Computational Fluid Dynamics

Turbulence

Motivations, Simulations and testing Hydra

Johannes Kerimo
Department of Aerospace Engineering
Texas A&M University

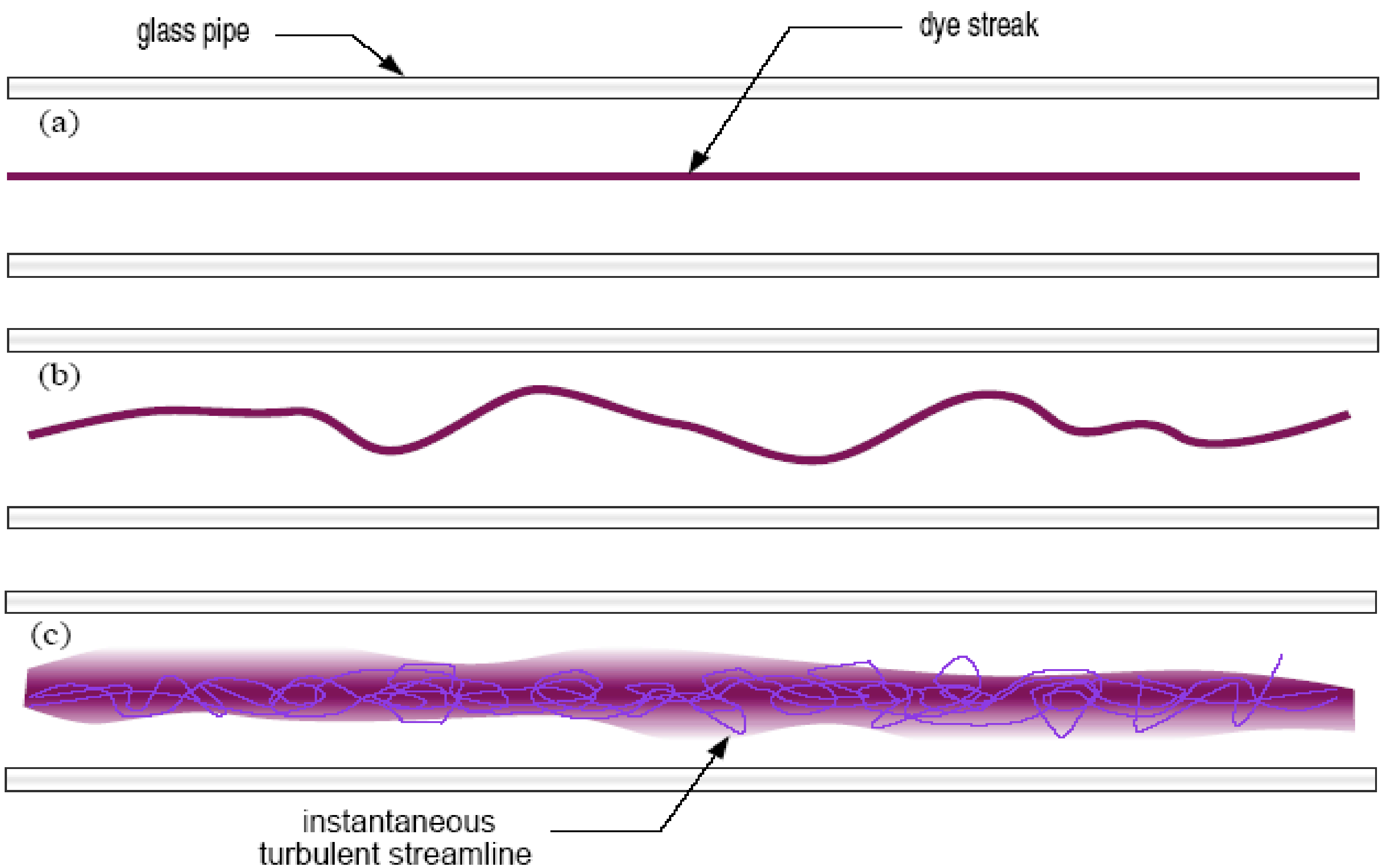
Research groups of Dr. Girimaji & Dr. Bowersox

Content

- Background (Motivation)
- Examples on numerical simulations we perform on Cosmos and Hydra.
- Speed comparisons between Cosmos and Hydra. Scalability checks.

