LES-Based Analysis of Film Cooling in a High-Pressure Turbine Rotor Including Effects of Purge and Tip Flow

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Outline

Introduction and Background

Numerical Setting

Grid Topology and Grid

- Smooth, as designed
- With two rows of film-cooling

Numerical Results

Conclusions

Introduction

A careful introduction of coolant airflows, which create the film protecting the turbine blade, is critical for a more fuel-efficient and environmentally friendly jet engine. Accurate prediction of streams mixing with the cooling airflows is of great interest for achieving a better design of a jet engine.

Background

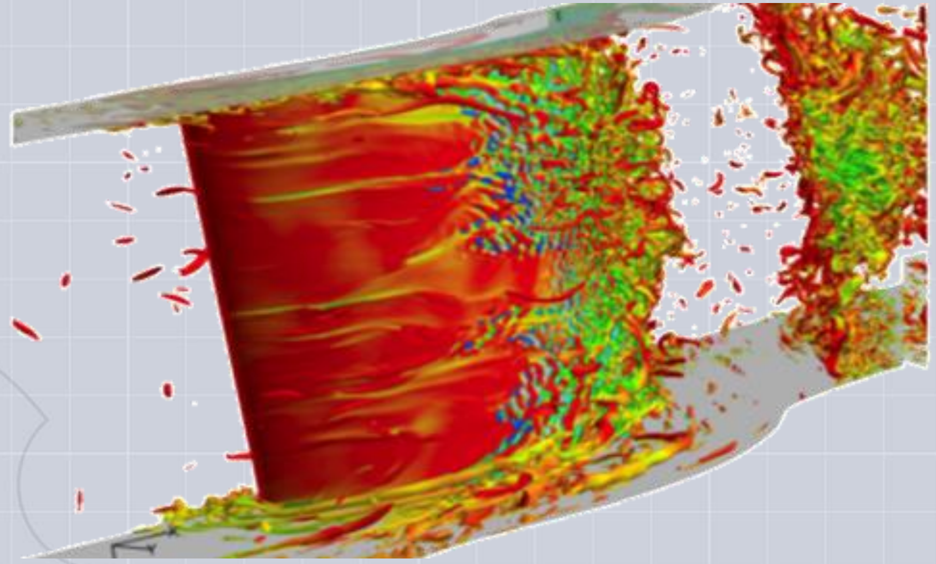
- When simulating film cooling, the effectiveness of film cooling is highly sensitive to the velocity and temperature profiles of the ejected coolant.
- Results from Reynolds-Averaged Navier-Stokes (RANS) solvers are influenced by the choice of turbulence models, introducing further uncertainty into the predictions.
- These sensitivities highlight the need for robust, high-fidelity modeling approaches. Large Eddy Simulation (LES) seems to be a good alternative choice.
- Past studies: An early LES of heat transfer on an HPT blade was conducted by Gourdaine *et al*. [1], who reported good agreement in predicting heat transfer coefficients, including the effects of free-stream turbulence and transition
- Recently, Miki *et al.* [2] performed a heat transfer analysis on a blade passage with an upstream purge slot (no cooling from the blade surface). They presented Nusselt number distributions for the hub, tip, and blade surfaces, and highlighted the impact of purge flow on blade heat transfer

[1] Gourdain, et al Proceedings of the ASME Turbo Expo 2010: Power for Land, Sea, and Air. Volume 7: *Turbomachinery*, Parts A, B, and C. Glasgow, UK. June 14–18, 2010. pp. 807-820. ASME.
[2] Miki, K., et al,Proceedings of the ASME Turbo Expo 2025: Turbomachinery Technical Conference and Exposition. Volume 12: Turbomachinery: Unsteady Flows in Turbomachinery. Paper No: GT2025-153348

NASA In-house CFD code, Glenn-HT

The in-house code, Glenn-HT, developed at the NASA Glenn Research Center, solves unsteady, non-reacting compressible Navier-Stokes equations using ***structured multiblock*** grids.

Features	**Applications**
Multi-block, structured, (U)RANS/LES (lots of turbulence models), flow-solid interactions, implicit N-S solver	Turbine/compressor efficiency, Turbine cooling (conjugate heat transfer), heat exchanger performance, etc.



