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UNIVERSITÀ DEGLI STUDI DI PADOVA

High fidelity simulations of high speed flows for aerospace problems

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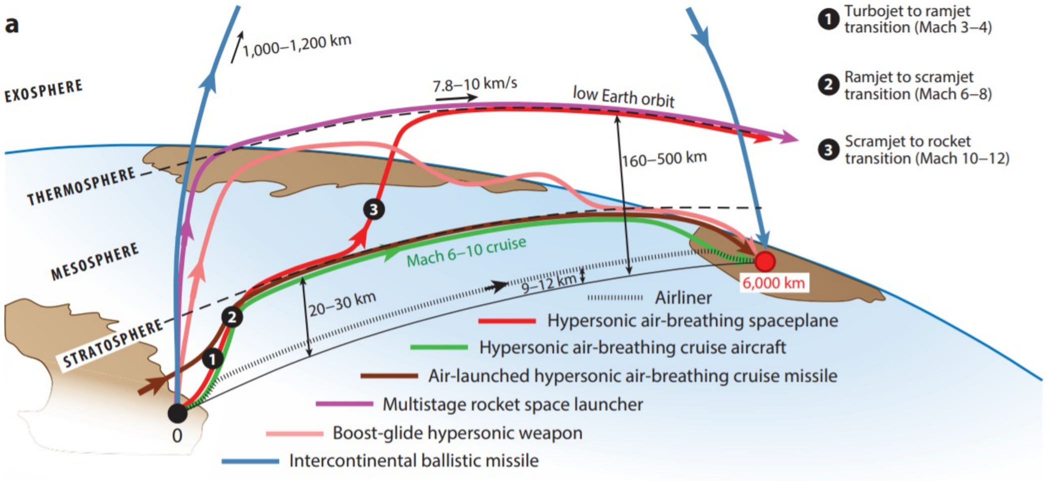
Admission to the second year - 05/09/2022

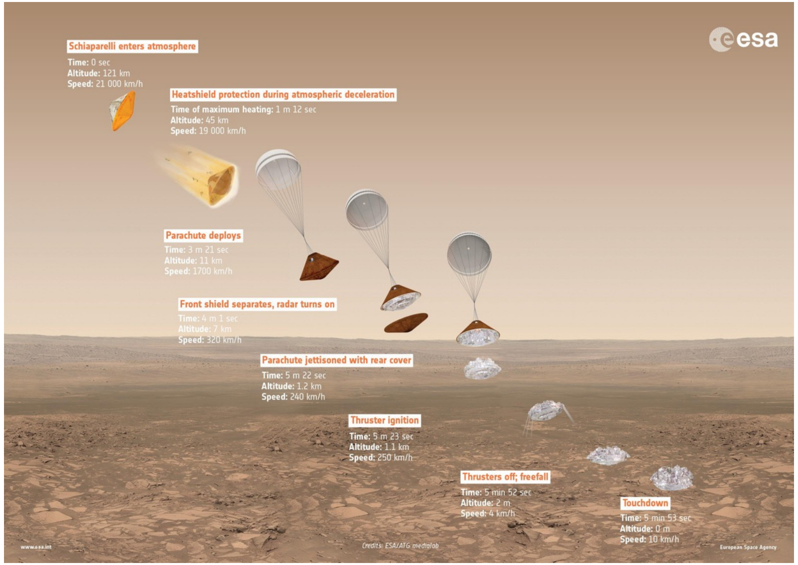
High-speed flows:

Flight trajectories on Earth…

…and reentry on Mars



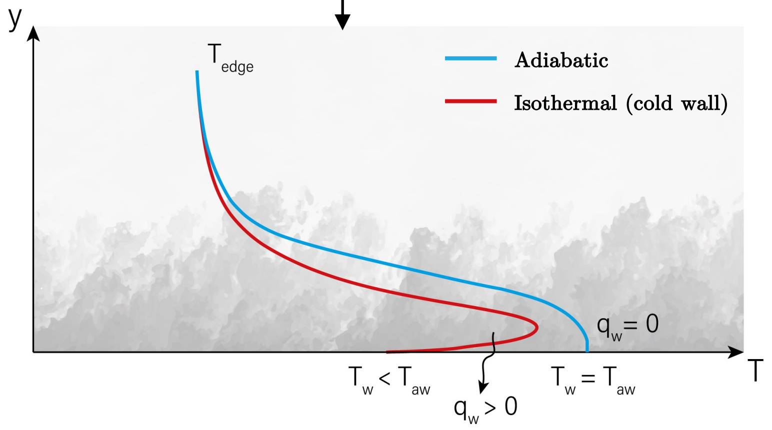
Adapted from Urzay, Annual Review of Fluid Mechanics [2018]