Background

What is Turbulence ?



a) Laminar flow; b) Transitional flow; c) Turbulence

da Vinci sketch

Turbulence Characteristics

- Chaotic, seemingly random behavior.
- Sensitive to initial conditions.
- Wide range of temporal and spatial scales.
- Rapid variation of pressure and velocity in space and time.
- Enhanced diffusion (mixing) and dissipation.

Background

(Why Study Turbulence?)

Most flows occurring in nature and engineering applications are turbulent:

- Flows around vehicles
- Mixing of fuel and air in engines
- Mixing of the reactants in chemical reactors
- Mixing of fluids
- Geophysical and Astronomical phenomena
- The interior of living biological systems
- The intellectual challenge

Background

(Navier-Stokes & Boltzmann Platforms)

Turbulence can be described by both Navier-Stokes equations and the Boltzmann kinetic equation.

Navier-Stoke platform:

$$\partial_t \rho + \nabla \cdot (\rho U) = 0,$$

$$\partial_t (\rho U_i) + \partial_j (\rho U_i U_j + p \delta_{ij}) = \partial_j \sigma_{ij}$$

$$\partial_t (\rho E) + \partial_i ((\rho E + p) U_i) = \partial_i \left[\kappa(T) \partial_i T + \sigma_{ij} U_j \right],$$

$$\sigma_{ij} = \mu \left[\partial_i U_j + \partial_j U_i - \frac{2}{3} \delta_{ij} \partial_k U_k \right]$$

Simplified model of the Boltzmann kinetic equation:

$$(\partial_t + u_i \partial_i) f = \frac{g - f}{\tau}$$

g = equilibrium state (or Maxwellian state)

where

$$g = \rho \left(\frac{\lambda}{\pi}\right)^{\frac{3}{2}} e^{-\lambda[(u-U)^2+(v-V)^2+(w-W)^2]}$$

τ = relaxation time (average time interval between successive particle collisions for the same particle)

$$\begin{pmatrix}\rho\\ \rho U\\ \rho V\\ \rho W\\ E\end{pmatrix} = \int \psi_\alpha f \, d\Xi$$

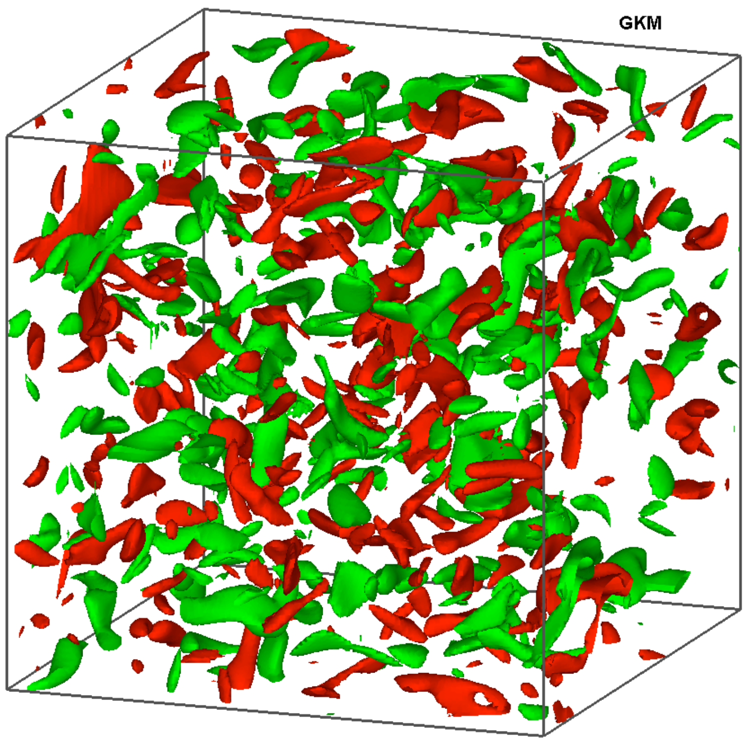
$$\begin{cases}\psi_\alpha = \left(1, u, v, w, \frac{1}{2}(u^2+v^2+w^2)\right)^T \\ d\Xi = du\,dv\,dw \\ E = \frac{1}{2}\rho\left(U^2+V^2+W^2+\frac{3}{2\lambda}\right), \quad \lambda = \frac{1}{2RT}\end{cases}$$