LES Model and Inflow Turbulence

Large-Eddy Simulation[1]

- Solve an additional equation (T.K.E) to capture "unresolved' turbulent motions.
- Two key model parameters in R-stress and dissipation term, which are *dynamically* evaluated at a local point under the assumption of isotropic turbulence in a small scale and scale-similarity[13].
- LDKM captures "*small-to-large scale energy cascade*" as well as "*transition*".

$$\frac{\partial \bar{\rho} k^{sgs}}{\partial t} + \frac{\partial \bar{\rho} k^{sgs} \tilde{u}_j}{\partial x_j} = \Gamma_k - D_k + P_k$$

Subgrid dissipation: $D_k = \frac{\bar{\rho}\, C_\varepsilon}{\bar{\Delta}} (k^{sgs})^{3/2}$

Subgrid production: $P_k = \tau_{ij}^{sgs} \frac{\partial \tilde{u}_j}{\partial x_j}$

[1] Kim, W.-W., and Menon, S., 1995, AIAA Paper 1995-356.
[2] Klein, M., Sadiki, A., and Janicka, J., 2003, Journal of Computational Physics: 186, pp. 652-665.

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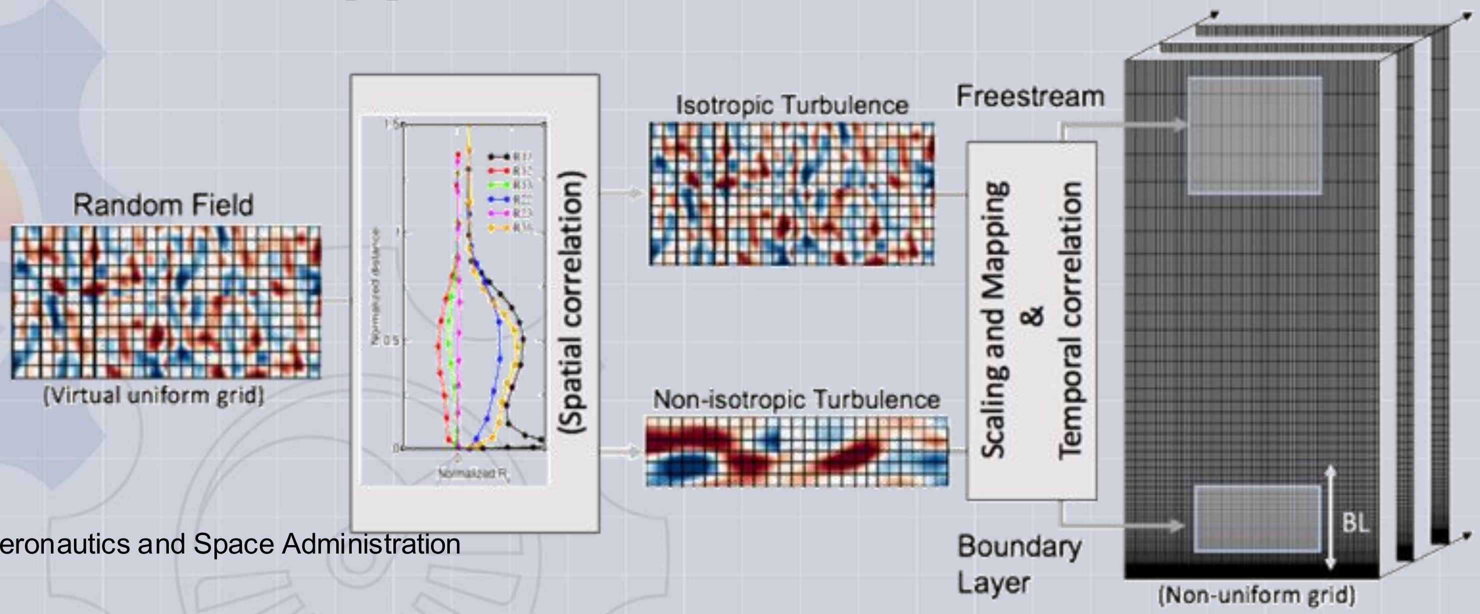
Inflow Turbulence[2]

