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Excellence in Simulation Technologies for Aeronautics

High fidelity simulations of the boundary layer transition on a high-pressure turbine vane in view of accurate predictions of the heat flux distribution

LUMI-BE user day
Brussels, Belgium
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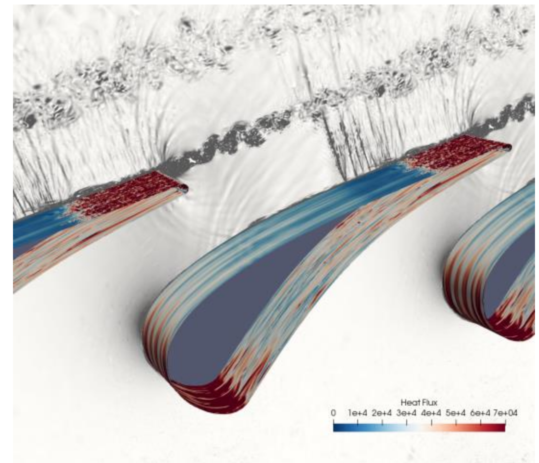
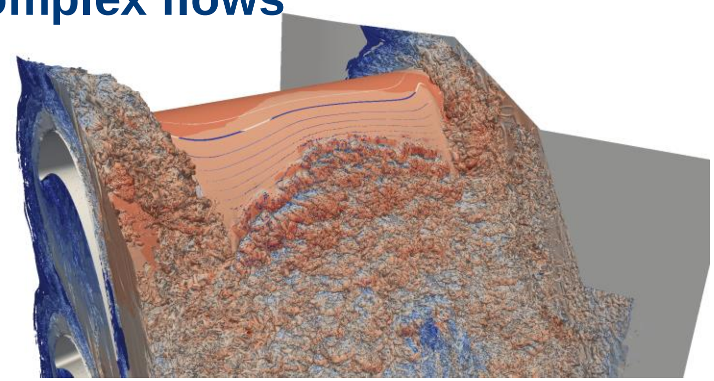
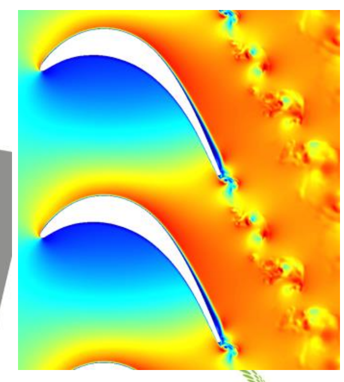
High-fidelity CFD @ Cenaero

- **High-resolution DNS and wall-resolved LES on realistic geometries**
  - **Accurate representation of flow phenomena in boundary layers near solid surfaces**
    - Separation
    - Shocks
    - Transition and turbulence
  - **Main enablers**
    - Superior accuracy of high-order methods like DGM
    - Access to and efficient exploitation of supercomputers



- **Research themes for the application of DNS and LES**
  - **Development of high-resolution numerical methods & tools**
  - **Applications: high fidelity CFD of complex flows**
  - **Data-driven turbulence modeling**





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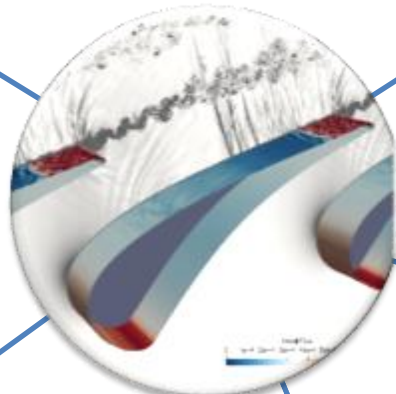
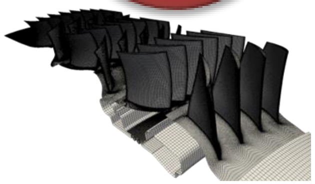
Development of high-resolution numerical tools

Highly accurate numerical wind tunnel for turbulence in turbomachinery



Turbo-machinery

- Generic frame of reference
- Parallel periodicity
- Dedicated BC (moving wall, total conditions, radial equilibrium, …)
- High order accurate non-matching connections



HPC capabilities

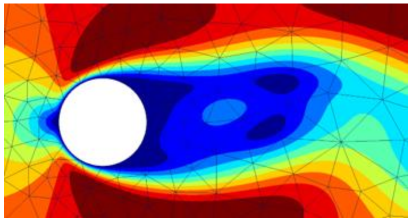
- Algorithmic efficiency
- Extreme scalability, including NMC
- Optimised IO
- *GPU implementation (ongoing)*

Lucia@Cenaero (#245 top500.org)

Lumi@CSC (#3 top500.org)

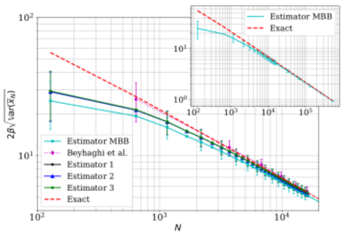
Advanced numerics

- DGM: high-accuracy on unstructured meshes
- High order time integrators
- *Dissipation-free shock capturing (ongoing)*
- *Mesh and order adaptivity (ongoing)*



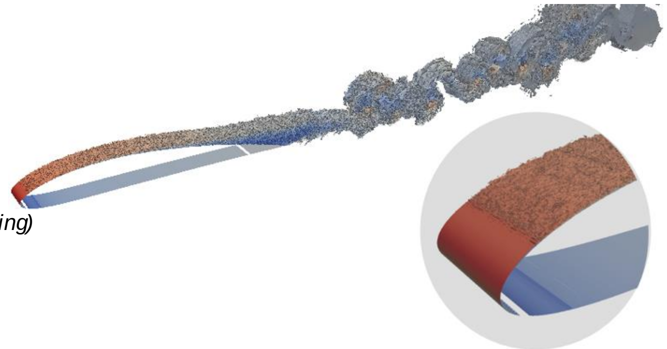
Co-processed analysis

- In-situ visualisation Catalyst
- Spatio-temporal statistics
- *Confidence intervals on statistics (ongoing)*



Resolved turbulence

- DNS, LES and wmLES
- Turbulence injection
- RANS turbulence budgets
- *Adaptation on TKE budget (ongoing)*
- *ML-based wall modeling (ongoing)*
- *Quality criteria for statistics (ongoing)*



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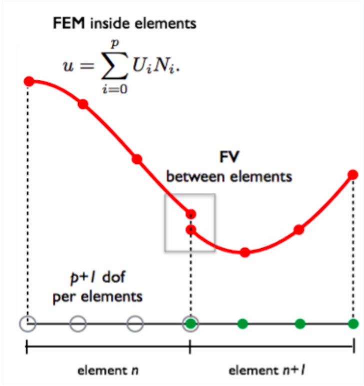
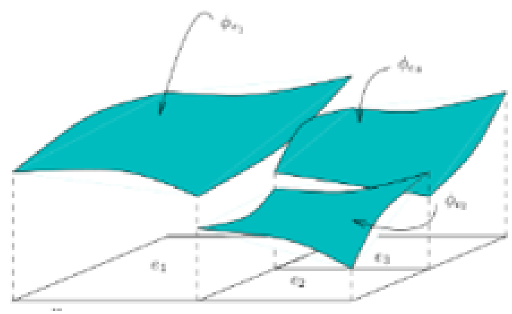
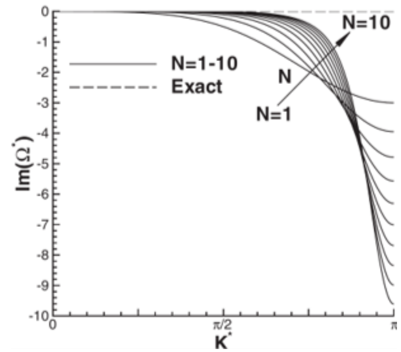
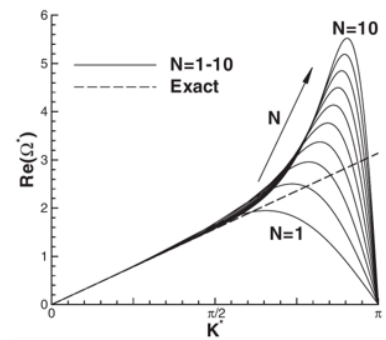
High-order Discontinuous Galerkin Method
Why DG?

