



# Computational Aerodynamic Analysis of Three-dimensional Ice Shapes on a NACA 23012 Airfoil

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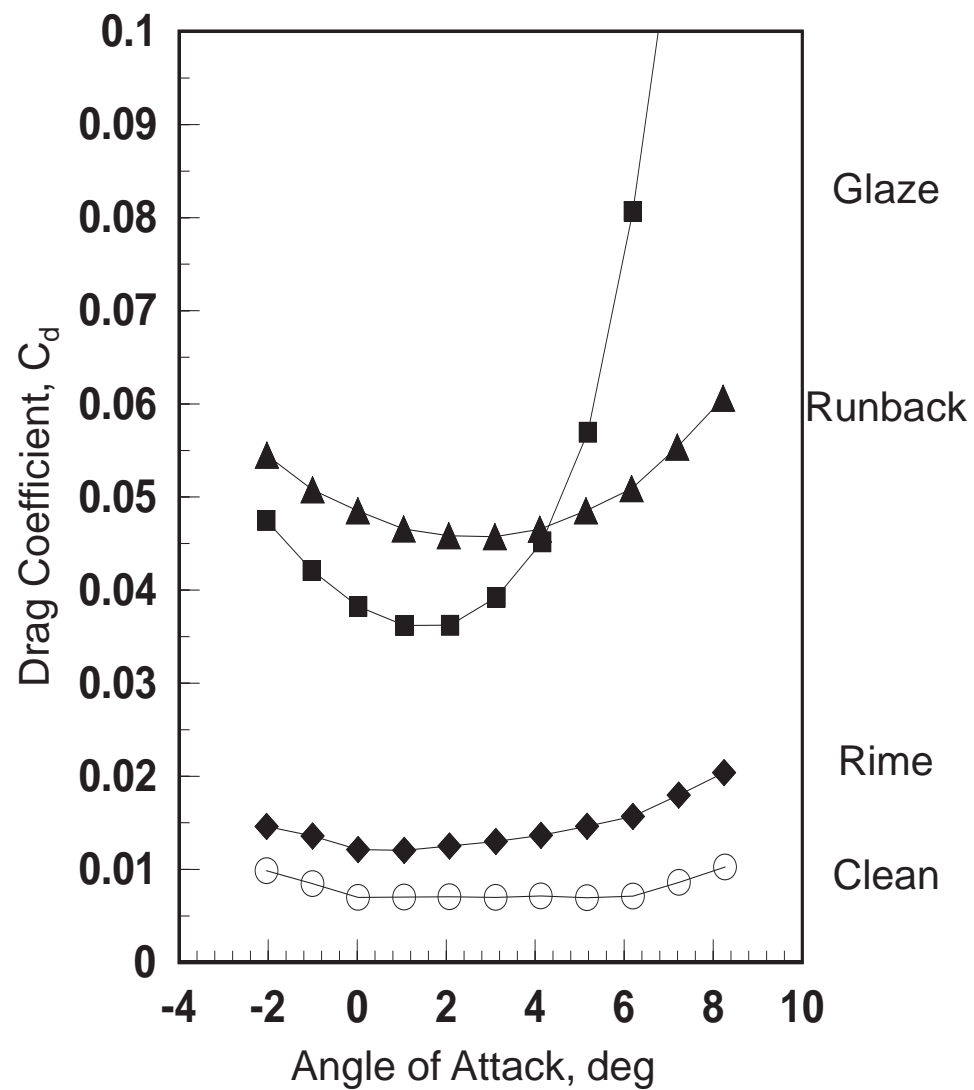
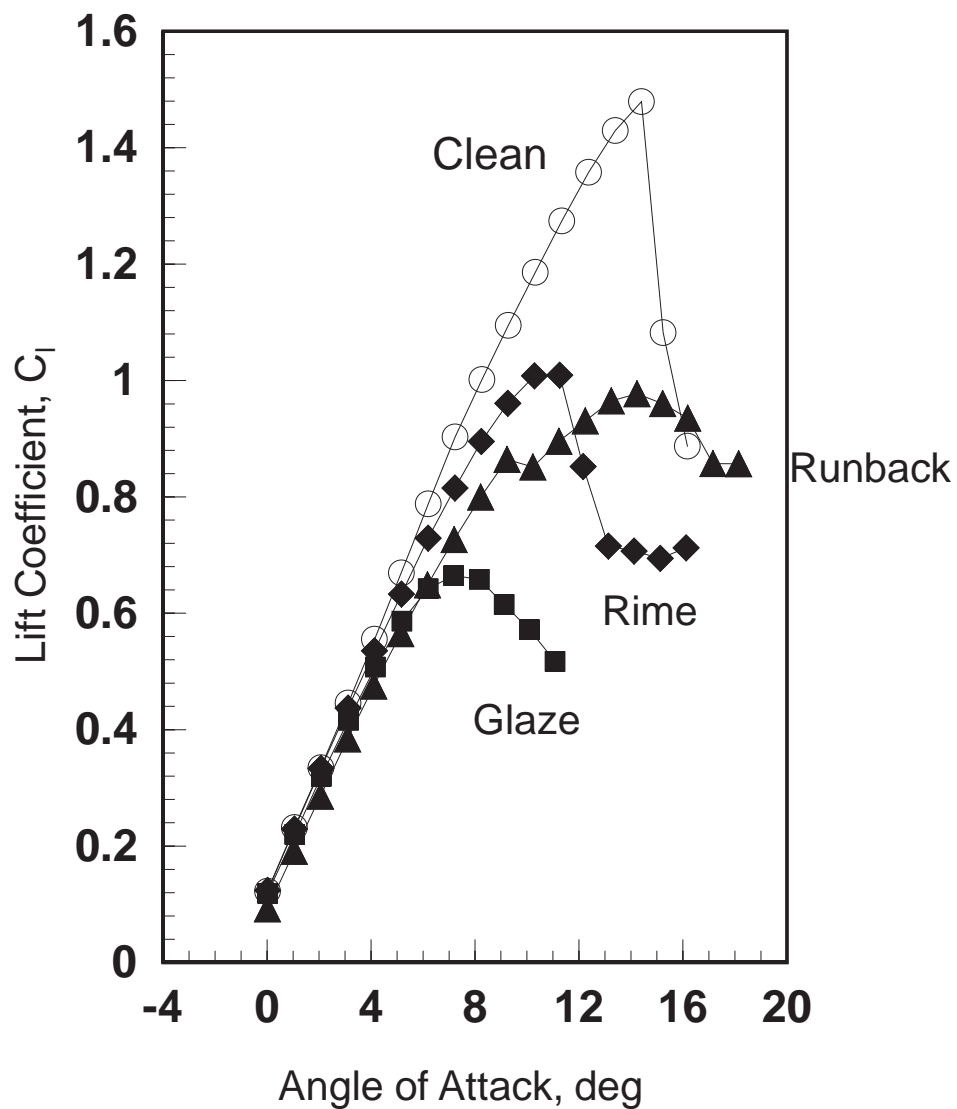


# Overview

- Background
- Motivation
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  - Workflow
- Approach
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- Future Work

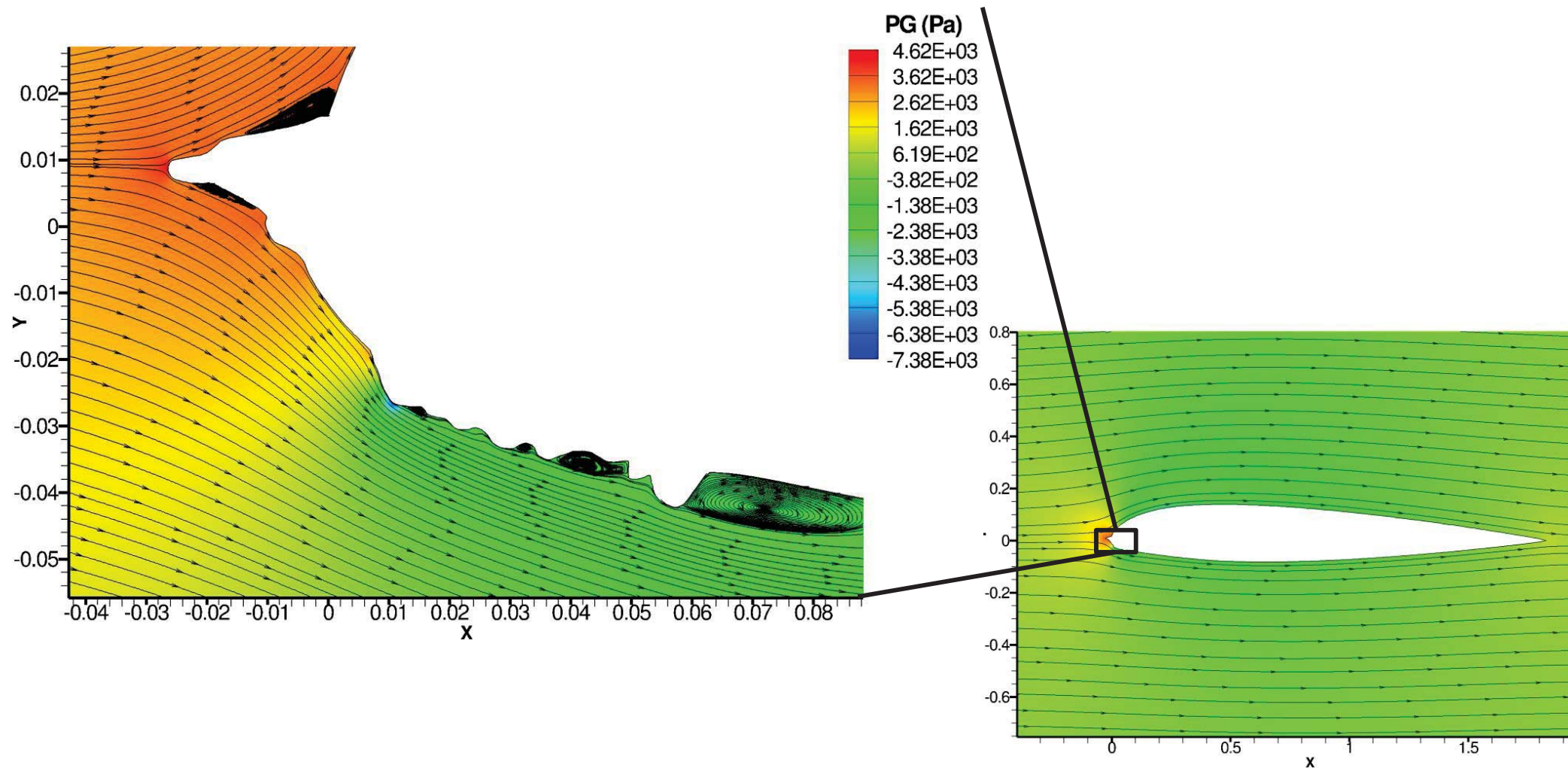


# Background



# Background

- To-date CFD analysis has been performed on, 2D cross-sections, 3D extrusions of 2D cross-sections, and 3D ice shapes generated by ice accretion codes



