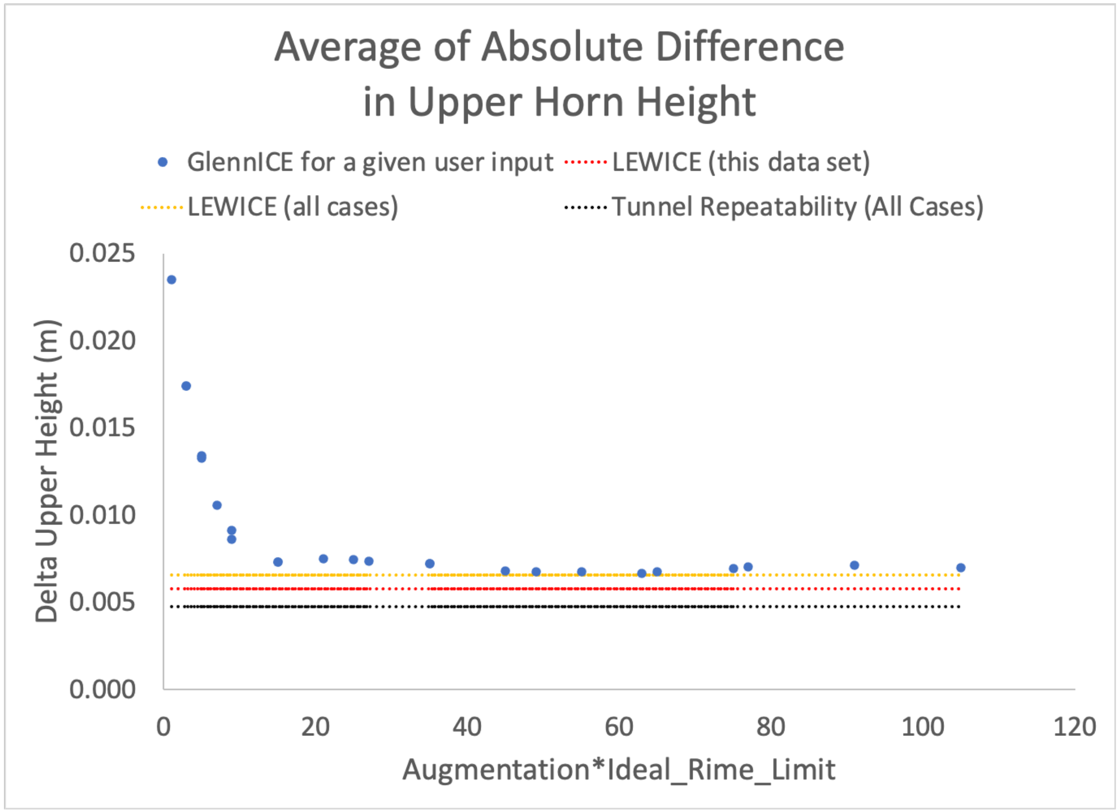


Example of Good Comparison



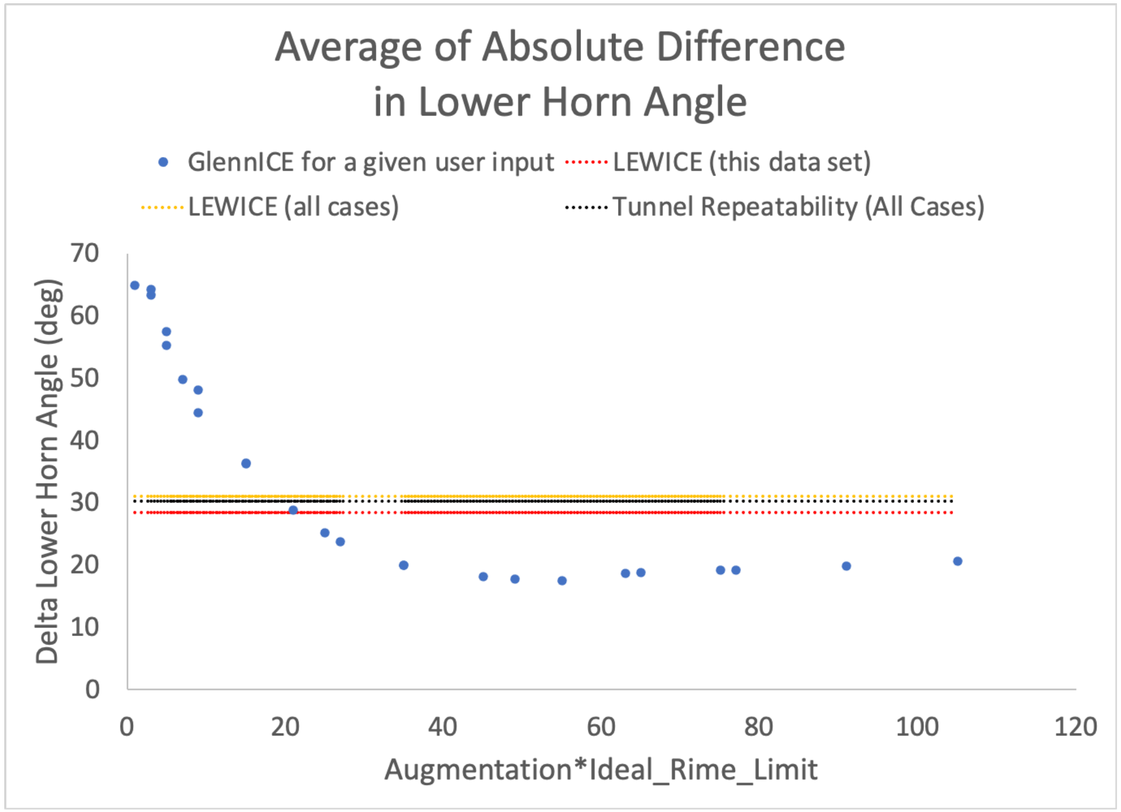
Results – Difference in Upper Horn Height

