High Order Workshop Results for Case 3.2 Turbulent Flow over DPW3 Wing

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Flow Solver

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- Discontinuous Galerkin Finite Element Method
- Modal basis functions
- Hybrid mixed element unstructured meshes (tetrahedra, prisms, pyramids, and hexahedra)
- p-enrichment and h-refinement using non-conforming elements (hanging nodes)
- Independent polynomial degree for solution and mapping basis
- Non-linear system solver: Newton-Rhapson method
- Linear system solver: preconditioned flexible-GMRES (Saad 1986)
- Line implicit Jacobi, Gauss-Seidel relaxation, ILU(0)

Physics

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- Compressible Navier-Stokes in conservative variables
- PDE-based Artificial Viscosity (Barter and Darmofal, Burgess)
- Spalart-Allmaras turbulence model (negative-SA variant)
- Inviscid flux: Lax-Friedrichs, Roe, AUFS
- Viscous flux: symmetric interior penalty (SIP)

Solver Variation

- Viscous flux
  - Symmetric Interior Penalty $\nu = \frac{N_m}{h} \quad h = \frac{V}{A_{max}}$
  - Max face area was chosen for $p = 0$ boundary layer
  - Traditionally surface area is used (and multiplied by a factor)
- Mesh Curving
  - Curved mesh is given online: cubic 64 node hexahedral elements
  - Modal mapping basis: Vandermode matrix approach
  - Need more quadrature points due to high order metric Jacobian
  - Slopes and curvature do not match between elements
  - Jumps in curvature leads to oscillating pressure
  - Need to align spline control points with grid points?

Drag and Lift Results

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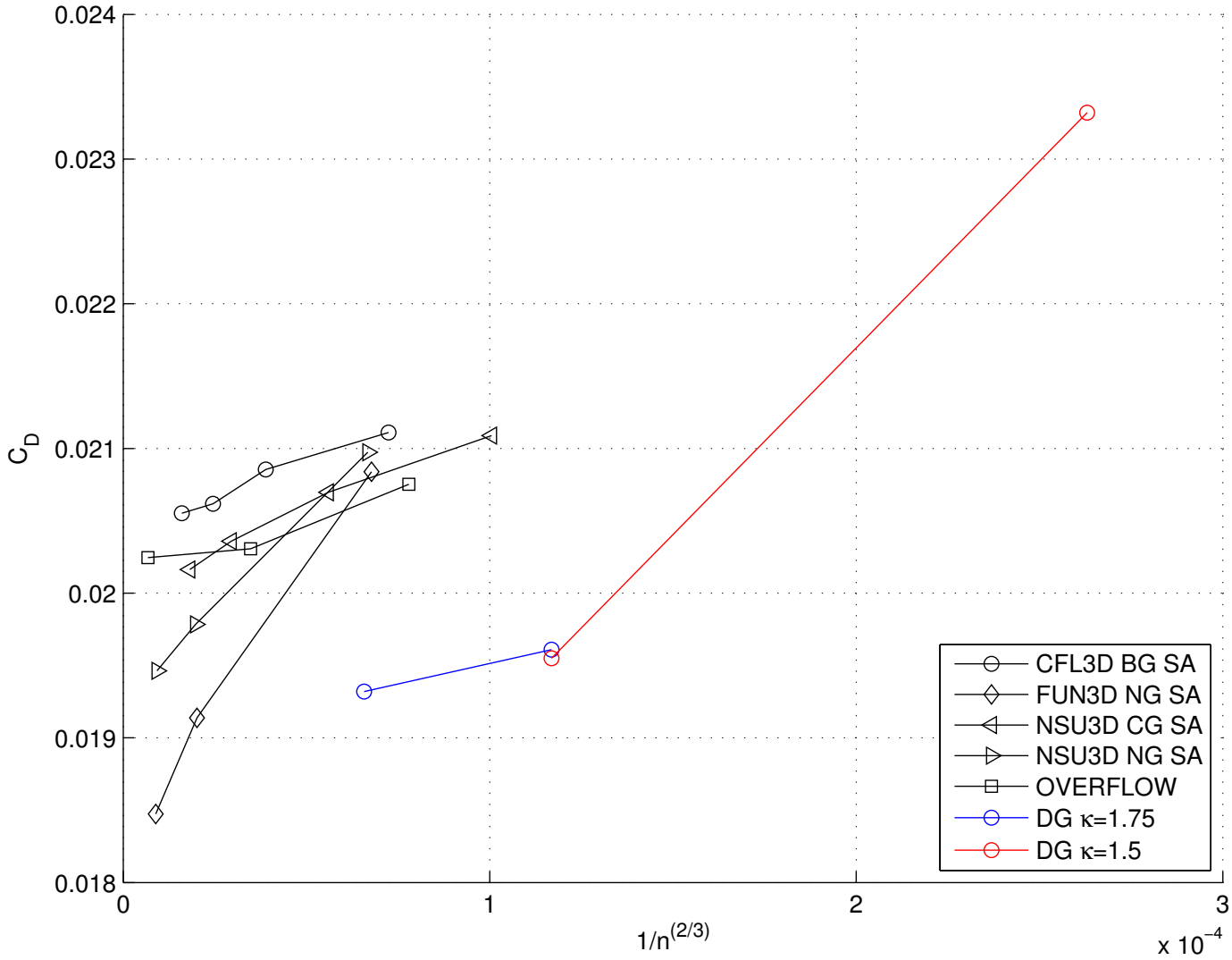
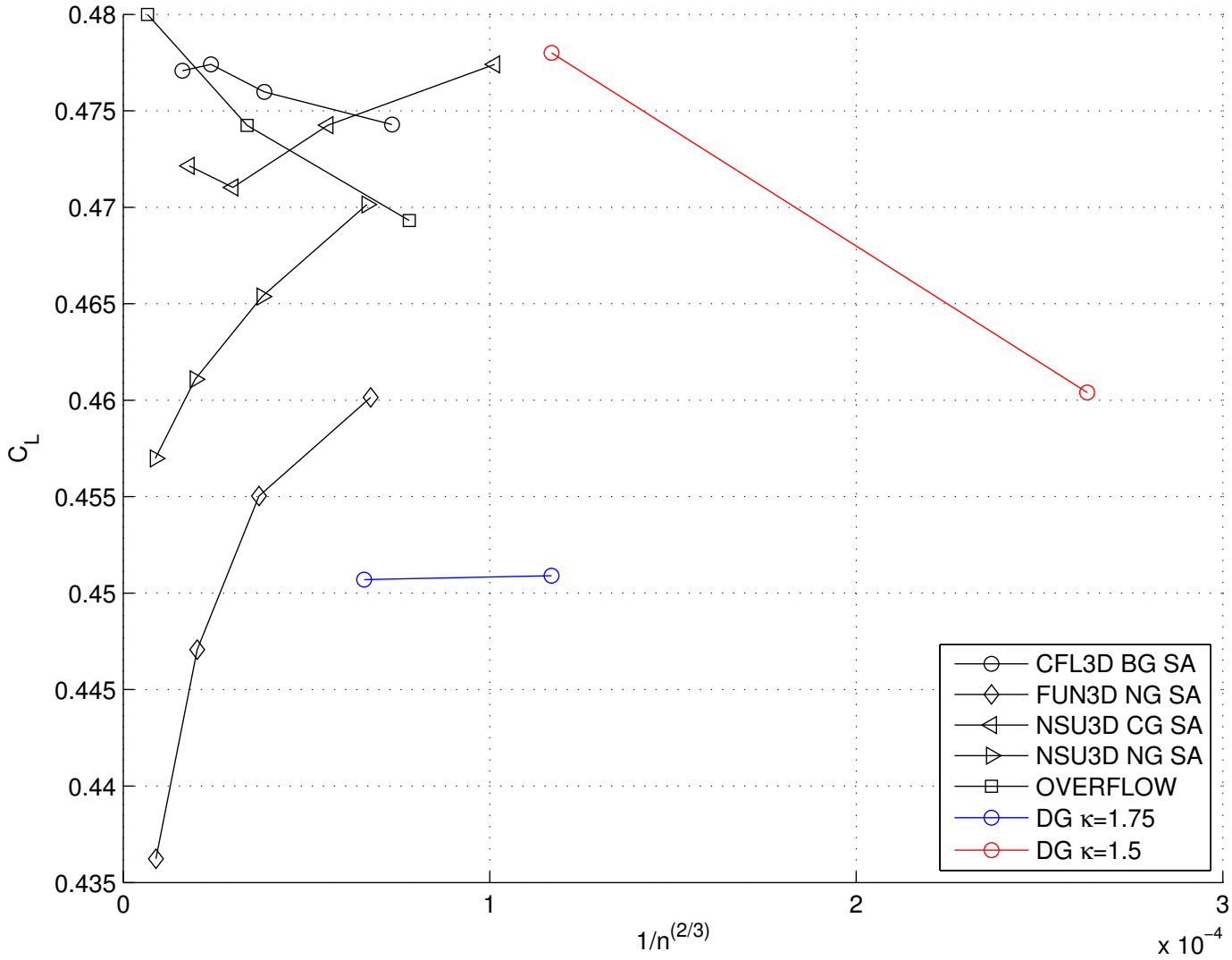
Drag and lift coefficients for varying polynomial degree p and artificial viscosity parameter κ