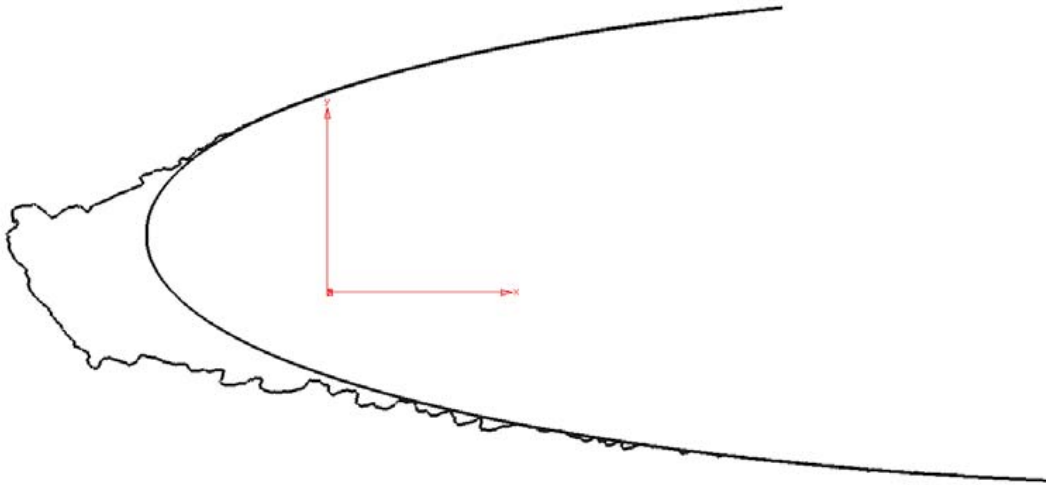


# Motivation

- Complex 3D ice shape geometry data can now be collected
  - In-situ laser scans of ice accretion shapes
  - CAT scans have also been performed
  - Complete ice shape documentation, including surface roughness elements
- How good is good enough?
  - What level of ice shape detail must be simulated by ice accretion codes?
  - Detailed analysis of the aerodynamics and heat transfer mechanisms at the ice-liquid-air interface can shed light on the parameters of importance

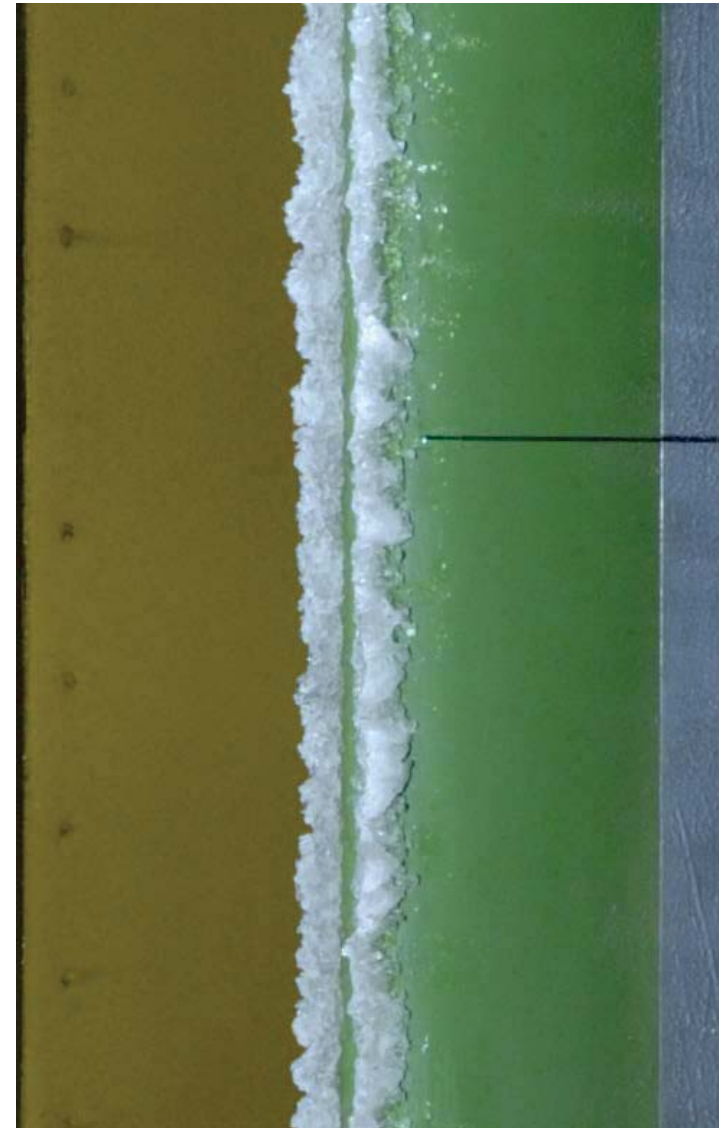
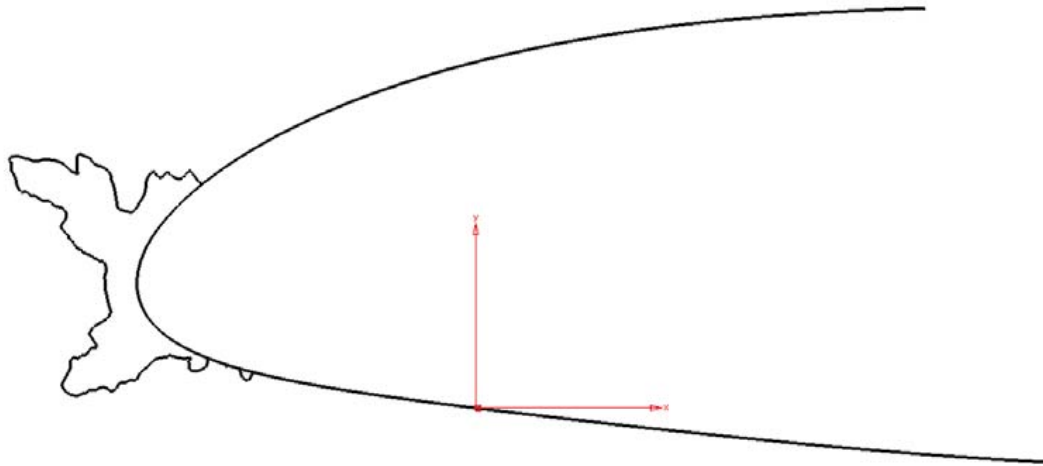
# Ice Accretion Shapes