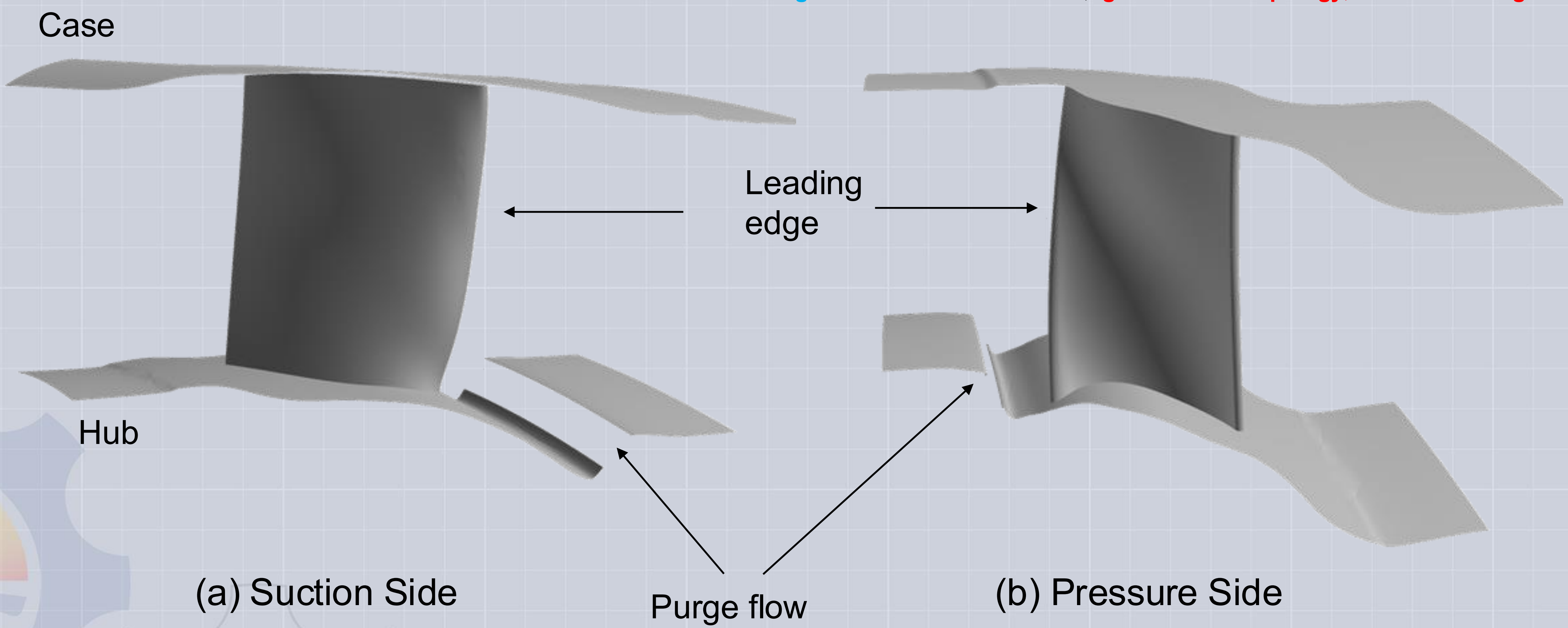


- Inflow turbulence is generated by *Tu* and *Ts* through the digital filtering approach
- Special and temporal correlation are imposed.

[1] Kim, W.-W., and Menon, S., 1995, AIAA Paper 1995-356.
[2] Klein, M., Sadiki, A., and Janicka, J., 2003, Journal of Computational Physics: 186, pp. 652-665.

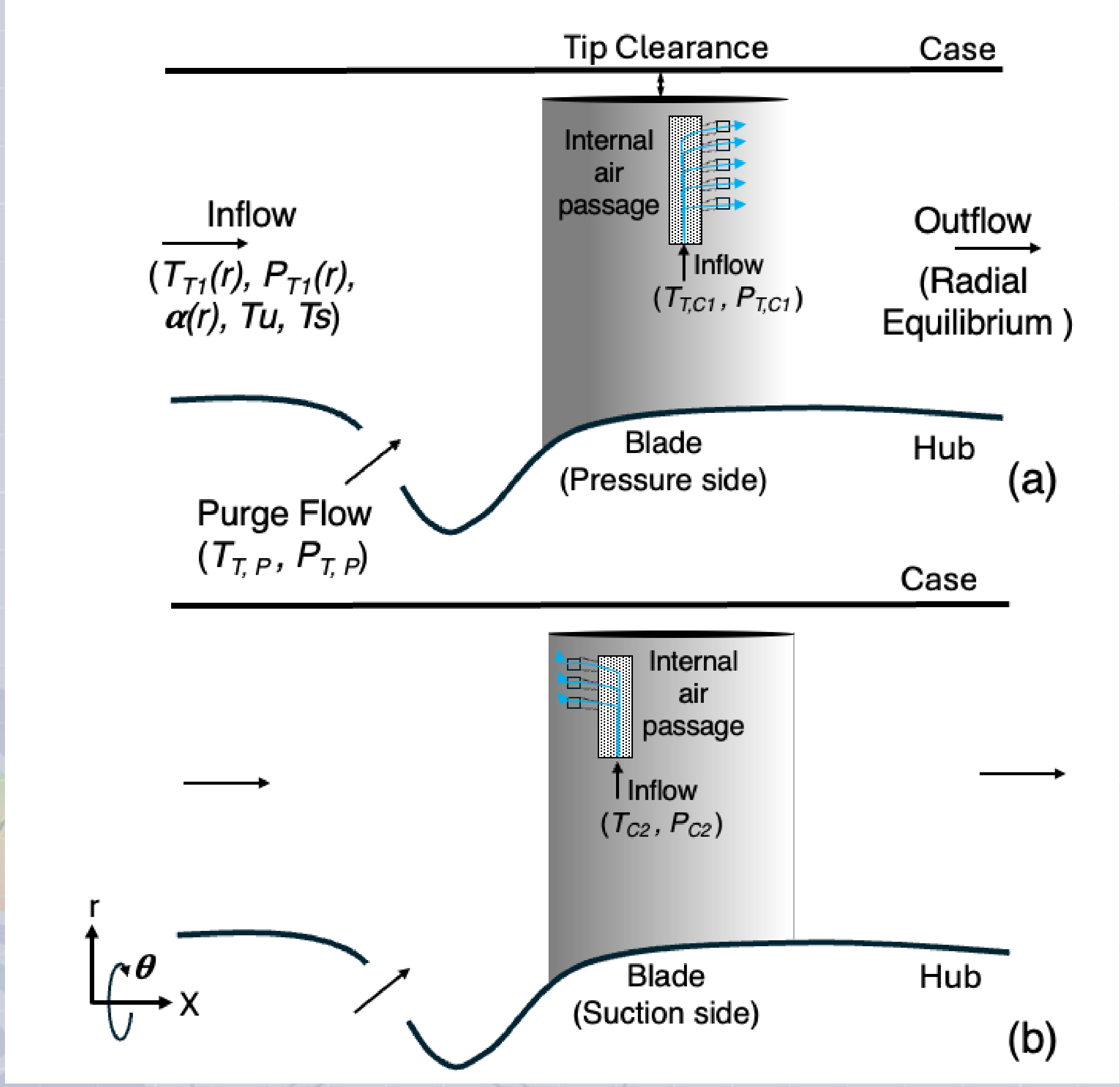
3D View of Computational Domain (Smooth Surface)

