AXISYMEMTRIC IMPLEMENTATION FOR 3D-BASED DSMC CODES

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The primary objective in developing NASA's DSMC Analysis Code (DAC) was to provide a high fidelity modeling tool for 3D rarefied flows such as vacuum plume impingement and hypersonic re-entry flows [1]. The initial implementation has been expanded over time to offer other capabilities including a novel axisymmetric implementation. Because of the inherently 3D nature of DAC, this axisymmetric implementation uses a 3D Cartesian domain and 3D surfaces. Molecules are moved in all three dimensions but their movements are limited by physical walls to a small wedge centered on the plane of symmetry (Figure 1). Unfortunately, far from the axis of symmetry, the cell size in the direction perpendicular to the plane of symmetry (the Z-direction) may become large compared to the flow mean free path. This frequently results in inaccuracies in these regions of the domain.

A new axisymmetric implementation is presented which aims to solve this issue by using Bird's approach for the molecular movement while preserving the 3D nature of the DAC software [2]. First, the computational domain is similar to that previously used such that a wedge must still be used to define the inflow surface and solid walls within the domain. As before molecules are created inside the inflow wedge triangles but they are now rotated back to the symmetry plane. During the move step, molecules are moved in 3D but instead of interacting with the wedge walls, the molecules are rotated back to the plane of symmetry at the end of the move step.

This new implementation was tested for multiple flows over axisymmetric shapes, including a sphere, a cone, a double cone and a hollow cylinder. Comparisons to previous DSMC solutions and experiments, when available, are made.

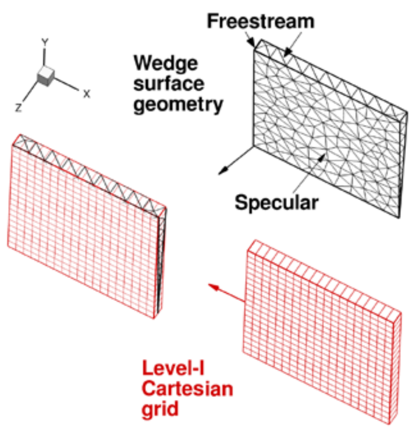

Figure 1. Simulation domain for DAC axisymmetric simulations.

[1] G. J. LeBeau and F. E. Lumpkin III, "Application highlights of the DSMC Analysis Code (DAC) software for simulating rarefied flows", *Computer Methods in Applied Mechanics and Engineering*, Vol. 191, Issue 6-7, pp. 595-609 (2001).

[2] G. A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*, Oxford University Press, Oxford, UK (1994).

Axisymmetric Implementation for 3D-Based DSMC Codes

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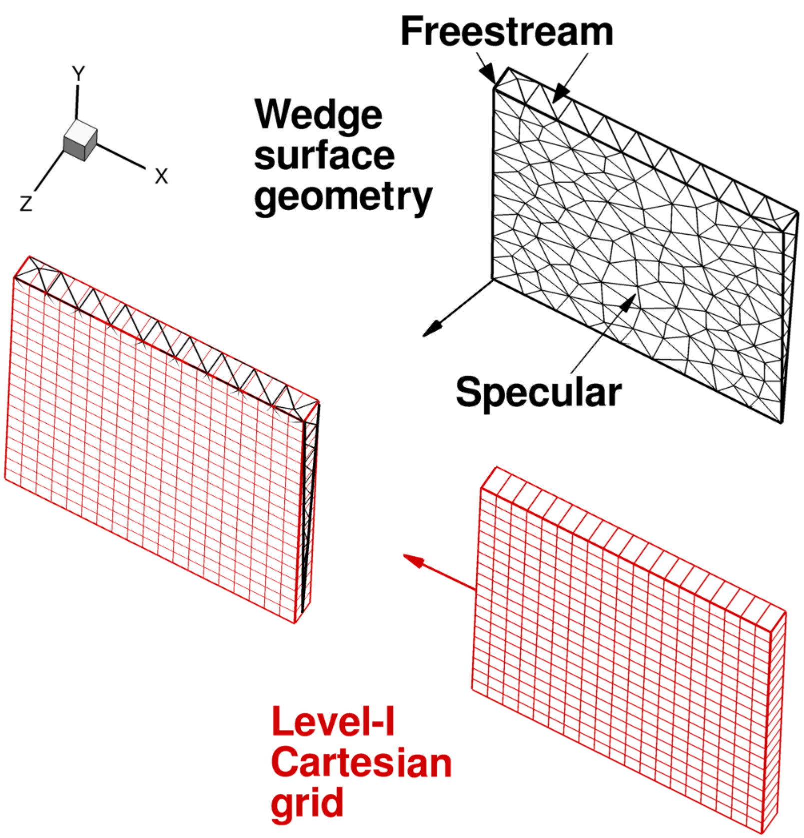
Overview