- Types of ice accretion
  - Rime



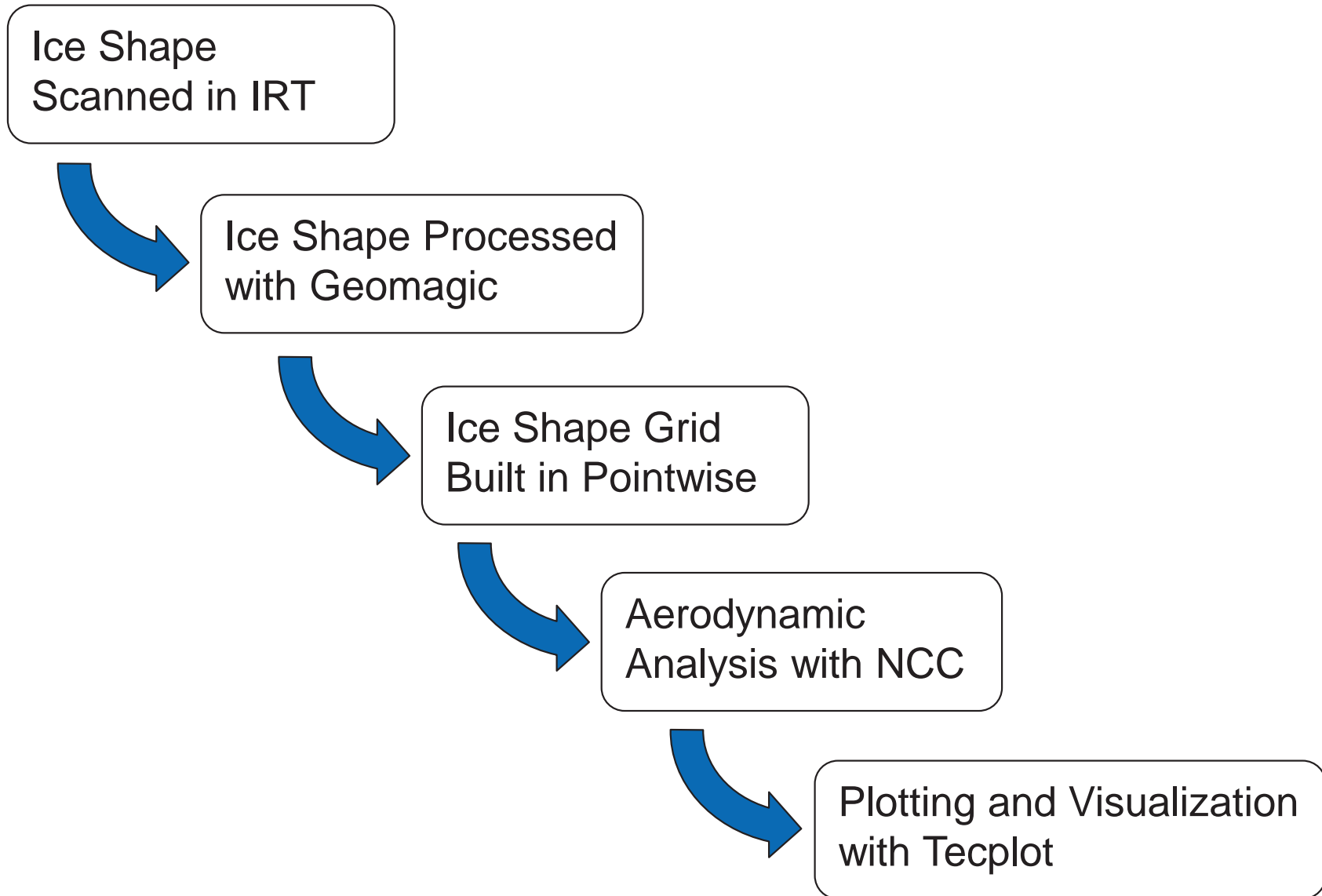
# Ice Accretion Shapes

- Types of ice accretion
  - **Glaze**





# Workflow

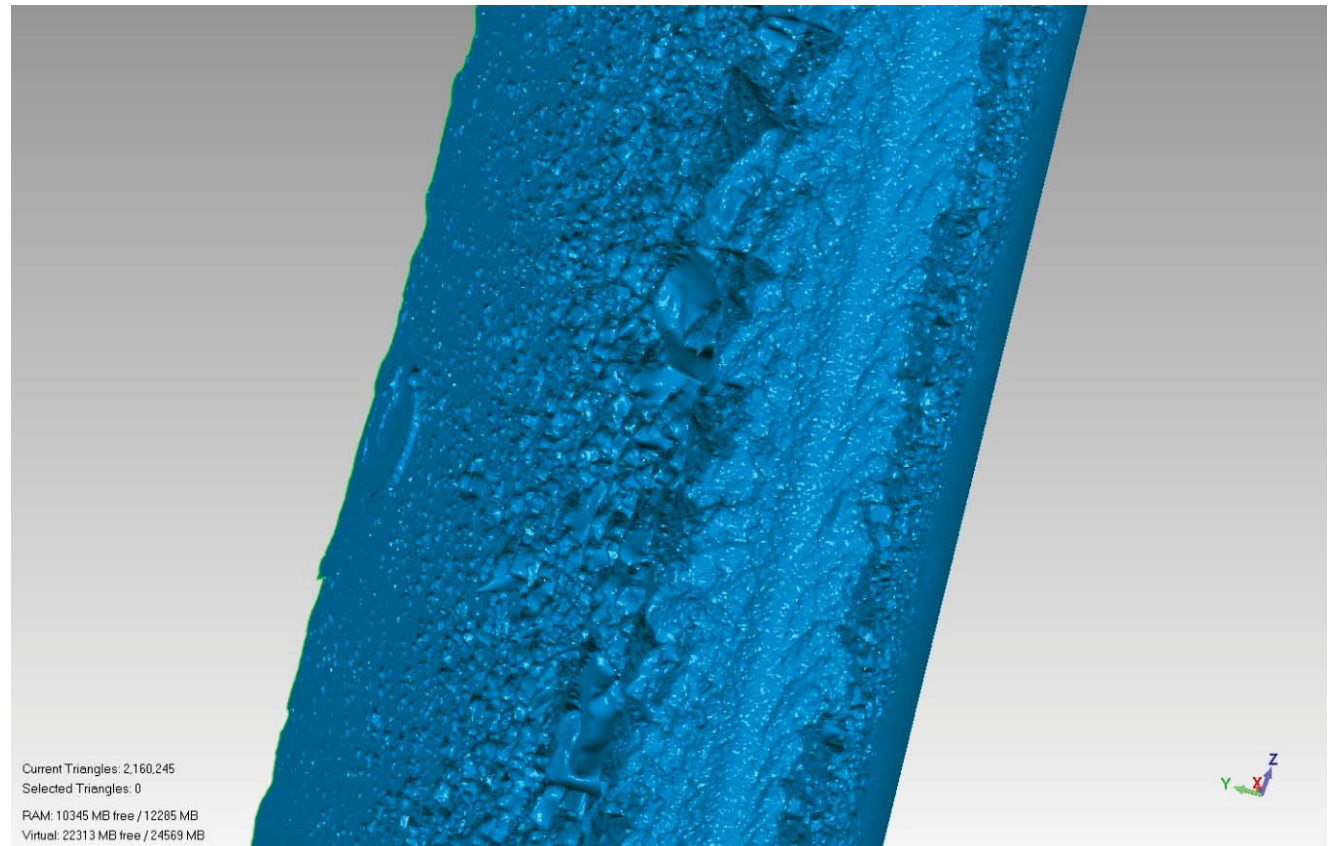




# Approach (Grid Generation)

## Geomagic

Commercial software used to create watertight surface from scanned point cloud data



Lee, S., Broeren, A. P., Addy, H. E., Jr., Sills, R., and Pifer, E. M., "Development of 3-D Ice Accretion Measurement Method," NASA/TM-2012-217702, AIAA Paper-2012-2938, 2012



# Approach (Grid Generation)

## Pointwise

Commercial software used to import ice shape geometry data and create grid for CFD analysis