case	p	κ	C_D	C_L
1	1	2	0.05271	0.1056
2	1	1.75	0.03747	0.0974
3	1	1.5	0.02332	0.4604
4	2	2	0.02247	0.3392
5	2	1.75	0.01961	0.4509
6	2	1.5	0.01955	0.4780
7	3	1.75	0.01932	0.4507

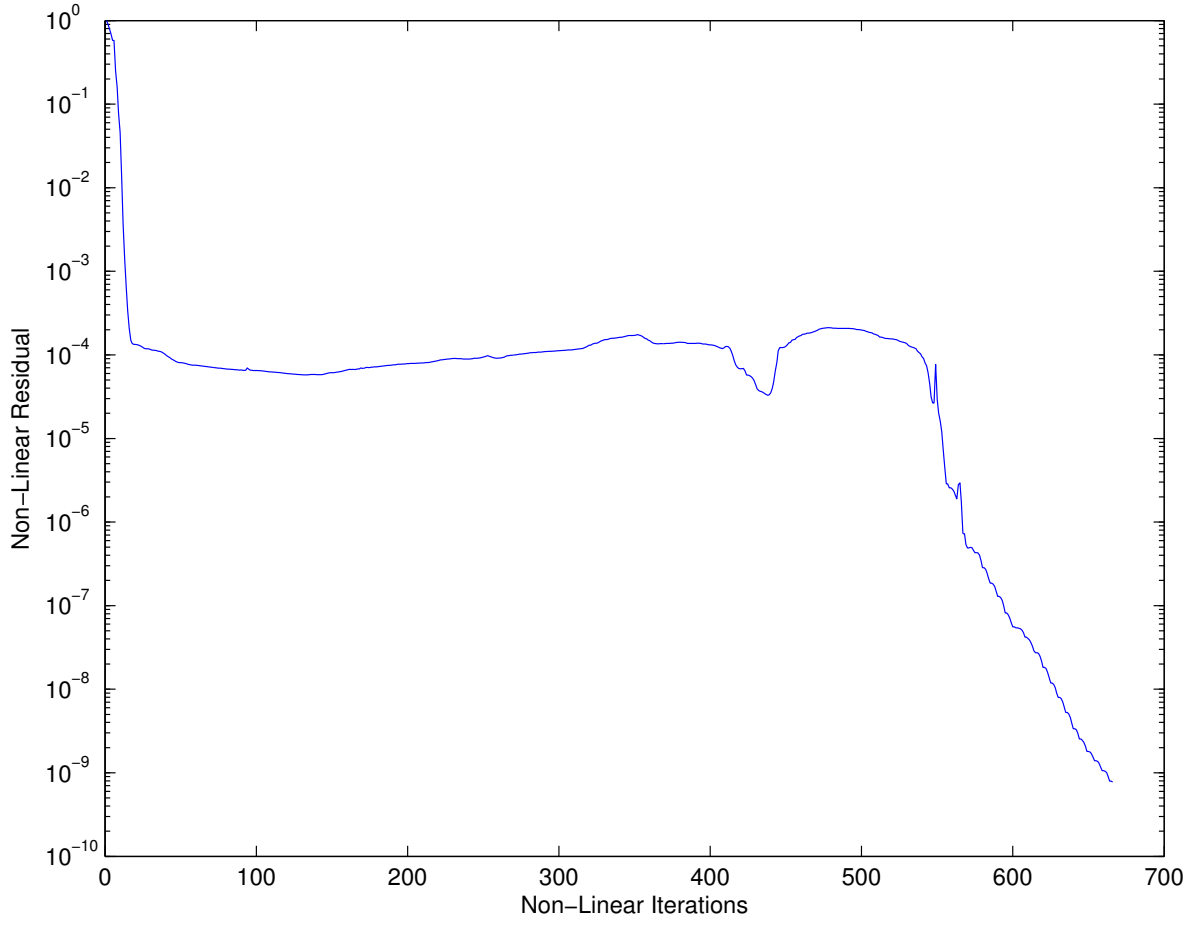
Drag Coefficient Comparison



Lift Coefficient Comparison

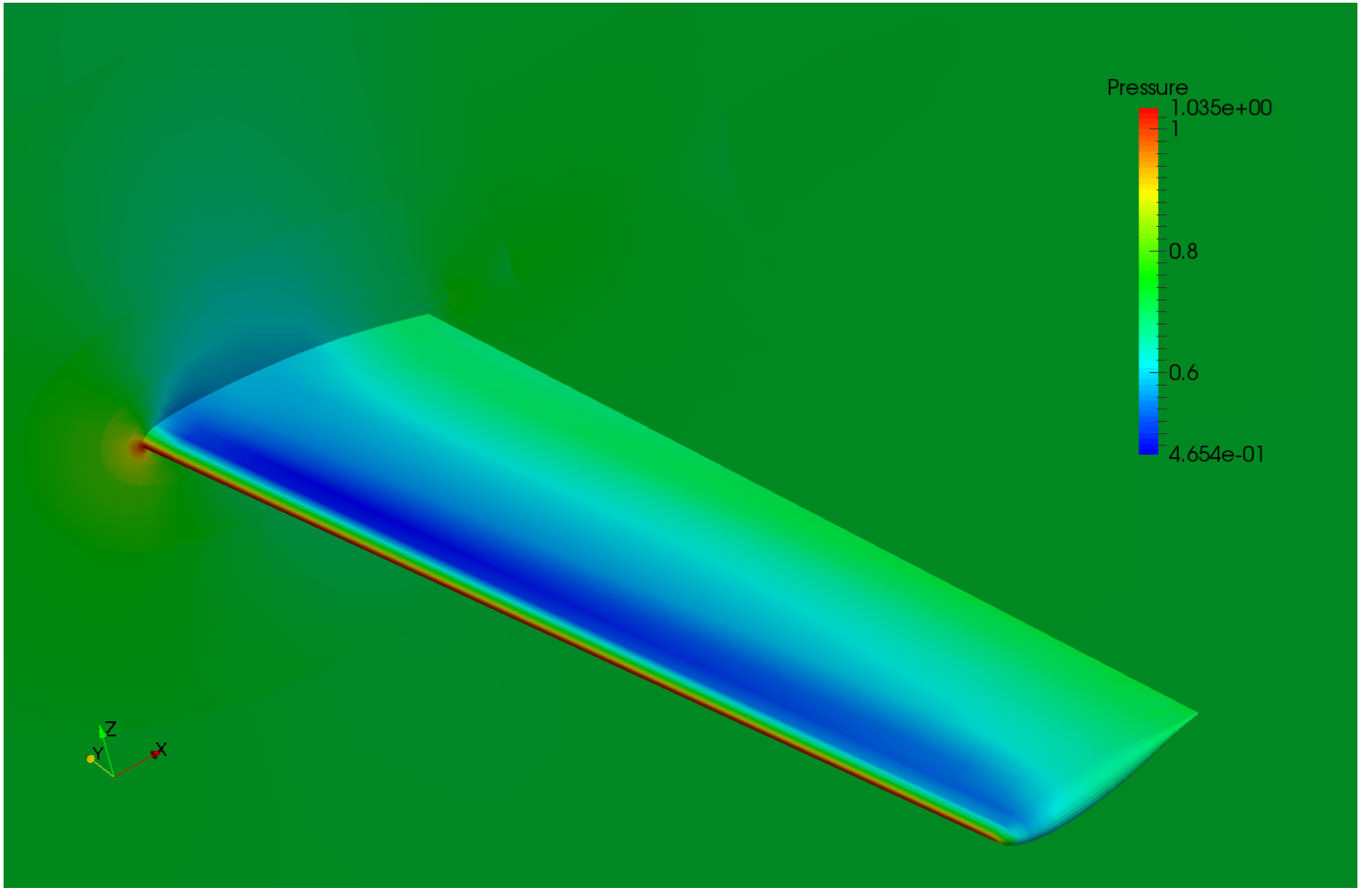


Non-Linear Residual Convergence



$p = 1$ and $\kappa = 1.75$