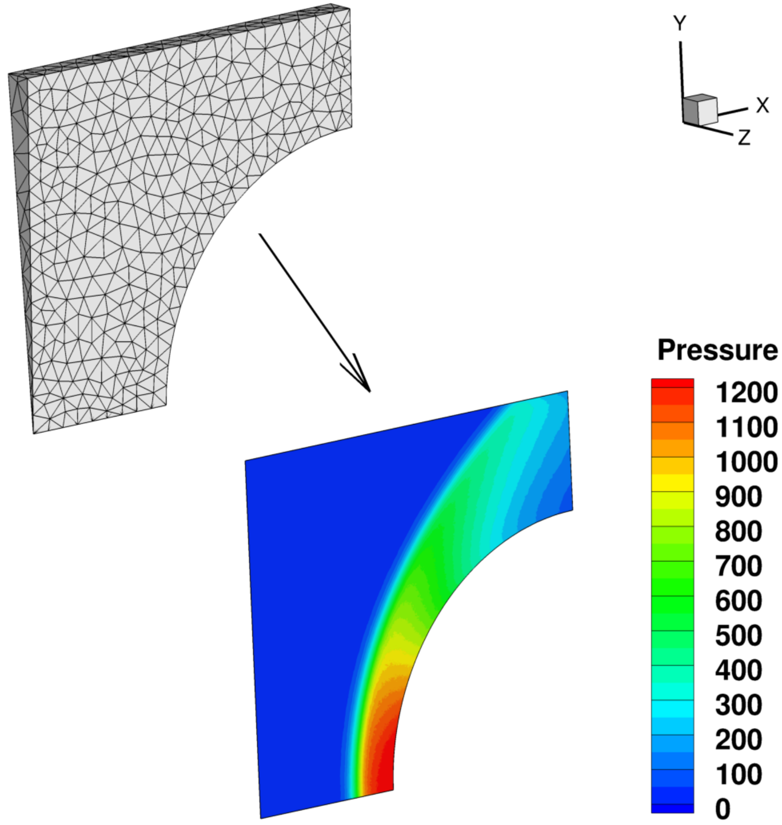
- Summary of the current axisymmetric implementation in NASA's DSMC code DAC and the limitations of that implementation
- Presentation of the new implementation
  - Surface geometry preprocessing
  - Molecules creation
  - Molecules move
- Results
  - Sphere
  - Cone
  - Double cone
  - Hollow cylinder
- Conclusions

Current DAC Axisymmetric Implementation



- **Overview:**
  - DAC was created as a 3D computational tool used to solve plume in a vacuum and hypersonic reentry flows
  - 3D domain meshed using a Cartesian grid
  - Water tight triangulated surface definition required
- **Current DAC Axisymmetric:**
  - Flowfield domain defined by physical walls forming a wedge centered at the symmetry plane
  - Use cell-based radial weighting factors
- **Implementation limitations:**
  - Molecules sorted into cells based on their Y-coordinate instead of their radial distance from the axis of symmetry
  - Mean free path requirements used to create the grid are not enforced in the Z direction