### 1. Import Geometry

- Database
- Surface Grid

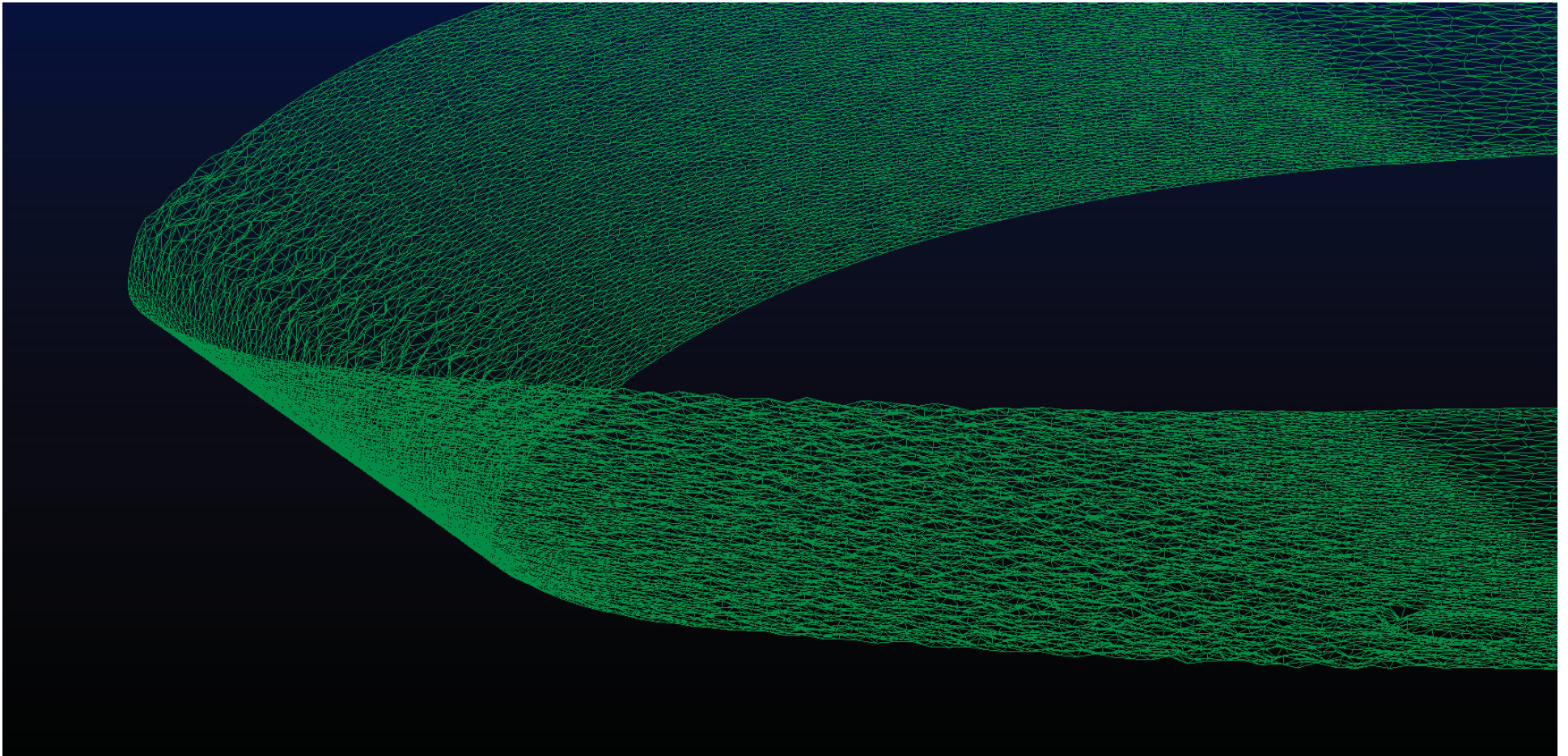




# Approach (Grid Generation)

## Pointwise

1. Import Geometry
2. **Create Surface Grid - Rime**

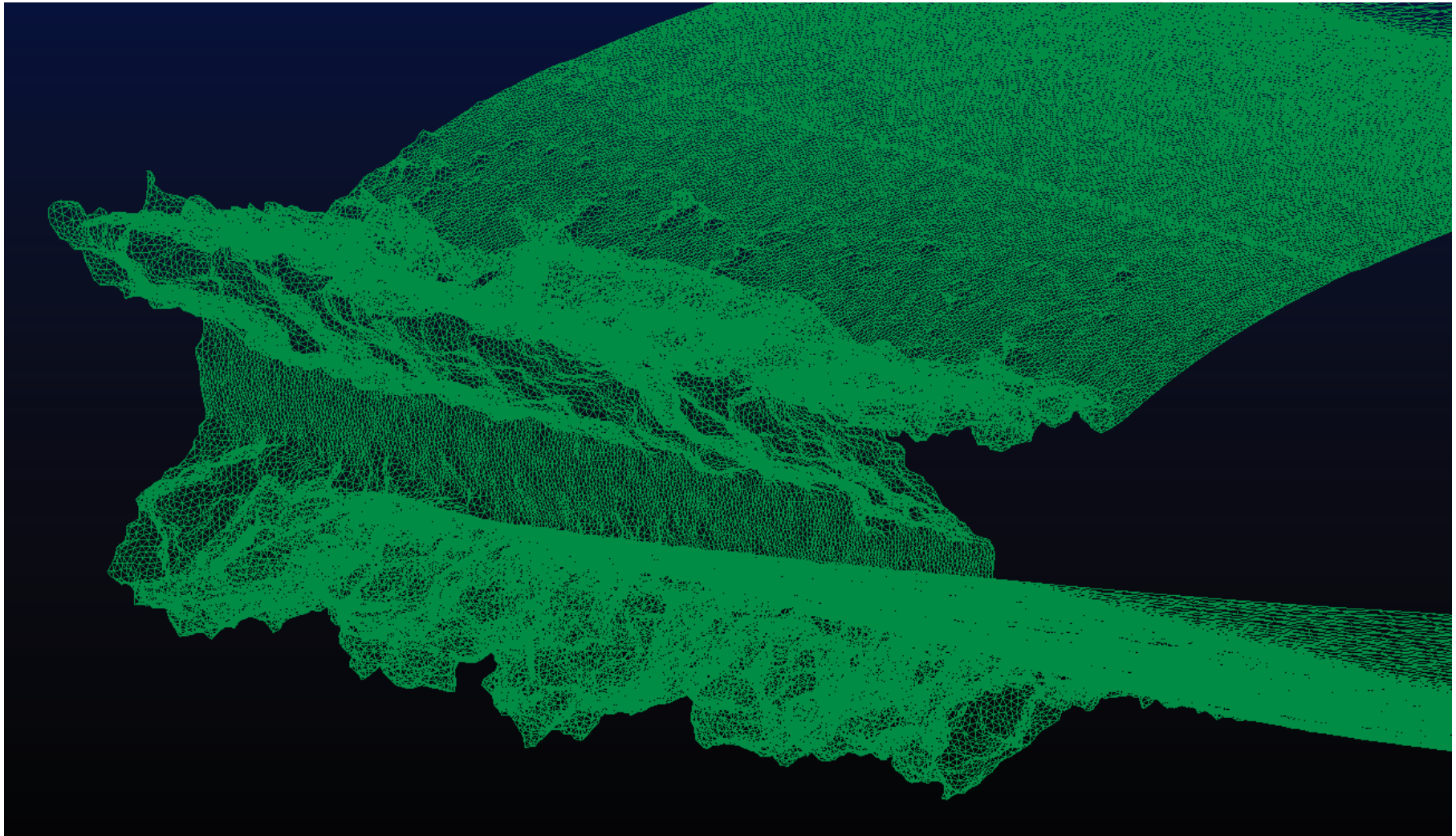




# Approach (Grid Generation)

## Pointwise

1. Import Geometry
2. **Create Surface Grid - Horn**

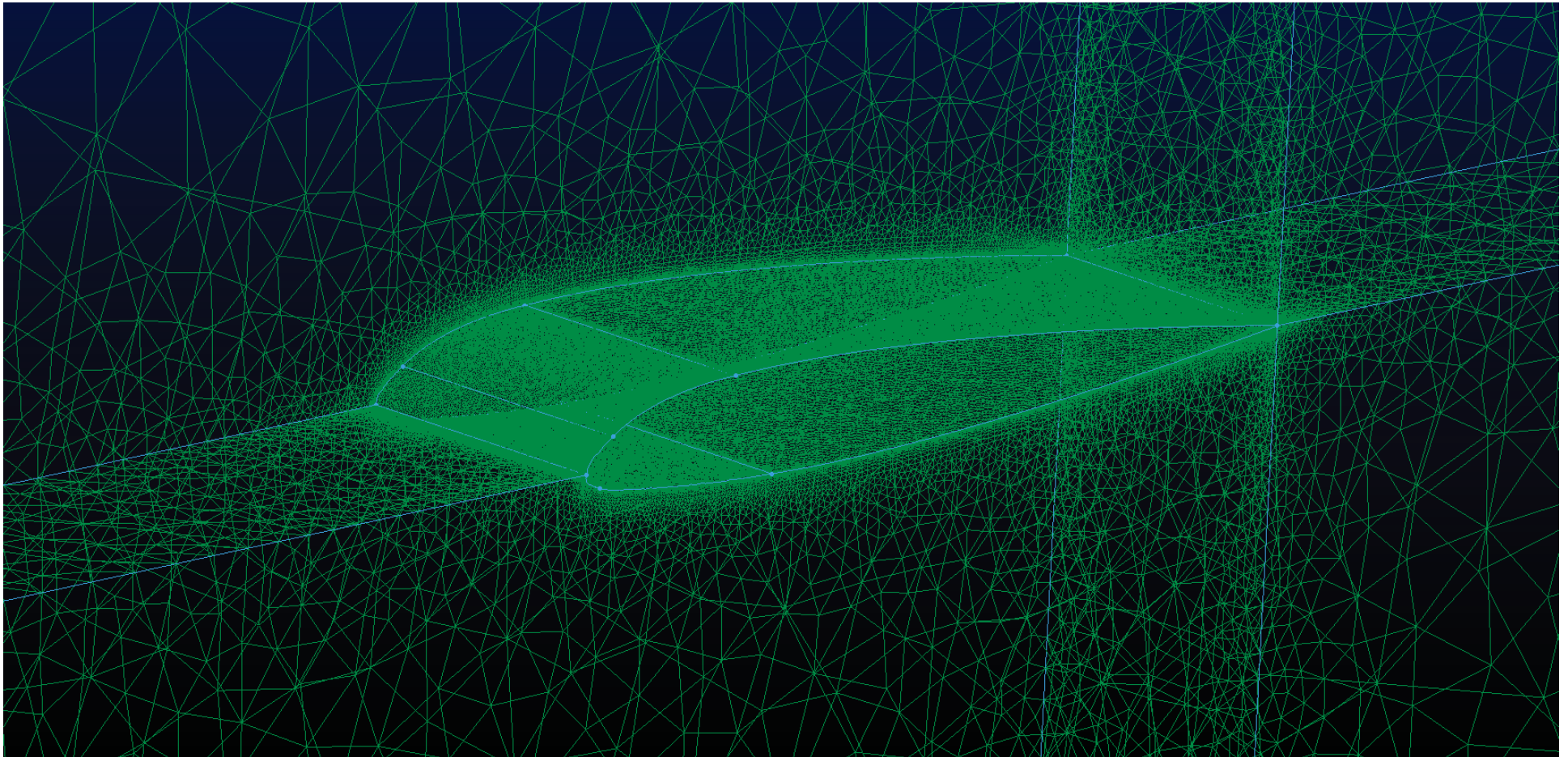




# Approach (Grid Generation)

## Pointwise

1. Import Geometry
2. Create Surface Grid
3. **Create Volume Grid - Rime**

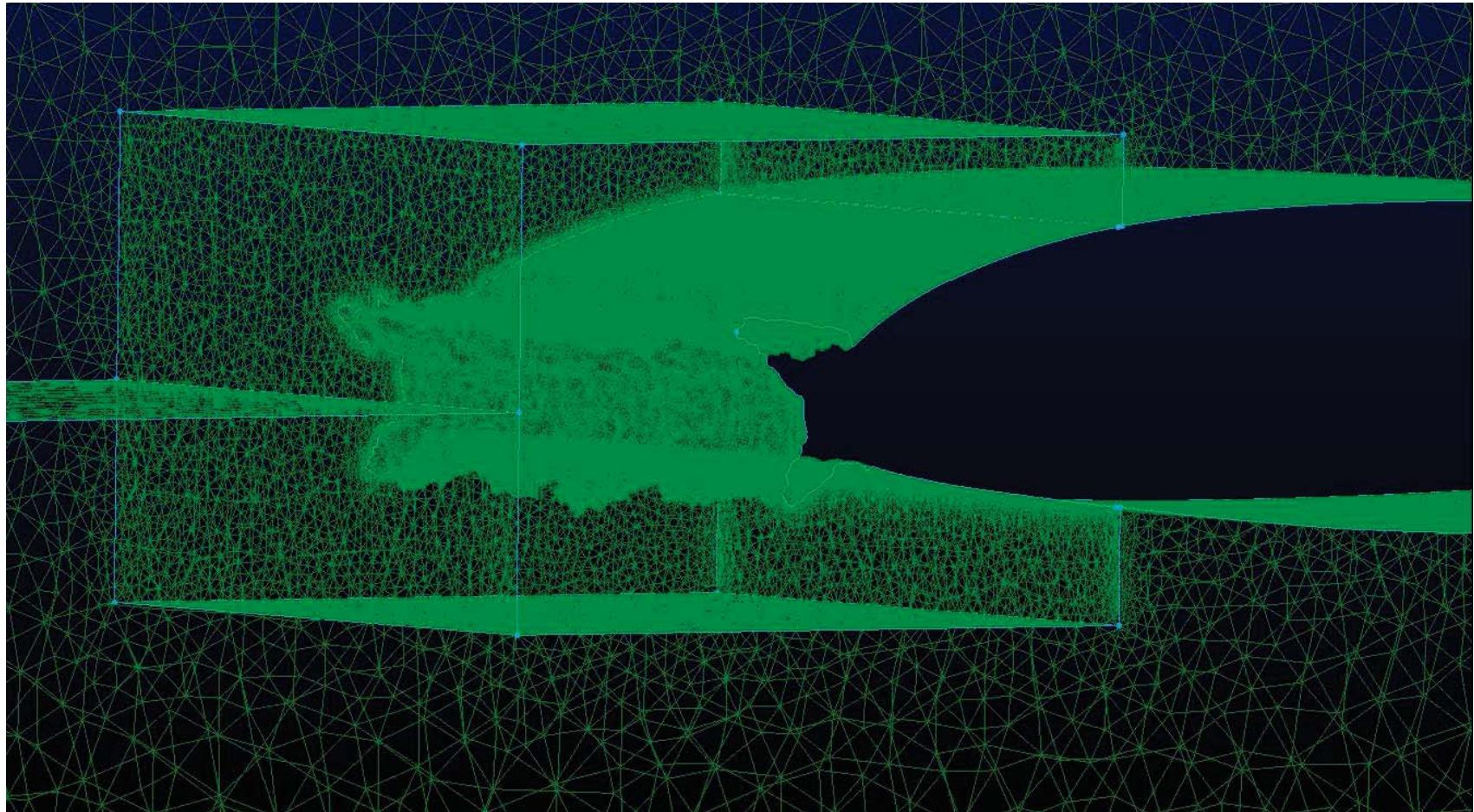




# Approach (Grid Generation)

## Pointwise

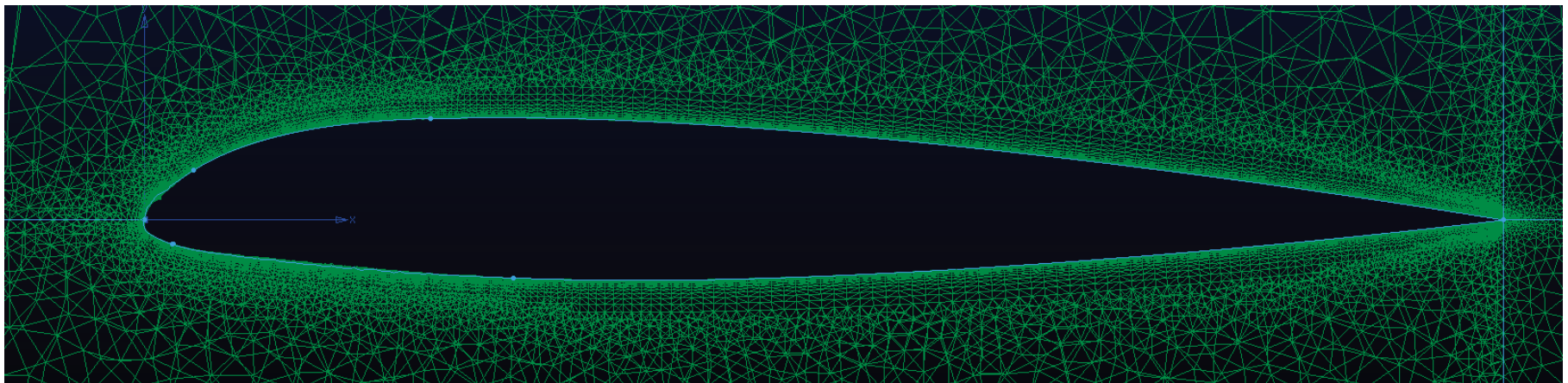
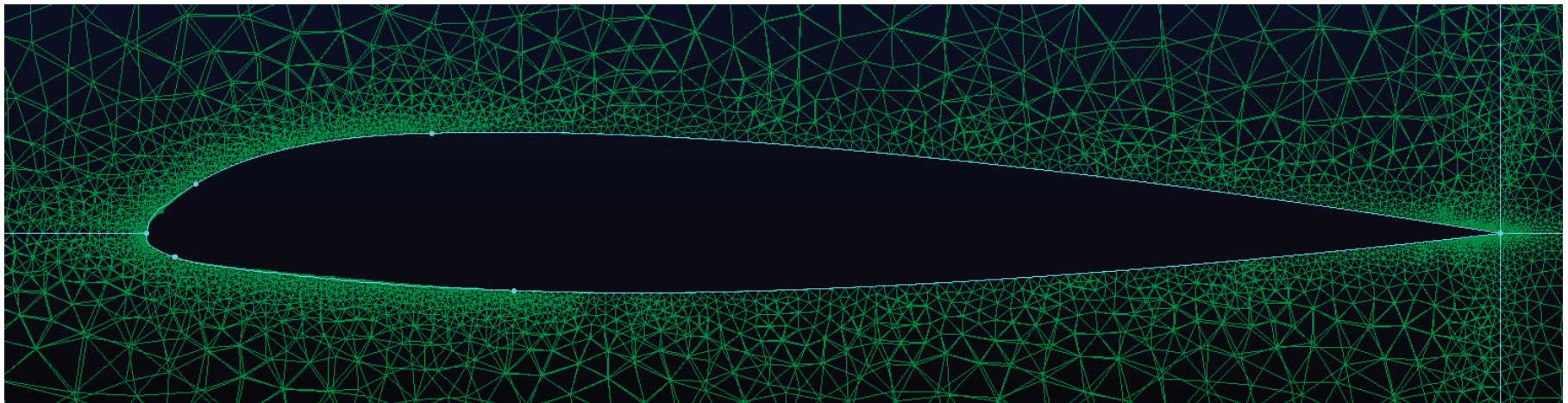
1. Import Geometry
2. Create Surface Grid
3. **Create Volume Grid - Horn**