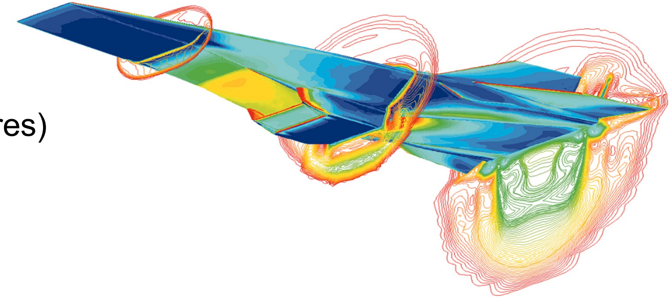


ESA website

Main features of high-speed flight at low altitudes:

- High Reynolds number (turbulent boundary layers)
- High freestream Mach numbers (intense shocks and large recovery temperatures)
- Aerodynamic heating (large thermal fluxes)





Source: NASA website

The presence of turbulent, hot and highly compressible boundary layers increase the mechanical and thermal loads on the vehicle!

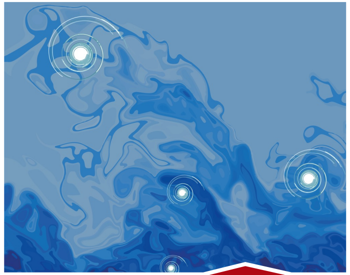
<u>A detailed description of the flow dynamics is essential to predict drag and thermal fluxes</u>

Task #1: Objectives

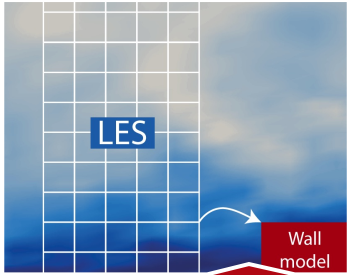
First task: Simulation of supersonic and hypersonic turbulent boundary layers over smooth wall with Direct Numerical Simulation (DNS)

Higher Reynolds number where considered than what is available in literature:

More representative of real cases



Greater separation of turbulent scales



Essential to improve wall models

Objectives of this study:

- Address the Mach and Reynolds numbers effect on instantaneous and mean properties of the flow
- Expand the range of validation of theoretical transformations and relations to higher *Re*
- Investigate the spatial organization of turbulent structures and thermal energy

Computational setup

Solver	Numerical method	Numerical schemes
STREAmS (Bernardini et al. CPC 2021): • Open-source numerical solver for compressible flows • Supports MPI parallelization and multi-GPU architectures	Direct Numerical Simulation: • Navier-Stokes equations are solved with very high temporal and spatial resolution, down to the Kolmogorov scale • No model is employed	State-of-the-art numerical schemes : • Convective terms: hybrid energy-conservative shock-capturing scheme + sixth-order energy consistent flux • Viscous terms: sixth-order schemes expanded in Laplacian form

Navier-Stokes equations in the conservative formulation:

$$\frac{\partial \mathbf{U}}{\partial t} = -\frac{\partial \mathbf{F_j}(\mathbf{U})}{\partial x_j} + \frac{\partial \mathbf{F_{\nu j}}(\mathbf{U})}{\partial x_j}$$

$$\mathbf{U} = \begin{bmatrix} \rho \\ \rho u_j \\ \rho E \end{bmatrix} \quad \mathbf{F_{\nu j}}(\mathbf{U}) = \frac{\sqrt{\gamma} M_\infty}{Re} \begin{bmatrix} 0 \\ \sigma_{ij} \\ \sigma_{ij} u_j - \frac{1}{Pr}\frac{\gamma}{\gamma-1} q_j \end{bmatrix} \quad \mathbf{F_j}(\mathbf{U}) = \begin{bmatrix} \rho u_j \\ \rho u_i u_j + p\delta_{ij} \\ \rho u_j H \end{bmatrix}$$

