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Analysis of supersonic combustion of a model scramjet using direct-numerical simulation

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UK Hypersonics: Status, Barriers, and Opportunities
Cosener's House, Abingdon, 6th September 2023

Outlines

- Background
- CFD code
- Computational setup
- Result & Discussion

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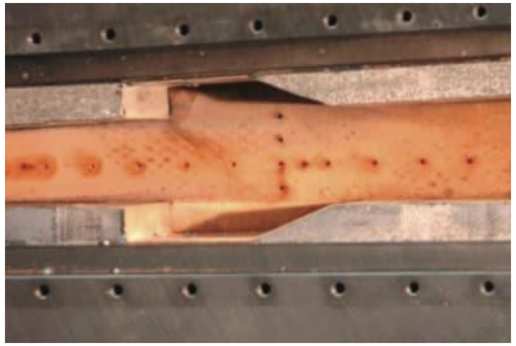
Background

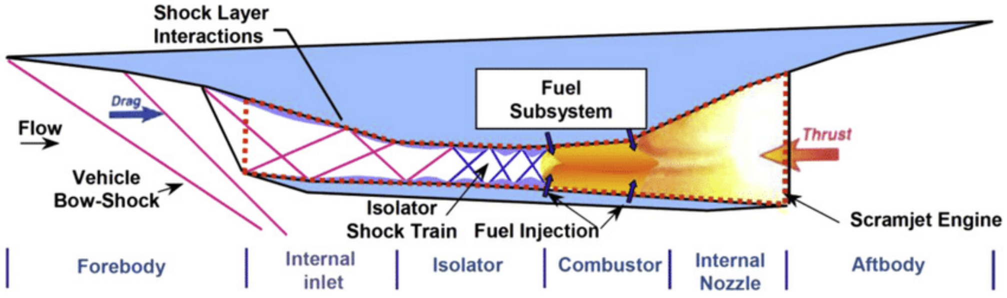
- Supersonic Combustion ramjet has been studied for many years as the propulsion system of hypersonic vehicles.

- The understanding of the flow physics caused by the interaction among shock-wave, turbulence, and flame in an internal flow over a cavity is important for the design of a scramjet combustor.

- Cavity flame holder:
  - ❖ Low-speed, high-temperature recirculation areas
  - ❖ Generate free radicals in the subsonic region
  - ❖ Have minimal impact on supersonic core flow

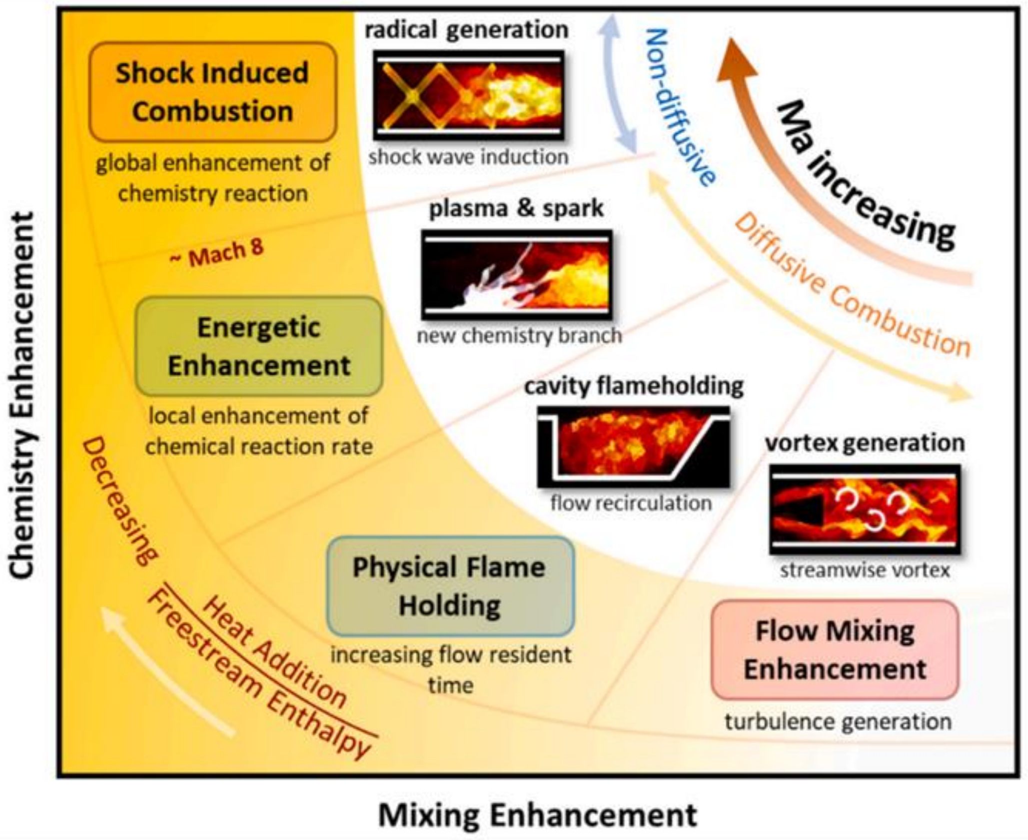


The Dual-Cavity combustor of the scramjet combustor tested in U.S. Air Force Research Laboratory



A model air-breathing hypersonic vehicle

Source: Bowcutt K. Hypersonic vehicles. In: Access science. McGraw-Hill Companies, 2009

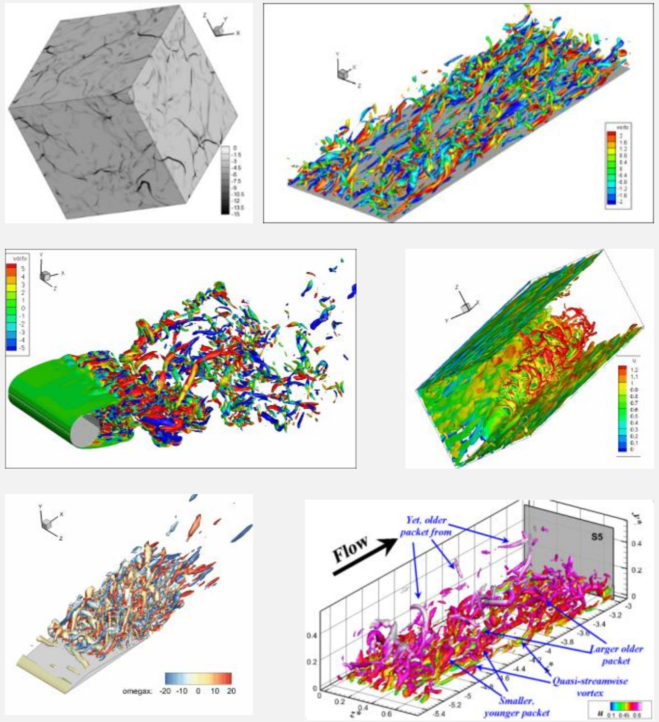


Liu, Q. et al. (2020). Prog. Aerosp. Sci. 119, 100636.

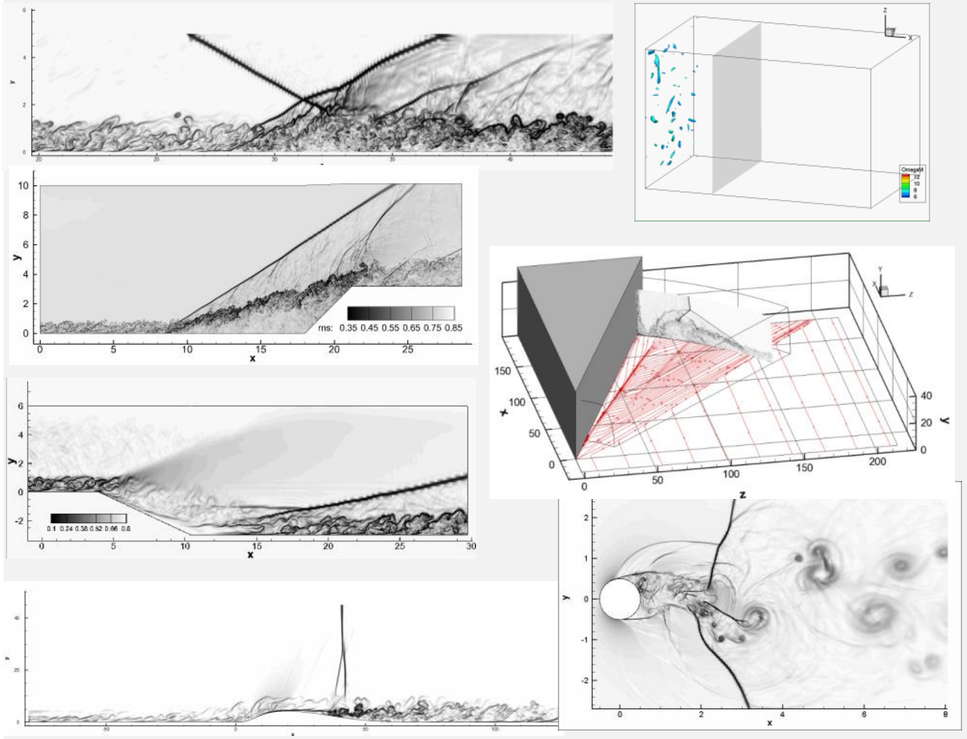
CFD software development

ASTR

- **Advanced flow-Simulator for Turbulence Research**
- Compressible flow solver
- High-order FDM
- Structured mesh
- High-order compact shock-capturing scheme