- Asymptotic behavior for a wide range of multipliers
- Average height difference (7 mm) slightly above tunnel repeatability (5 mm)



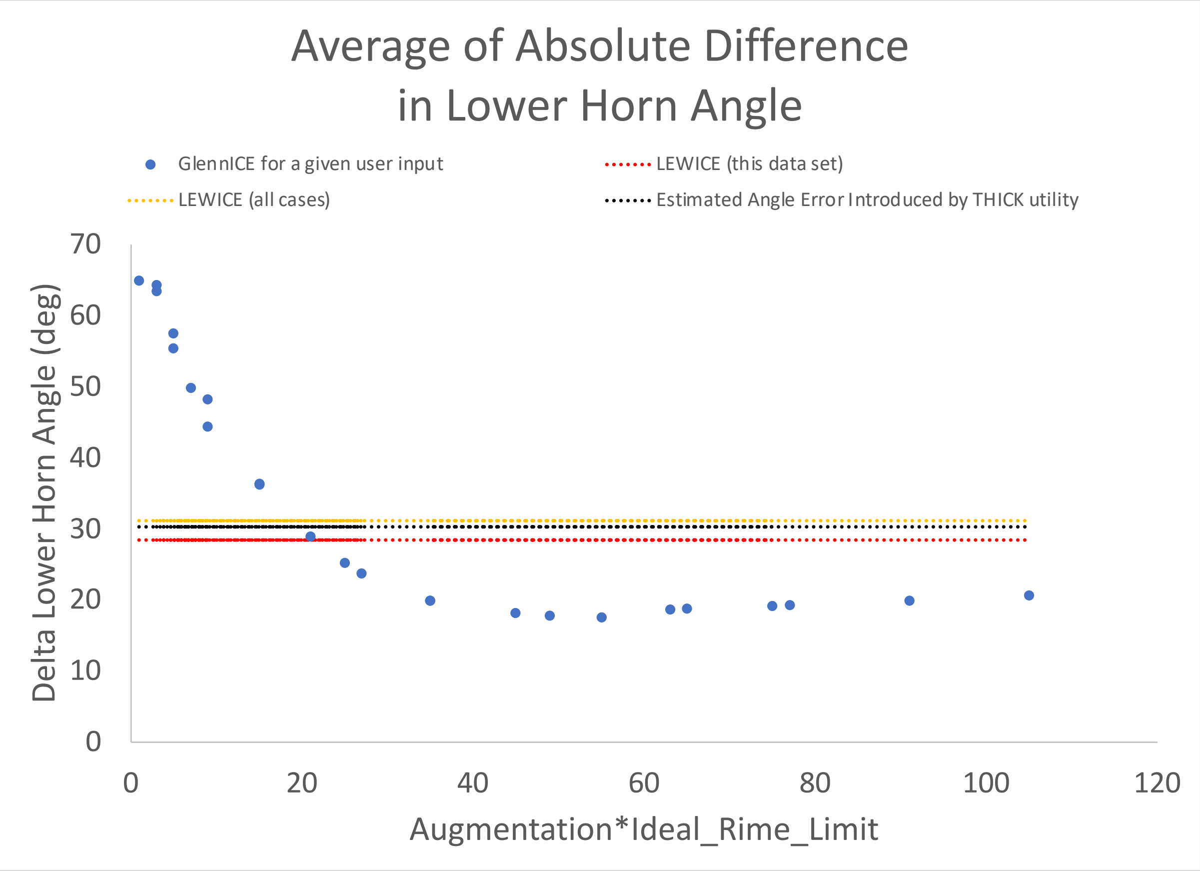
Results – Difference in Lower Horn Angle

- Similar behavior to Upper Horn Angle
- Differences are also within Tunnel Repeatability



Results – Difference in Lower Horn Height

- Minimum Difference at 18 but exhibits similar asymptotic behavior
- Difference of 8.5 mm slightly higher than tunnel repeatability



Conclusion

- **User inputs successfully calibrated to experimental data**
  - Defaults set to augmentation of 5 and ideal rime limit of 9 mm (product = 45)
- **Augmentation multiplier and ideal rime limit exhibit similar behavior**
  - Results plotted as the multiple of those factors
- **Similar behavior on all cases above a multiplier of about 20**
- **Augmentation used is far higher than the measured augmentation of heat transfer due to roughness**
  - Augmentation will need to be re-evaluated if multi-shot capability is implemented.
- **This study only examined differences in geometry**
  - Changes in aerodynamic performance were not examined.