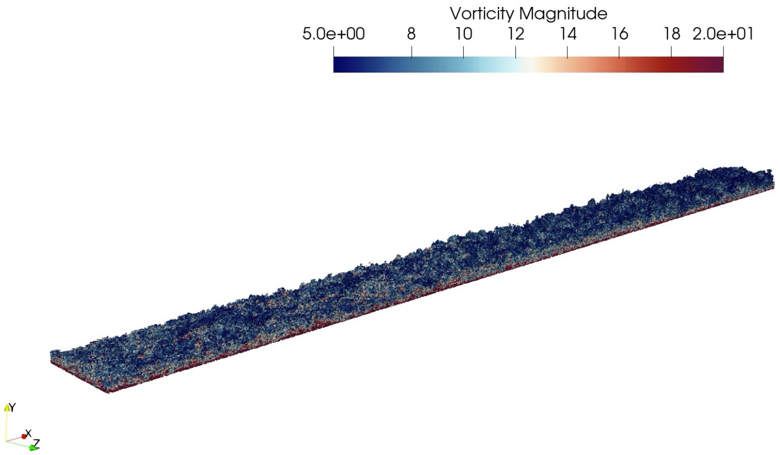
Calorically-perfect gas:

$$E = c_v T + u_i u_i / 2$$
$$H = E + p/\rho$$
$$p = \rho T$$

Task #1: Database

Four simulations have been performed:

- We addressed supersonic (M=2) and hypersonic (M=6) turbulent boundary layers
- Two Reynolds numbers where studied for each Mach number
- Every simulation falls in the *cold wall* case, $\frac{T_w}{T_r} < 1.$



Summary of parameter for DNS study

Run	M_∞	Re_τ	T_w/T_r	N_x	N_y	N_z
M2Tw076/1	2.00	340 – 620	0.76	4096	320	512
M2Tw076/2	2.00	1240 – 2300	0.76	16384	832	2048
M6Tw076/1	5.86	290 – 520	0.76	4096	320	512
M6Tw076/2	5.86	1080 – 1953	0.76	16384	832	2048

Task #1: Selected Results

- Intense gradients separate the turbulent region from the freestream flow
- Finer-scale features are present at high *Re*
- Acoustic radiation is significantly higher for hypersonic cases

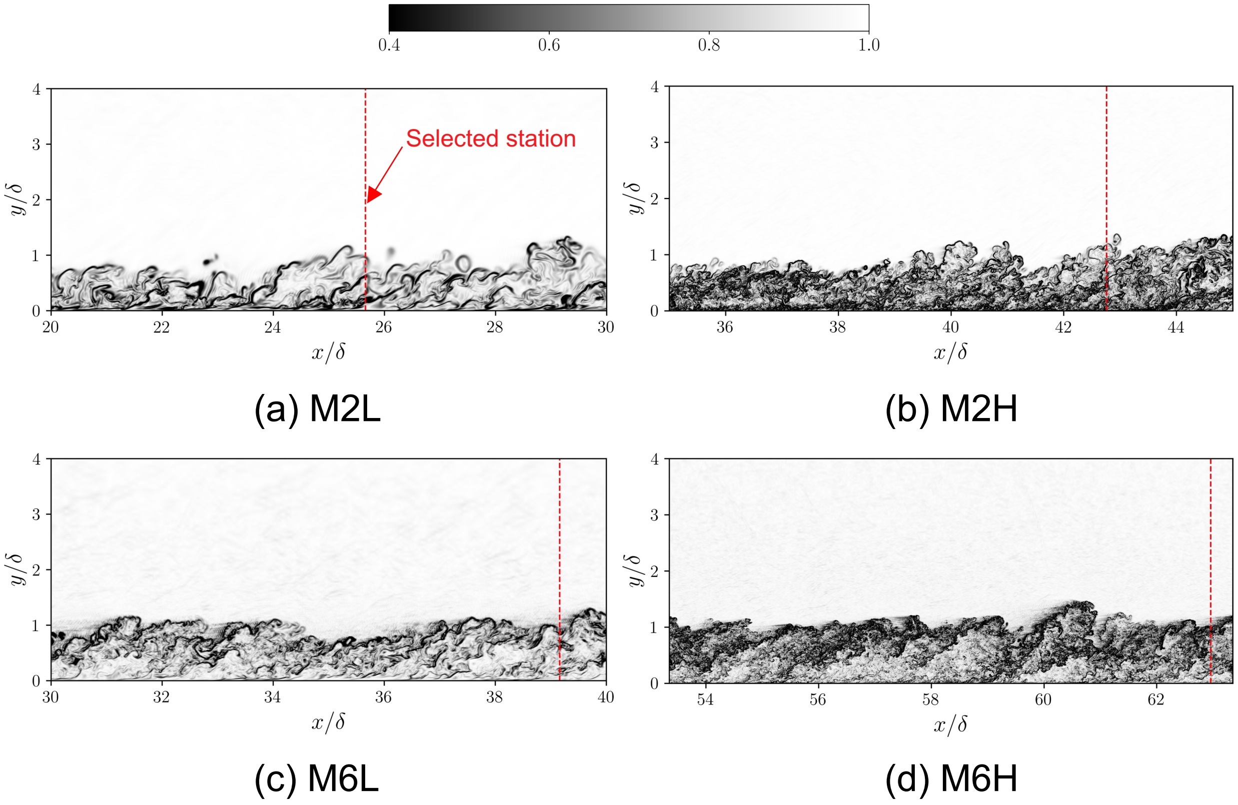
Boundary layer properties at selected stations