# Approach (Grid Generation)

## Pointwise

1. Import Geometry
2. Create Surface Grid
3. Create Volume Grid
4. **Refinement**

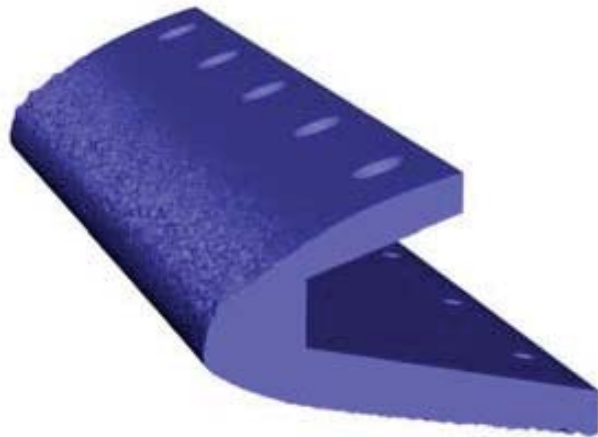




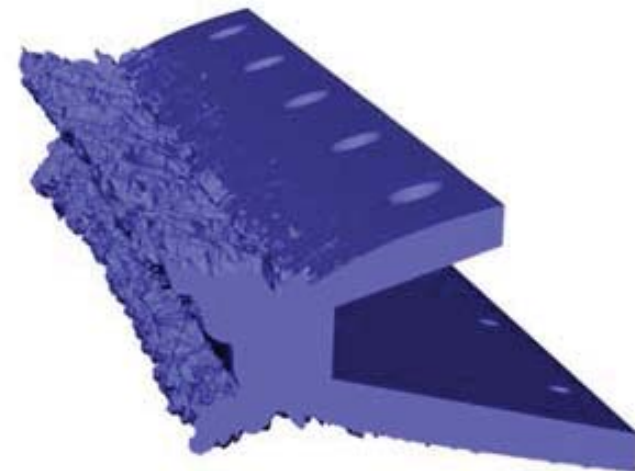
# Statistics of Initial Grids

	Ice Shape Geometry	Chord length (in)	Span length (in)	Grid Type	Volume grid cell count
Clean	-	18	12	Structured	0.5 million
Rime	ED1966	18	6	Unstructured	1.6 million
Glaze	ED1978	18	6	Unstructured	3.7 million

Broeren, A.P., Addy, H.E., Lee, S., and Monastero, M.C., "Validation of 3-D Ice Accretion Measurement Methodology for Experimental Aerodynamic Simulation," AIAA 6<sup>th</sup> Atmospheric and Space Environments Conference, Atlanta, GA, June 16-20, 2014



**ED1966**



**ED1978**





# National Combustion Code (NCC)

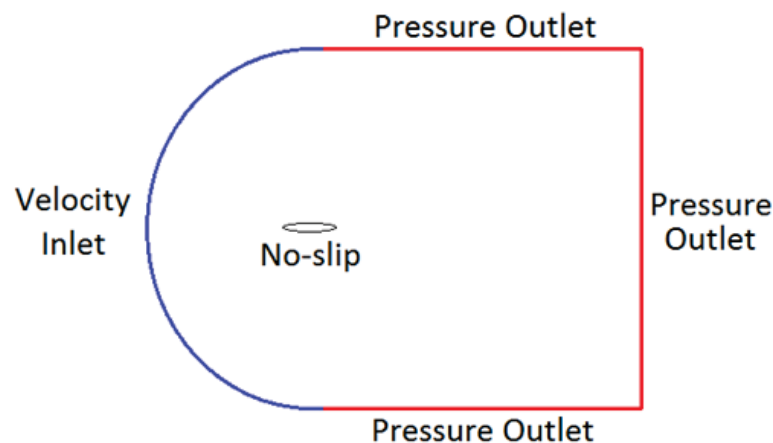
- Solver
  - Finite-volume
  - Explicit, four-stage Runge-Kutta integration algorithm
  - RANS, URANS
- Turbulence
  - $k - \epsilon$  model
  - higher order, non-linear method
  - Partially Resolved Numerical Simulation (PRNS)
- Parallel Computing
  - Parallel Virtual Machine (PVM)
  - Message Passing Interface (MPI)

Liu, N.-S. and Shih, T.-H., "Turbulent Modeling for Very Large-Eddy Simulation," AIAA Journal, Vol. 44, No. 4, April 2006