Turbulence Study



Turbulence with Shock-waves

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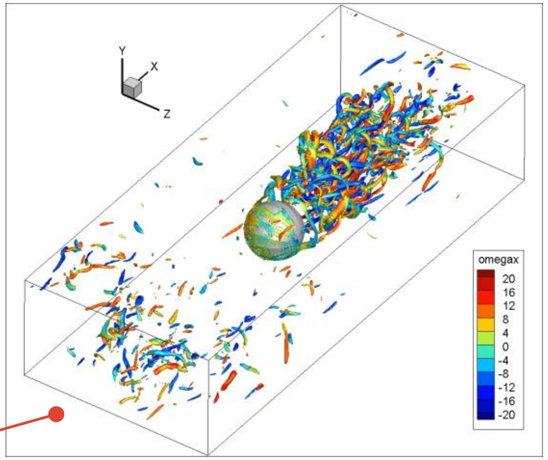
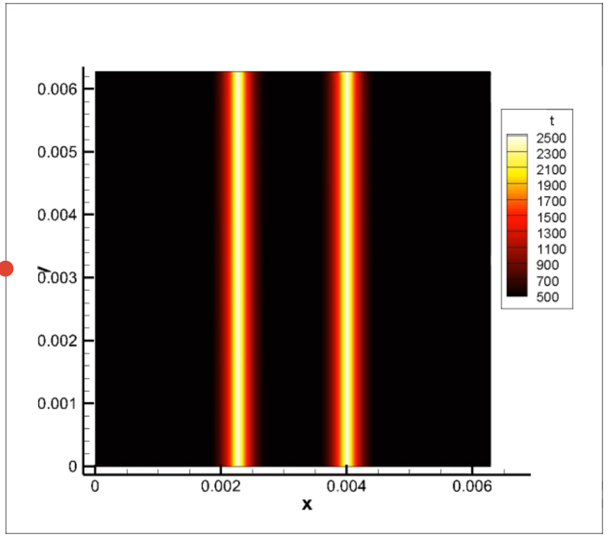
CFD software development

ASTR

- **High-speed, complex geometry, multi-physics problems**
- Compressible flow solver
- High-order FDM
- Structured mesh

✓ Object-oriented FORTRAN
✓ User-defined transport equations (5+x equations)
✓ Parallel HDF5 I/O
✓ Crash control
✓ Fully compact
❖ Immersed boundary
❖ Chemical reaction
❖ Machine-learning model
❖ Method of Moment
○ Multi-block mesh
○ Adaptive mesh refinement





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Chemical reaction

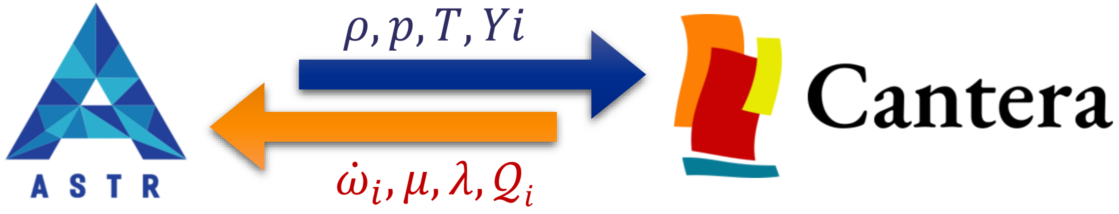
$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \left(\rho u_i u_j + p\delta_{ij}\right)}{\partial x_j} = \frac{\partial \sigma_{ij}}{\partial x_j}$$

$$\frac{\partial \rho e}{\partial t} + \frac{\partial (\rho e + p) u_j}{\partial x_j} = \frac{\partial \left(\sigma_{ij} u_i - q_j\right)}{\partial x_j} + \boxed{\dot{Q}}$$

external heat source term

$$\frac{\partial \rho Y_i}{\partial t} + \frac{\partial \left(\rho u_j Y_i\right)}{\partial x_j} = \frac{\partial \left(\rho D_i \frac{\partial Y_i}{\partial x_j}\right)}{\partial x_j} + \boxed{\dot{\omega}_i}$$

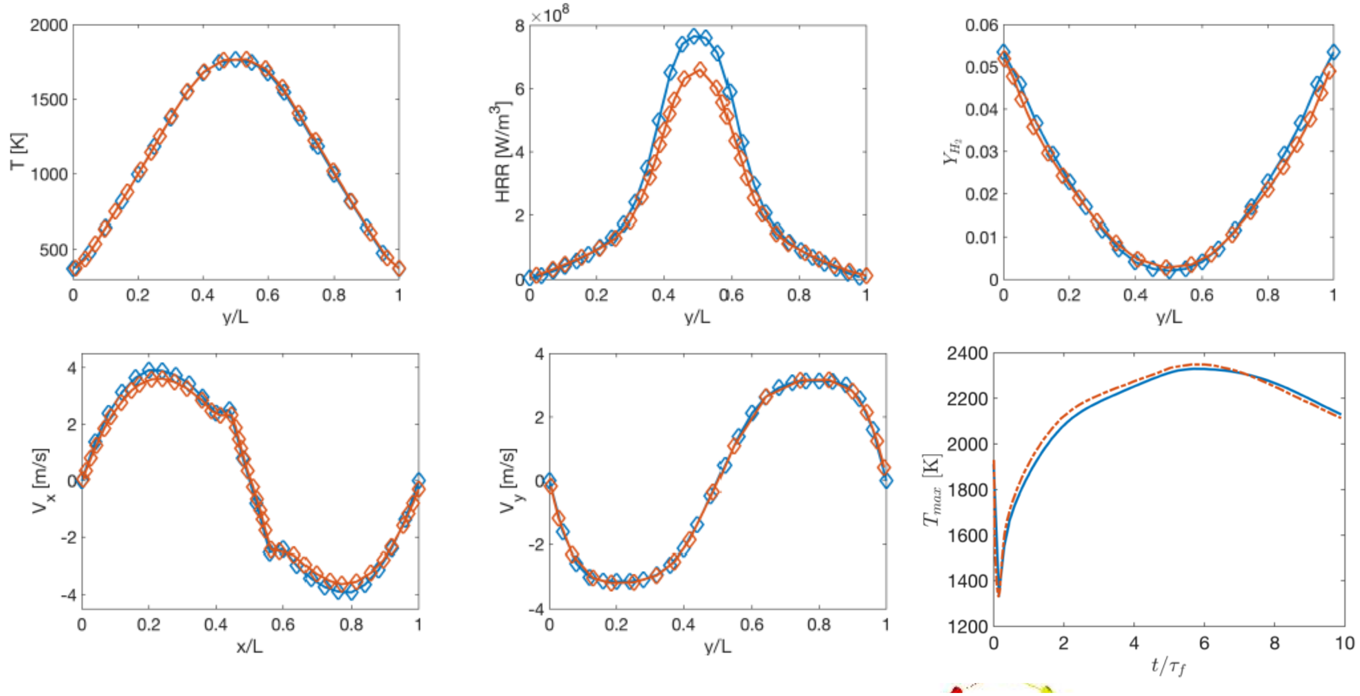
mass based chemical source term of species



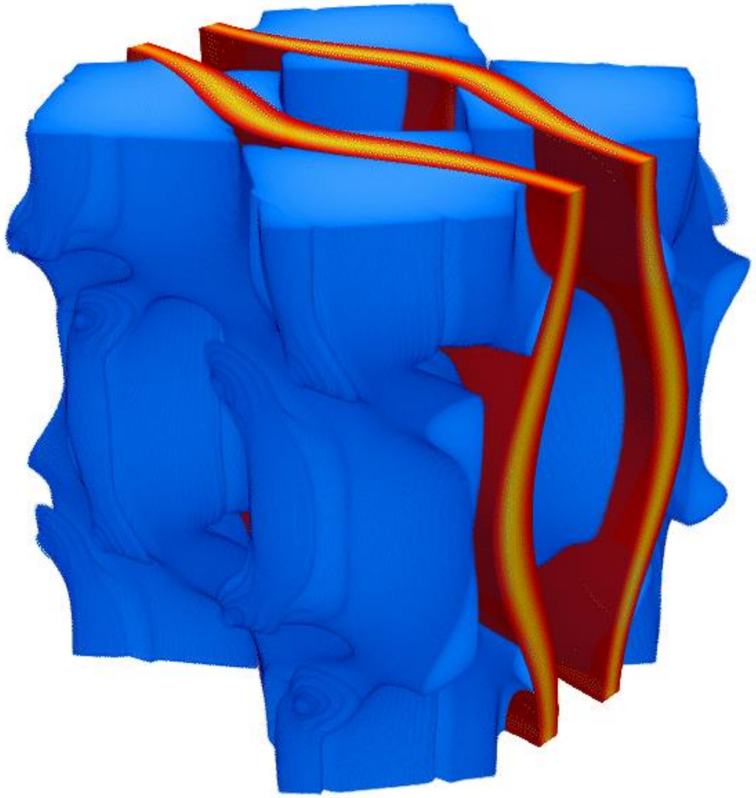
ASTR: an open-source high-order compressible flow solver

Cantera: an open-source chemical kinetics software.