Pressure Contours



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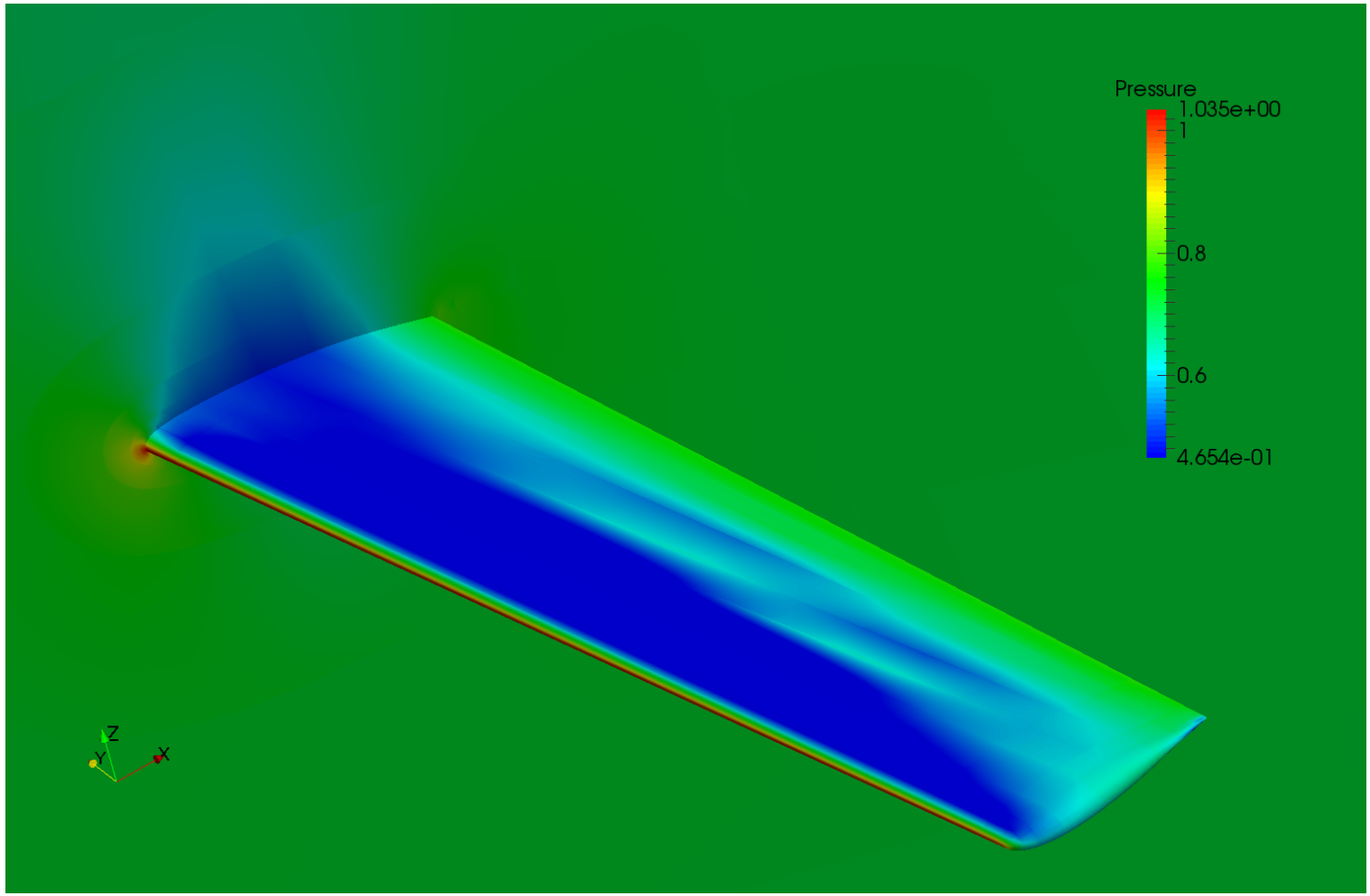
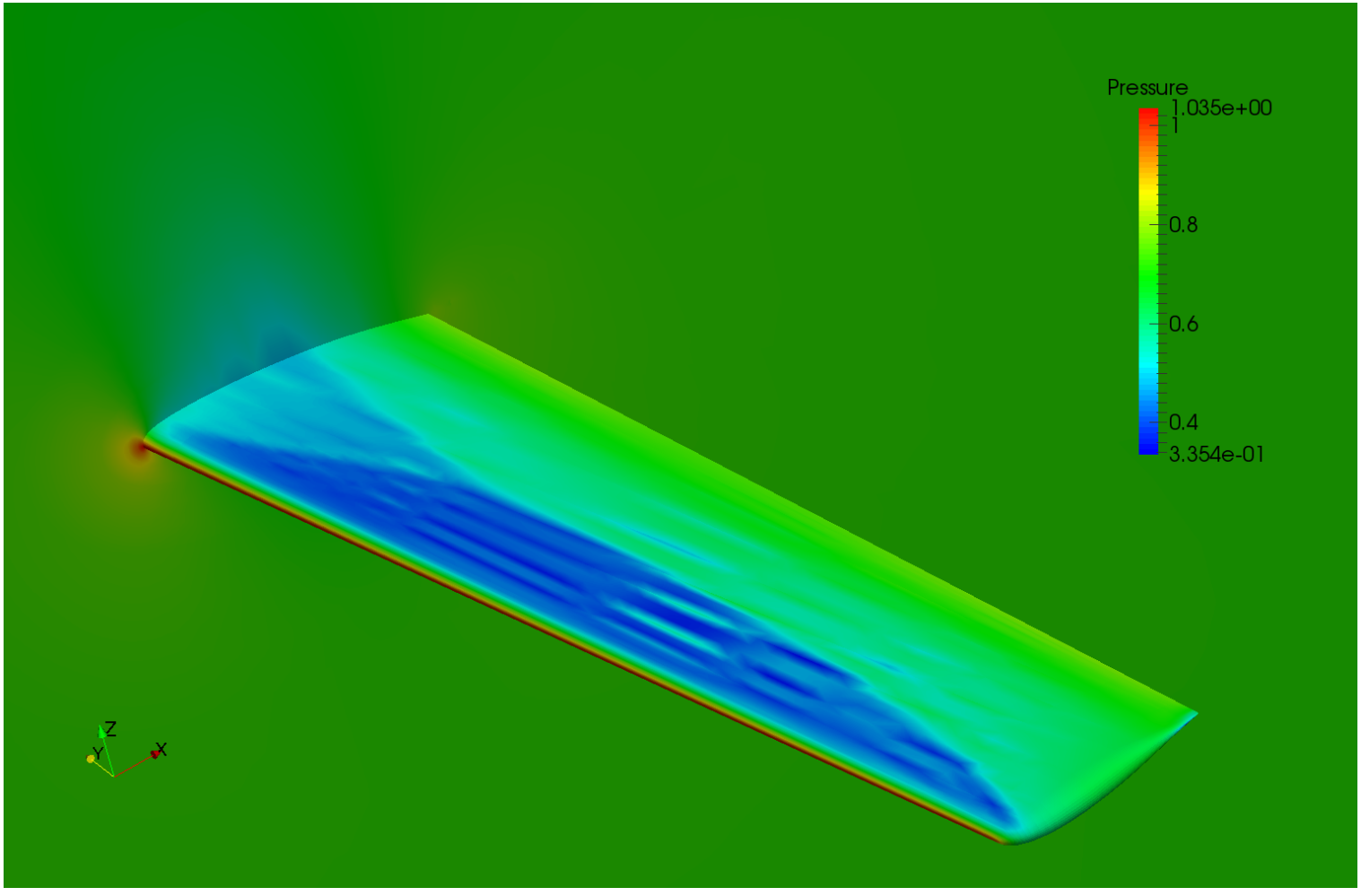
Pressure Contours