# Domain Conditions

- **Boundary Conditions**

- Velocity Inlet
- Pressure Outlet
- No-slip Airfoil Wall
- Periodic Side Walls



**Side View**

- **Freestream Conditions**

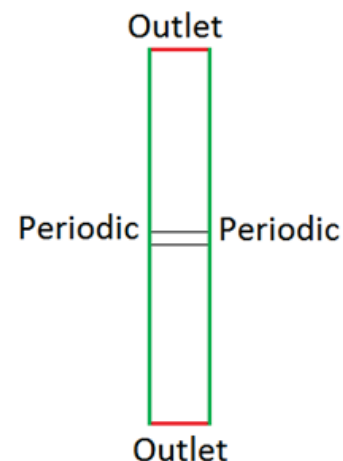
$$M = 0.10, 0.18$$

$$Re = 1.0 \times 10^6, 1.8 \times 10^6$$

$$P_\infty = 98,595 \text{ [Pa]}$$

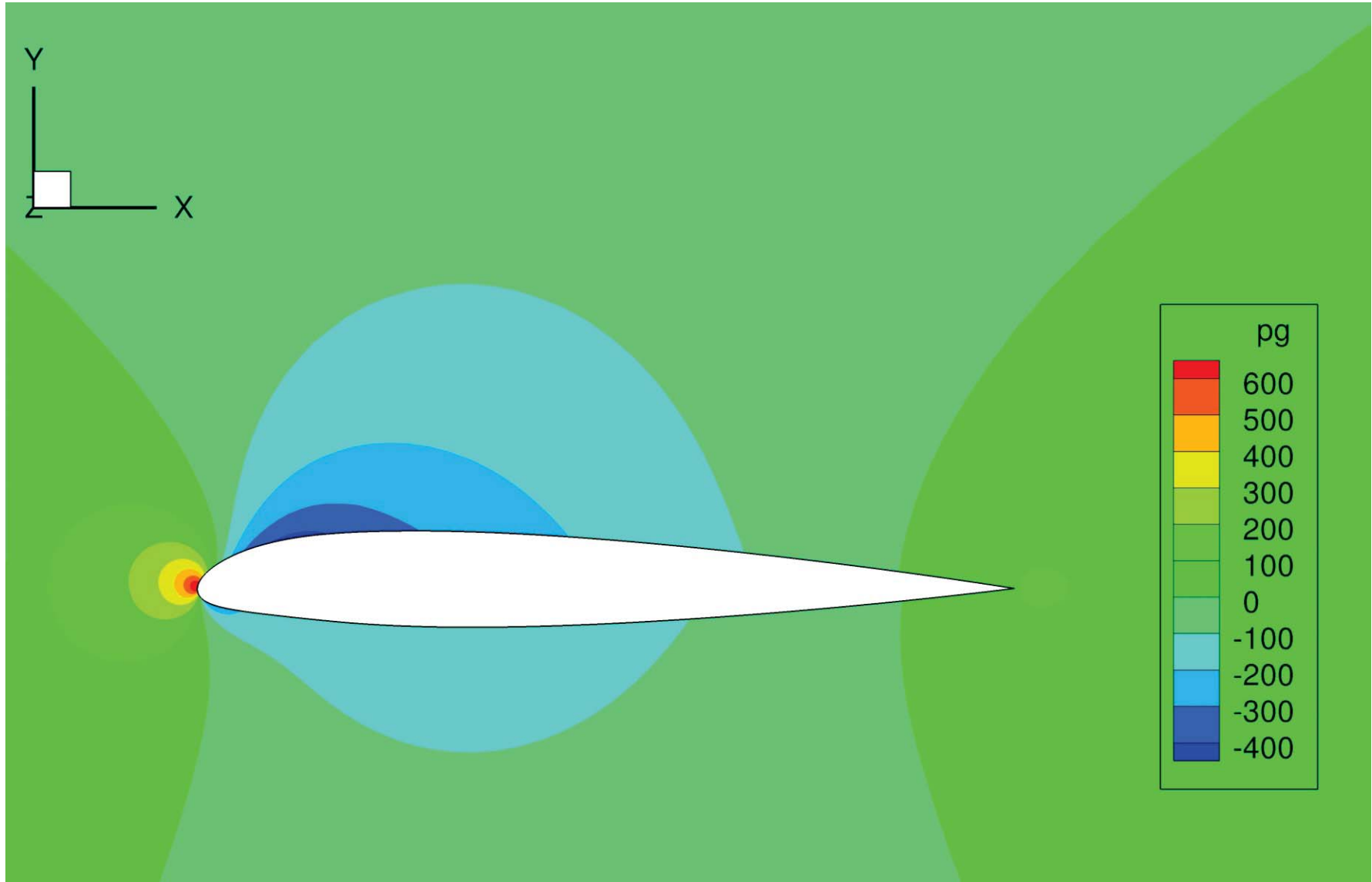
$$T_\infty = 294.3 \text{ [K]}$$

$$\alpha = 0^\circ \text{ to } 10^\circ$$



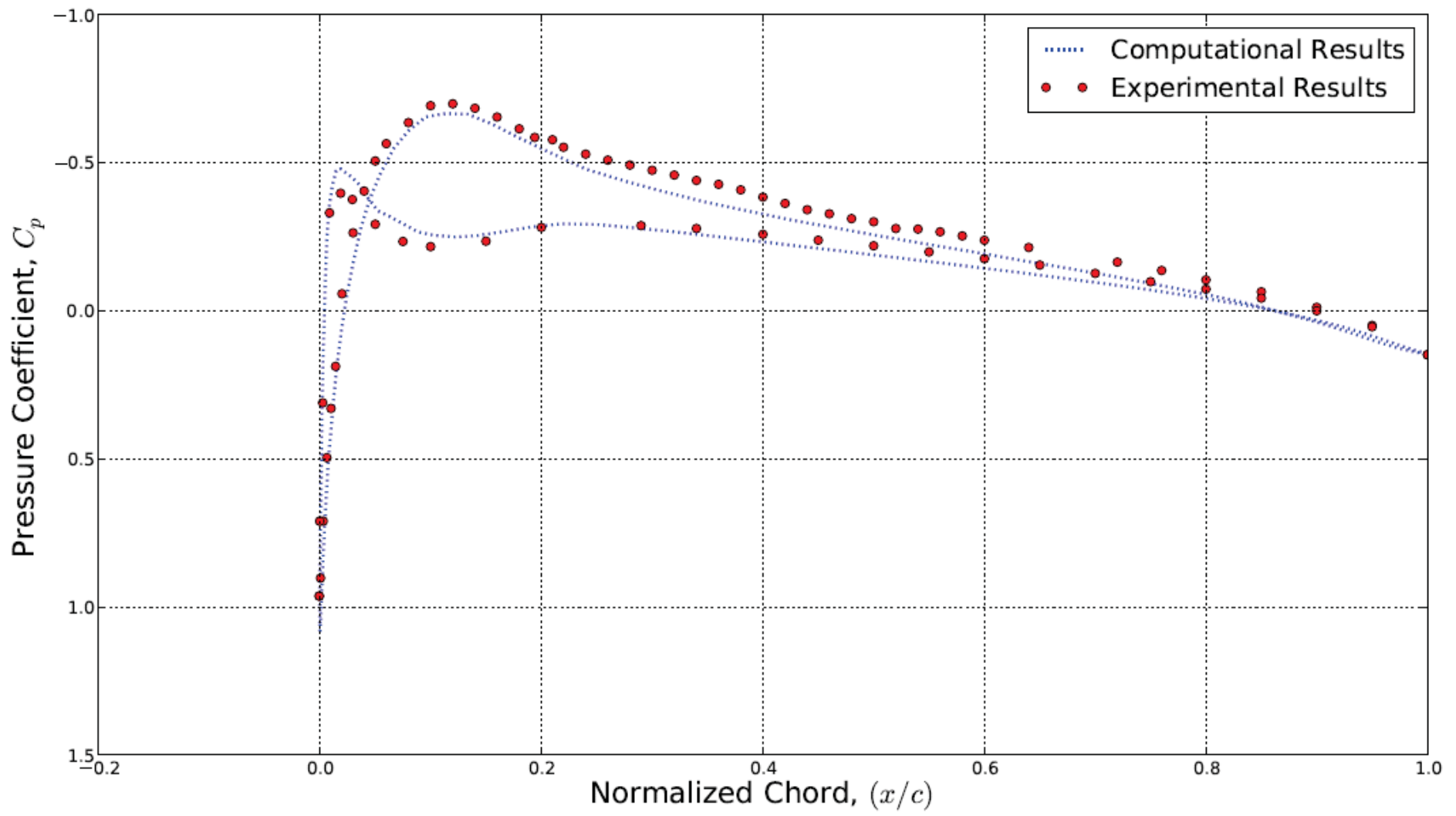
**Front View**

# Clean Wing ( $M=0.10$ @ $0^\circ$ )





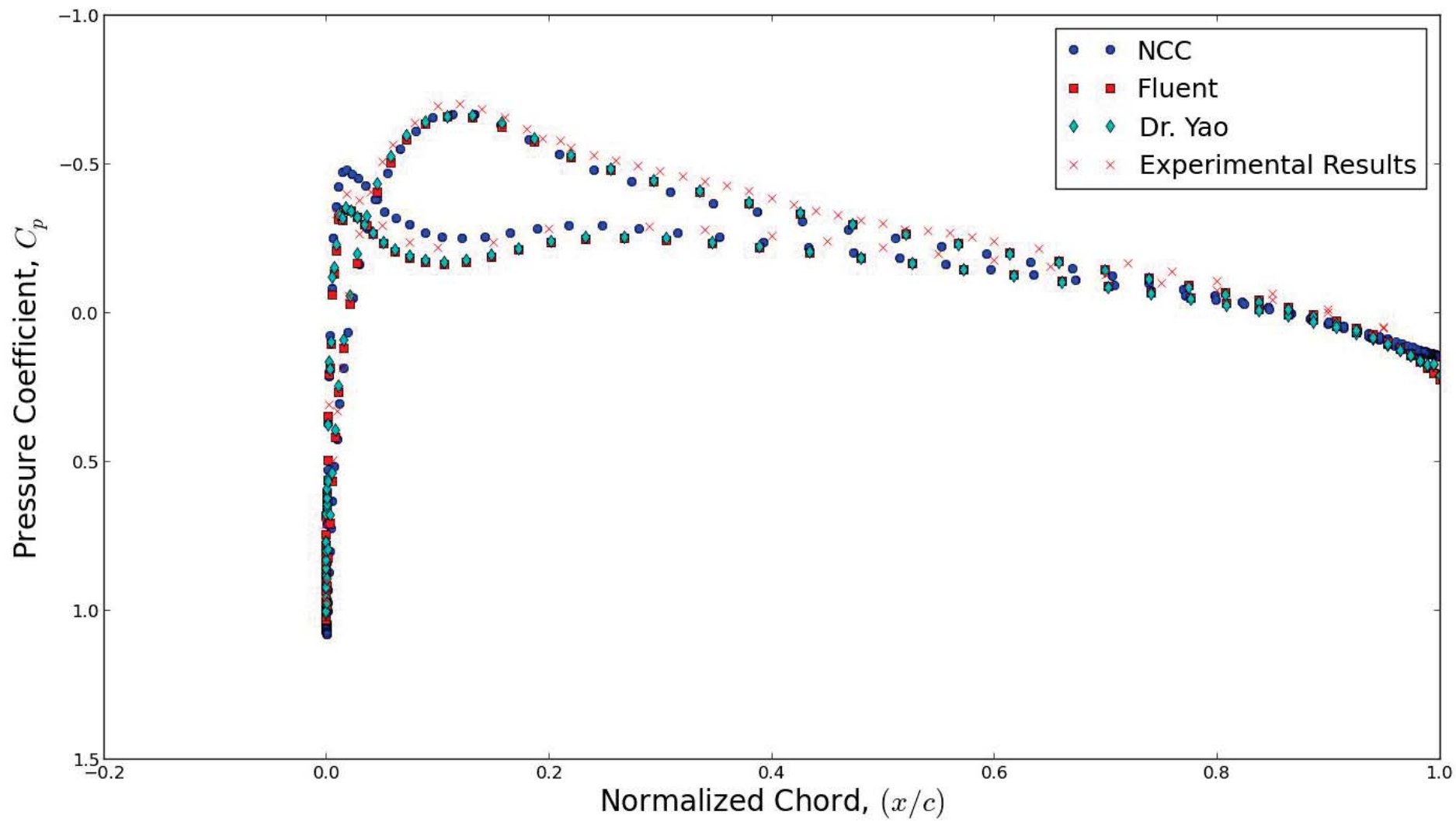
# Clean Wing ( $M=0.10$ @ $0^\circ$ )





# Clean Wing ( $M=0.10$ @ $0^\circ$ )

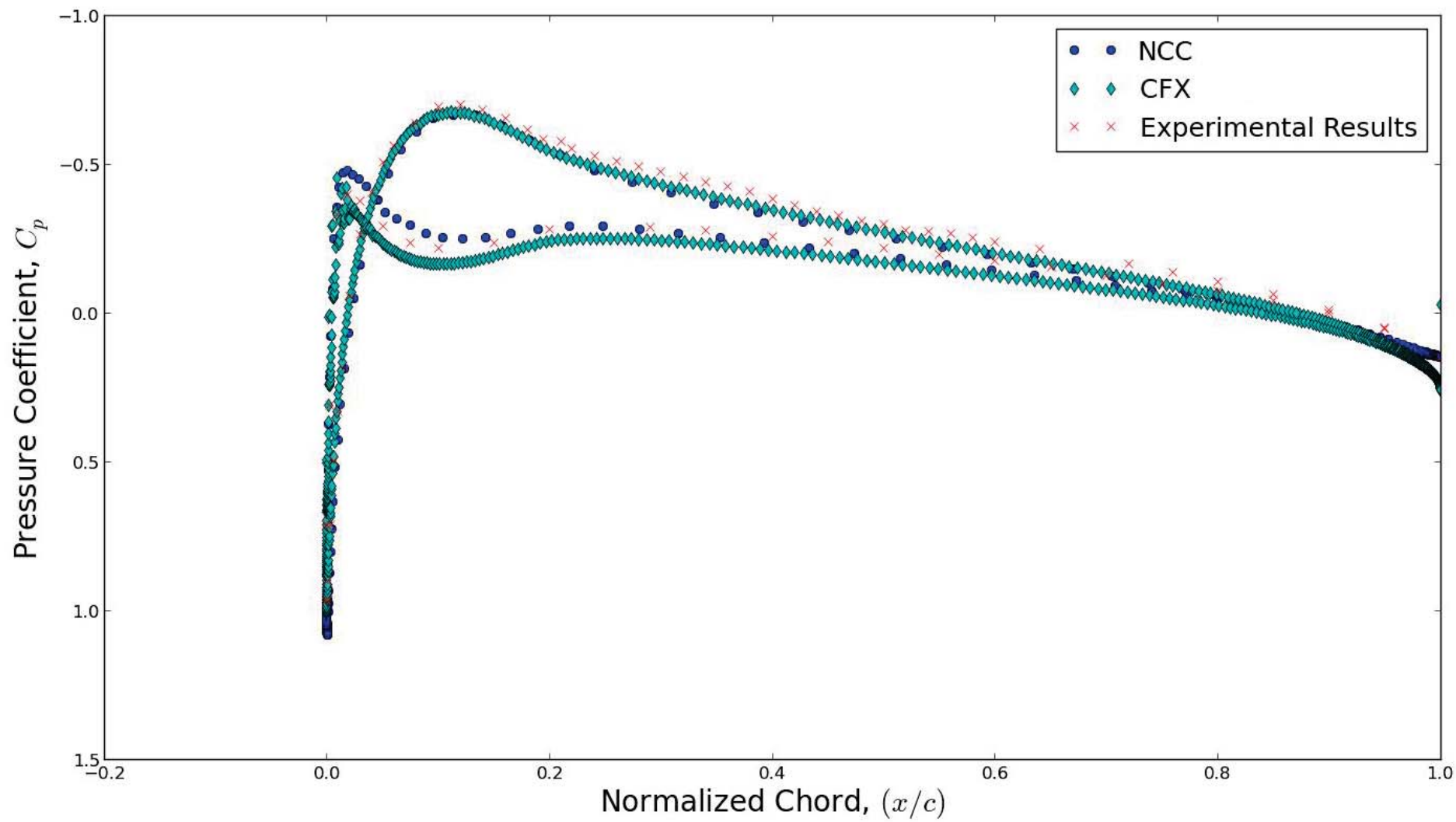
## Other CFD Solvers





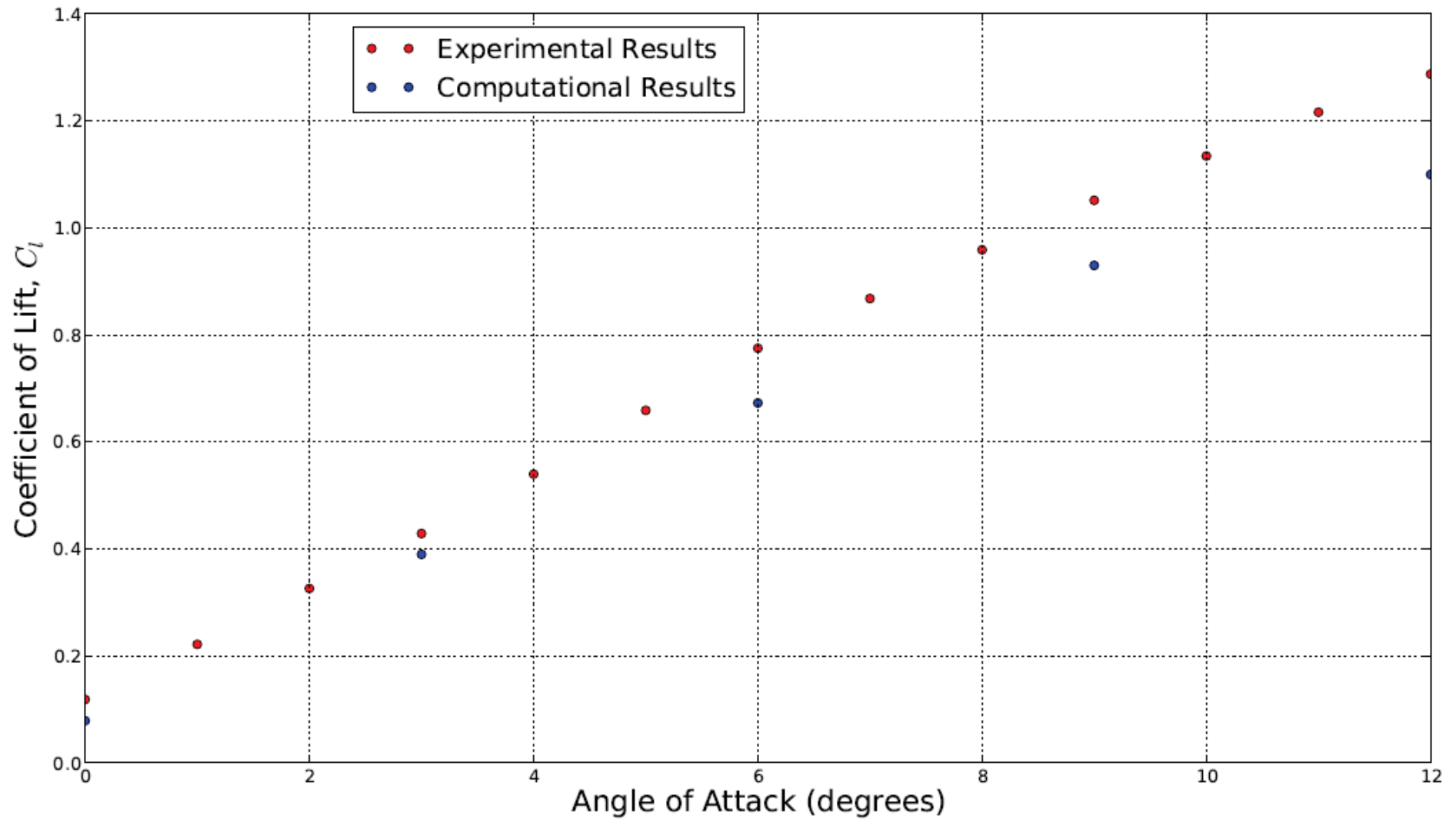
# Clean Wing ( $M=0.10$ @ $0^\circ$ )