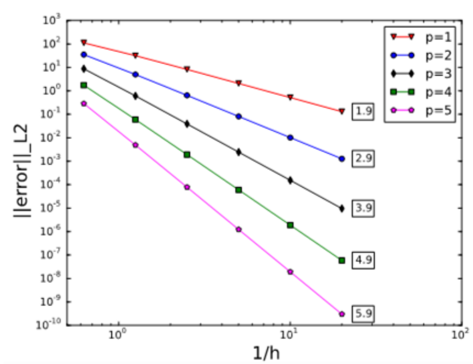
- **Unstructured meshes and complex geometries**
- **High accuracy**
  - **Guaranteed order of convergence p+1**
  - **No degradation near size jumps/walls**
  - **Low dissipation/dispersion error**
- **High efficiency**
  - **Data locality**
  - **Compact matrix-matrix operations**
  - **High scalability (MPI/OpenMP/GPU)**

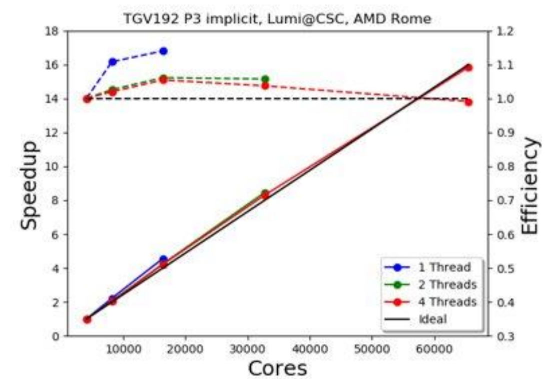


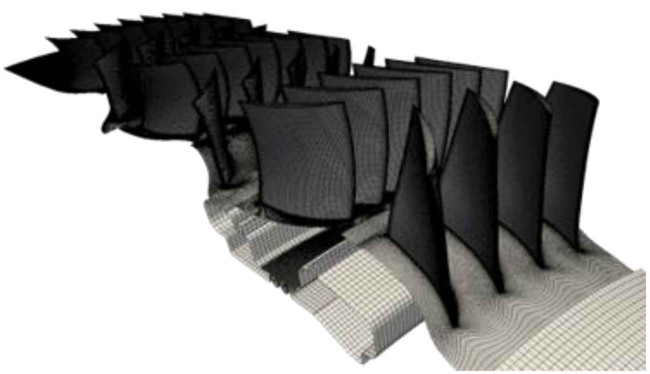












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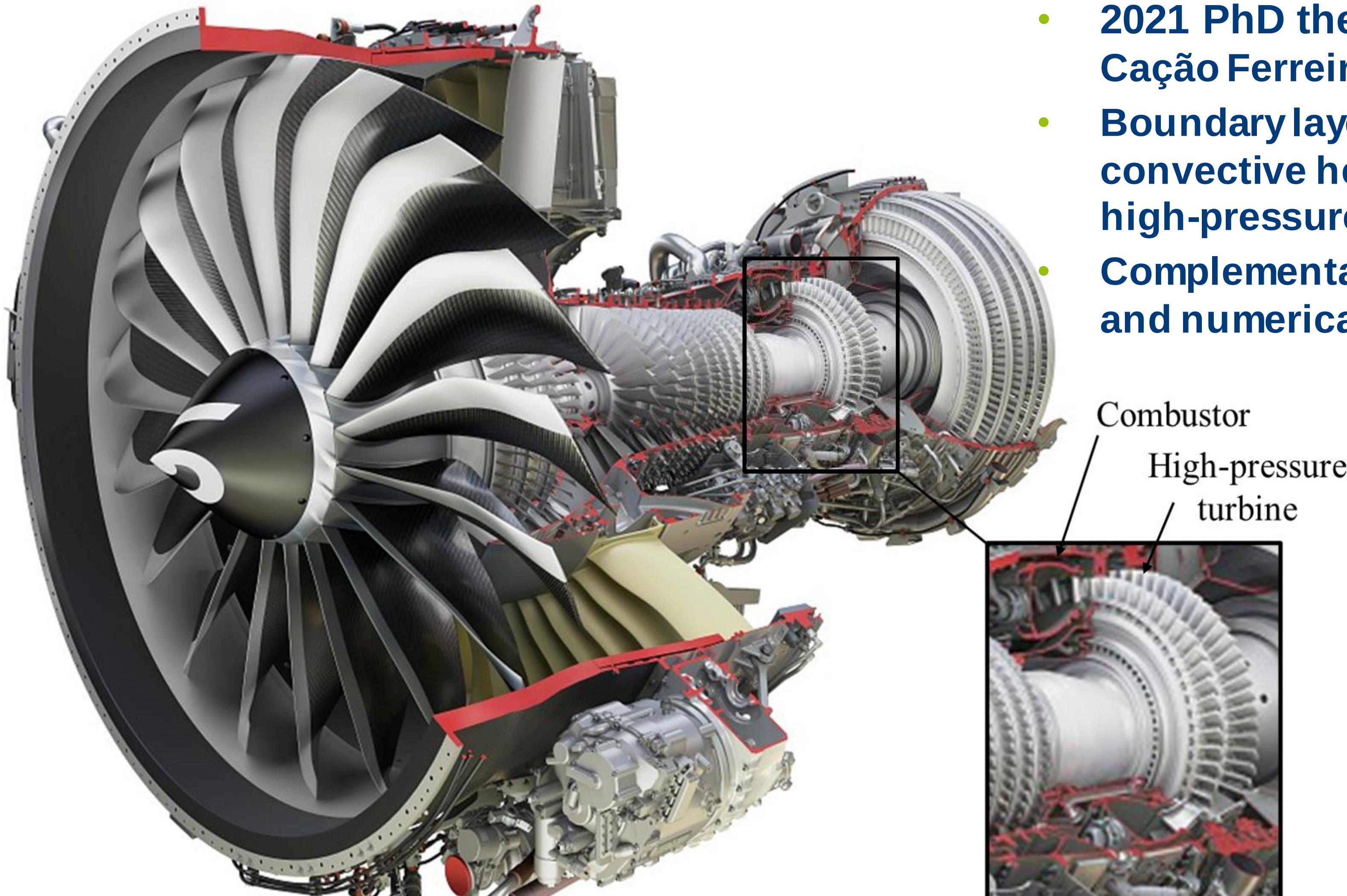
Aircraft gas turbine engine
High pressure turbine vane LS89

- **2021 PhD thesis Tânia Sofia Cação Ferreira + follow up**
- **Boundary layer transition and convective heat transfer of the high-pressure turbine vane LS89**
- **Complementary experimental and numerical work**



Edited, LEAP engine (CFM)

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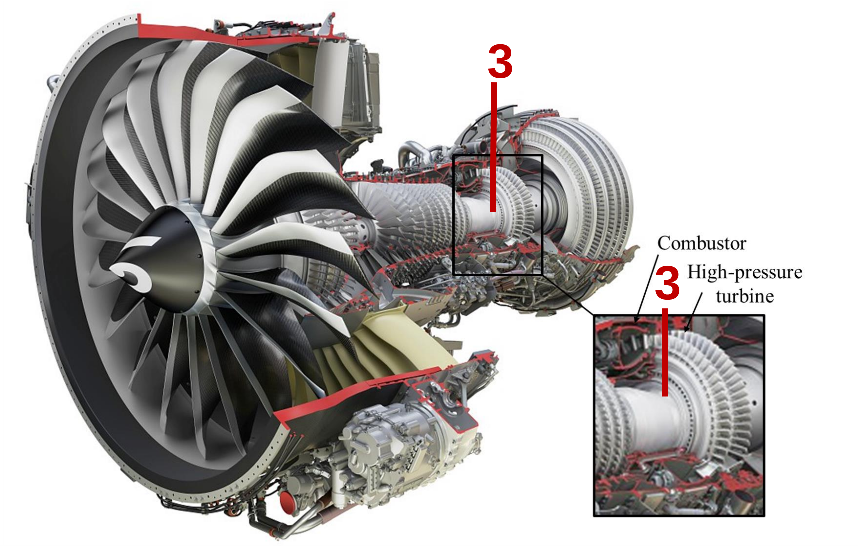
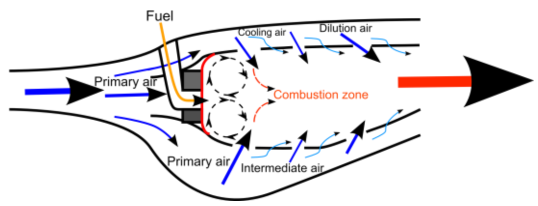
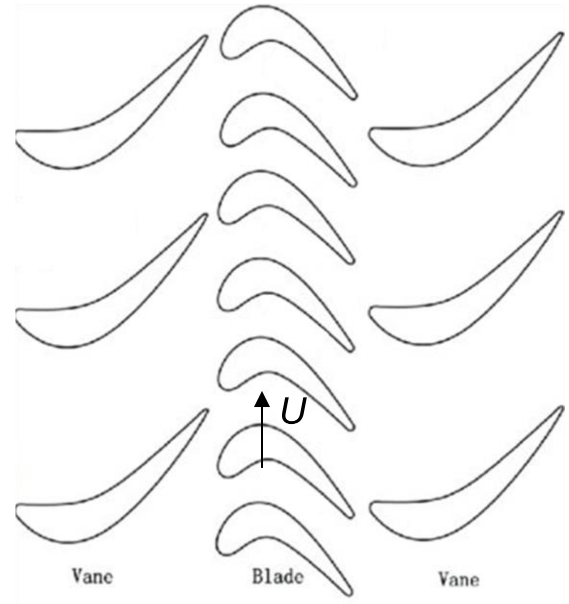
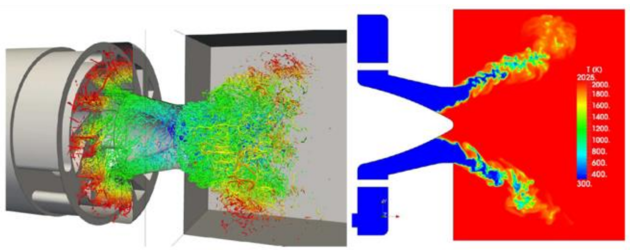
Aircraft gas turbine engine
Highest temperature during engine cycle







DNS of an isothermal and reacting combustion swirler (Moureau et al. 2010)



Combustor exit/HPT inlet flow:

- **Temperature = 500-2000K**
- **Turbulence intensity = 10-30%**

1st turbine stator
faces the **hot turbulent combustion flow**

- **Accurate heat transfer predictions are crucial!**
- **Requires accurate prediction of the boundary layer**

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Boundary layer transition is affected by:

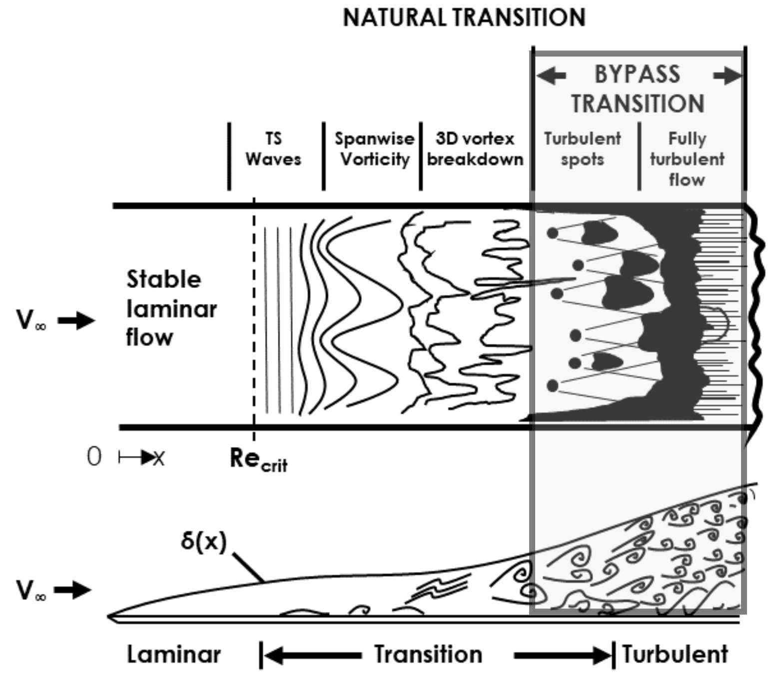
1st order

- High turbulence levels (1 to 30 %)
- Reynolds number $(10^5 - 10^7)$
- Acceleration parameter $\left(K = \frac{\nu}{U_\infty{}^2}\frac{dU_\infty}{ds} = -2 \leftrightarrow 1 \cdot 10^6\right)$

2nd order

- Variable surface curvature and roughness
- Secondary flows
- Wide range gas-to-wall temperature ratios $(1.1 - 1.6)$

And can occur through:



Schlichting (2000)

… and also **separated-flow** transition, **reverse** transition, **wake-**, **shock-**, **film-cooling-induced** transition, …

Deeper understanding of transition -> design improvement -> efficient cooling **-> overall higher efficiency**

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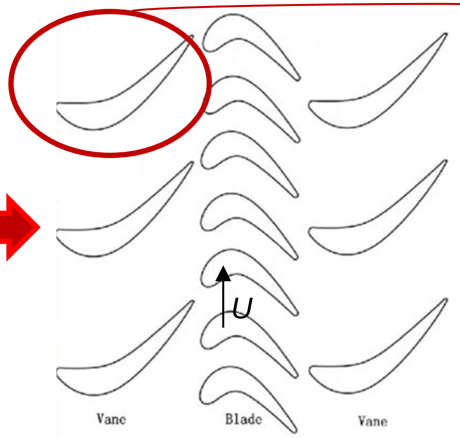
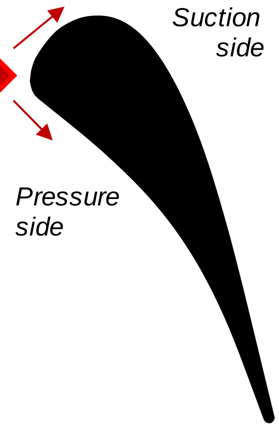
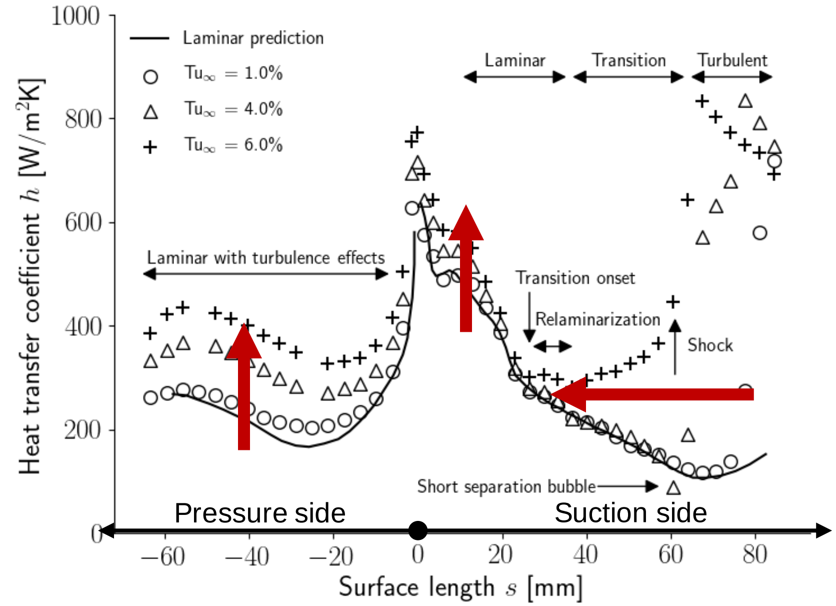
Flow



Flow



Heat transfer along the turbine vane

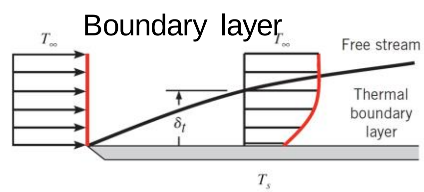


Edited, Arts et al. 1990

1st turbine stator faces the **hot turbulent combustion flow**

↑ Shear stress
↑ **Heat transfer**
↑ Losses

Earlier boundary layer laminar-to-turbulent **transition**



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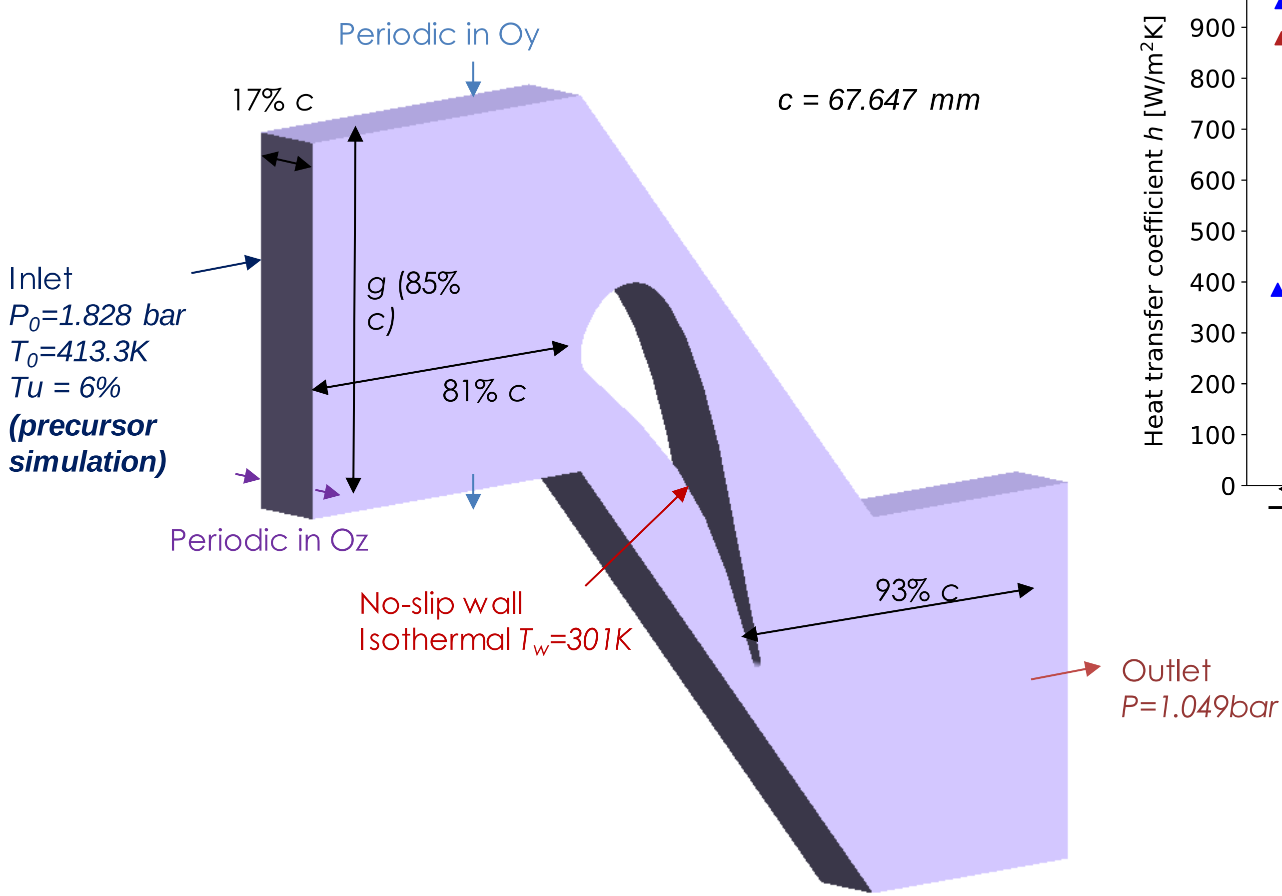
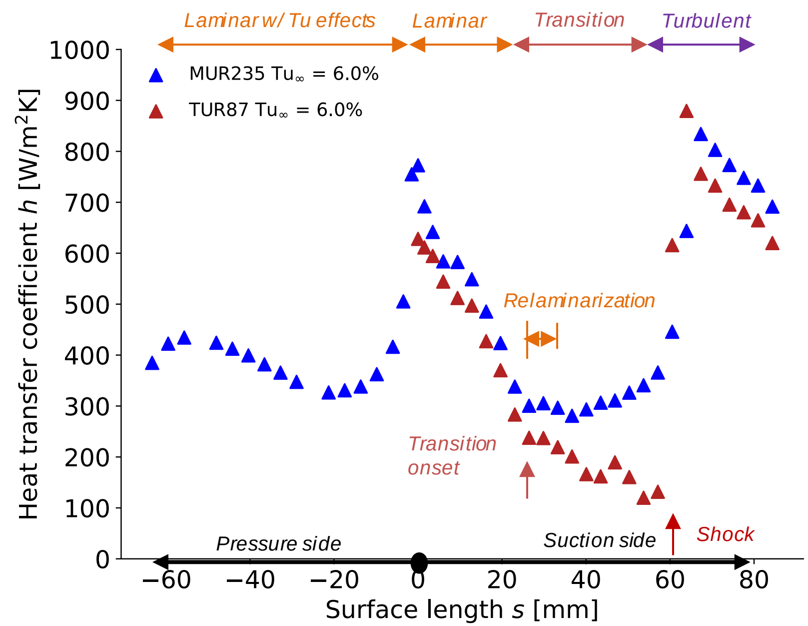
Domain and boundary conditions
MUR235 configuration