New Axisymmetric Implementation

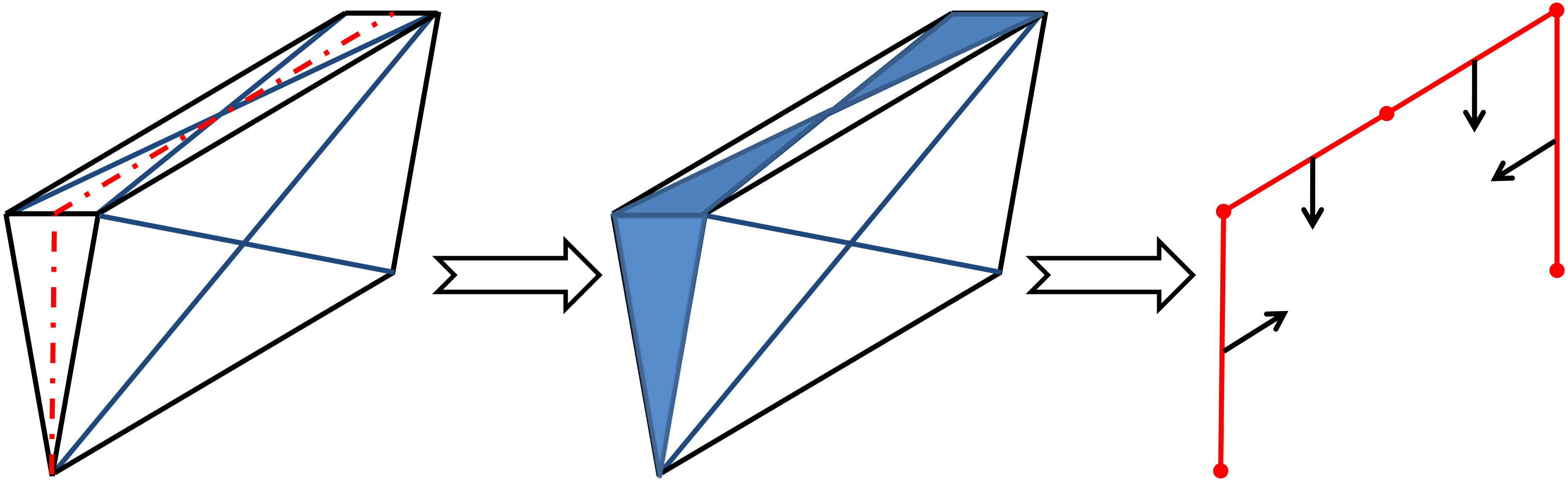


New implementation is a hybrid between the original DAC implementation and the standard implementation*(Bird)

- 3D Cartesian grid
- Solid walls encompassed into a wedge with specular and inflow surfaces to form a water tight surface
- **3D surface is preprocessed into line segments representing the intersection between the inflow and solid walls and the symmetry plane (ignore the specular wedge walls)**
- Cell-based radial weighting factor
- Molecules created inside inflow triangles
- **Newly created molecules are rotated back to the symmetry plane before being moved**
- **Molecules are rotated back into the symmetry plane by the end of the move step**

* Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Bird, 1994

Surface Geometry Preprocessing



Flag the triangles cutting the symmetry plane

- *Store the intersection points*
- *Update the vector normal for those triangles to be 2D*