## Other CFD Solvers



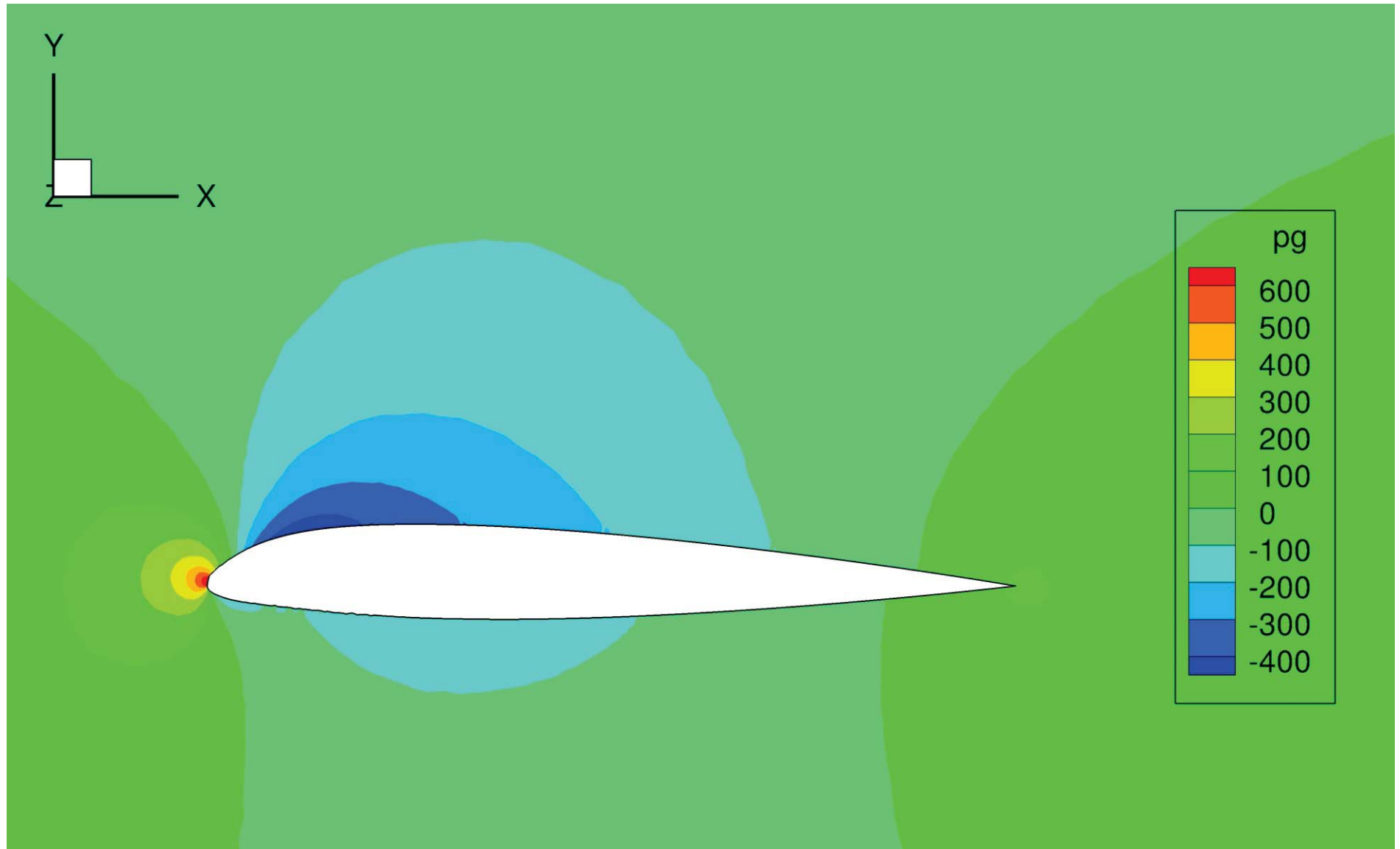


# Clean Wing $C_L$ Curve ( $M=0.10$ )





# ED1966 Wing ( $M=0.10 @ 0^\circ$ ) Rime Shape

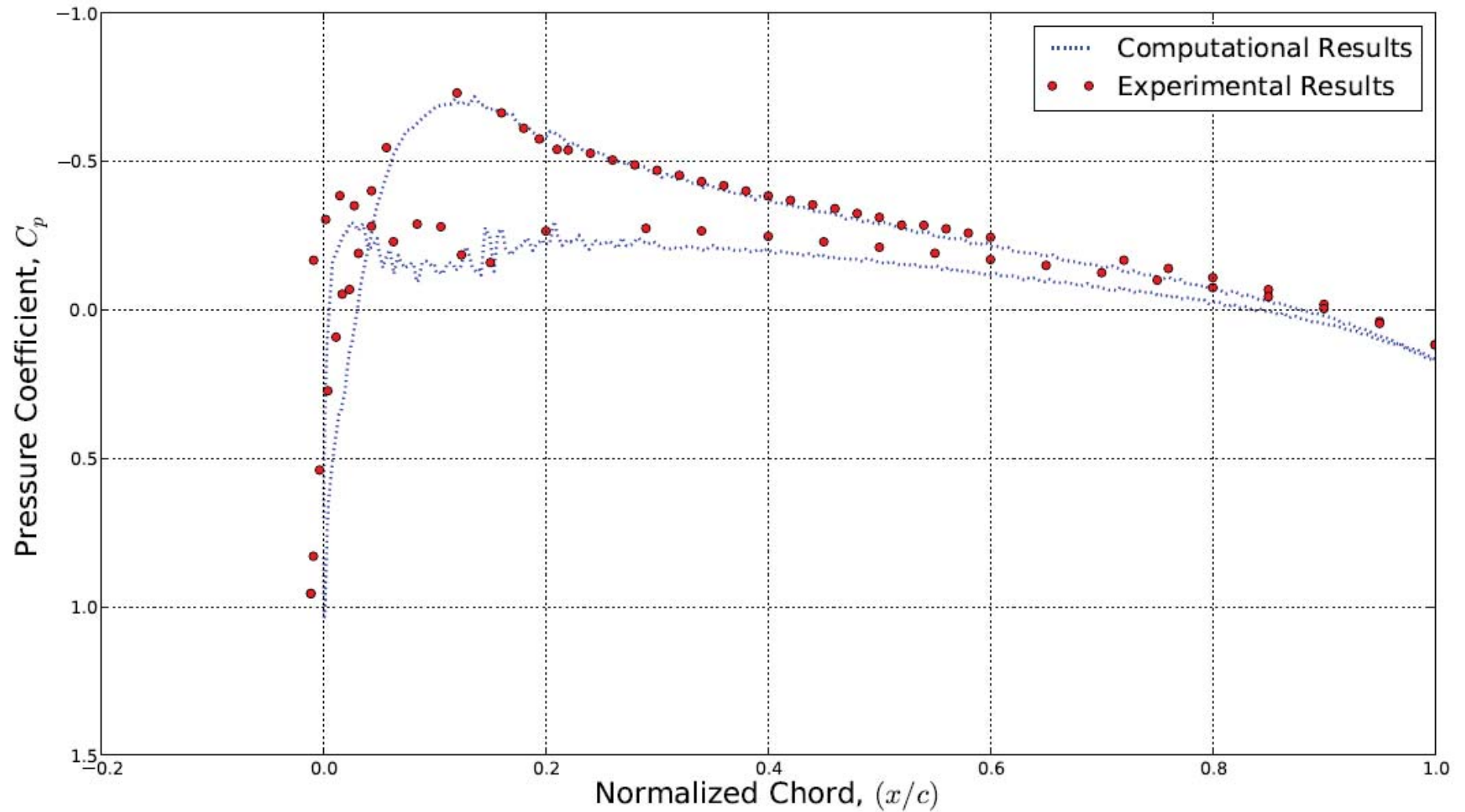






# ED1966 Wing ( $M=0.10$ @ $0^\circ$ )

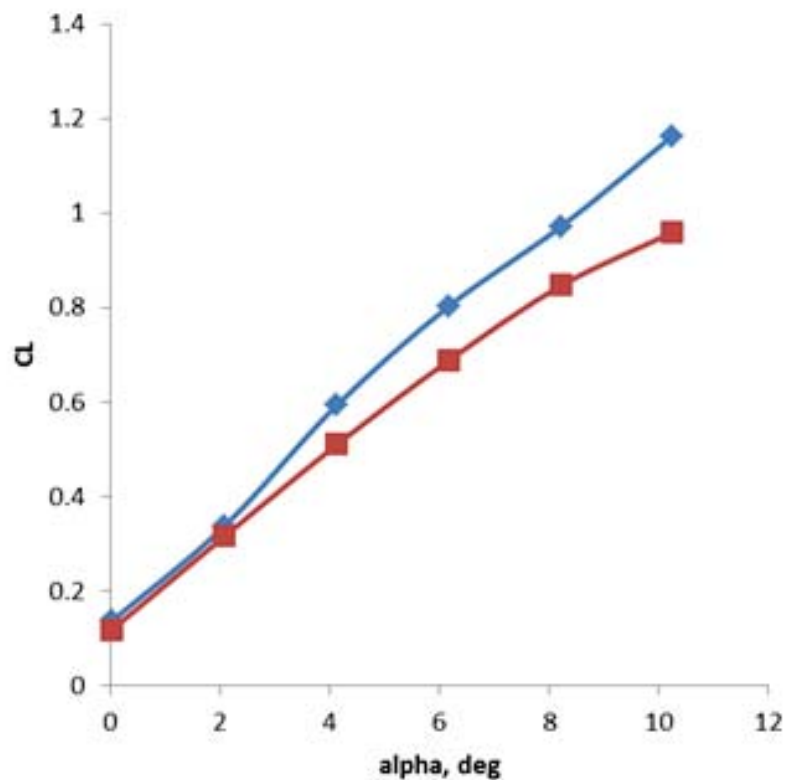
## Rime Shape



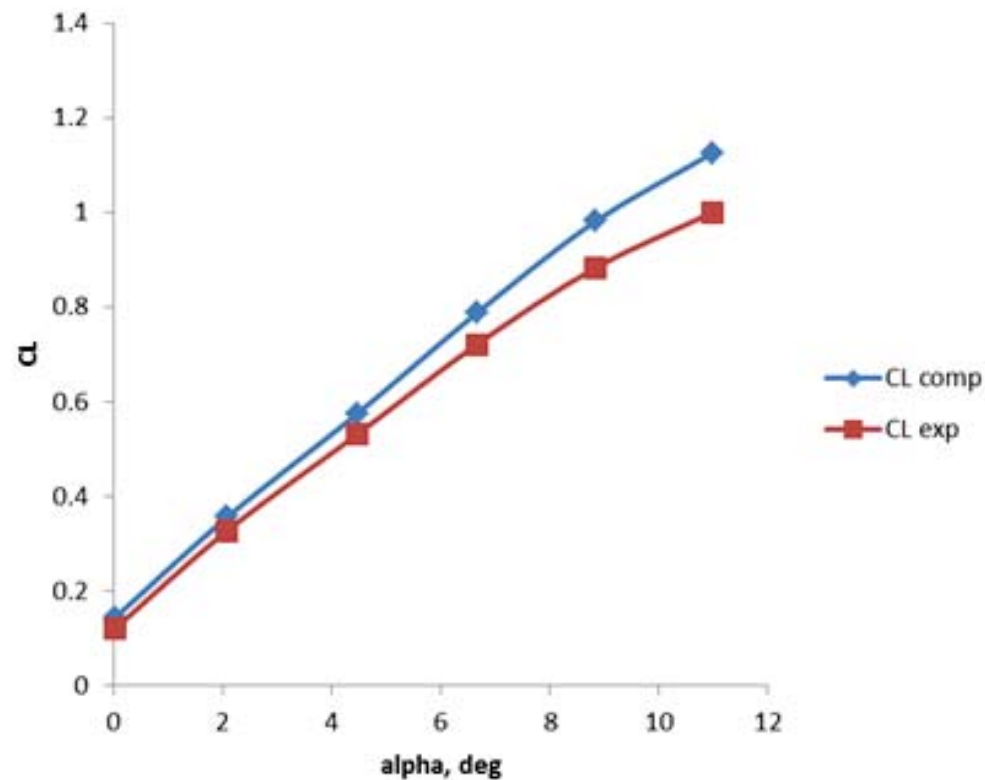


# ED1966 Wing Lift Coefficient Results

## Rime Shape



Re =  $1.0 \times 10^6$ , M = 0.1

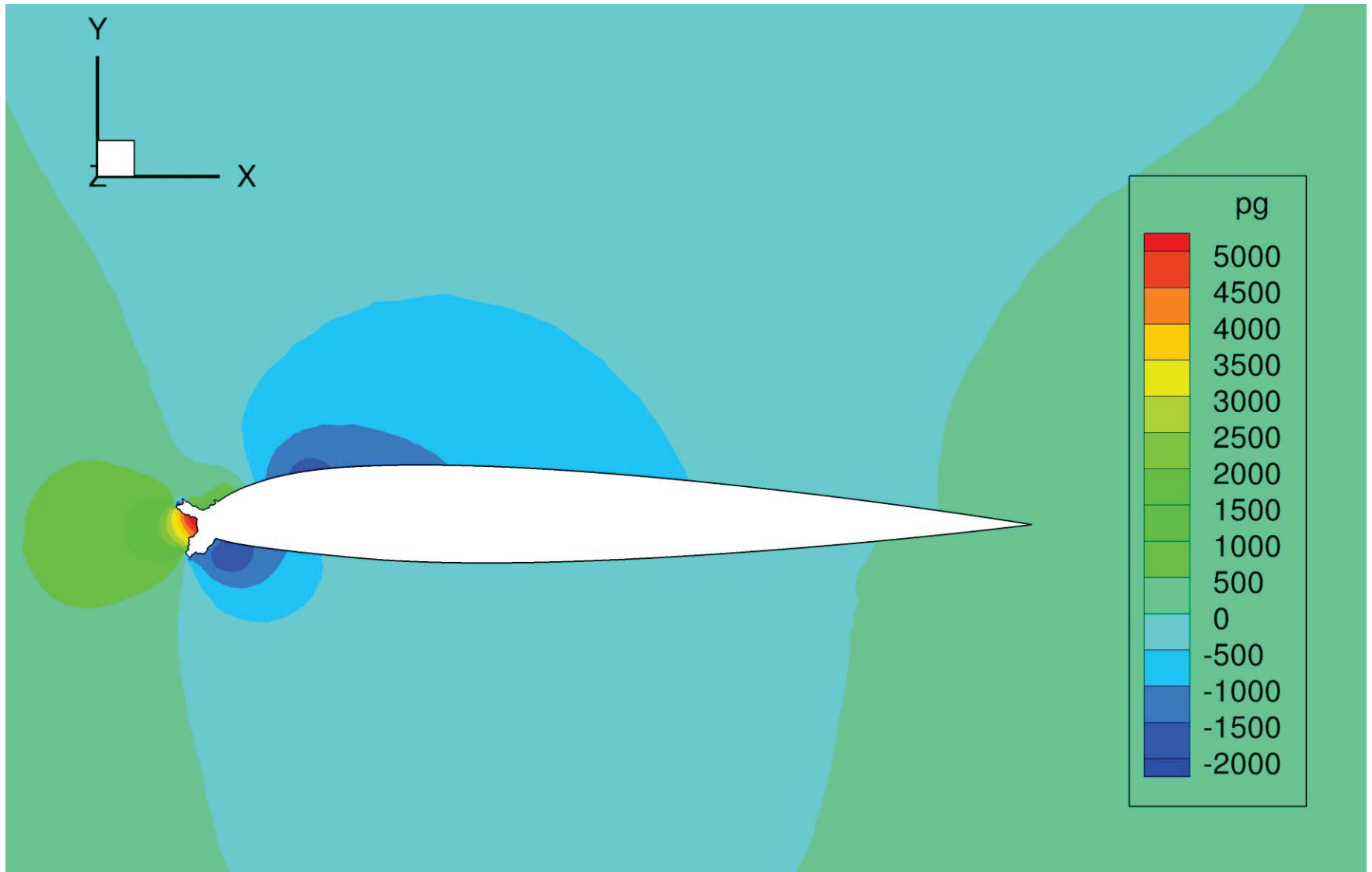


Re =  $1.8 \times 10^6$ , M = 0.18

- Results suggest that viscous effects play a role for the rime ice case, consistent with expectations
- Results from a single instantaneous pressure profile, used in the computation, need to be replaced with time averaged and spatially integrated results