(**edited**, *Arts et al., 1990)*

Test case	MUR235	TUR87
$M_{is,out}$	0.93	0.92
$Re_{is,out}$	1.15×10^6	1.15×10^6
$T_{0,in}/T_{s,wall}$	1.37	1.37
Tu_∞	6%	6%

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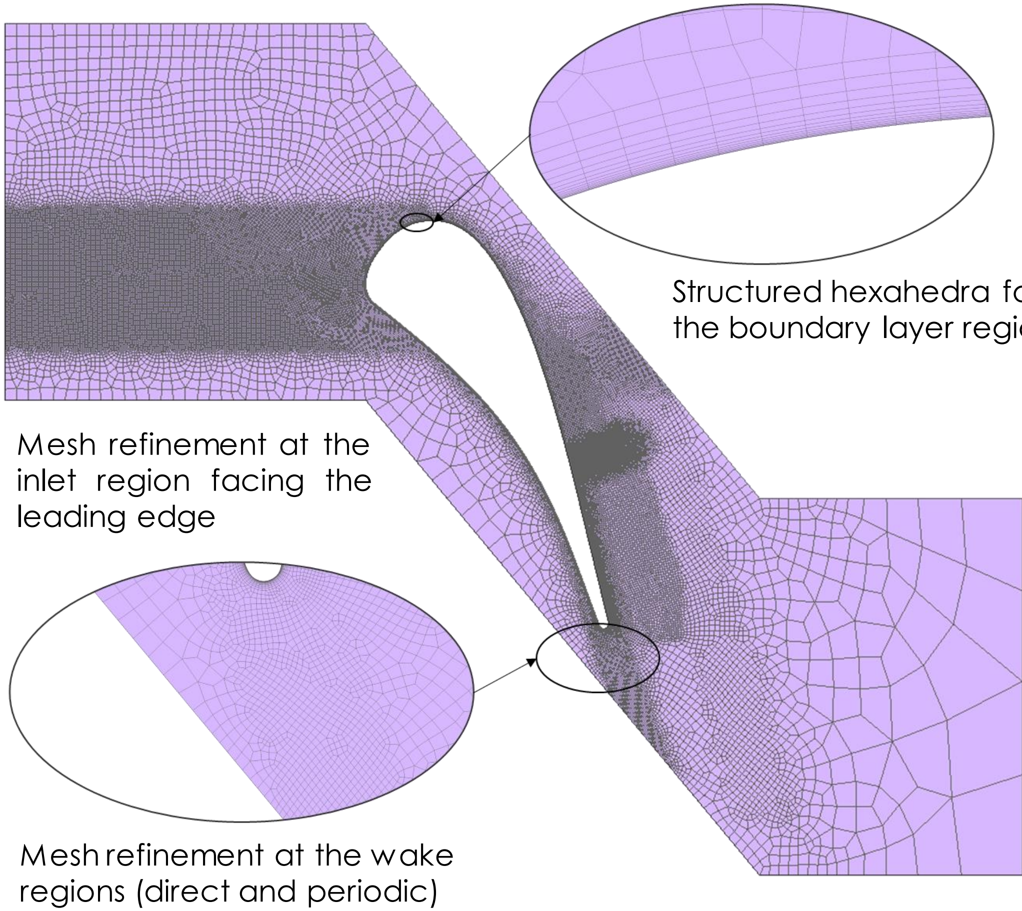
High-order numerical simulations with Argo
Mesh M1

2nd order curvilinear mesh generated with GMSH

Mesh	M1
Oz layers	40
Prism elements	80
Hexahedron elements	2M
Degrees of freedom	127M
Maximum x^+	83
Maximum y^+	~1
Maximum z^+	~100
CPU hours/flow over inlet + chord	1M *Zenobe*



Mesh cross section (2D)

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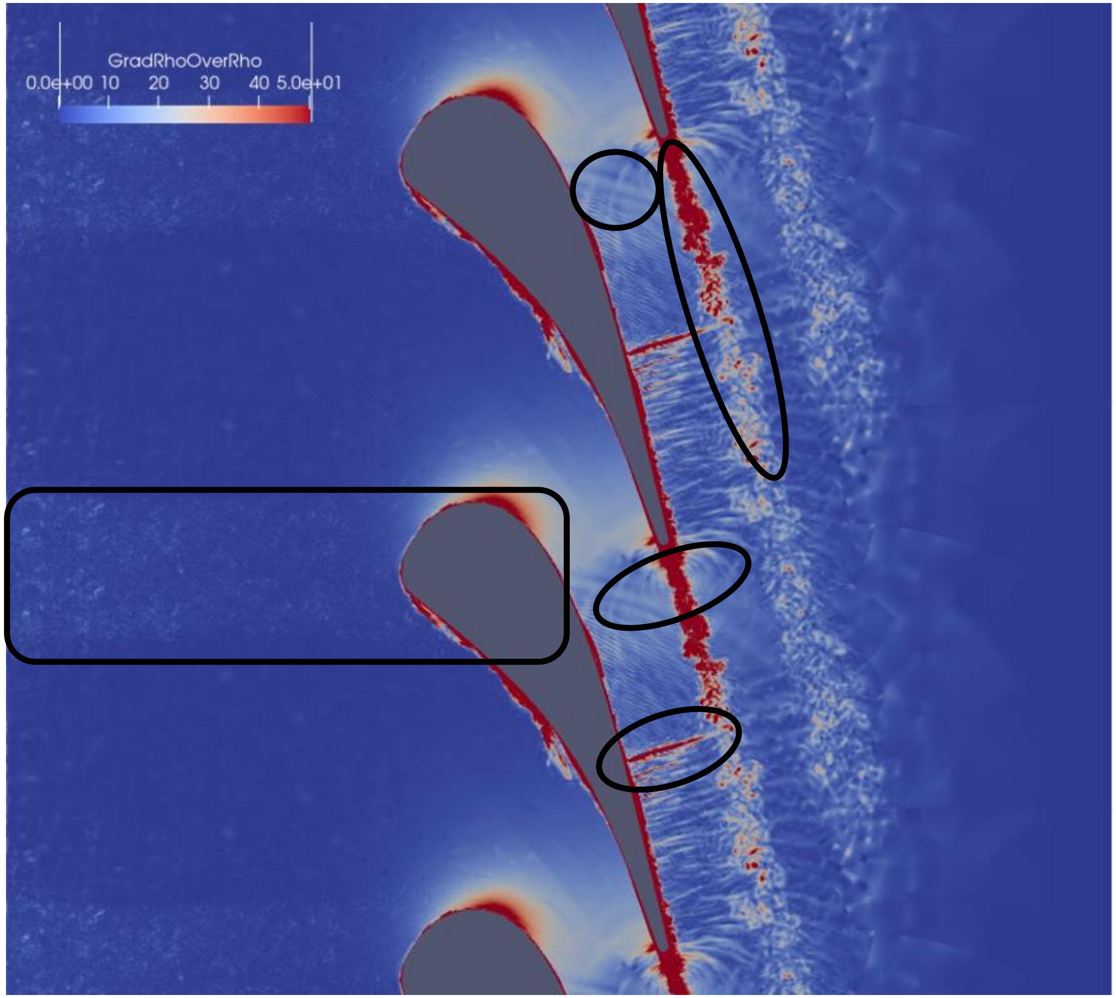
Flow visualisation
Density gradient