TGV-flame



Comparison of ASTR and NEK5000



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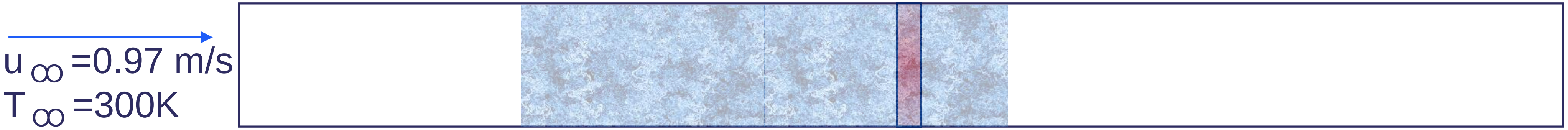
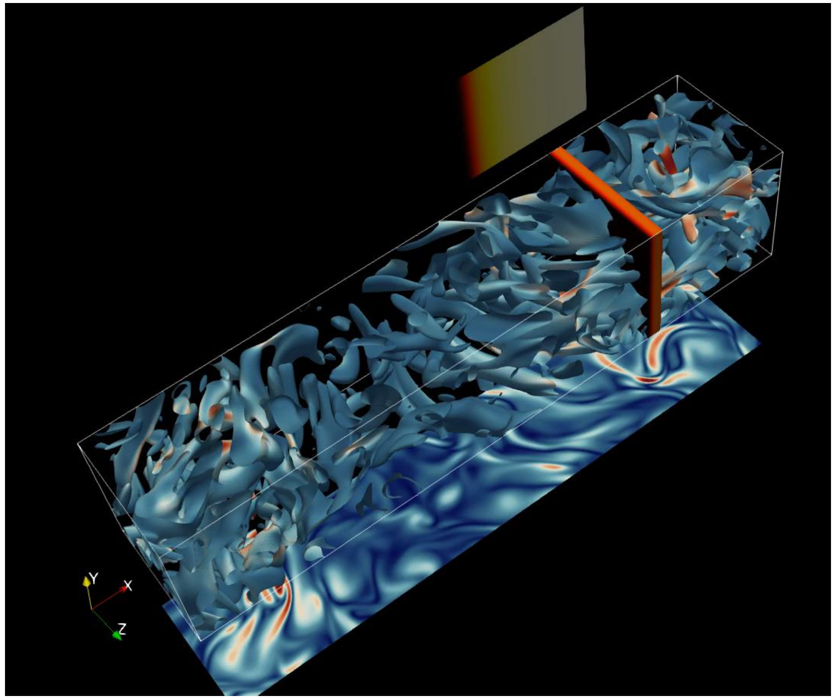
Y. Xu, and Z. X. Chen, Direct numerical simulations of the Taylor-Green Vortex interacting with a hydrogen diffusion flame: Reynolds number and non-unity Lewis number, Physics of Fluids, (2023).

1-D flame/turbulence interaction

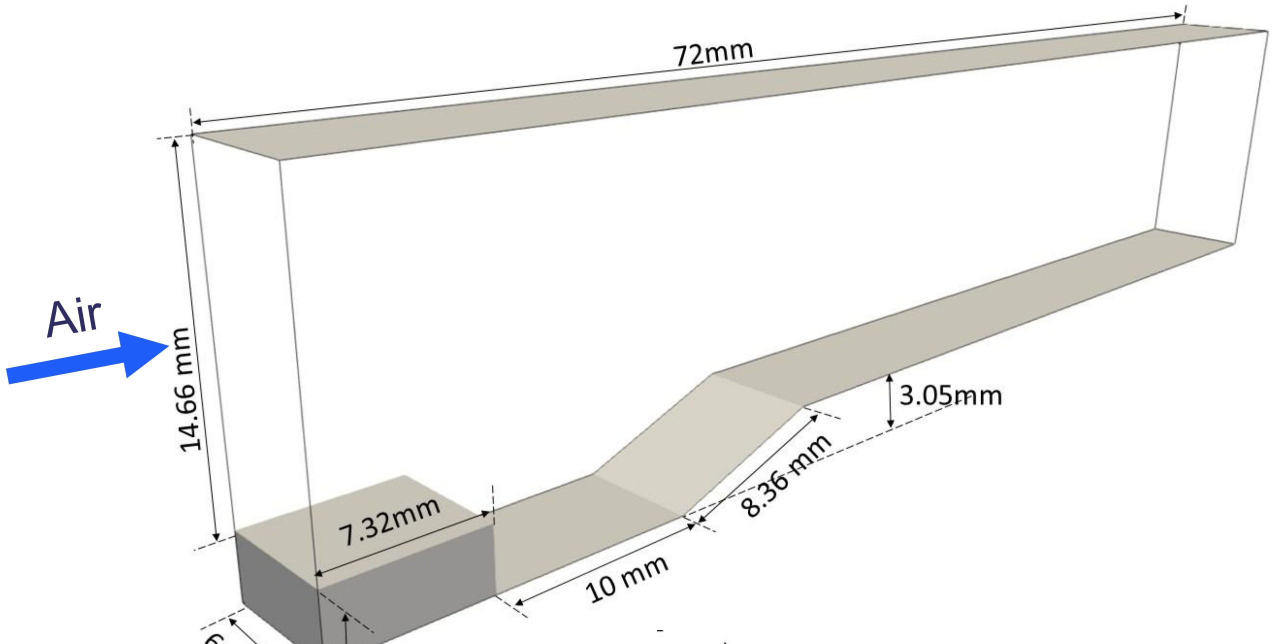


u_{∞} =0.97 m/s
T_{∞} =300K
p_{∞}=101325Pa
v=w=0

p_{out}=101325Pa

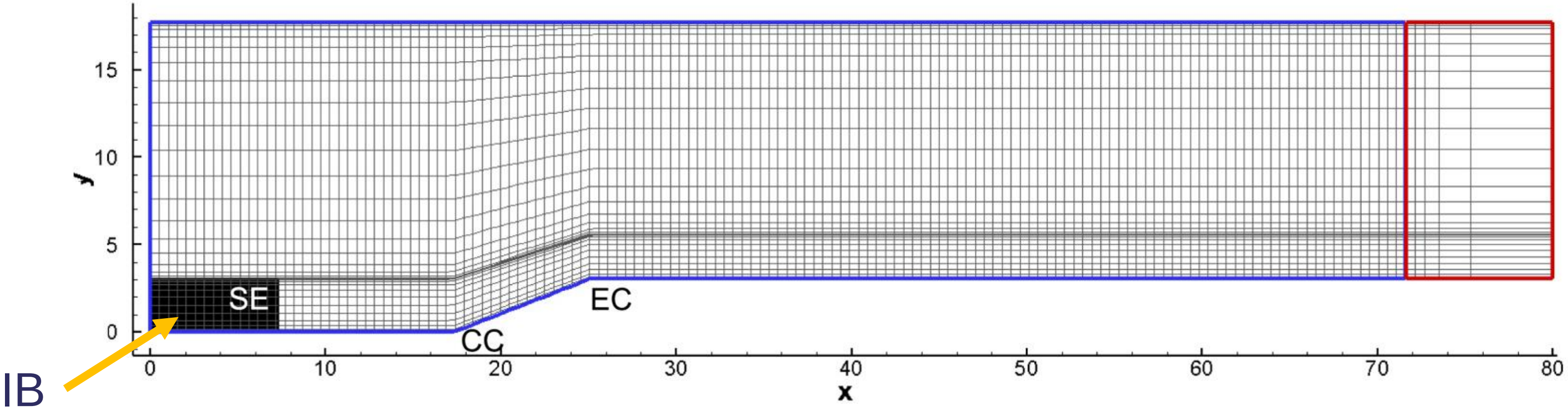


Computational setup



- u_∞=951 m/s; Ma=1.5
- p_∞=50,060 Pa; T_∞=1,000 K
- δ=1.47mm;
- Re=4×10^6 /m; Re_δ =5,871