Station	Run	Re_τ	Re_θ	Re_τ^*
M2L	M2Tw076/1	453	1423	654
M2H	M2Tw076/2	1947	7562	3504
M6L	M6Tw076/1	453	5632	2815
M6H	M6Tw076 /2	1947	29349	14709

$$Re_\tau = \bar{\rho}_w u_\tau \delta / \bar{\mu}_w; \; Re_\theta = \rho_\infty u_\infty \theta / \mu_\infty;$$

$$Re_\tau^* = \sqrt{\rho_\infty \tau_w} \delta / \mu_\infty$$

Contours of the instantaneous field of density gradient in a streamwise wall-normal plane



Task #1: Selected Results

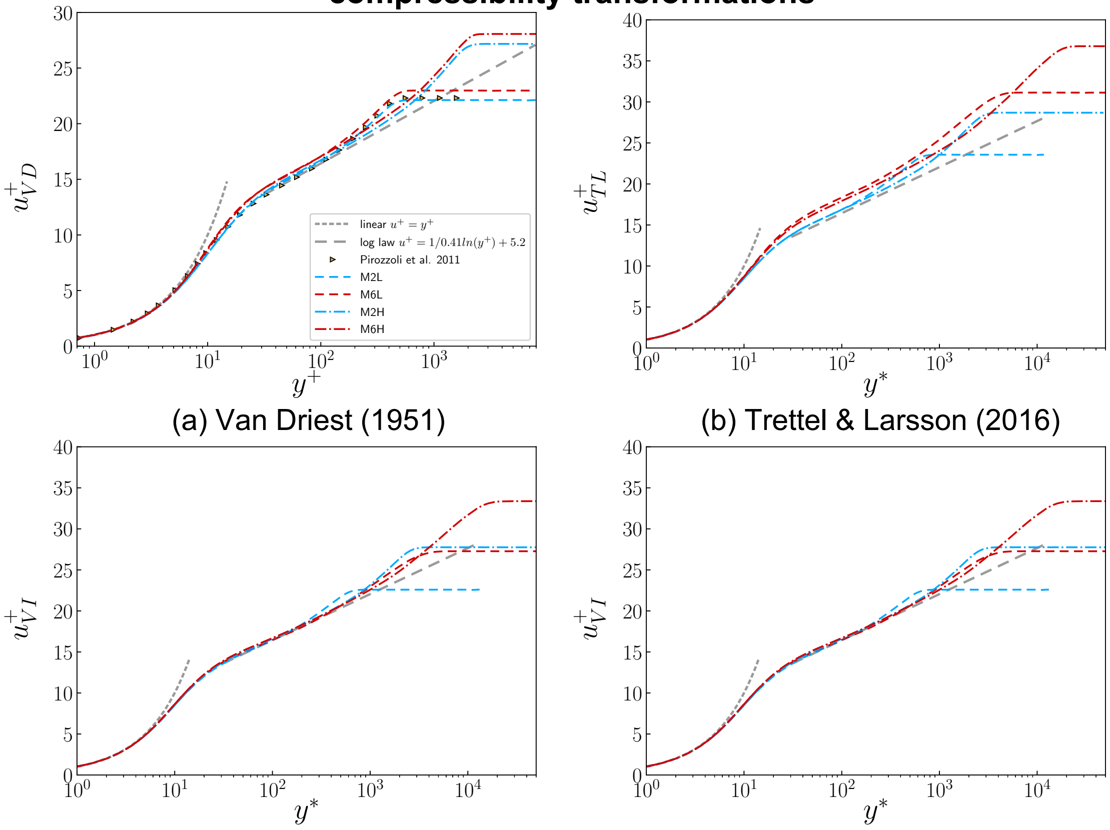
Key concept:

The mean velocity profile in a compressible boundary layer can be mapped to an equivalent incompressible distribution by taking into account the variation of mean properties along the boundary layer (ρ, T, etc.)

$$y_I = \int_0^y f_I dy, \quad u_I = \int_0^{\tilde{u}} g_I d\tilde{u}.$$

- The recent transformations of Volpiani et al. and Griffin et al. yields excellent collapse to the incompressible law of the wall even at higher Reynolds numbers.

Mean velocity profile scaled accordingly to different compressibility transformations



(a) Van Driest (1951)

(b) Trettel & Larsson (2016)

(c) Volpiani et al.(2020)

(d) Griffin et al.(2021)

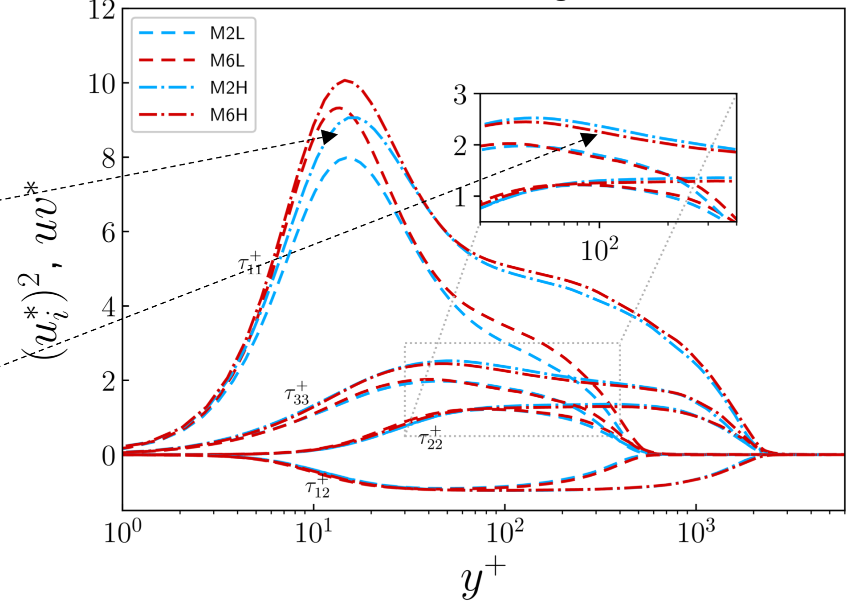
Task #1: Selected Results

Morkovin scaling for turbulent velocity fluctuations:

$$(u_i^*)^2 = \frac{\widetilde{u_i''^2}}{u_\tau^2}\frac{\bar{\rho}}{\bar{\rho}_w}, \qquad (uv)^* = \frac{\widetilde{u''v''}}{\overline{u_\tau^2}}\frac{\bar{\rho}}{\bar{\rho}_w}$$

- The peak on streamwise component increase with Mach number (in accordance with previous studies)
- At high Reynolds and Mach numbers, τ_{22}^+ and τ_{33}^+ have reduced intensities: less efficient turbulent kinetic energy redistribution

Turbulent velocity fluctuations and Reynolds' stress scaled according to Morkovin



More details are present in the recently published paper:
Cogo, M., Salvadore, F., Picano, F., & Bernardini, M. (2022). Direct numerical simulation of supersonic and hypersonic turbulent boundary layers at moderate-high Reynolds numbers and isothermal wall condition. *Journal of Fluid Mechanics, 945*, A30. doi:10.1017/jfm.2022.574