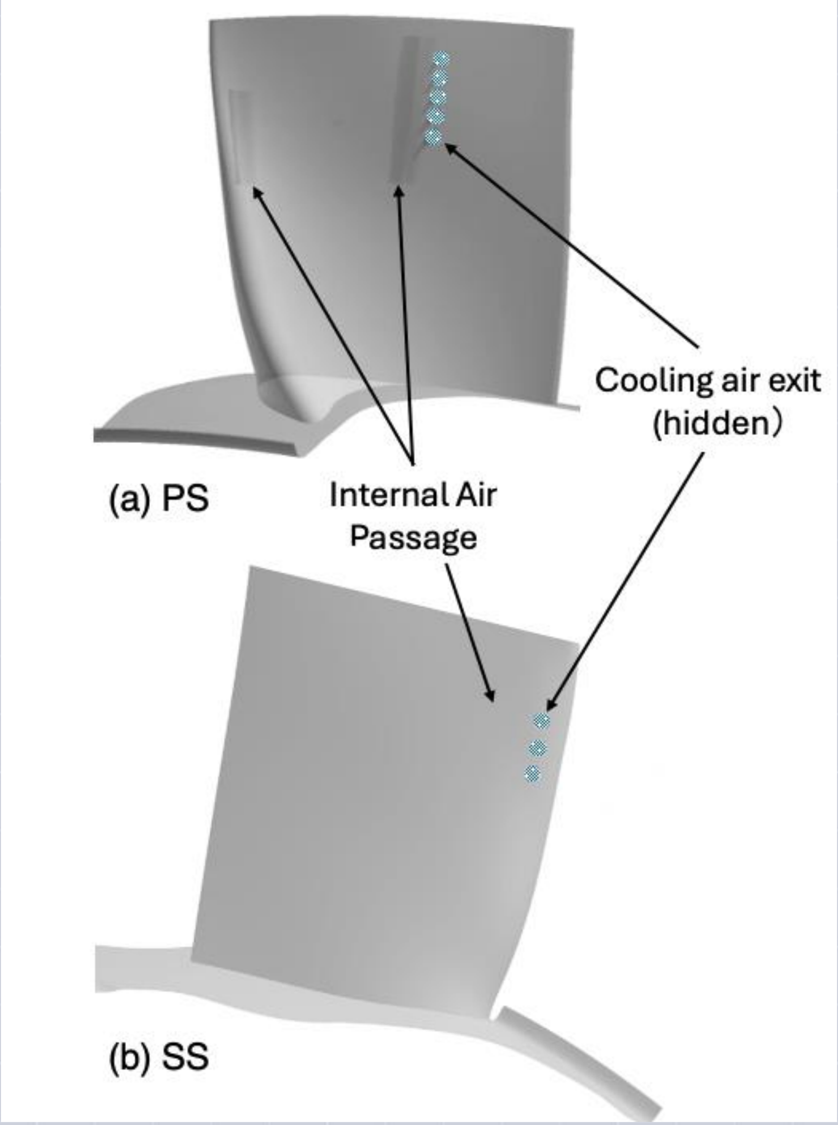
generation of clean surface, generation of topology, and then mesh generations