- MP7-LD + CC6 + RK3



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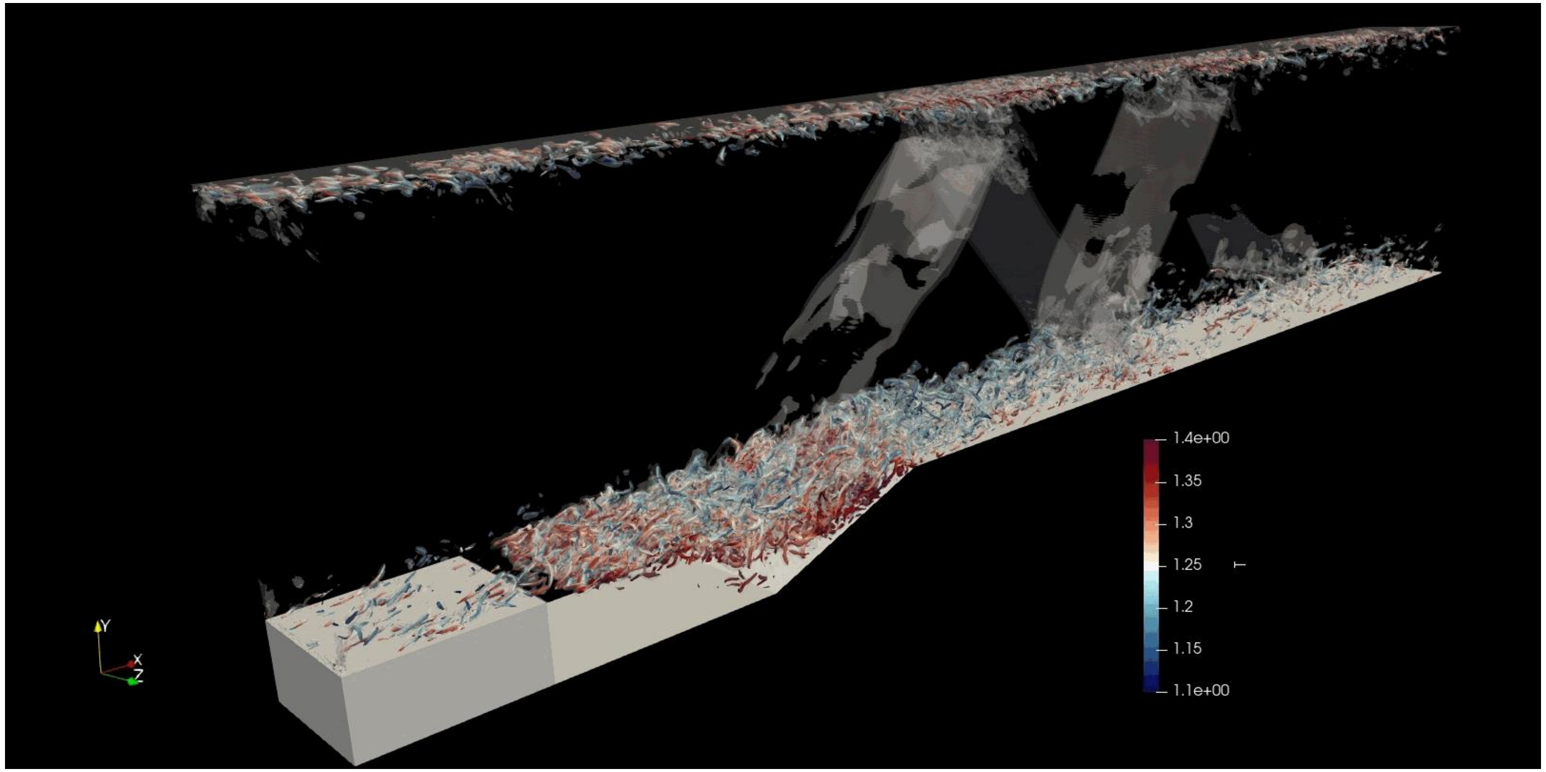
Results at cold condition



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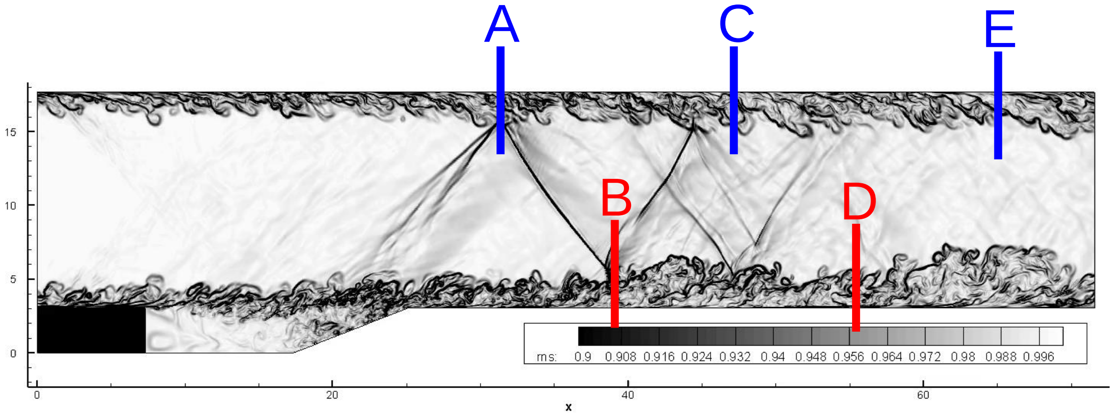