Refined inlet turbulent structures

Acoustic waves reflection on the suction side

Wake vortex shedding

Acoustic waves formation at the trailing edge

Normal shock

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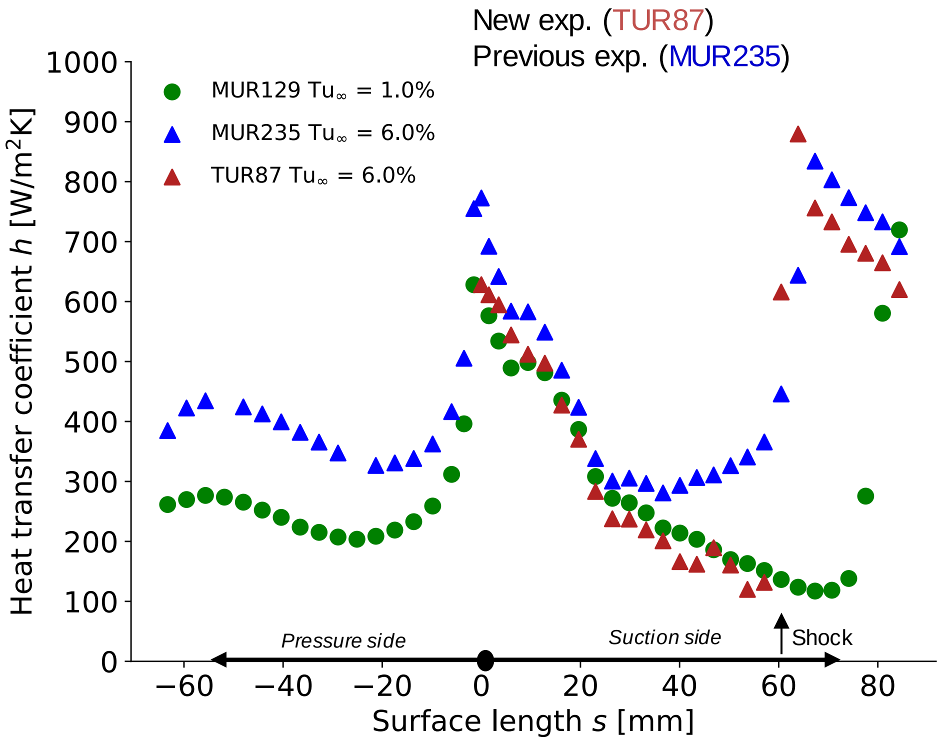
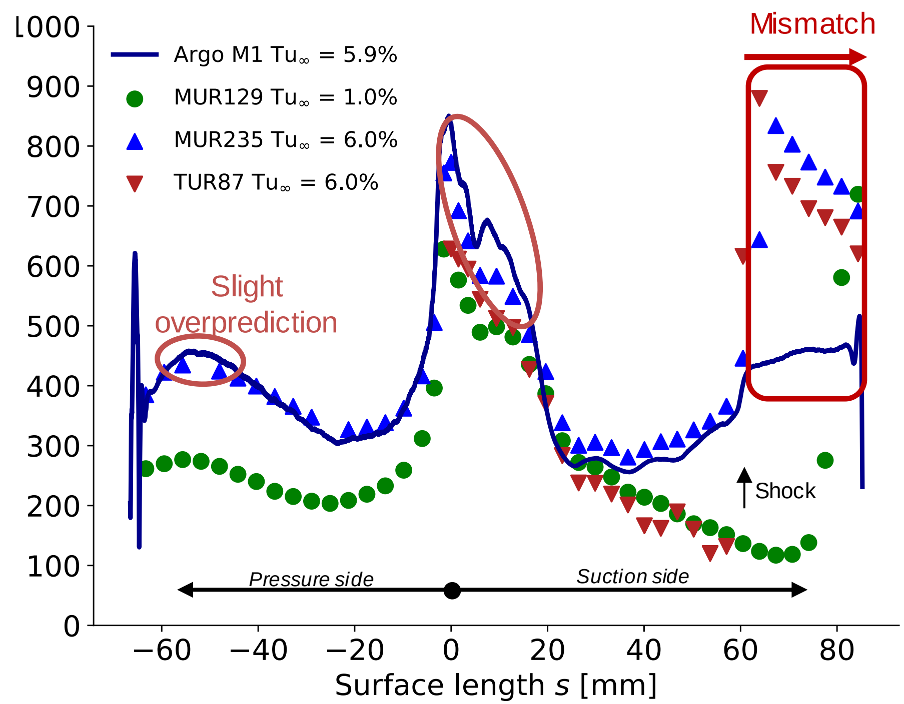
Heat transfer for past and recent experiments
Mesh M1





Artificial viscosity acting not only on the shock but also on the boundary layer
–> try to decouple!

Line – CFD
Symbols - EXP

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Artificial viscosity effect
Mesh M1

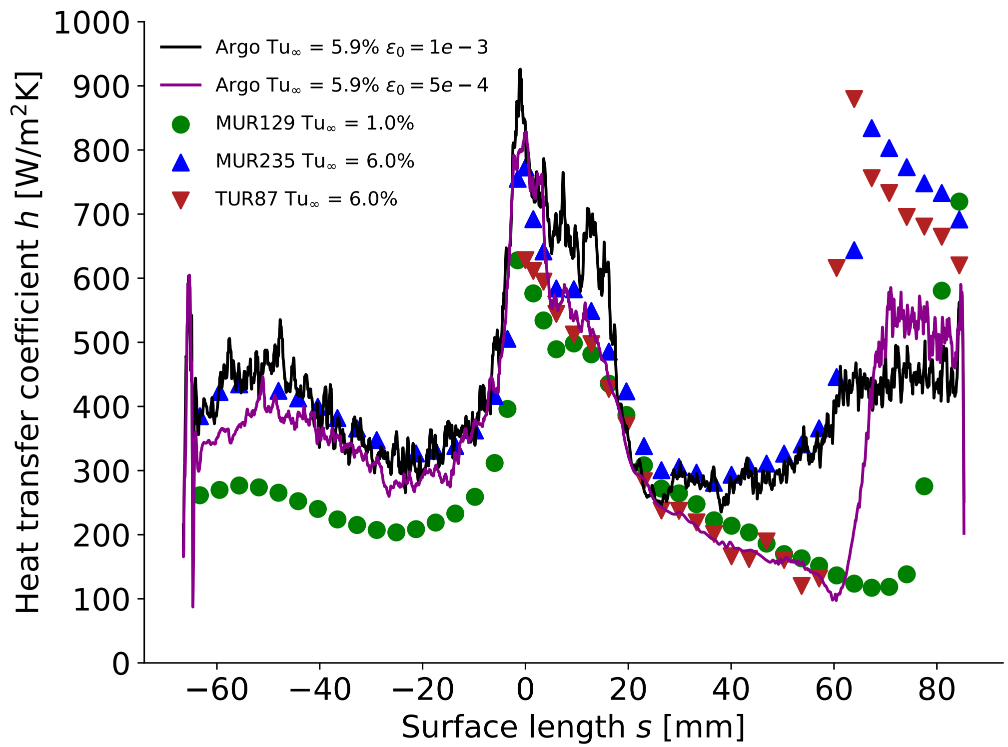
Two values of artificial viscosity considered:

- Nominal AV
- Lower AV (halved AV)

↓

Very different heat transfer profiles

Take-away: artificial viscosity was not possible to be decoupled from the under-resolved boundary layer
--> keep AV value and refine mesh