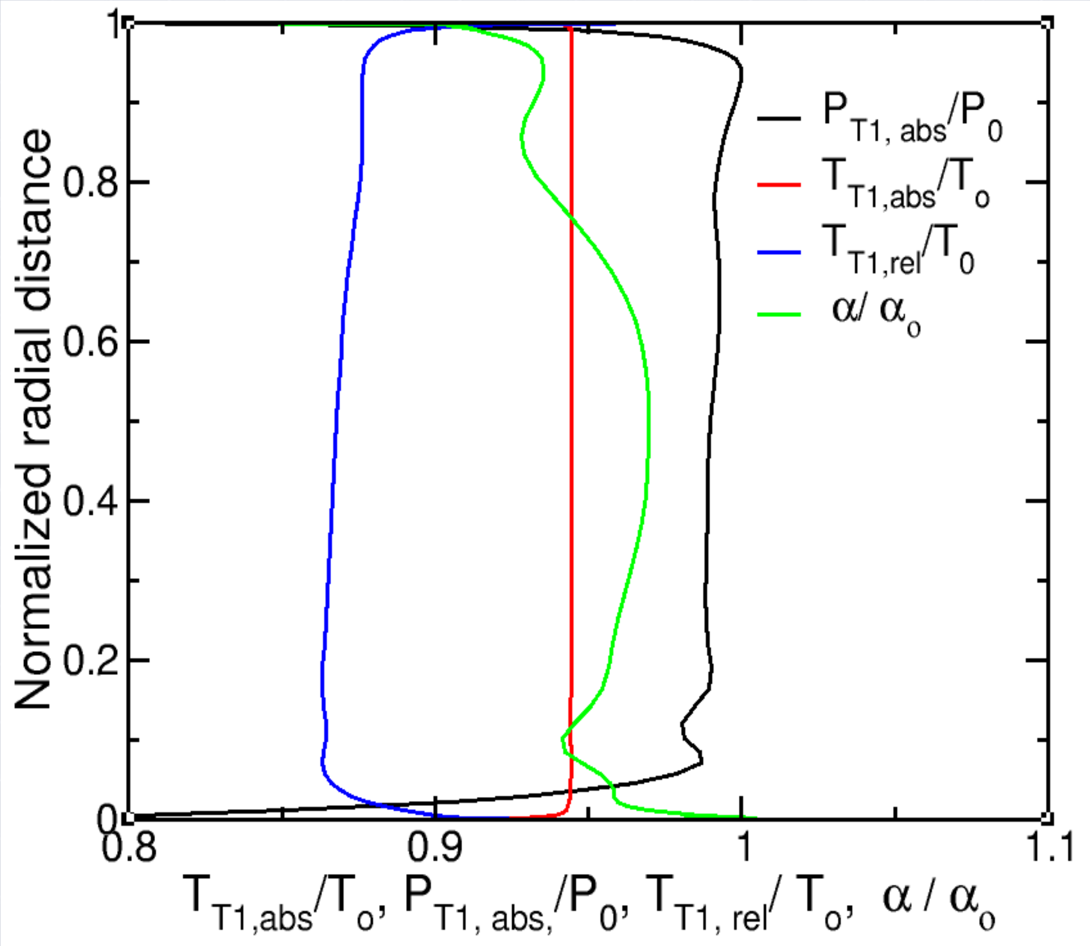
In GridPro, there are three generation processes: **generation of clean surface**, **generation of topology**, and then **mesh generations**

Computational Configuration and Plan (with cooling)