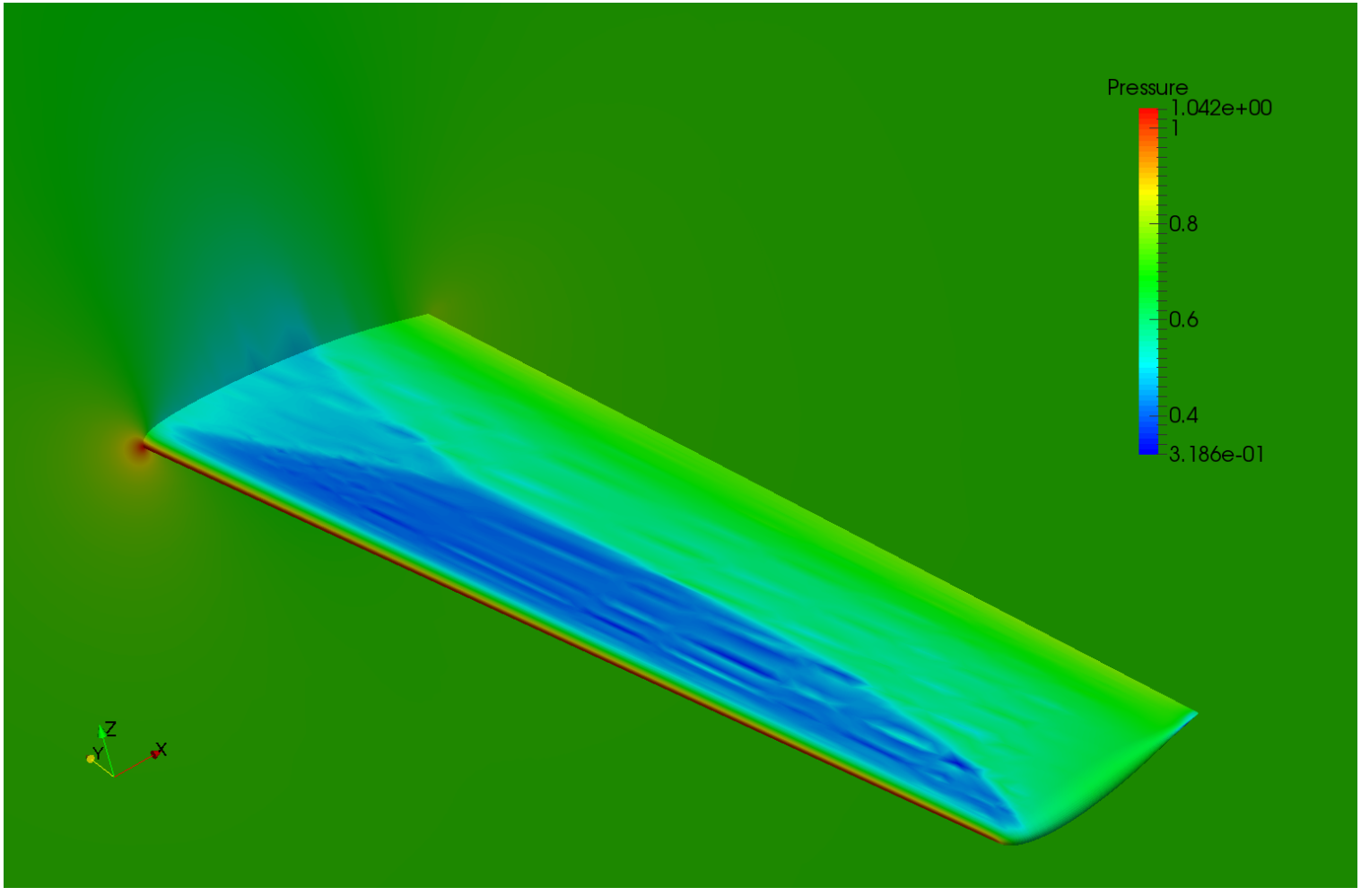
$p = 1$ and $\kappa = 1.5$

Pressure Contours



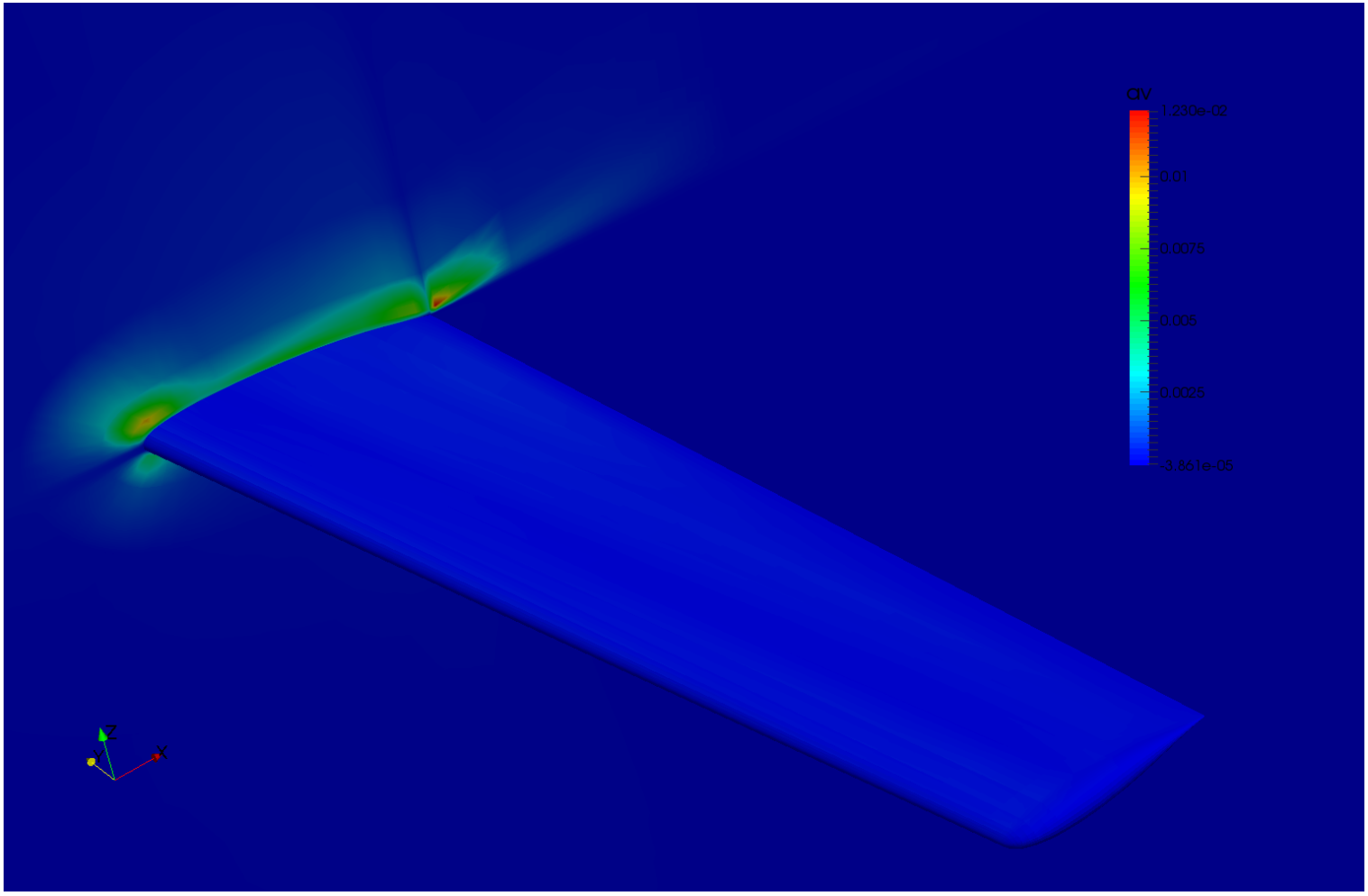
$p = 2$ and $\kappa = 1.75$

Pressure Contours



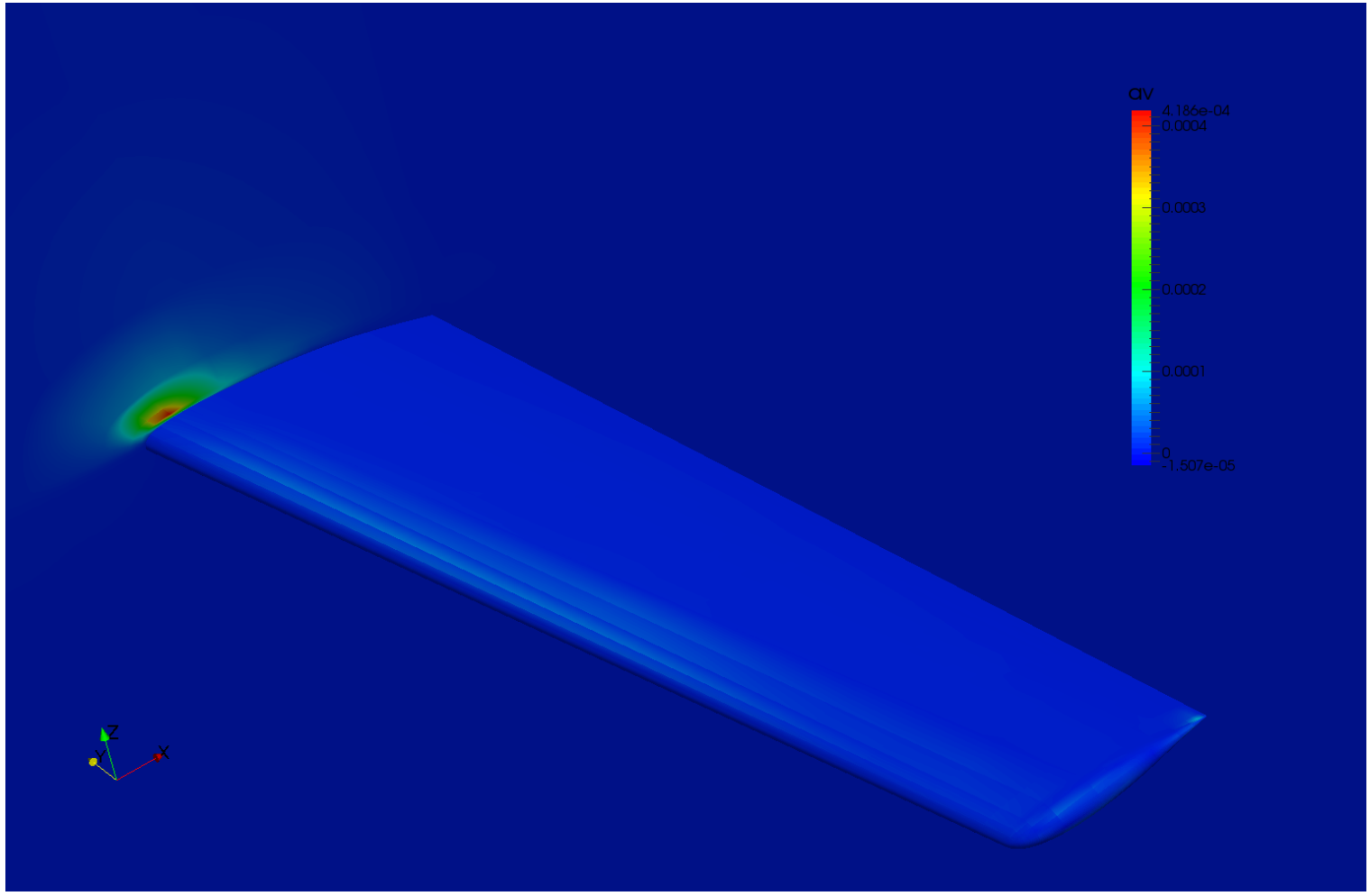
$p = 3$ and $\kappa = 1.75$

Artificial Viscosity Contours



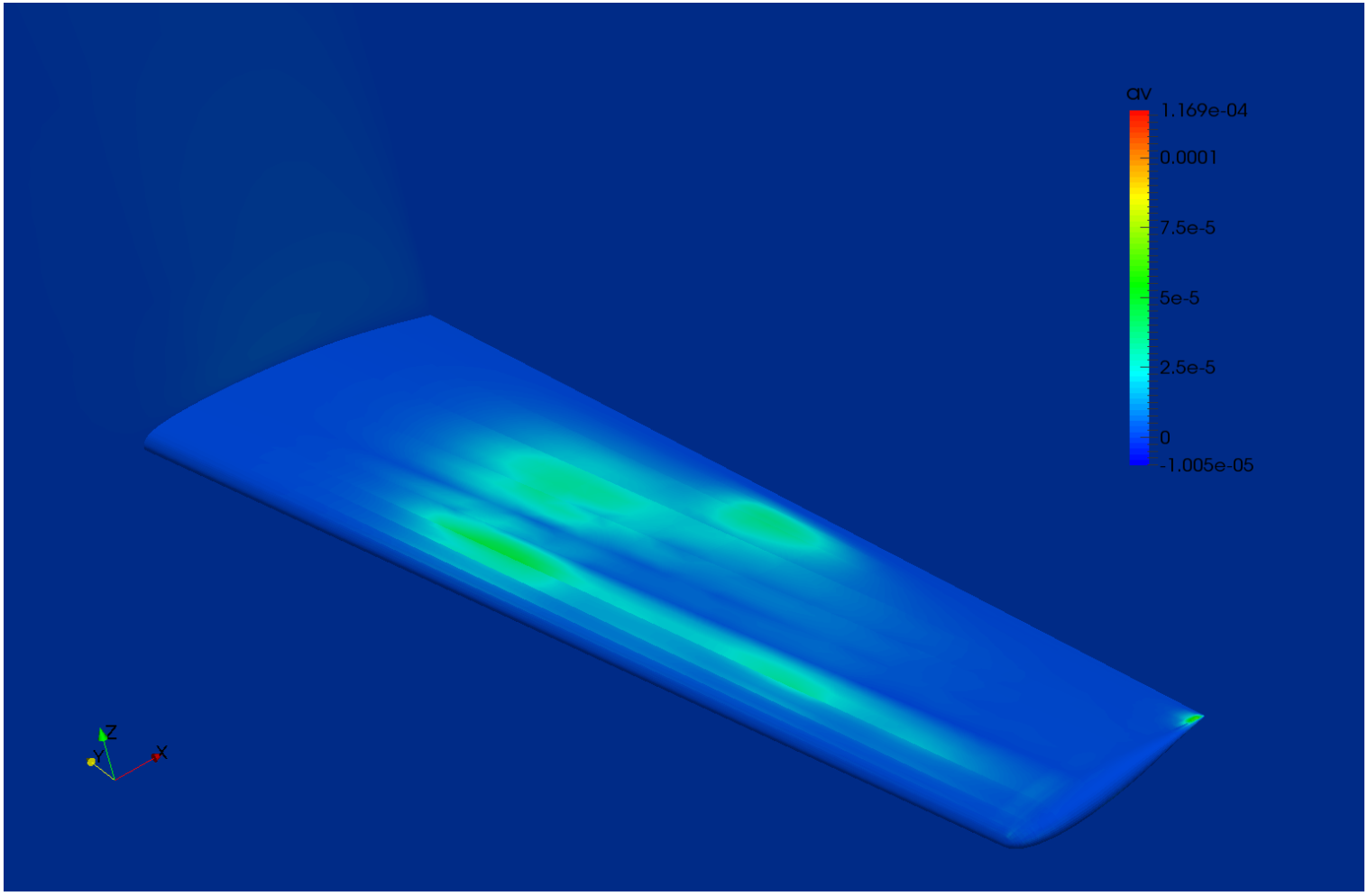