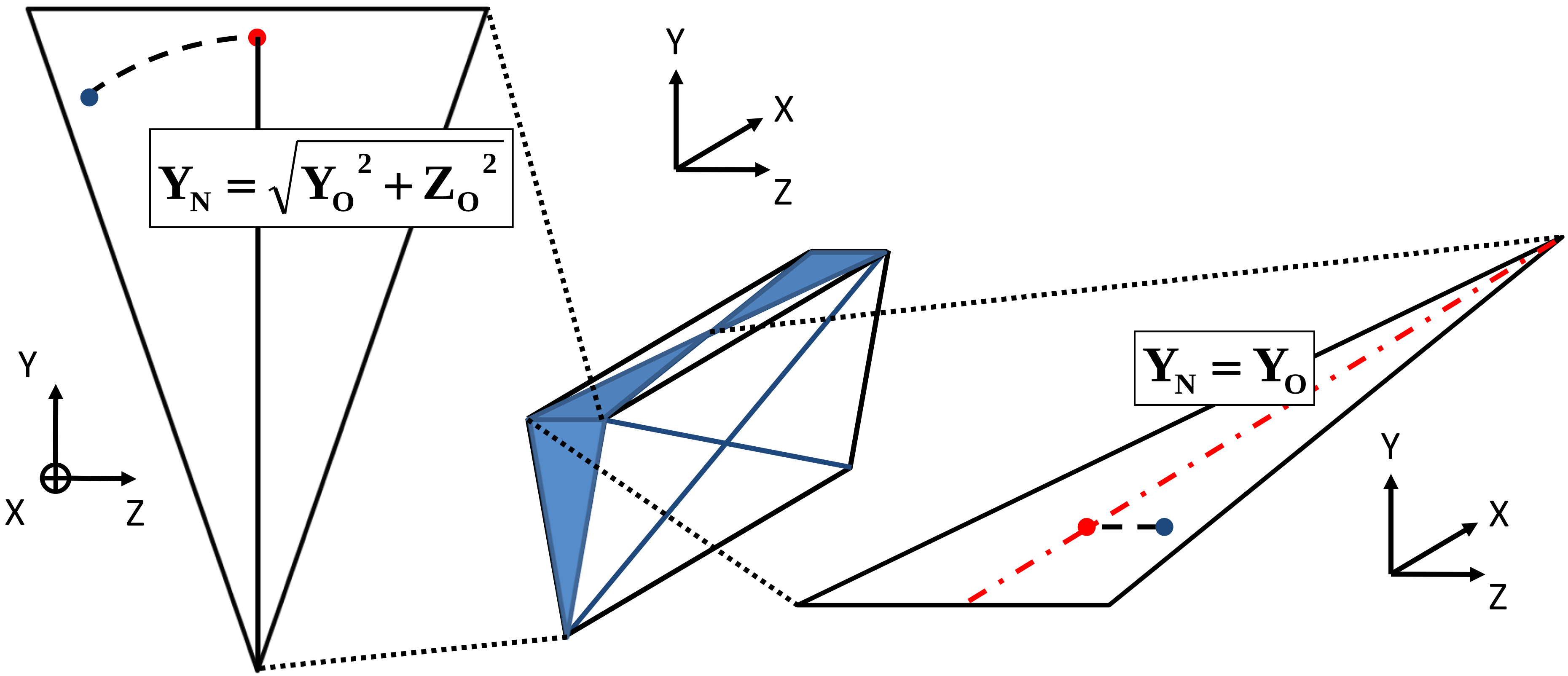
Molecules Creation

How do you create molecules while using the wedge fluxing triangles?

↳ Molecules are created at random locations in each fluxing triangle and then are rotated back to the symmetry plane

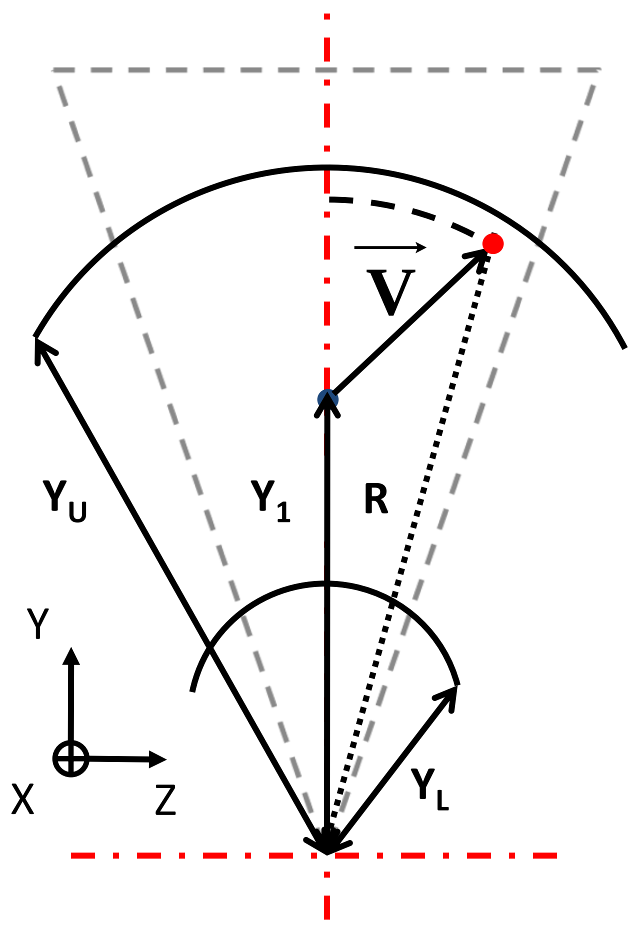
Case 1: Δ orthogonal to X

Case 2: All other configurations



Molecules Ray Tracing

Schematic assumes $V_X = 0$



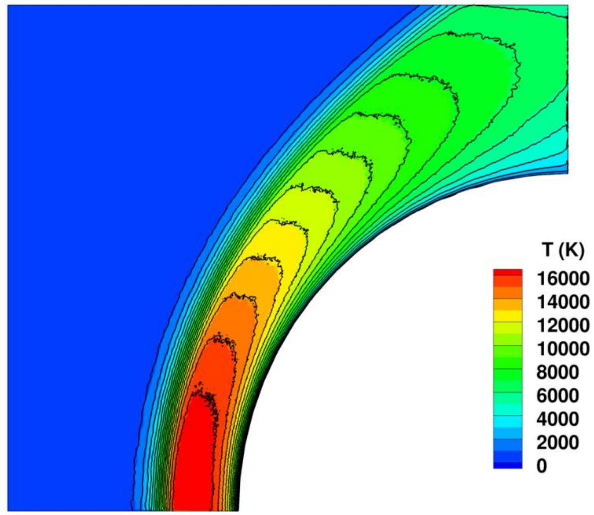
Cartesian cells use different timestep sizes and FNUM → Use a ray tracing technique to move the molecules (i.e. compute the time it takes the molecule to reach the edge of the Cartesian cell)