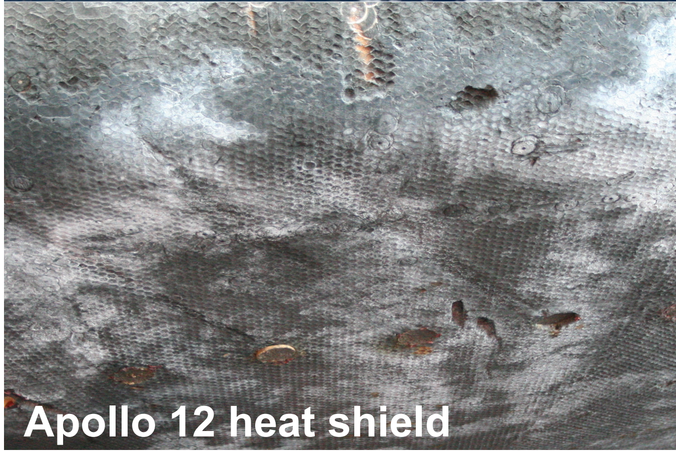
Task #2: Future work

Boundary layer with sourface roughess:

Tipically high-speed vehicles exhibit regular or irregular patterns of roughness.
Turbulent boundary layers exhibit higher skin friction and mixing, causing increased vehicle drag and heating.

Key questions:

- How does surface roughness affects turbulence near the wall at high speeds?
- What is the effect of <u>Mach number</u> and <u>roughness level</u> in the alteration of drag and heat transfer?



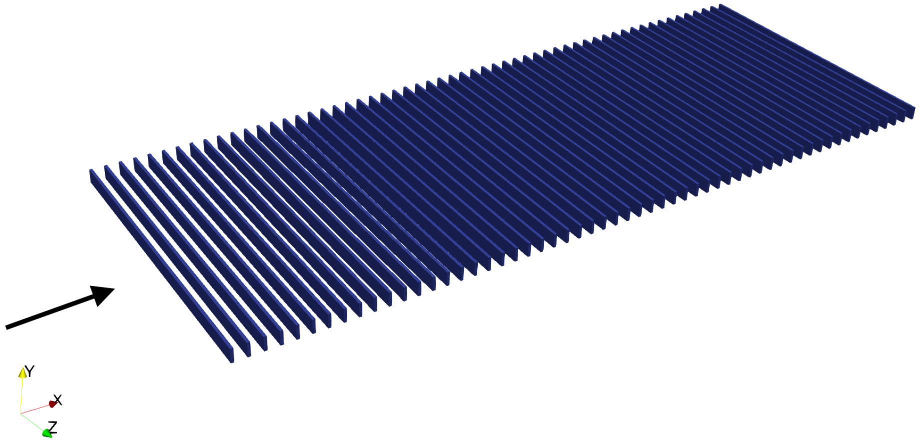
Task #2: Numerical Methods

Numerical methods

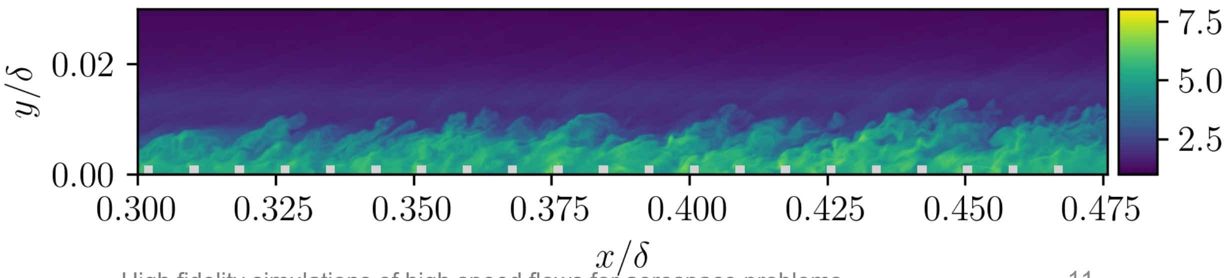
Direct Numerical Simulation:
- Navier-Stokes equations are solved with very high temporal and spatial resolution, down to the Kolmogorov scale
- No model is employed

Immersed Boundary Method:
- Numerical method capable of representing the solid boundary on structured cartesian grids
- Ghost-Point-Forcing Method -> the mesh nodes inside the solid boudary are used as ghost points to give the right boundary conditions (Piquet et al. [2016], De Vanna et al. [2020])

Preliminary test: 2D square bars



Preliminary visualization of temperature contours at Mach 7.5 with 2D square bars



Task #3: Future work

Boundary layer with permeable wall

Hypersonic vehicles can take advantage of porous coatings to stabilize the flow or limit the heat transfer with the surface.