# ED1978 Wing ( $M=0.18 @ 0^\circ$ )

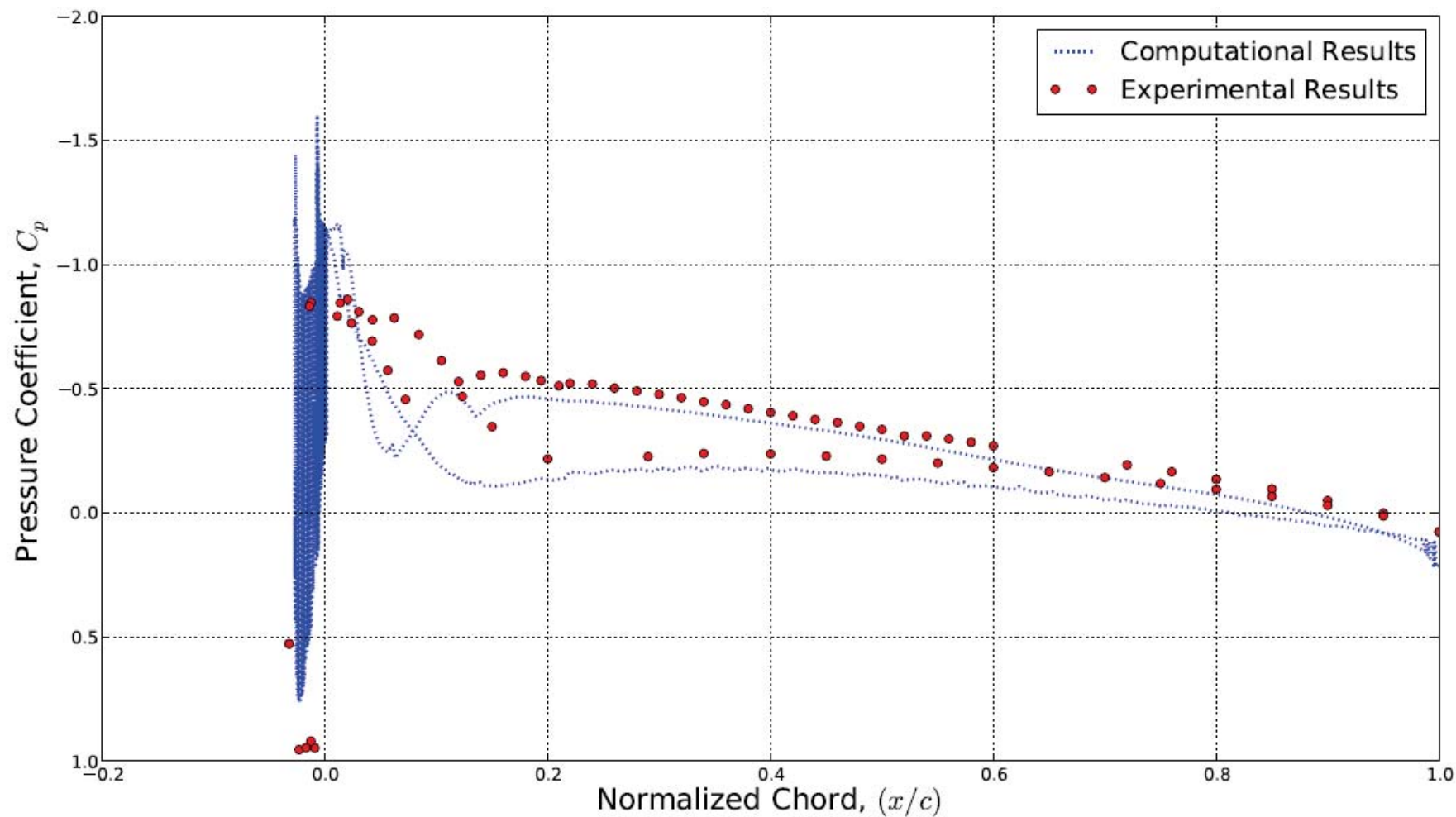
Glaze shape





# ED1978 Wing ( $M=0.18$ @ $0^\circ$ )

## Glaze Shape





## Future Work

- Detailed examination of solutions
  - Both ice shapes (ED1966 and ED1978)
    - Variations in flow field results across the span
    - Time averaging of unsteady results
    - Spatial integration across the span
    - Grid resolution studies
    - Turbulence models
  - Glaze ice shape (ED1978)
    - Investigate cause of pressure fluctuations near leading edge
- Parametric study of mesh quality
  - Establish minimum amount of grid points along airfoil surface
- Perform detailed analysis of ice surface roughness region
- Develop post-processing modules for NCC to calculate standard external aerodynamic parameters



**Thank You!**

Questions?