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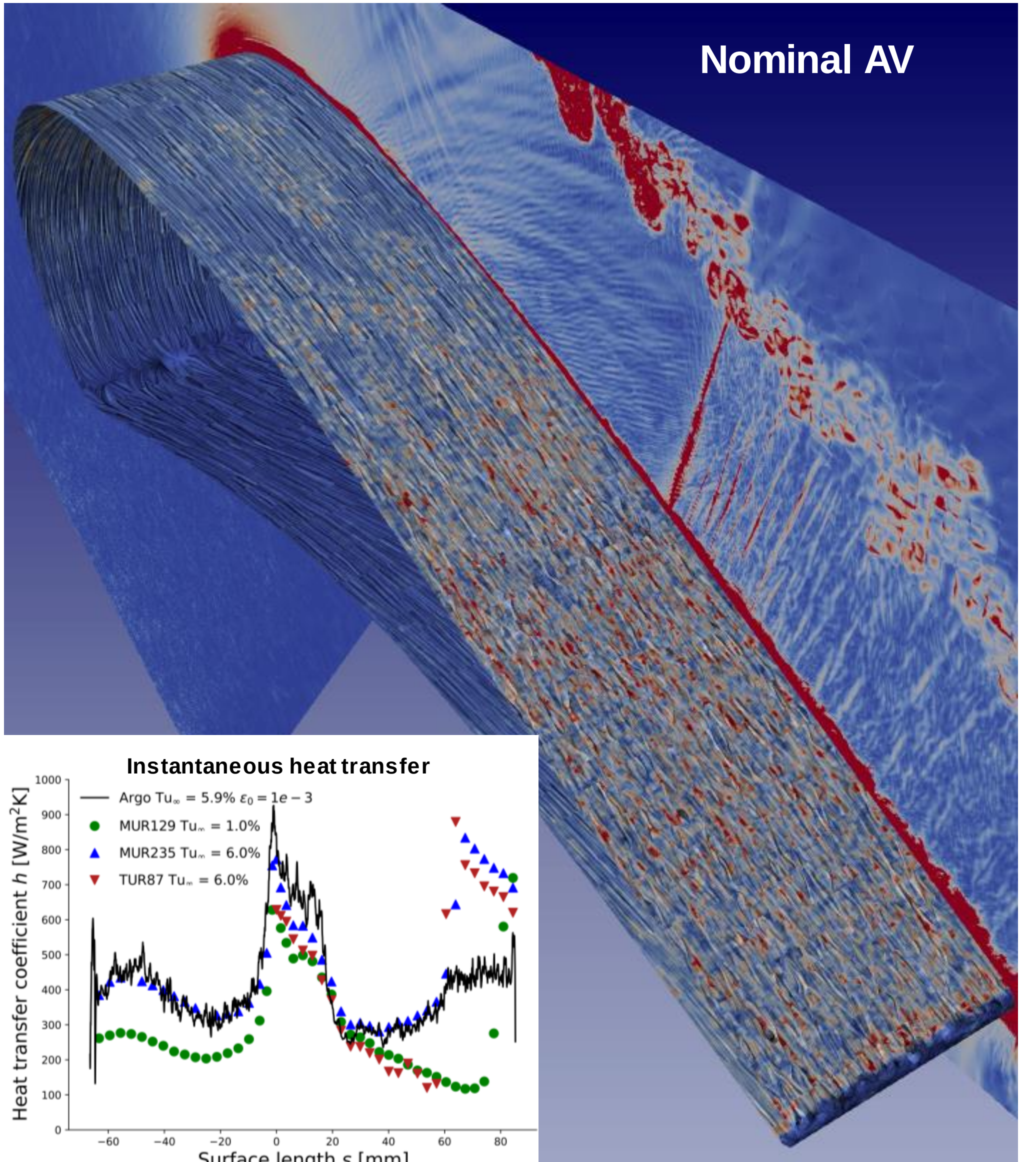
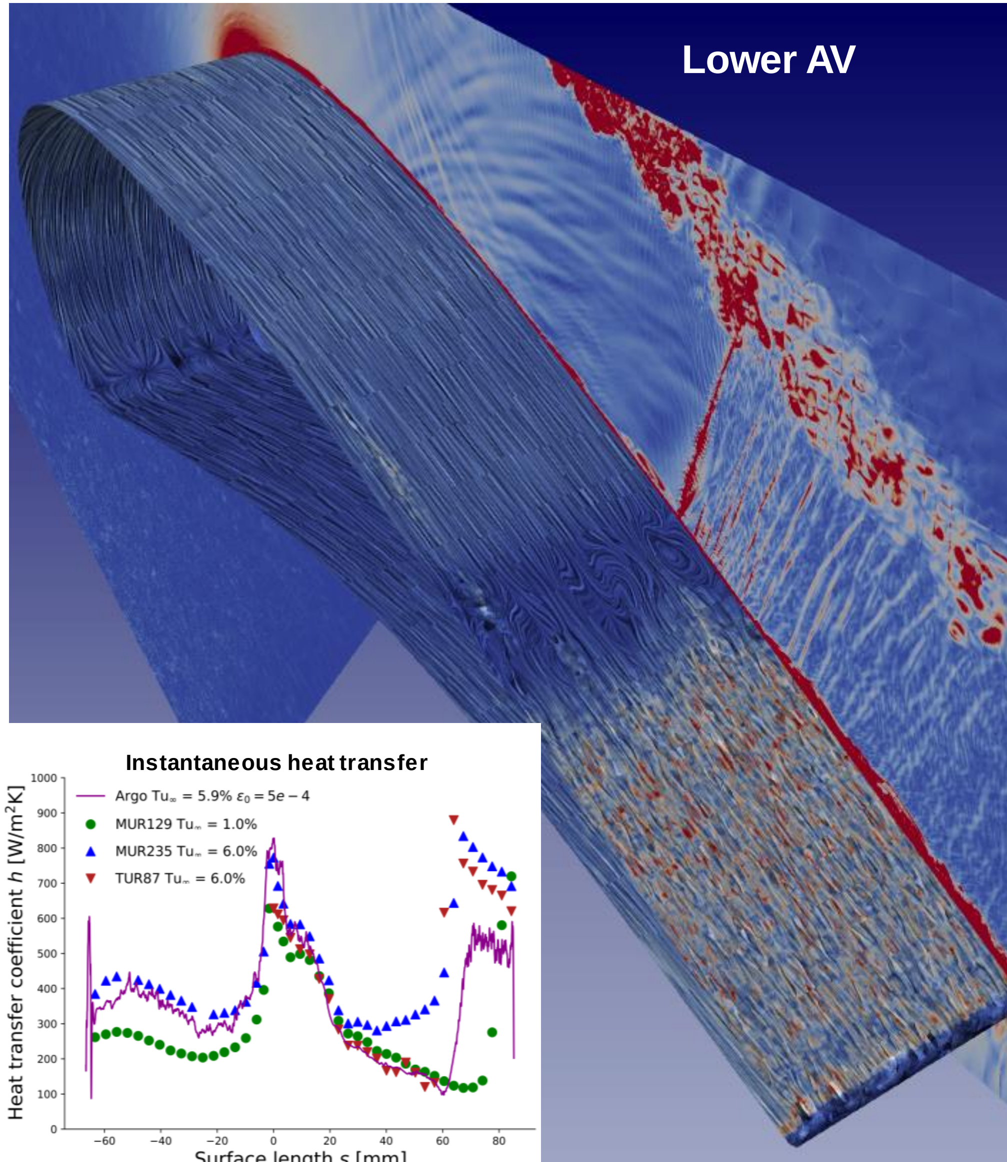
Artificial viscosity effect
Mesh M1





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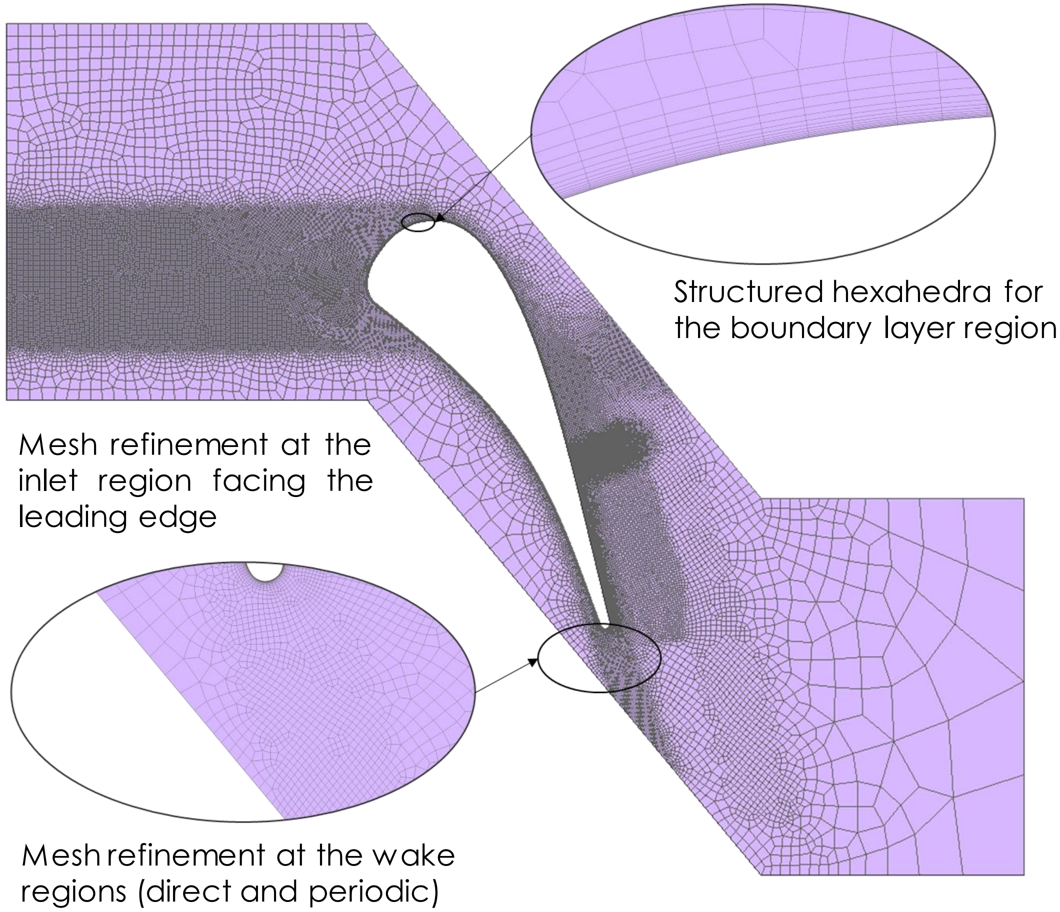
2^{nd} order curvilinear mesh generated with GMSH

Mesh	M1	M2
Oz layers	40	**74**
Prism elements	80	**148**
Hexahedron elements	2M	**3.7M**
Degrees of freedom	127M	**236M**
Maximum x^+	83	**83**
Maximum y^+	~1	**~1**
Maximum z^+	~100	**~50**
CPU hours/flow over inlet + chord	1M *Zenobe*	**0.95M Galileo**



Mesh cross section (2D)