Inlet Boundary Condition



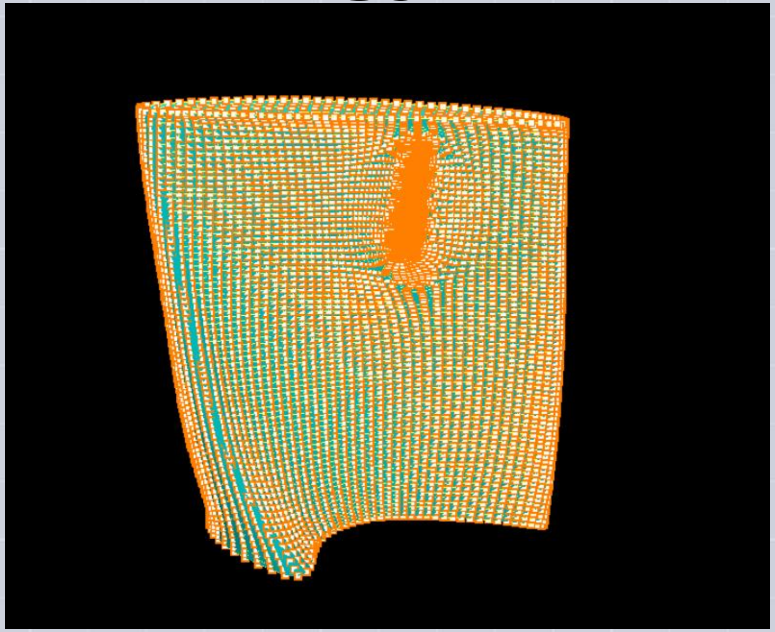
NORMALIZED INFLOW PROFILE

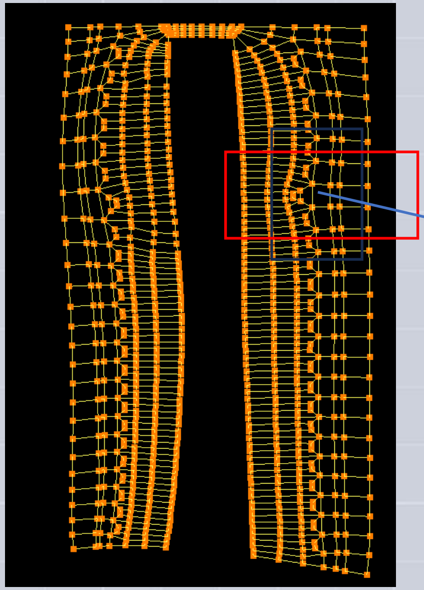
- Radially non-uniform profiles of P_{T1}, T_{T1}, and flow angles are specified at the inlet.
- The normalized tip clearance is set to 0.014 x C_x.

Mesh

- Mesh with two rows of cooling holes are generated.
- The total number of 800M cells was resulted.
- Simple tip clearance is adopted.
- A patch of the hub is utilized for purge.
- Reference is made to a (second) configuration (adiabatic) without holes. (120M cells)

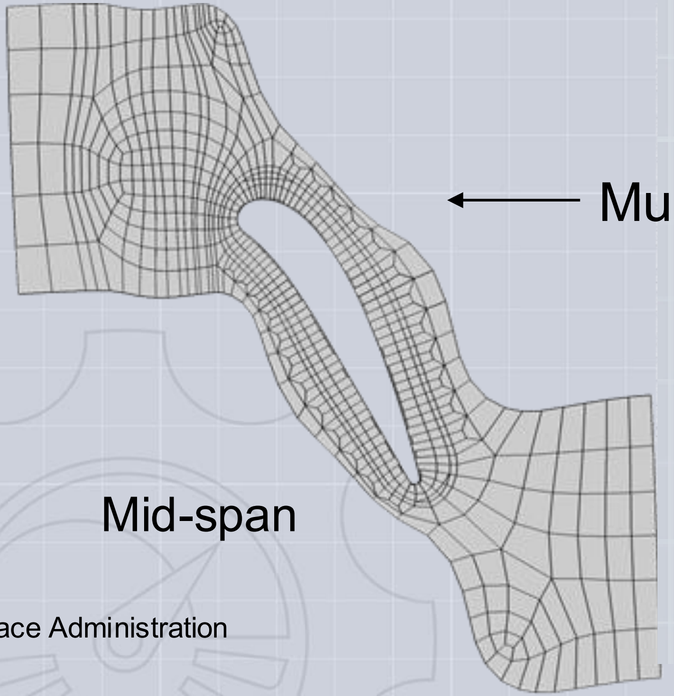
Topology and Multi-Block (smooth surface)