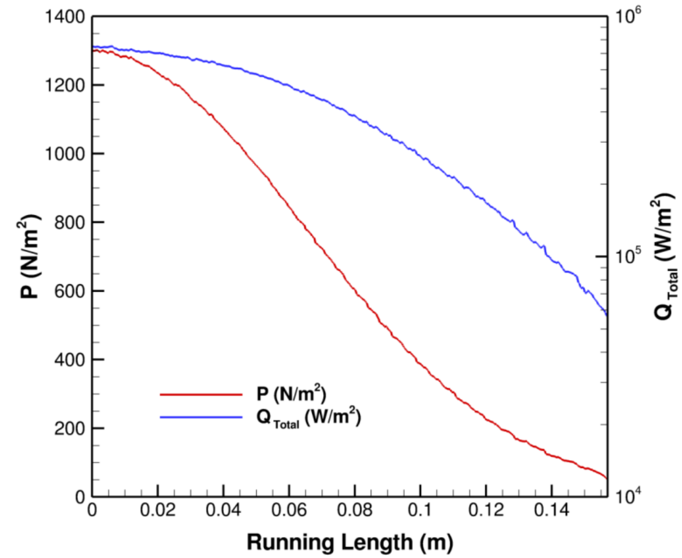
- Trivial in the X direction
- In the Y-direction, the code must take into account the fact that the molecule will be rotated back to the plane of symmetry ↔ cell edge is equivalent to a circle

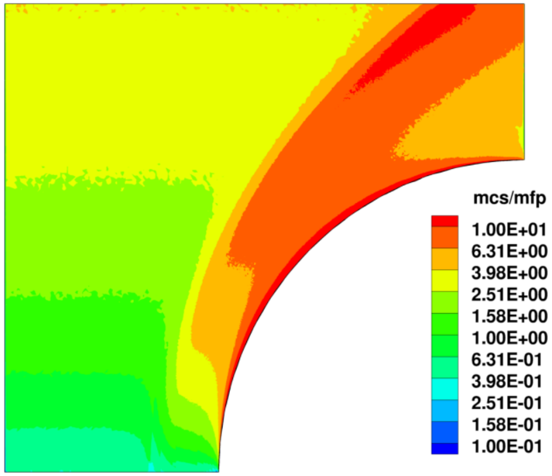
Sphere

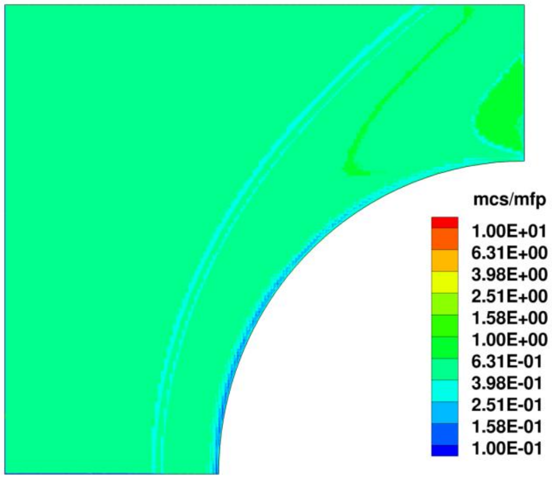
Gas: N_2
Number Density: 1.2×10^{21}
Velocity: 5.1 km/s
Gas temperature: 190 K
Wall temperature: 500 K