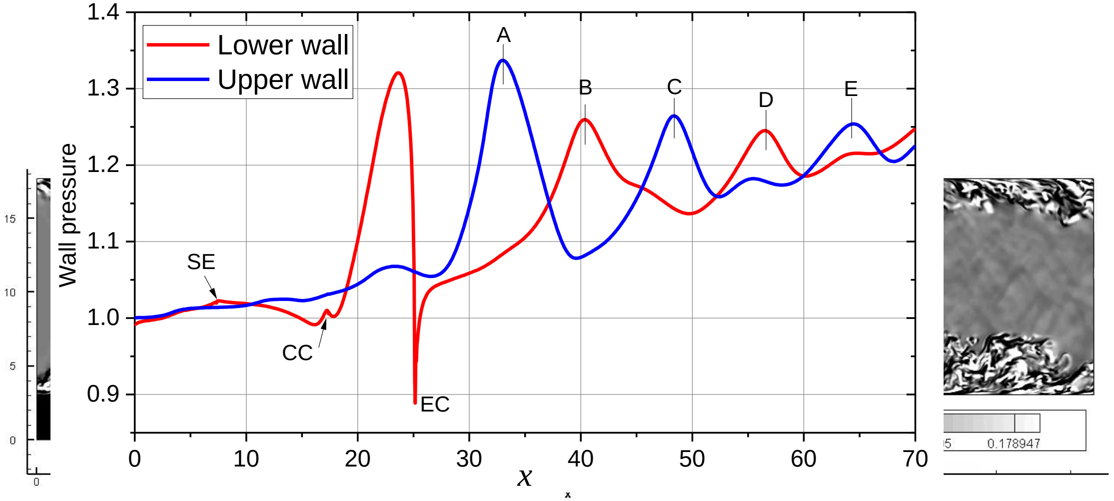

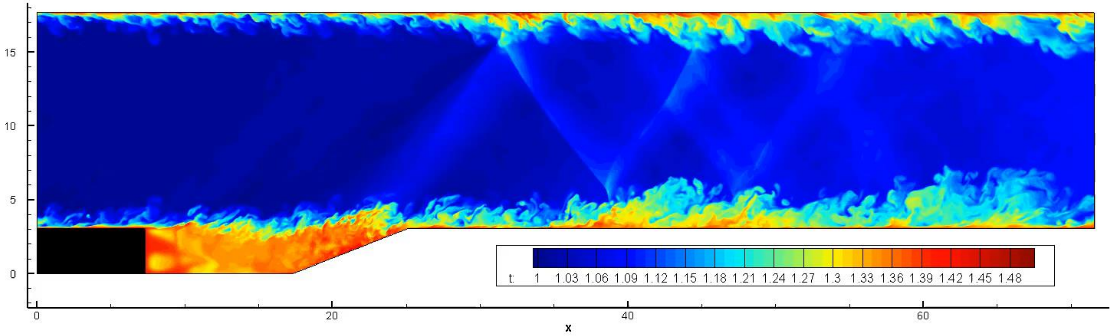

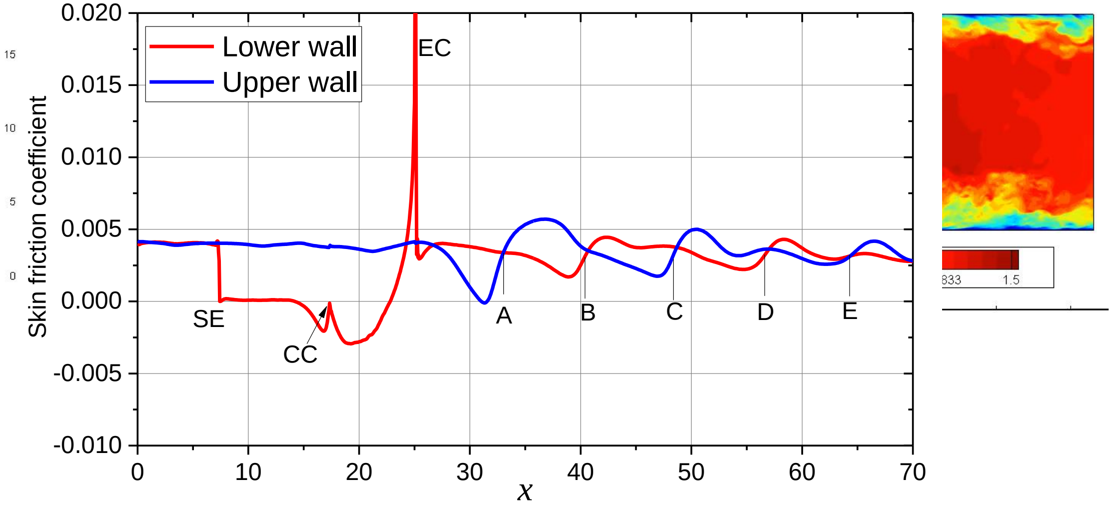

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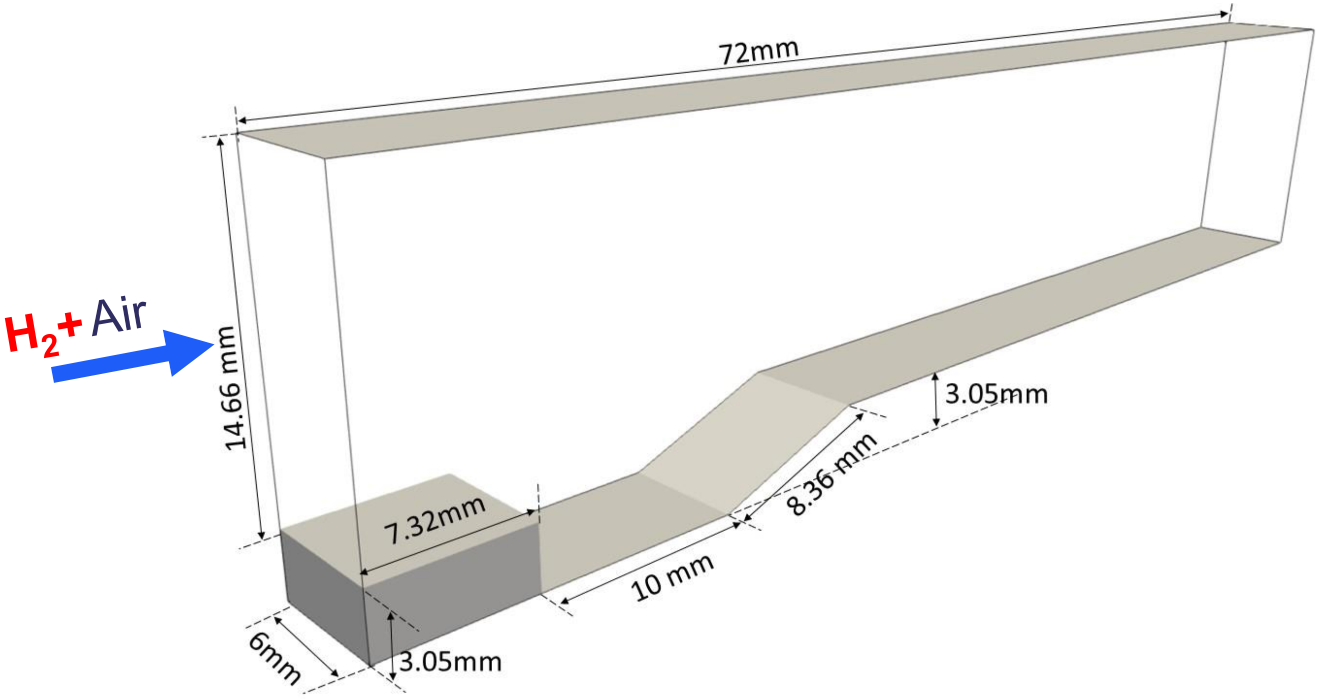
- J. Fang, X. Deng, and Z. X. Chen, Direct numerical simulation of supersonic internal flow in a model scramjet combustor under a non-reactive condition, Physics of Fluids 35, 26103, (2023).

Results at hot condition



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- MP7-LD + CC6 + RK3

H_2	O_2	N_2	$H/OH/O/H_2O/HO_2/H_2O_2$
0.87%	23.09%	76.04%	<0.01%

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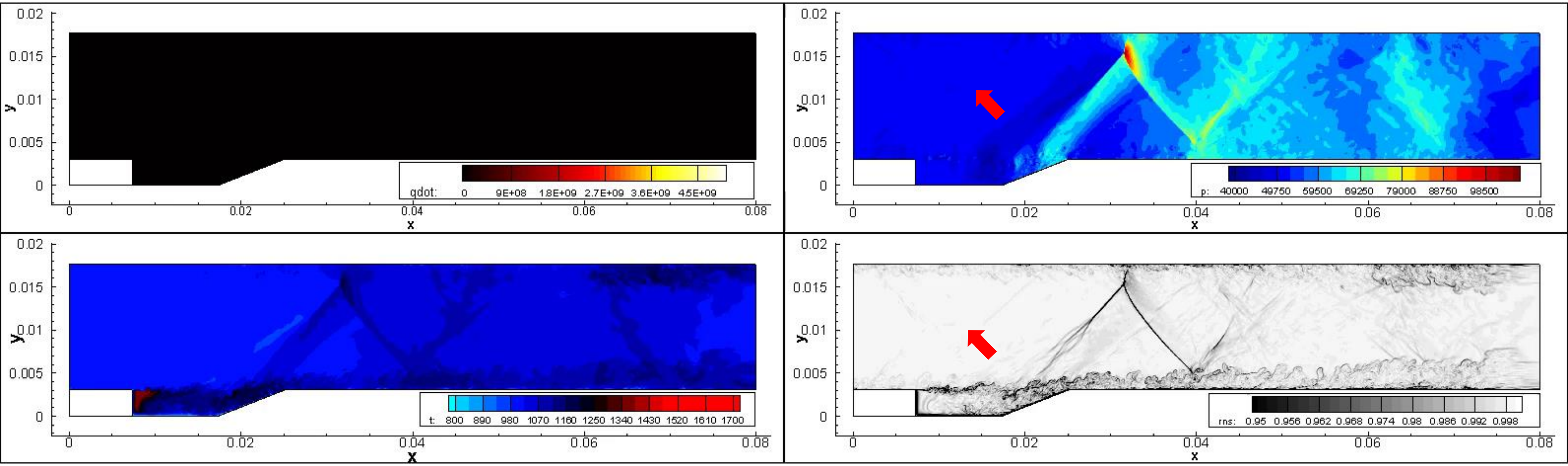
Results at hot condition



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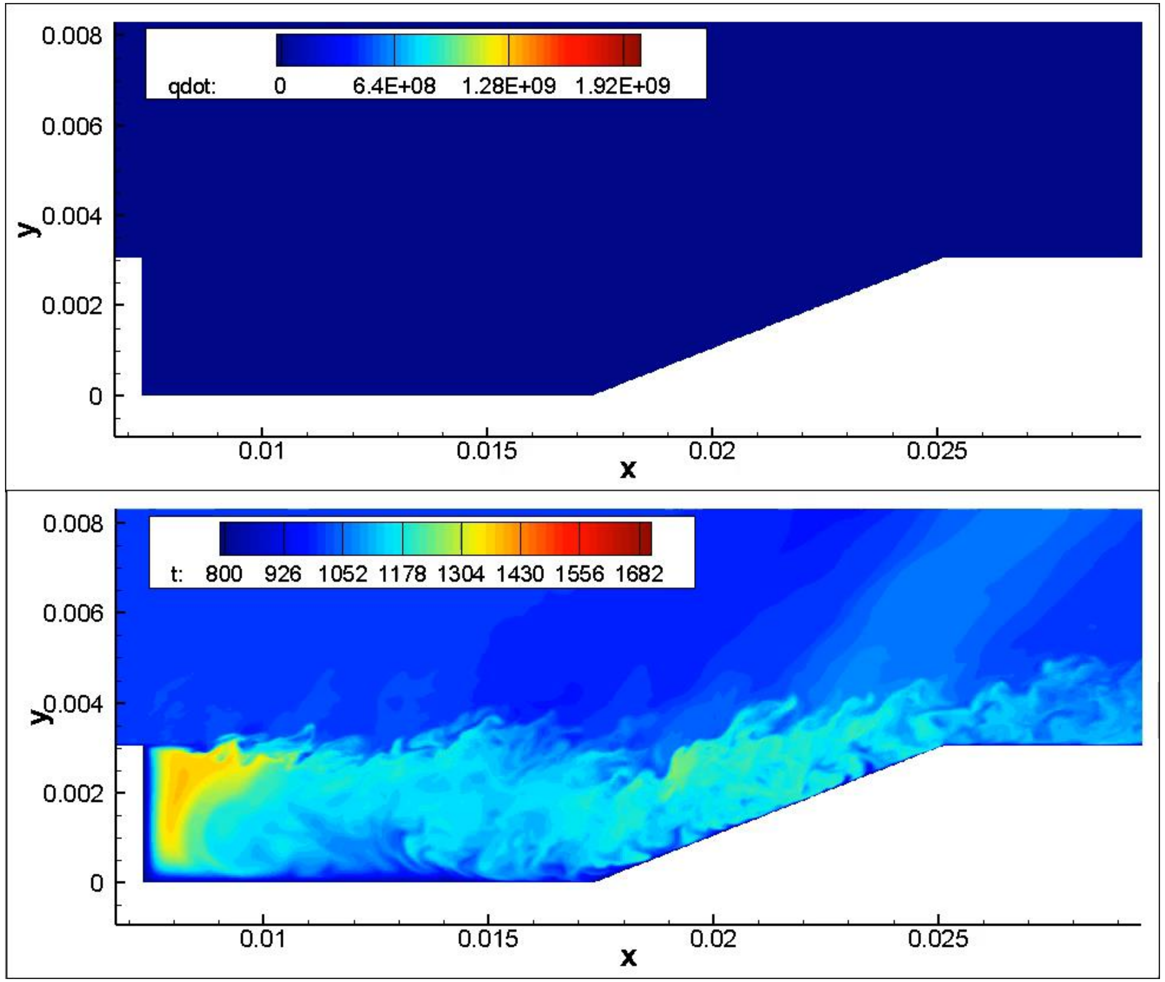
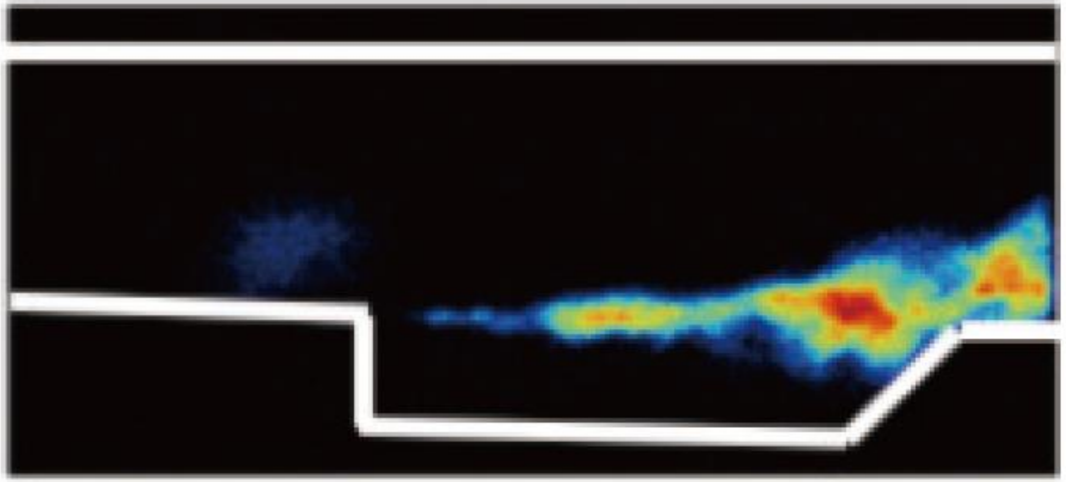
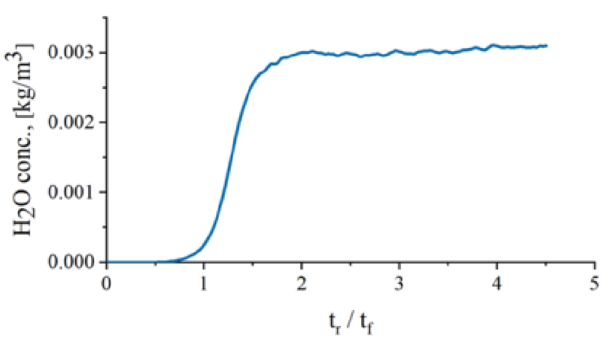
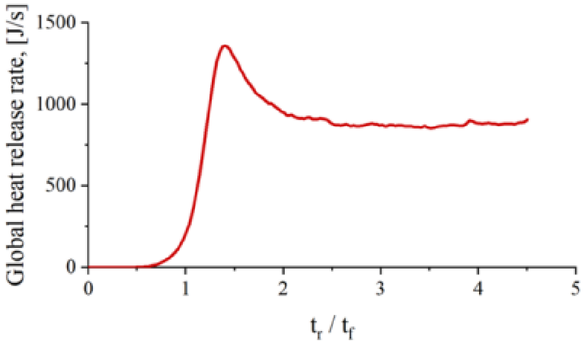
Results at hot condition