$p = 1$ and $\kappa = 1.75$

Artificial Viscosity Contours



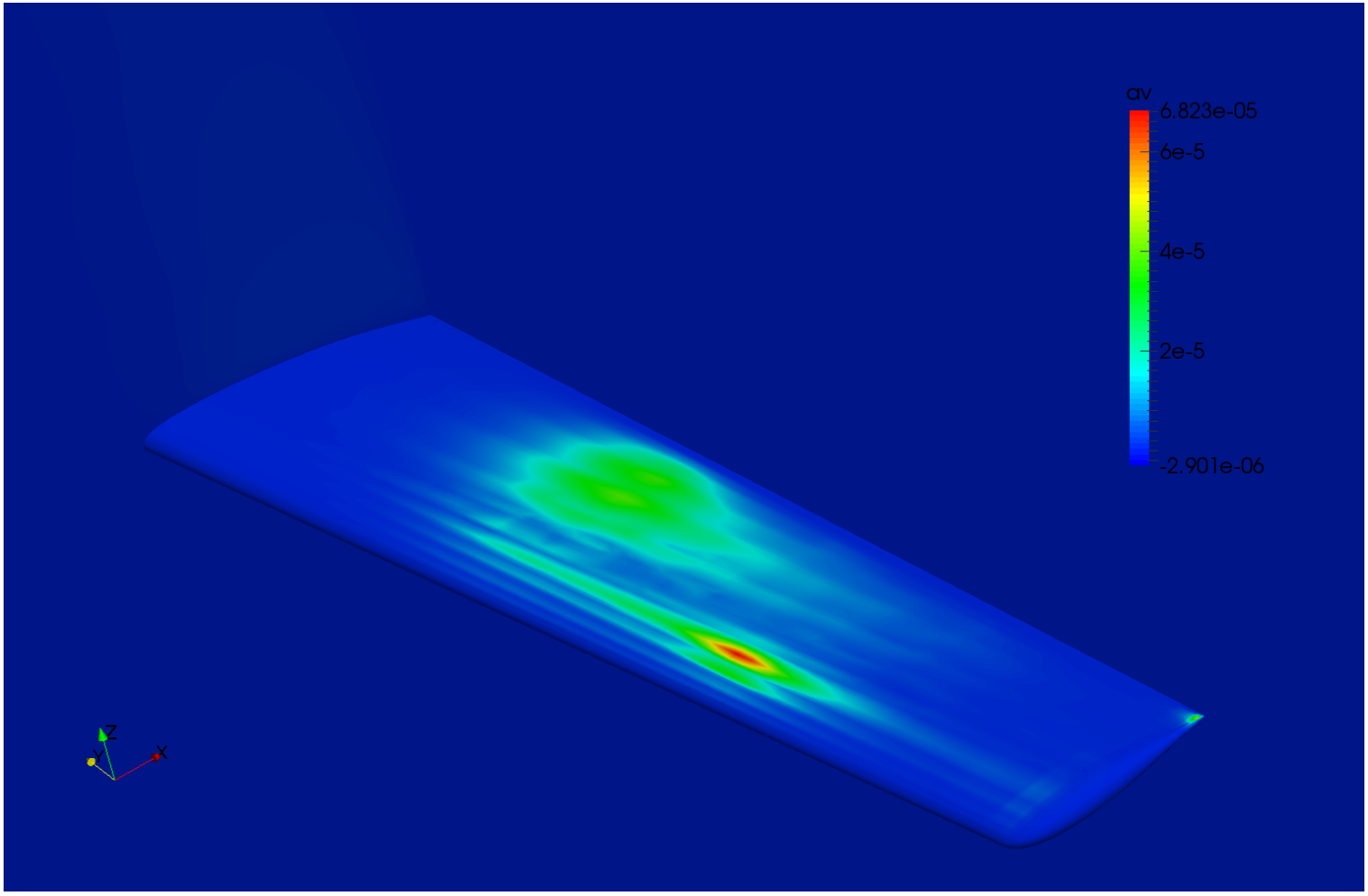
$p = 1$ and $\kappa = 1.5$

Artificial Viscosity Contours



$p = 2$ and $\kappa = 1.75$

Artificial Viscosity Contours



$p = 3$ and $\kappa = 1.75$

Conclusions

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- Results for Drag and Lift are within bounds of Drag prediction workshop
- High order issues:
  - Viscous flux method and penalty parameter
  - Mesh curvature: align grid points with spline control points
- Interaction between shock and boundary layer with artificial viscosity?