Kn = 0.1



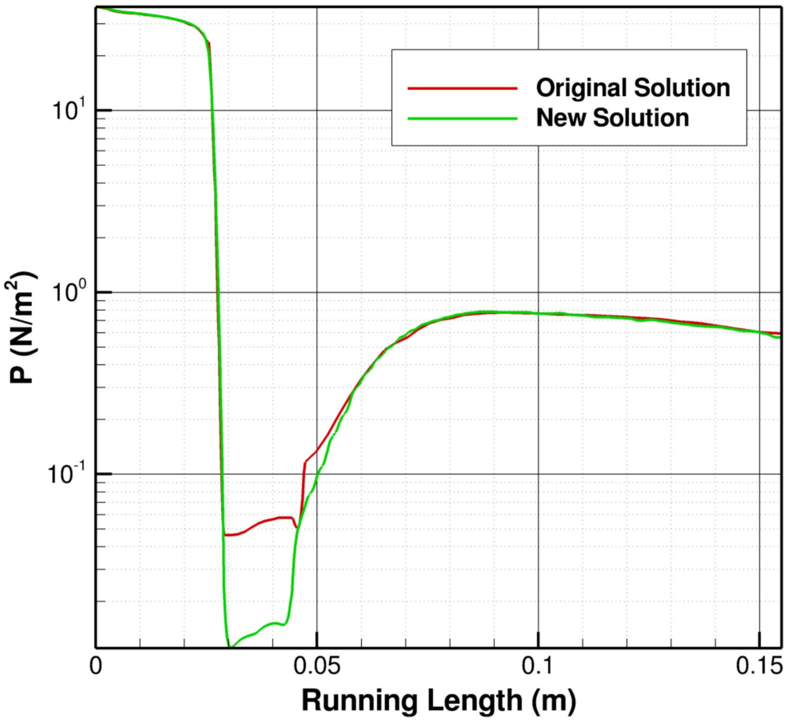






- No depleted contours near the axis of symmetry (Liechty, RGD, 2010)
- Good agreement with original DAC solution