Experimental CH* luminosity image of Li et al. (2022)





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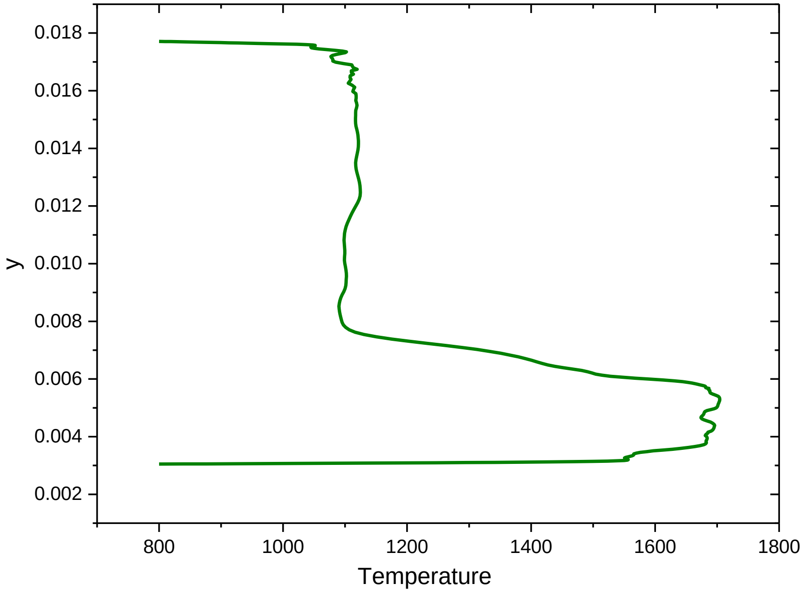
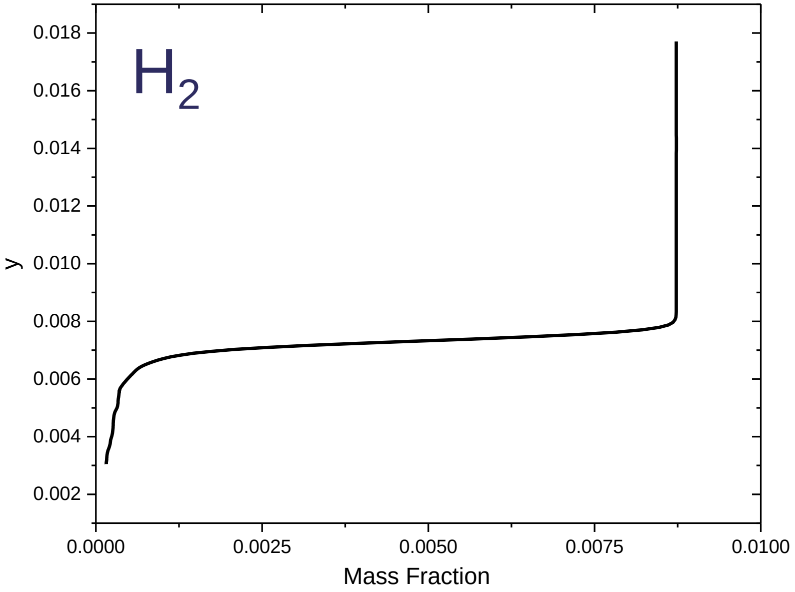
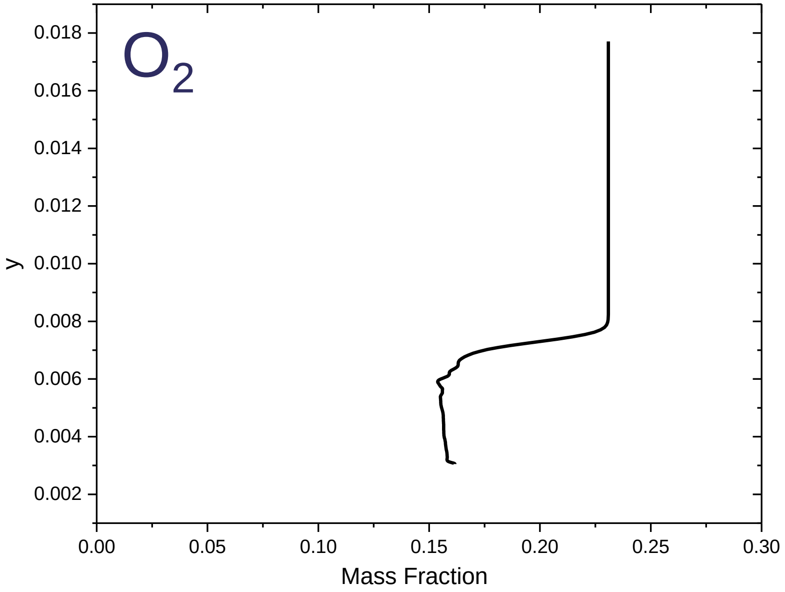
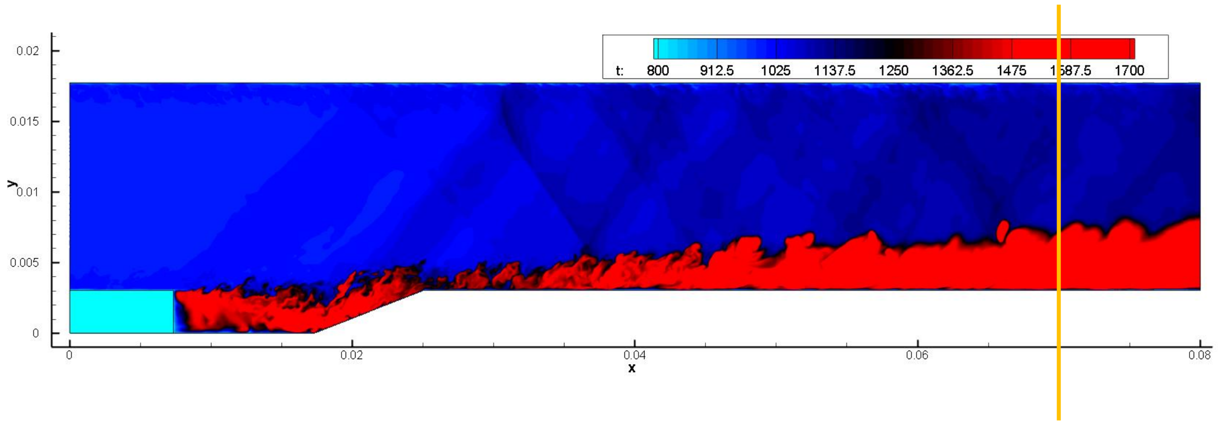
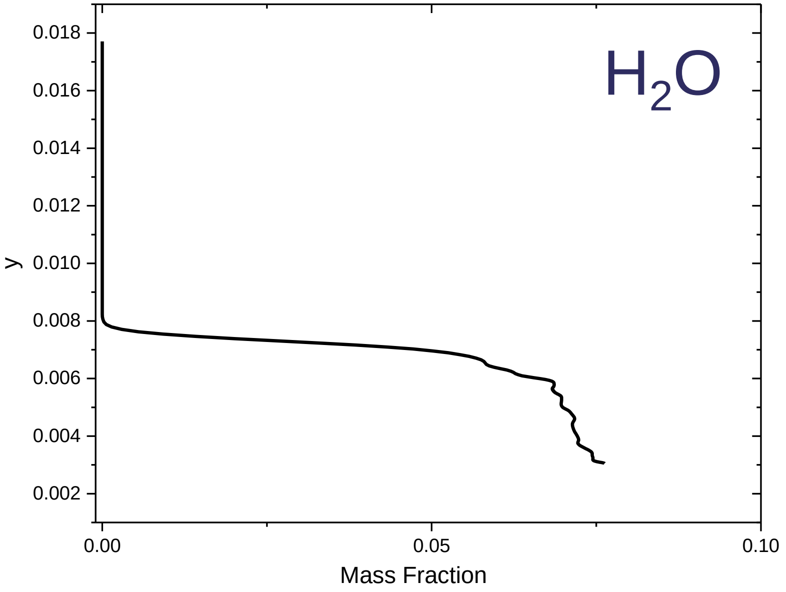
Results at hot condition