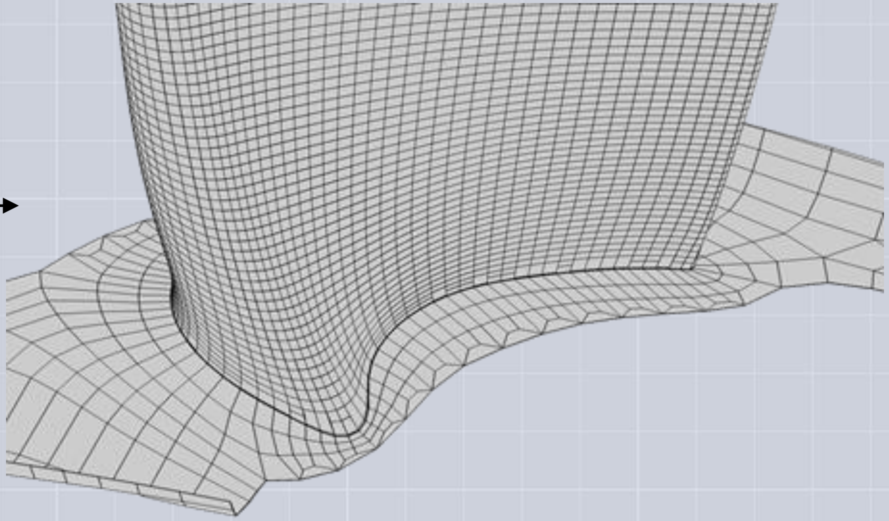




Nesting is necessary for fine grid topology

← Topology nodes →



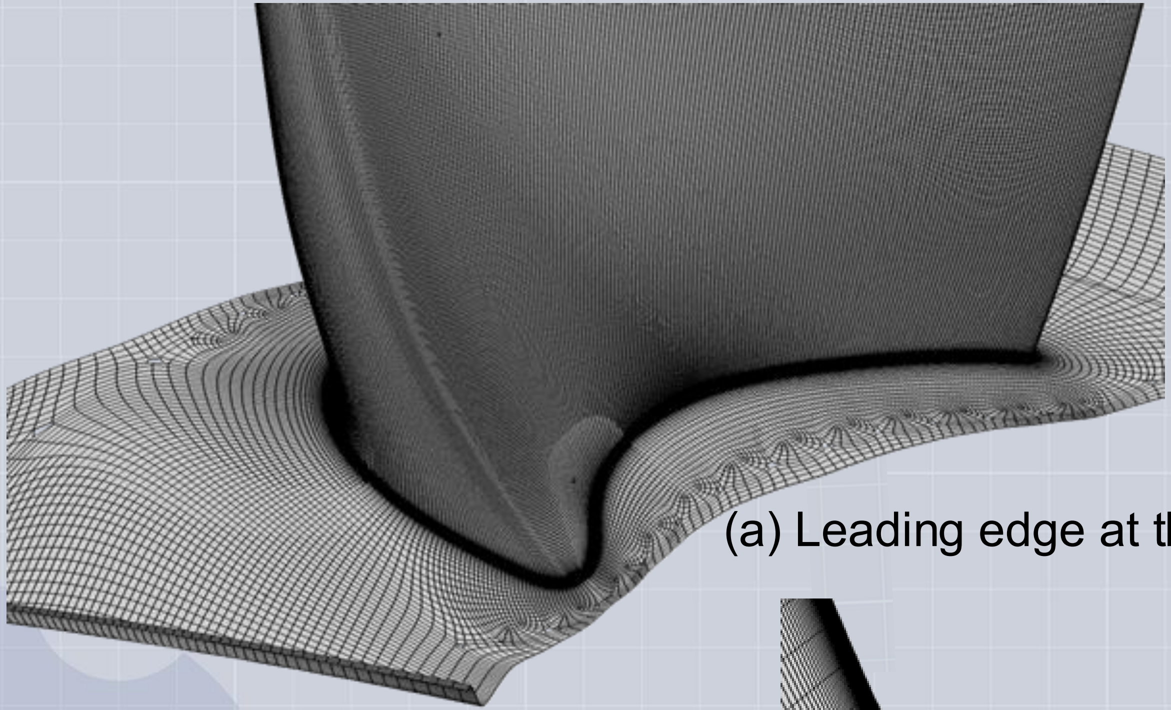


← Multi-block →

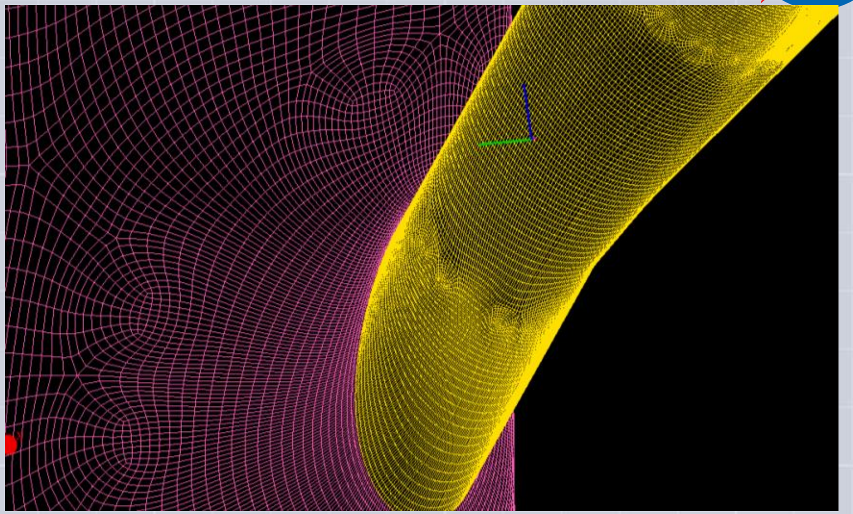
Mid-span

- In GridPro, topology nodes are manually selected.
- Once the topology is created, it can be applied to a similar geometry.