Cone



Gas: N_2

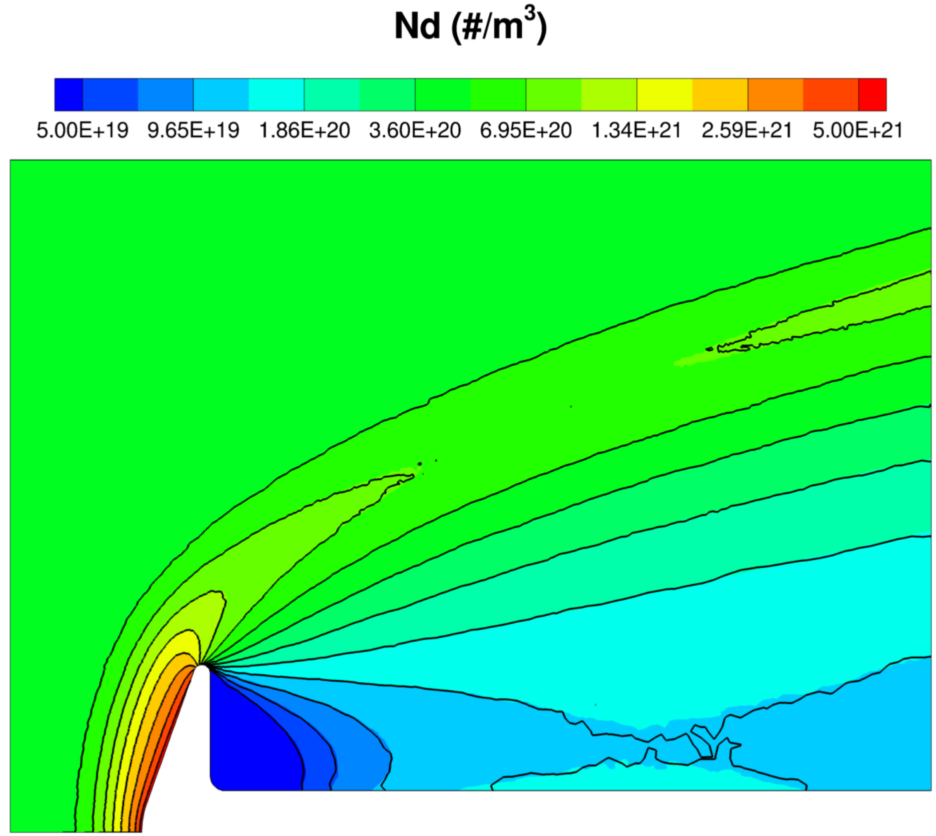
Number Density: 3.707×10^{20}

Velocity: 1.5 km/s

Gas temperature: 13.3 K

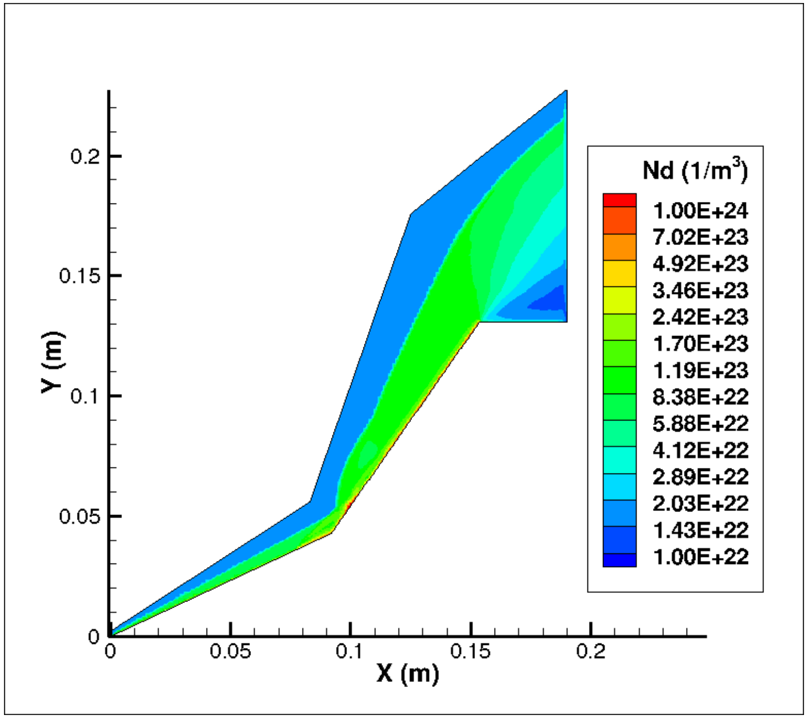
Wall temperature: 300 K

Good agreement with original DAC solution

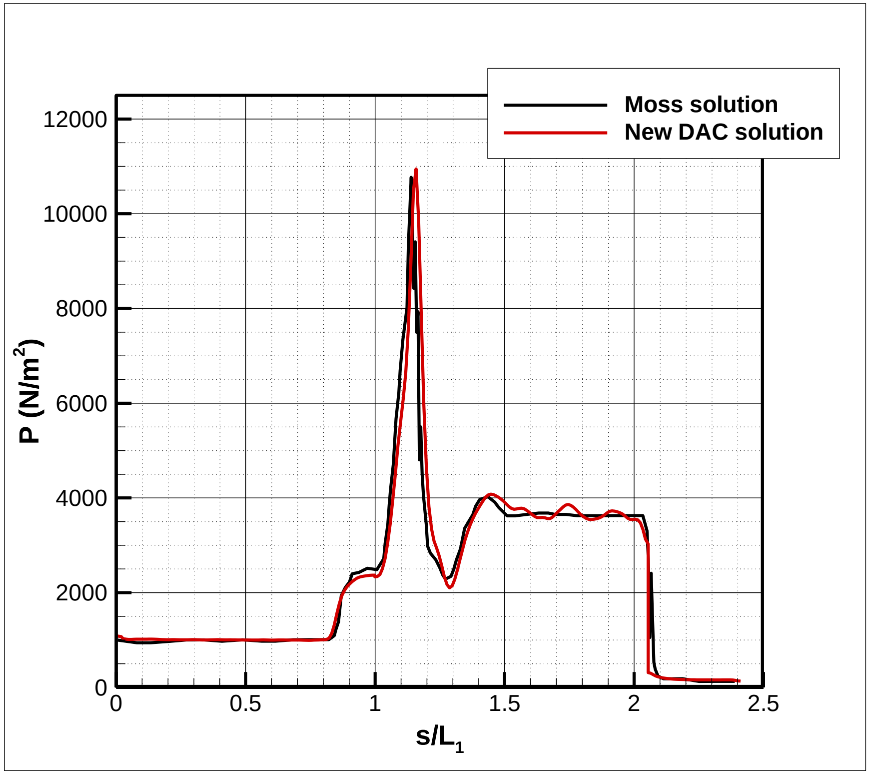


Double Cone

LENS-A conditions*
Gas: N_2
Number Density: 1.463×10^{22}
Velocity: 2.7136 km/s
Gas temperature: 194.1 K
Wall temperature: 297.8 K