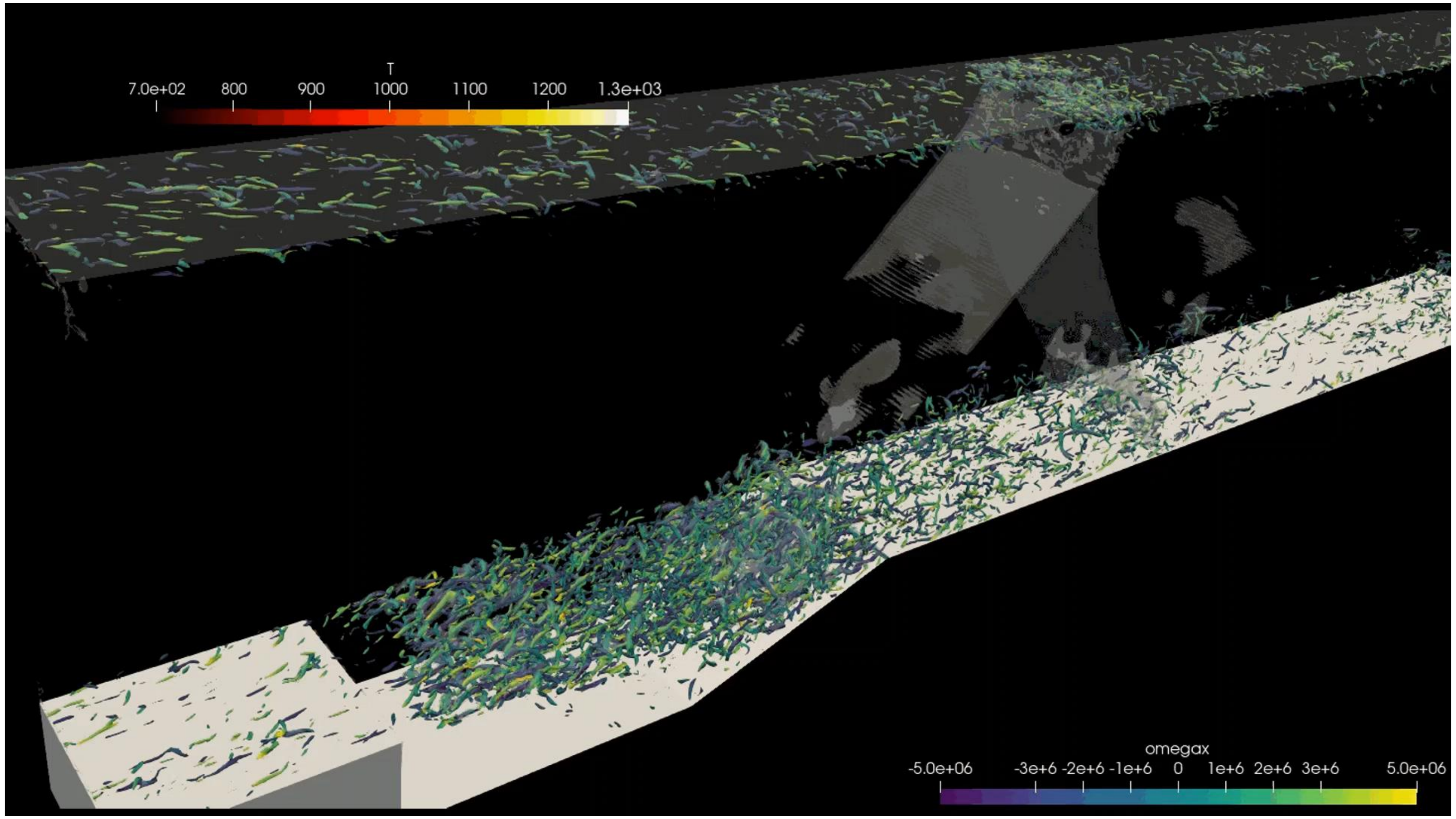








Results at hot condition



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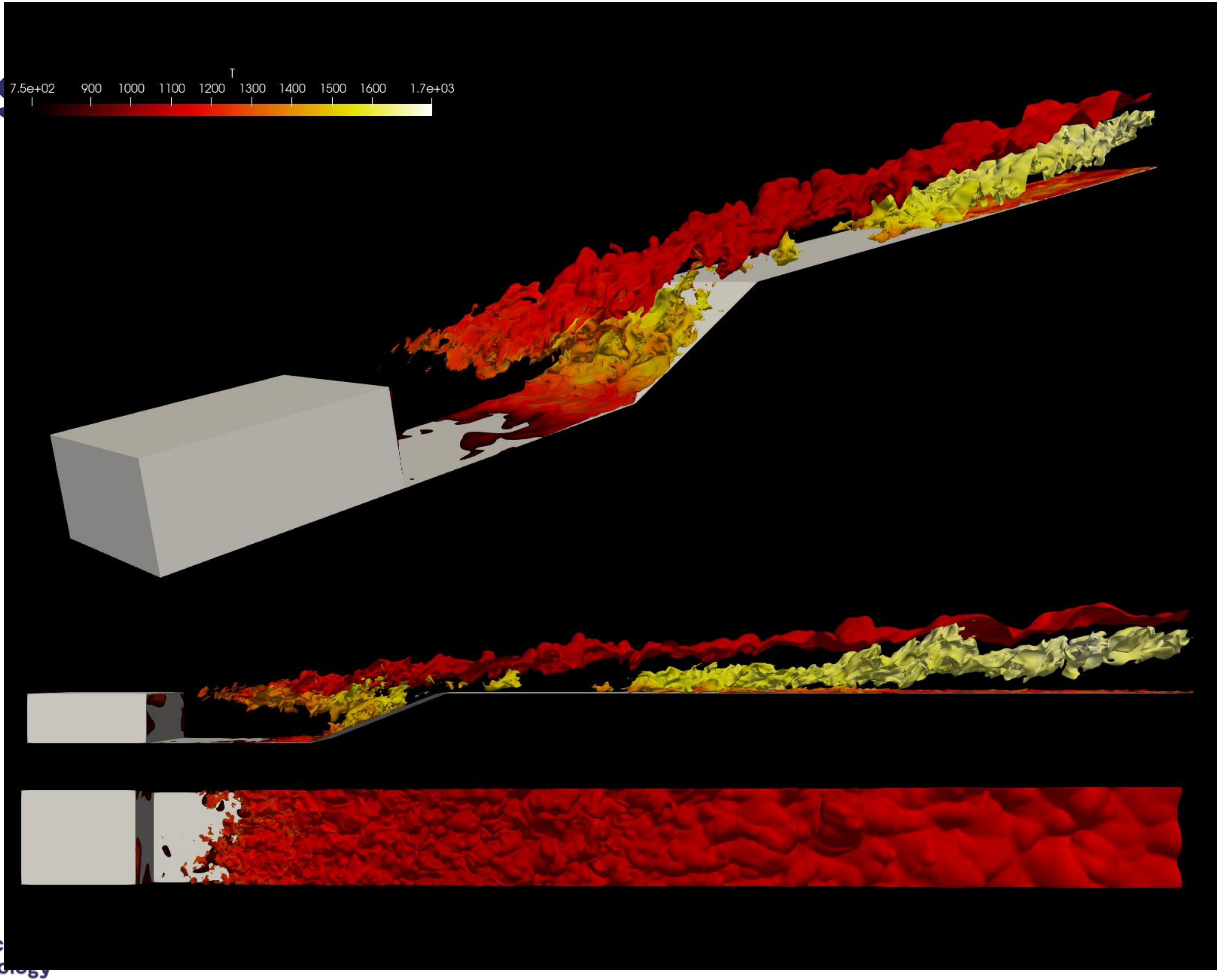
Results