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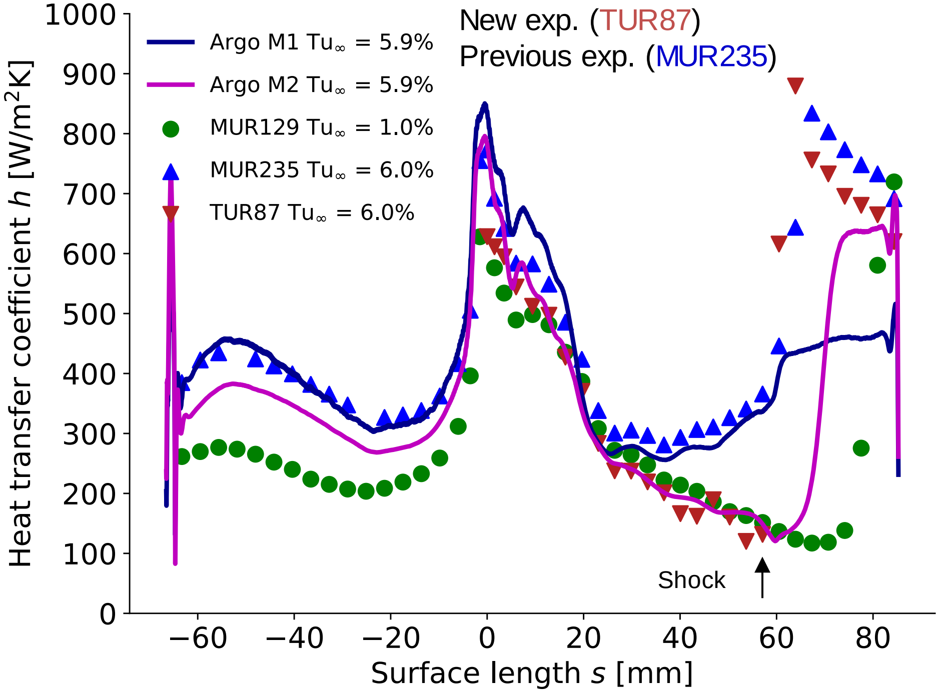
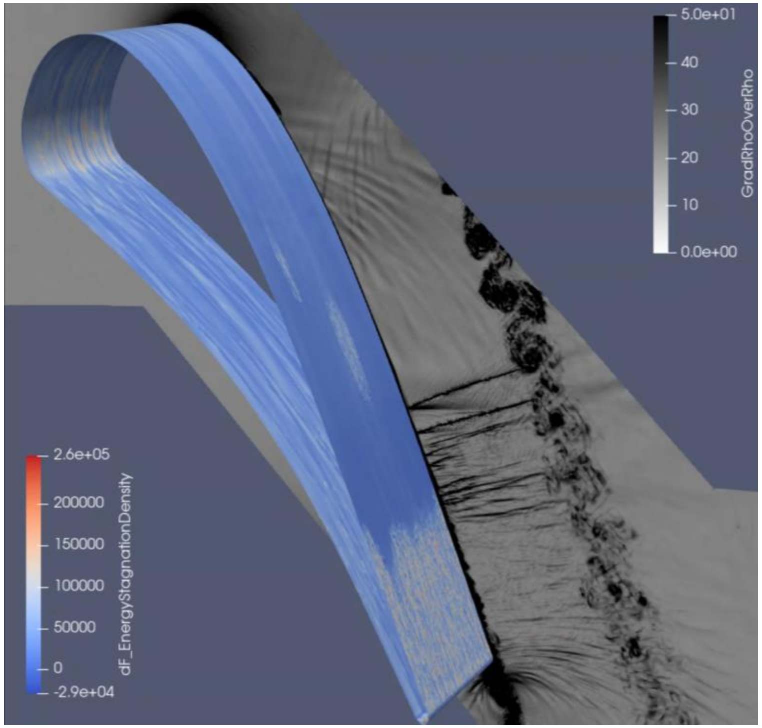
Heat transfer for **mesh M2**





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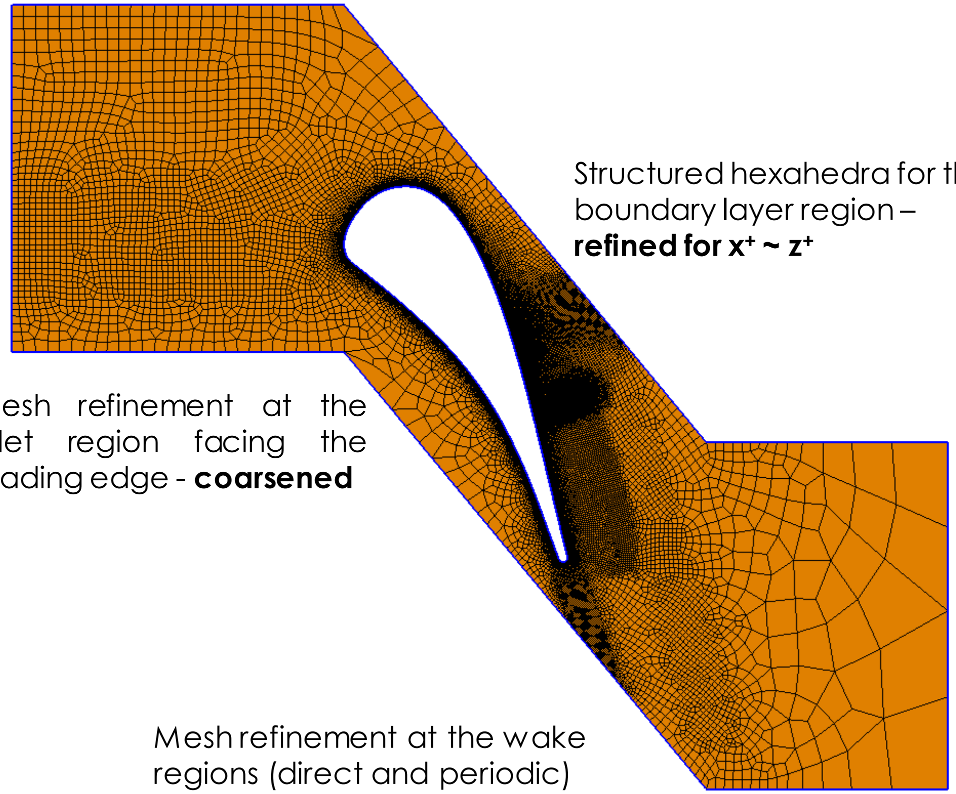
Numerical simulation
Mesh M3

2nd order curvilinear mesh generated with GMSH

Mesh	M1	M2	M3
Oz layers	40	**74**	**85**
Prism elements	80	**148**	**510**
Hexahedron elements	2M	**3.7M**	**3.3M**
Degrees of freedom	127M	**236M**	**212M**
Maximum x^+	83	**83**	**50**
Maximum y^+	~1	**~1**	**~1**
Maximum z^+	~100	**~50**	**~45**
CPU hours/flow over inlet + chord	1M *Zenobe*	**0.95M Galileo**	**0.8M Zenobe + Lumi**



Mesh cross section (2D)

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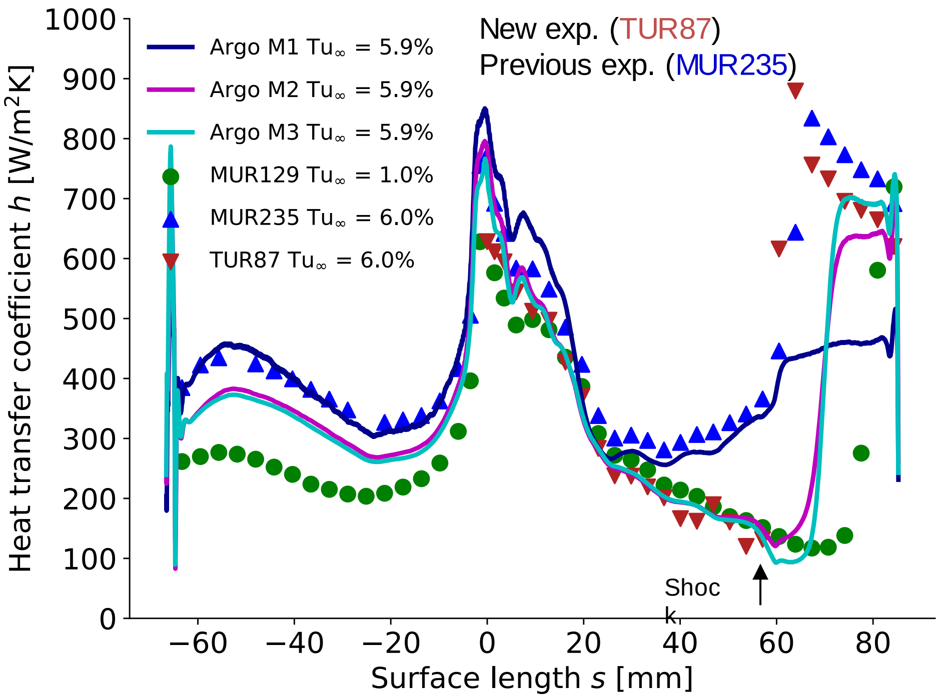
Heat transfer for **mesh M3**



Parameters			
Mesh	M1	M2	M3
Oz layers	40	74	85
Prism elements	80	148	510
Hexahedron elements	2M	3.7M	3.3M
Degrees of freedom	127M	236M	212M
x^+	**83**	**83**	**50**
y^+ (max)	~1	~1	~1
z^+	**~100**	**~50**	**~45**
Partitions	2160	3960	3456
CPU hours/flow over inlet + chord**	1M *Zenobe*	0.95M *Galileo*	0.8M *Zenobe + Lumi*