Numerical Simulations

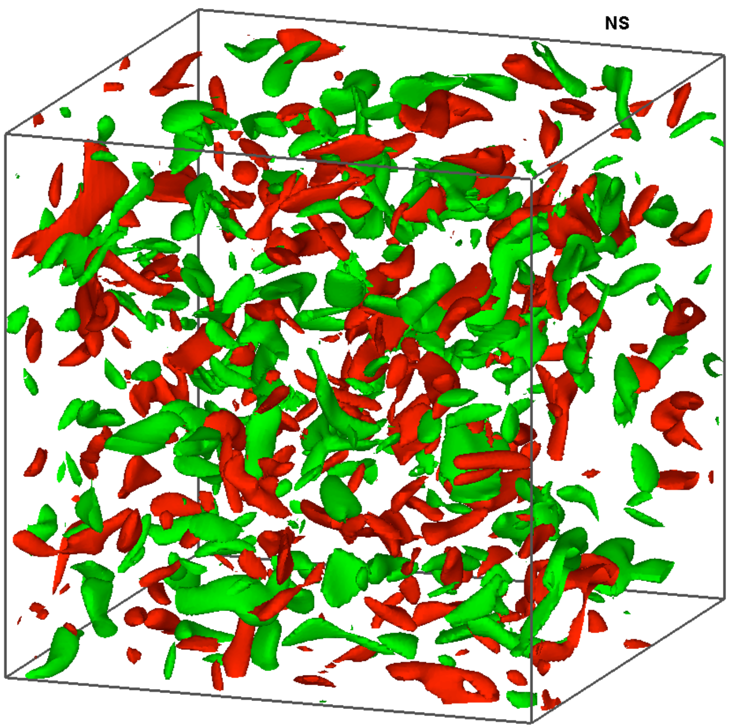
(A box of Turbulence)