Key challegenges:

- Accurately resolve the flow inside the porous media
- Model the possible transpiration in the material
- Simulate the heat exchange between the solid and fluid domain

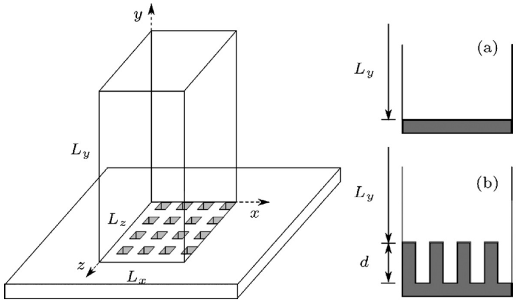
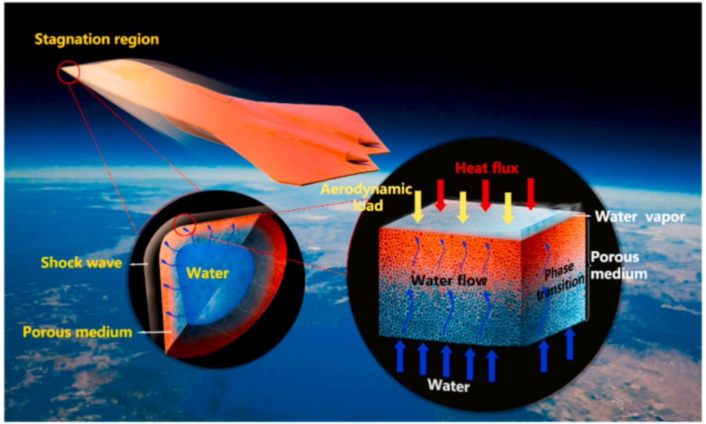


FIG. 1. Computational domain. (a) smooth wall and (b) porous wall.

De Tullio et al. [2010]



Zhang et al. [2021]

Task #3: Future work

Boundary layer with permeable wall

Interesting applications (DNS + IBM) for hypersonic flows in:

- Delaying the laminar-turbulent transition (ultrasonically absorptive coating, Zhou et al. [2020])
- Reducing wall heat transfer by means of gas injection (Zhang et al. [2021], Ifti et al. [2022])

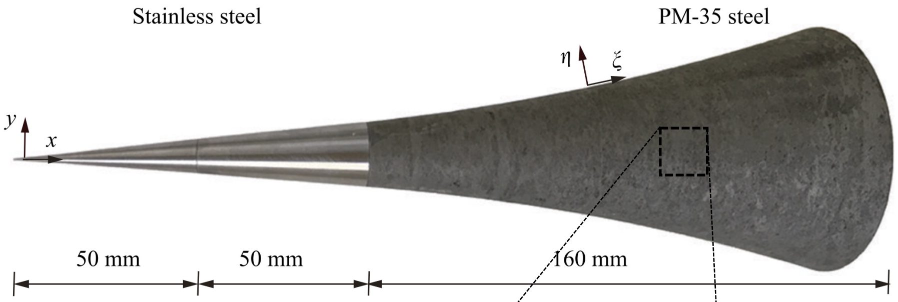
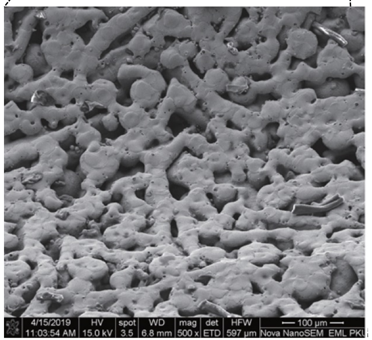
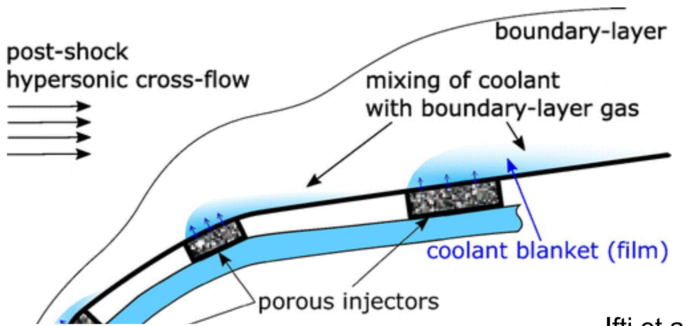