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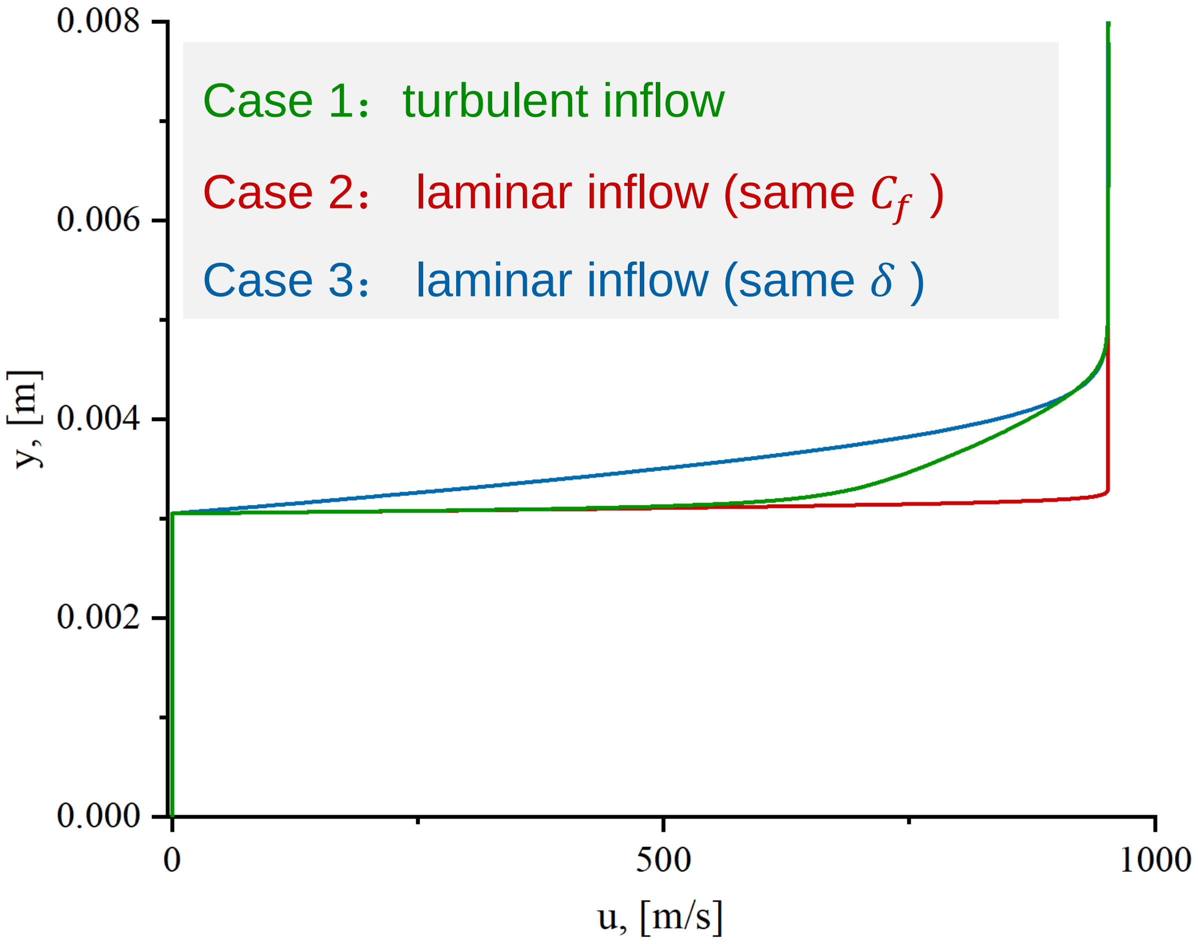
Impacts of inflow boundary layer



Inflow <mean> velocity profile

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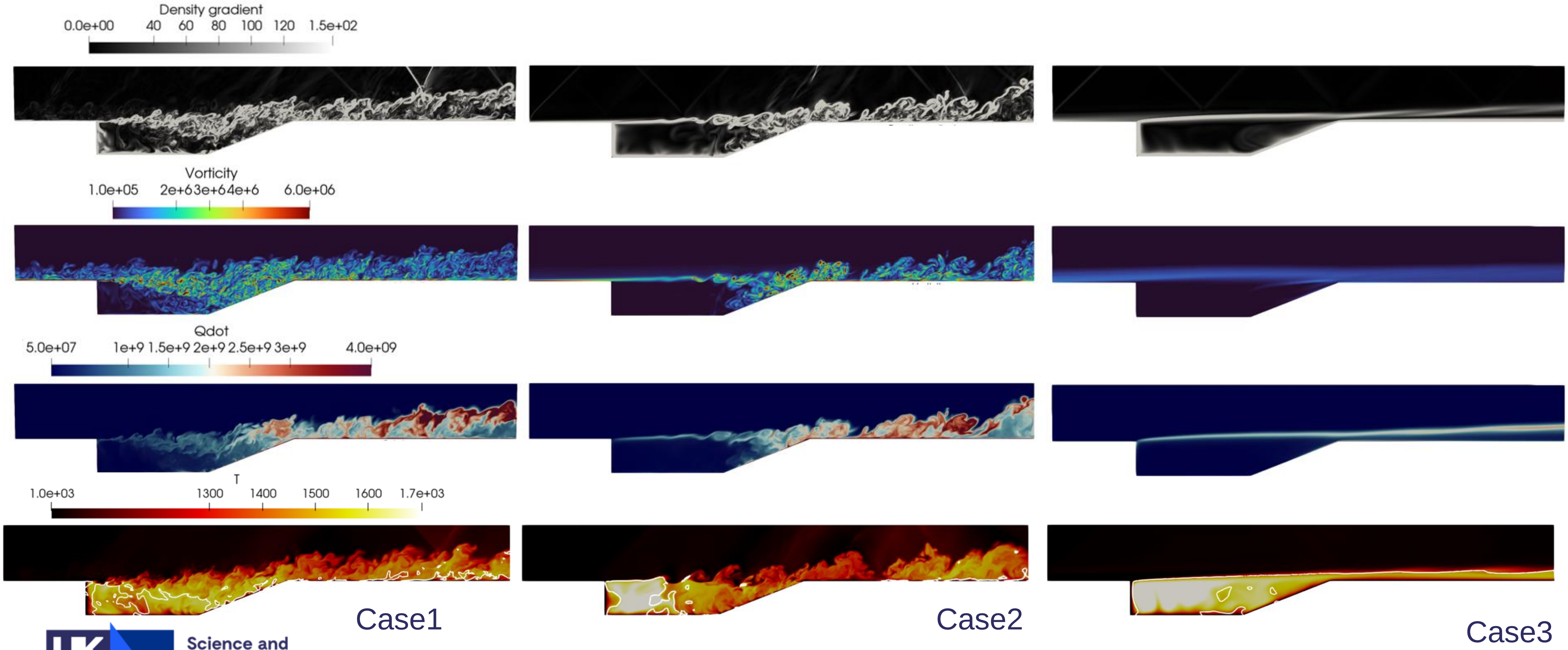
Impacts of inflow boundary layer



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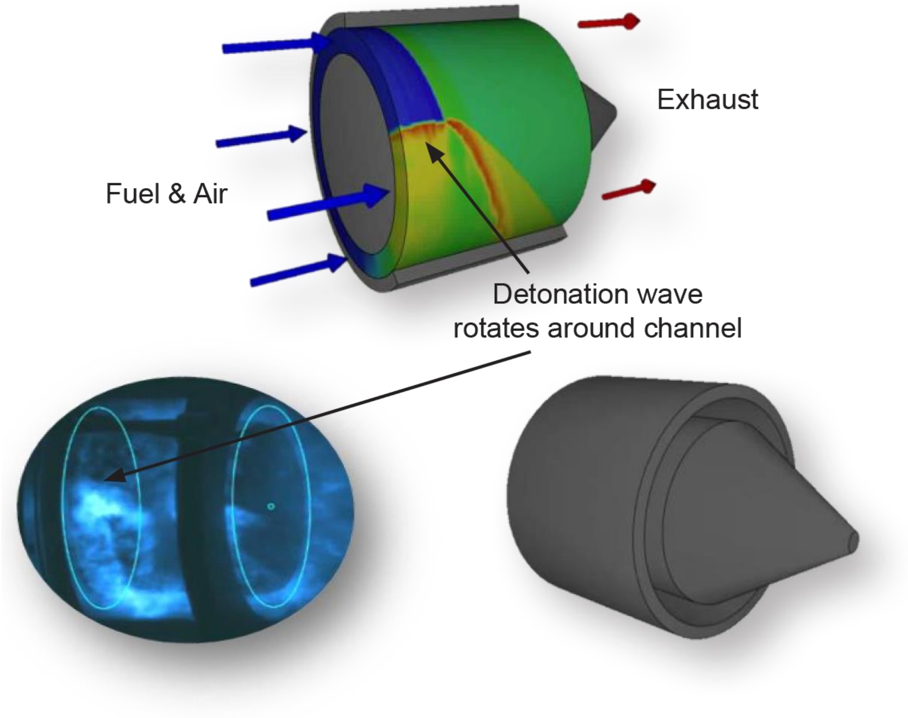
Summary

- The IBM and Reaction capabilities have been enabled in the ASTR code.
- A series of DNS of Ma=1.5 flow in a model combustor of a scramjet have been conducted.
- The preliminary analysis has shown some interesting phenomena involving the interaction among shock-wave, turbulence and flame.
- The impact of inflow boundary layer is analysed:
  - Inflow turbulence leads to larger flame surface and reaction zone, with stronger mass exchange and transport process, but also greater cavity drag.
  - For laminar inflow cases, the shear strength shows a great influences on the shear-layer structures and the characteristics of reaction zone.

Future plans

- To analysis the close coupling between shock-wave, flame and turbulence, such as the combustion in a Rotating Detonation Engine (RDE) engine



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https://afresearchlab.com/technology/rotating-detonation-engines-rde/

Acknowledgement

- The research is support by the EPSRC through CoSeC, and the UK Turbulence Consortium (EP/R029326/1).
- The simulation were conducted on ARCHER2, and the computing time is awarded via the UKTC.