- ## Conclusions:
  - **Highly sensitive boundary layer to the facility environment**
  - **Strong dependence on the mesh resolution, and consequently, on the artificial viscosity**
  - **New experimental facility and refined numerical simulations tend to converge towards the same heat flux prediction**

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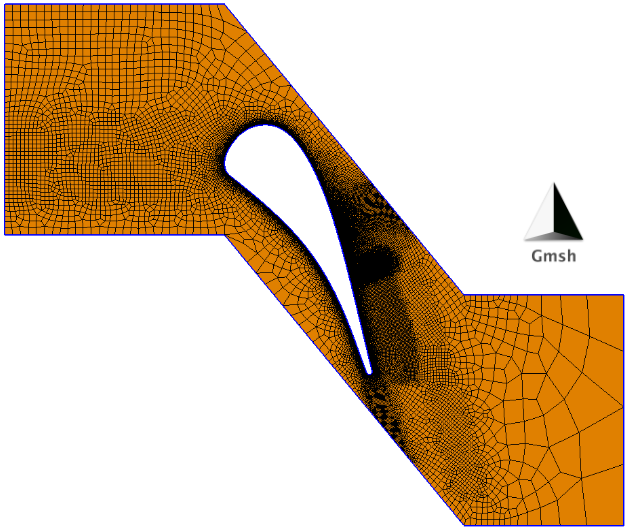
Ongoing work and perspectives

- Investigate the effect of mesh resolution and artificial viscosity -> Mesh M4

  Lumi impact!

- Simulate a similar experimental test case at higher turbulence intensity (Tu_∞=22%) for more engine representative numerical studies.

- Investigate the temperature effect on the heat flux, complementary to dedicated experimental campaigns



Parameters				
Mesh	M1	M2	M3	***M4***
Oz layers	40	74	85	***153***
Prism elements	80	148	510	***918***
Hexahedron elements	2M	3.7M	3.3M	***10.9M***
Degrees of freedom	127M	236M	212M	***700M***
x^+	**83**	**83**	50	***25***
y^+ (max)	~1	~1	~1	***~1***
z^+	**~100**	**~50**	~45	***25***
Partitions	2160	3960	3456	***9984***
CPU hours/flow over inlet + chord**	1M *Zenobe*	0.95M *Galileo*	0.8M Zenobe + Lumi	***Lumi***

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Wallonie PRACE EuroHPC Joint Undertaking

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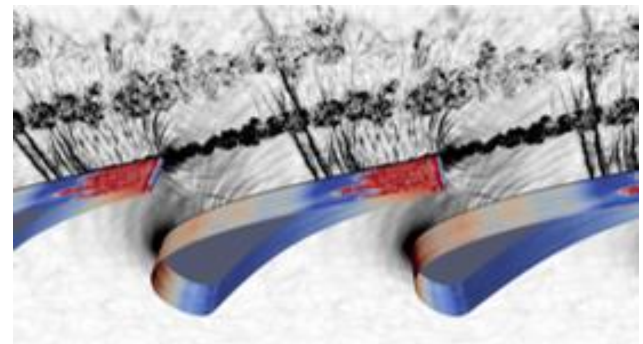
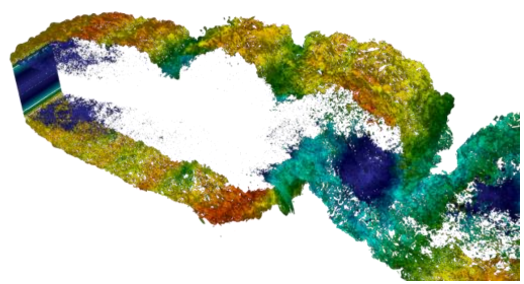
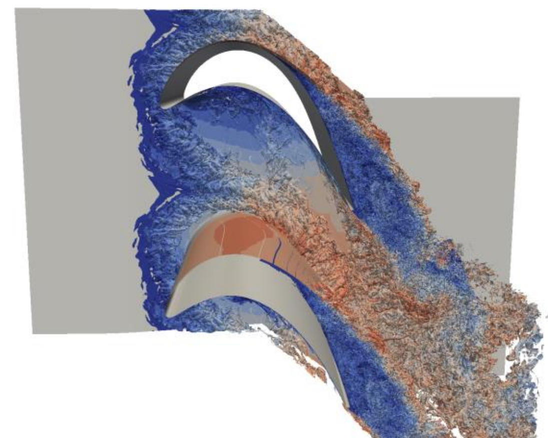
Broader view

- **High-resolution simulations as part of a "multi-fidelity" paradigm**
  - Physical understanding to support and complement experimental testing
  - Performance prediction in off-design conditions
  - Data generation for lower-fidelity model calibration (RANS, wall models)



- **Advanced numerical framework**
  - High-order numerical scheme
  - Scalable
  - Post-processing and statistical analysis
- **Improved physical fidelity**
  - Turbulence injection in DNS/LES for aerodynamics (free stream, turbulent BL)
  - Shock capturing (ULiège)
- **Applications**
  - Academic aerodynamic flows
  - Turbomachinery flows





➡ Access to computational resources is essential

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Acknowledgments

- The present research benefited from computational resources made available on the Tier-1 supercomputer of the Fédération Wallonie-Bruxelles, infrastructure funded by the **Walloon Region** under grant agreement numbers 1117545
- We acknowledge **PRACE** for awarding us access to Gallileo hosted by CINECA in Bologna, Italy
- We acknowledge **EuroHPC** for awarding us access to LUMI hosted by CSC in Kajaani, Finland

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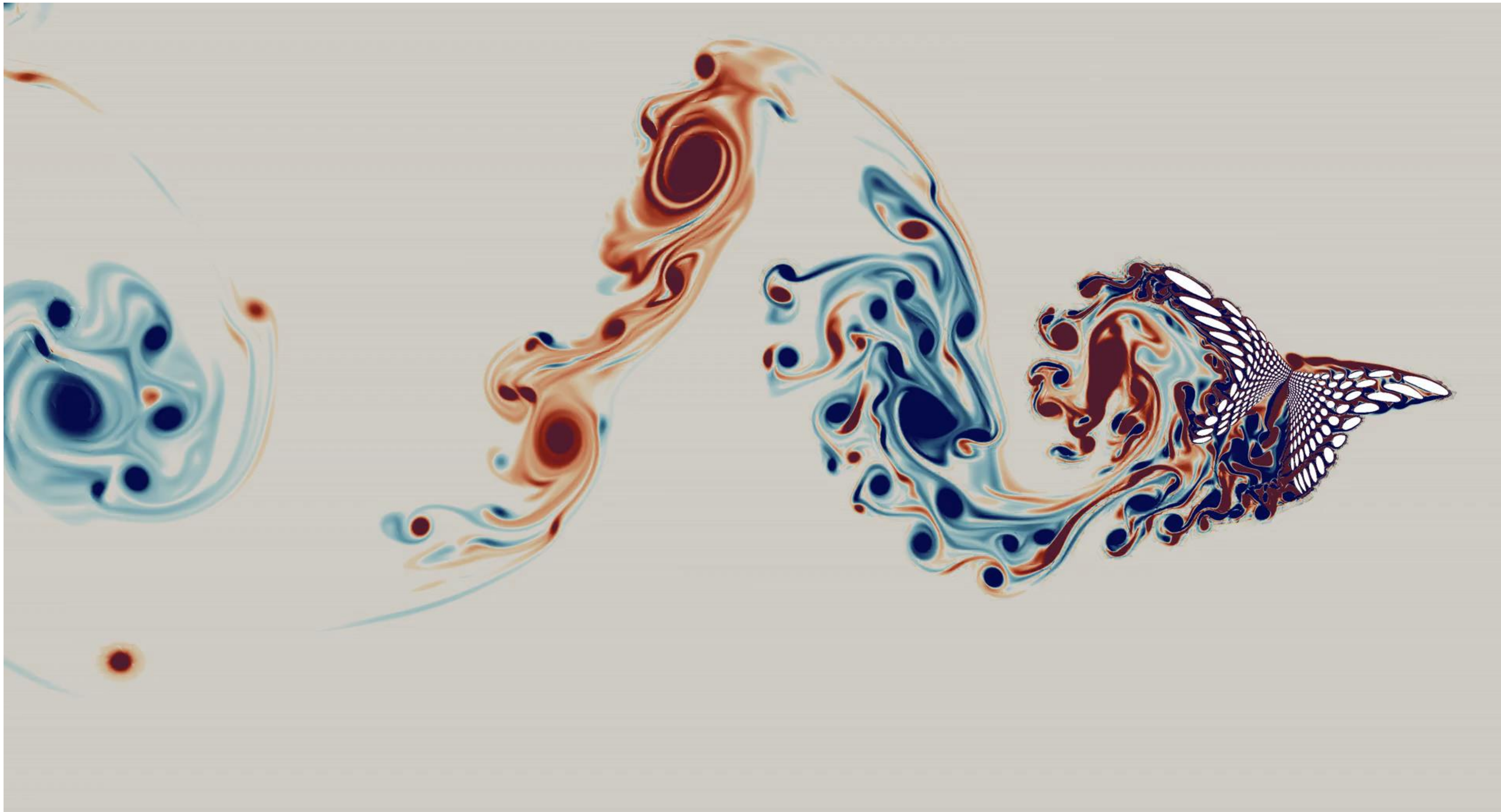
Thank you for your attention



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