FIG. 1. The flared cone is made of the permeable material PM-35. ξ–η represents the body-oriented coordinate, and x–y represents the Cartesian coordinate. This figure is modified from the work of Zhu *et al.*[47]



Zhou et al. [2020]



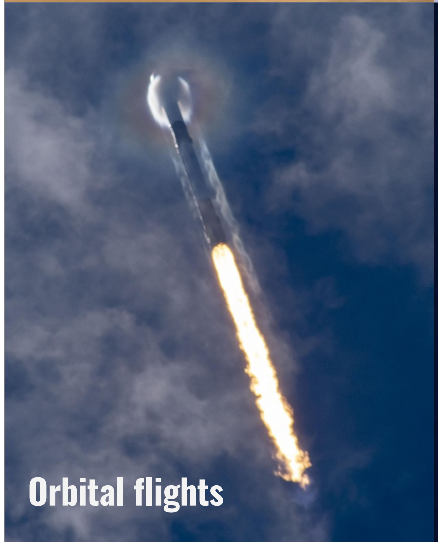
Ifti et al. [2022]

Final remarks

Summary of the past and future activities

- Investigation of the physics phenomena related to high-speed turbulent flows using high fidelity methodologies (DNS) on simple geometries.
- Application of high fidelity methodologies (DNS + IBM) on rough surfaces. Investigation of different geometries and Mach number effect.
- Application of high fidelity methodologies (DNS + IBM) on permeable walls. Investigation of possible improvements on heat transfer reduction techniques.

Several other applications are directly related to the research activity!



Conferences, Publications, Grants

Publications:

- Cogo, M., Salvadore, F., Picano, F., & Bernardini, M. (2022). *Direct numerical simulation of supersonic and hypersonic turbulent boundary layers at moderate-high Reynolds numbers and isothermal wall condition. Journal of Fluid Mechanics, 945*, A30. doi:10.1017/jfm.2022.574

Grants:

- Awarded with the Fulbright Scholarship for a visiting research period at Stanford University

Conferences:

- **33rd Parallel CFD International Conference in Alba, Italy (25-27 May 2022).** Presentation of “DNS of supersonic and hypersonic turbulent boundary layers at moderate-high Reynolds numbers with heat transfer” and participation to the seminars.

- **14th European Fluid Mechanics Conference in Athens, Greece (13-16 September 2022).** Presentation of “Compressibility effects in supersonic and hypersonic turbulent boundary layers at high Reynolds numbers” and participation to the seminars.

GANNT chart

Activity plan

WBS NUMBER	TASK TITLE	% OF TASK COMPLETE	T1			T2			T3			T4			T1			T2			T3			T4			T1			T2			T3			T4		
			O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
1	DNS - Attached flows over smooth plates																																					
1.1	Analysis of the state of the art	100%																																				
1.2	Hypersonic turbulent boundary layer over a flat plate with DNS	100%																																				
1.3	Investigation of the non-ideal gas effects in a hypersonic boundary layer	50%																																				
2	DNS - Attached hypersonic flows over rough plates																																					
2.1	Analysis of the state of the art	50%																																				
2.2	Hypersonic turbulent boundary layer over a rough plate with DNS - simulation setup	20%																																				
2.3	Hypersonic turbulent boundary layer over a rough plate with DNS - geometry effect	0%																																				
2.4	Hypersonic turbulent boundary layer over a rough plate with DNS - Mach number effec	0%																																				
3	DNS - Attached hypersonic flows over porous plates																																					
3.1	Analysis of the state of the art	0%																																				
3.2	Hypersonic turbulent boundary layer over a porous with DNS - simulation setup	0%																																				
3.3	Hypersonic turbulent boundary layer over a porous with DNS - geometry effect	0%																																				
3.4	Hypersonic turbulent boundary layer over a porous with DNS - Mach number effect	0%																																				
4	Writing thesis and reports																																					
4.1	Reports for admission to the next year or conferences	30%																																				
4.2	Writing scientific papers	30%																																				
4.3	Writing thesis	0%																																				

Thanks for the attention