Iso-vorticity surfaces

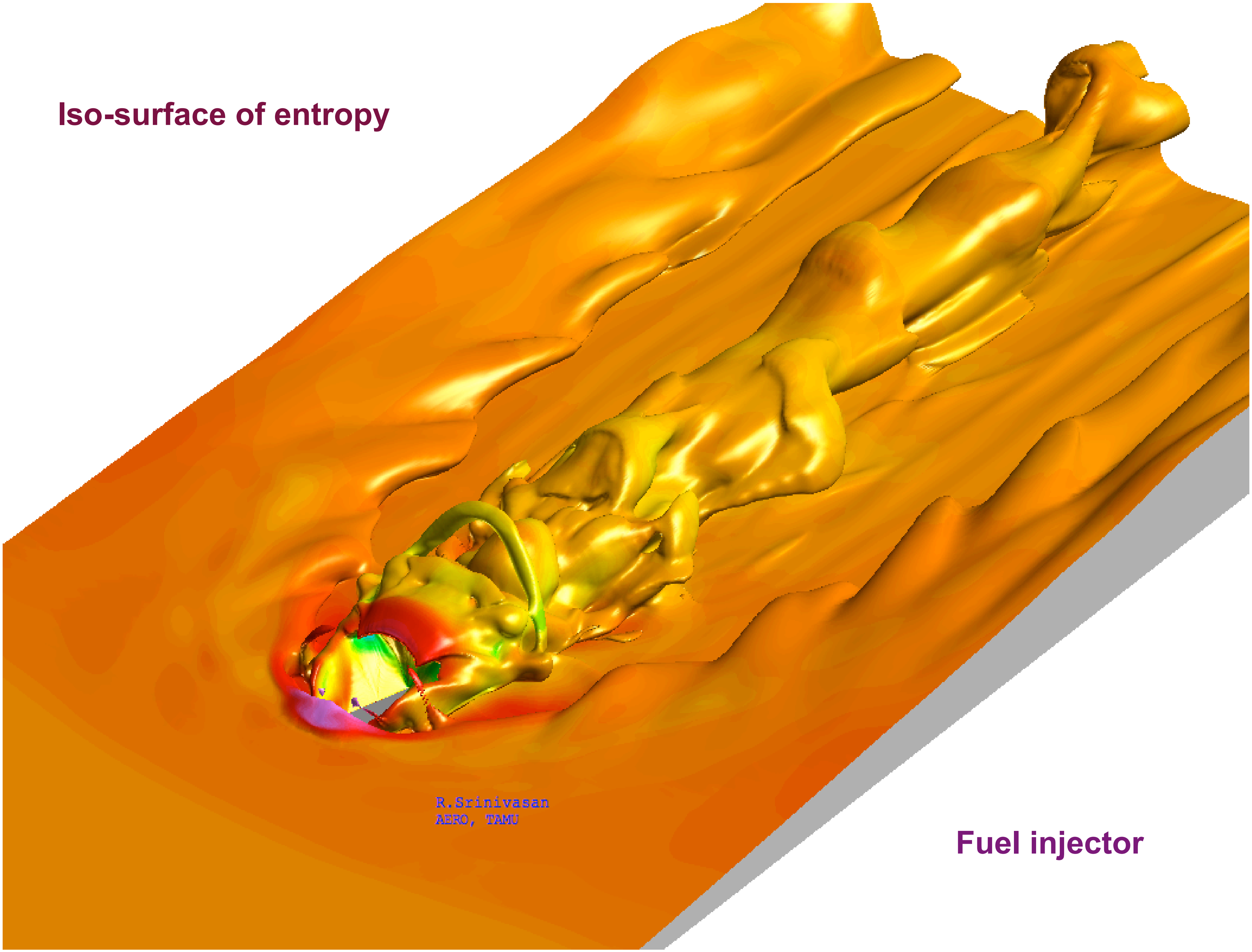
Kinetic method

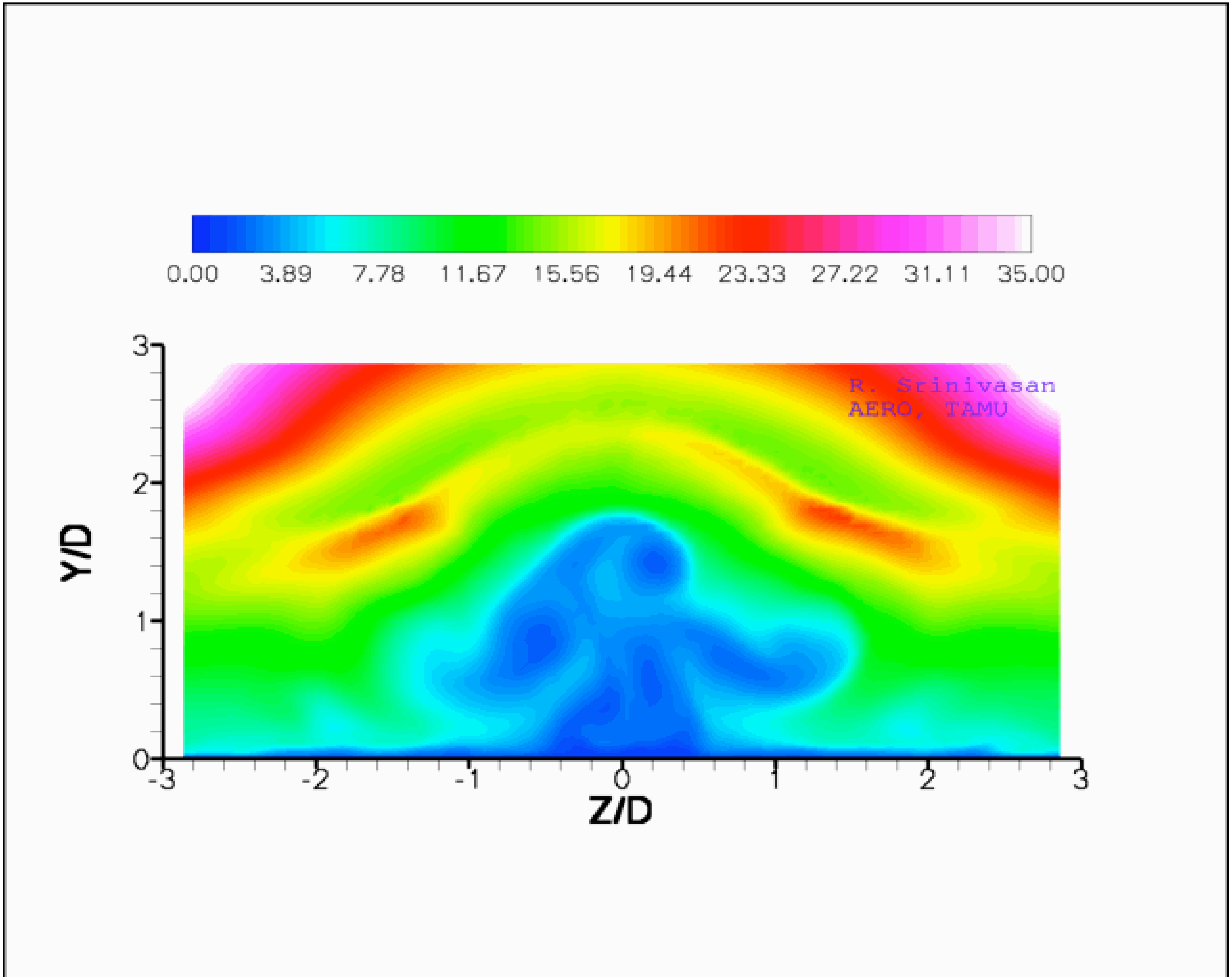


Navier-Stoke method

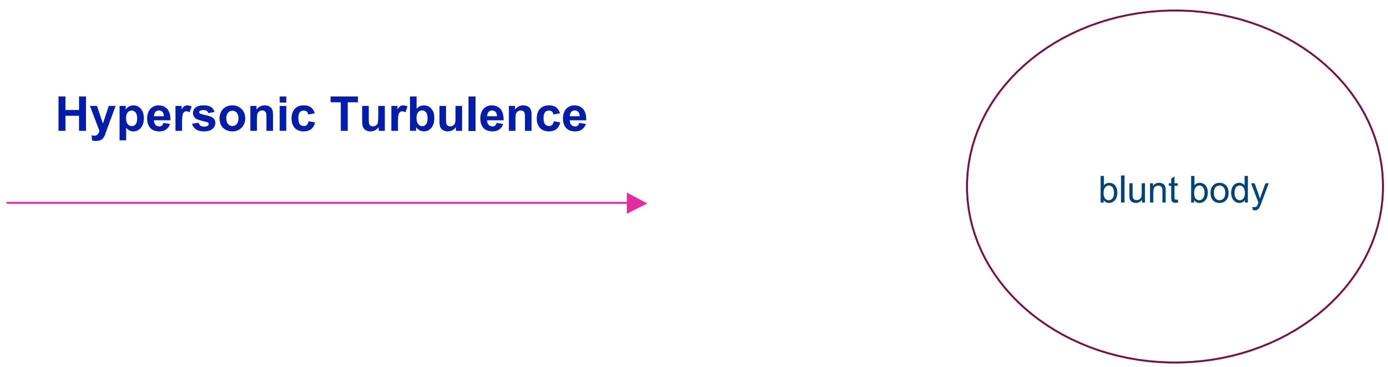


Grid resolution: 128 x 128 x 128


Iso-surface of entropy
R.Srinivasan
AERO, TAMU
Fuel injector


0.00 3.89 7.78 11.67 15.56 19.44 23.33 27.22 31.11 35.00
R. Srinivasan
AERO, TAMU
Y/D
Z/D
-3 -2 -1 0 1 2 3
0 1 2 3

Blunt Body Simulations



- **Excitation of internal degrees of freedom (rotation, vibration, etc)**
- **Direct Numerical Simulations not feasible:**

  → **Large Eddy Simulations + Modeling of small scales.**
- **Goal: Put forward a working model capable of capturing small scale physics.**

Speed Comparisons

The tests where performed using a Fortran serial code.
n = optimization level.

Cosmos	**Hydra**
128 sec, n=0	13.5 sec, n=0
5.7 sec, n=1	6.1 sec, n=2
2.8 sec, n=2	5.8 sec, n=3
2.4 sec, n=3	3.8 sec, n=4
	4.1 sec, n=5

Scalability tests

The tests where performed using a parallelized (MPI) Fortran code.
n = optimization level, p = number of processors

Cosmos n=1	**Cosmos** n=2	**Hydra** n=2	**Hydra** n=4
1 (p=1)	1 (p=1)	1 (p=1)	1 (p=1)
2.02 (p=2)	2.04 (p=2)	1.92 (p=2)	1.94 (p=2)
2.97 (p=3)	3.18 (p=3)	2.95 (p=3)	2.90 (p=3)
3.96 (p=4)	3.5 (p=4)	3.86 (p=4)	3.86 (p=4)
4.91 (p=5)	4.4 (p=5)	8.18 (p=8)	7.9 (p=8)
5.90 (p=6)	6.09 (p=6)	17.2 (p=16)	15.0 (p=16)
		32.6 (p=32)	28.4 (p=32)
		62.1 (p=64)	62.3 (p=64)