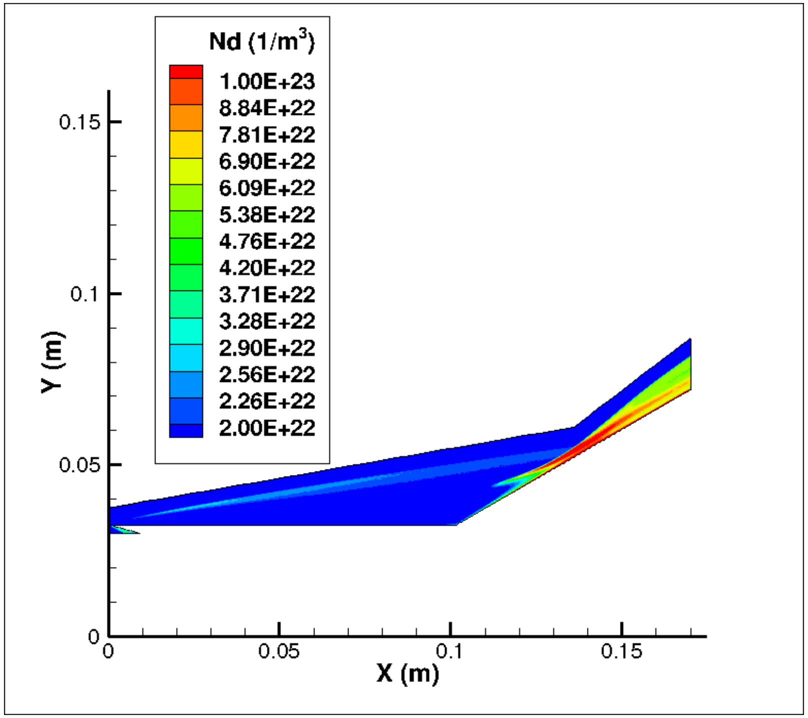
- Input based on benchmarking work done in the early 2000's, comparing experiments and numerical computations
- Good agreement with G2 simulations



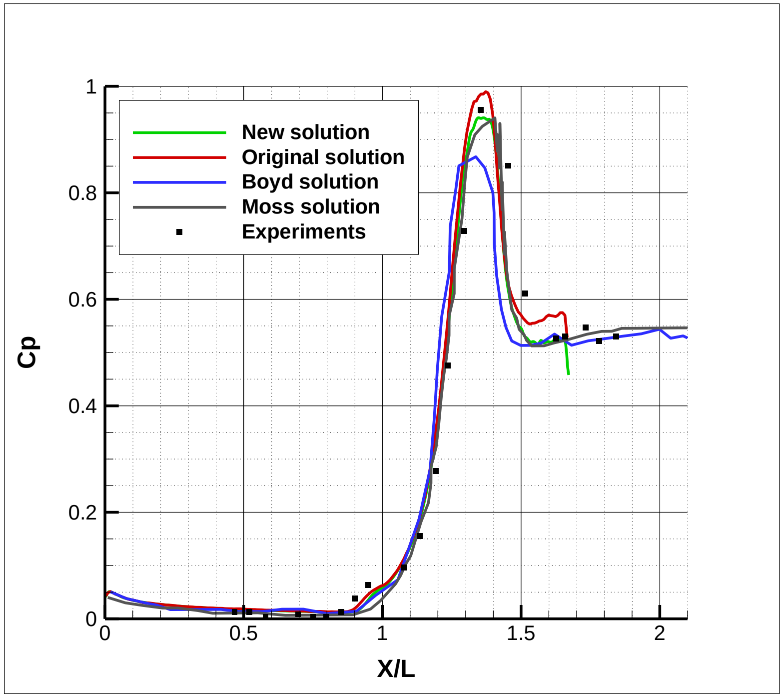
*DSMC Simulations of Shock Interactions About Sharp Double Cones, Moss, 2000, NASA TM-2000-210318

Hollow Cylinder

LENS Test 11*
Gas: N_2
Number Density: 1.0889×10^{22}
Velocity: 2.6091 km/s
Gas temperature: 128.9 K
Wall temperature: 297.2 K



- Input based on benchmarking work done in the early 2000's, comparing experiments and numerical computations
- Good agreement with other DSMC codes and with experiments



*Code Validation Study of Laminar Shock/Boundary Layer and Shock/Shock Interactions in Hypersonic Flow, Harvey, Holdens and Wadhams, 2001, AIAA-2001-1031

Conclusions

- Presented a new axisymmetric implementation for DAC
- Good agreement has been obtained with other DSMC codes and experiments for simple and more complex hypersonic flows