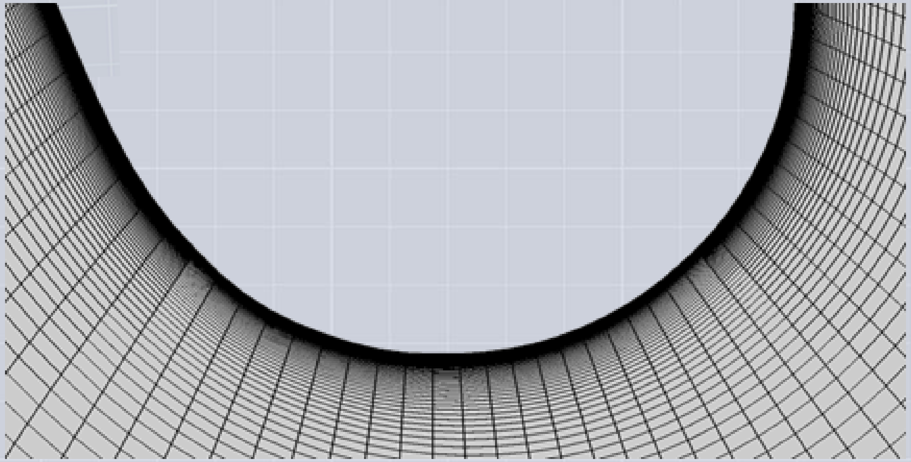
Mesh



(a) Leading edge at the hub (PS)



(b) Leading edge of tip



(c) Near trailing edge

A high-quality structured grid with **800 million** cells was used to resolve the high-Reynolds-number flow and the complex secondary flow structures.

Computing Effectiveness, η

- To compute the film cooling effectiveness, we would need to compute two values for T_{aw}

That gives:

$$\eta = (T_{aw\_no\ cooling} - T_{aw\_cooling})/(T_{aw\_no\ cooling} - T_{coolant})$$

Computing *Nusselt Number, Nu,* and $T_{aw\_cooling}$

- Use two separate isothermal conditions on the cooled blade:
  Linear extrapolation of the Q_{wall} to zero at each surface location yields:

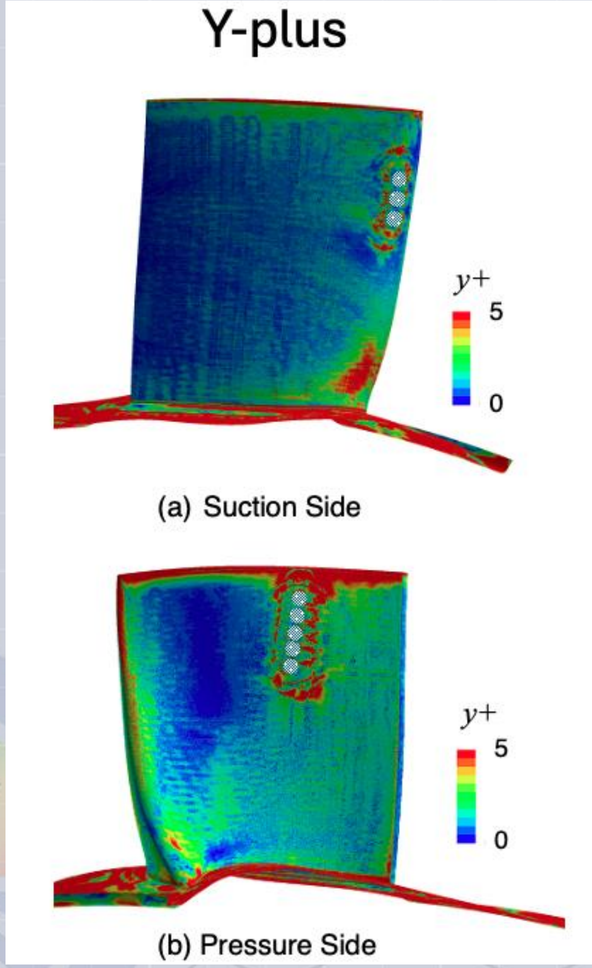
  1. The adiabatic wall temperature, $T_{aw\_cooling}$
  2. The Nusselt Number, *Nu*

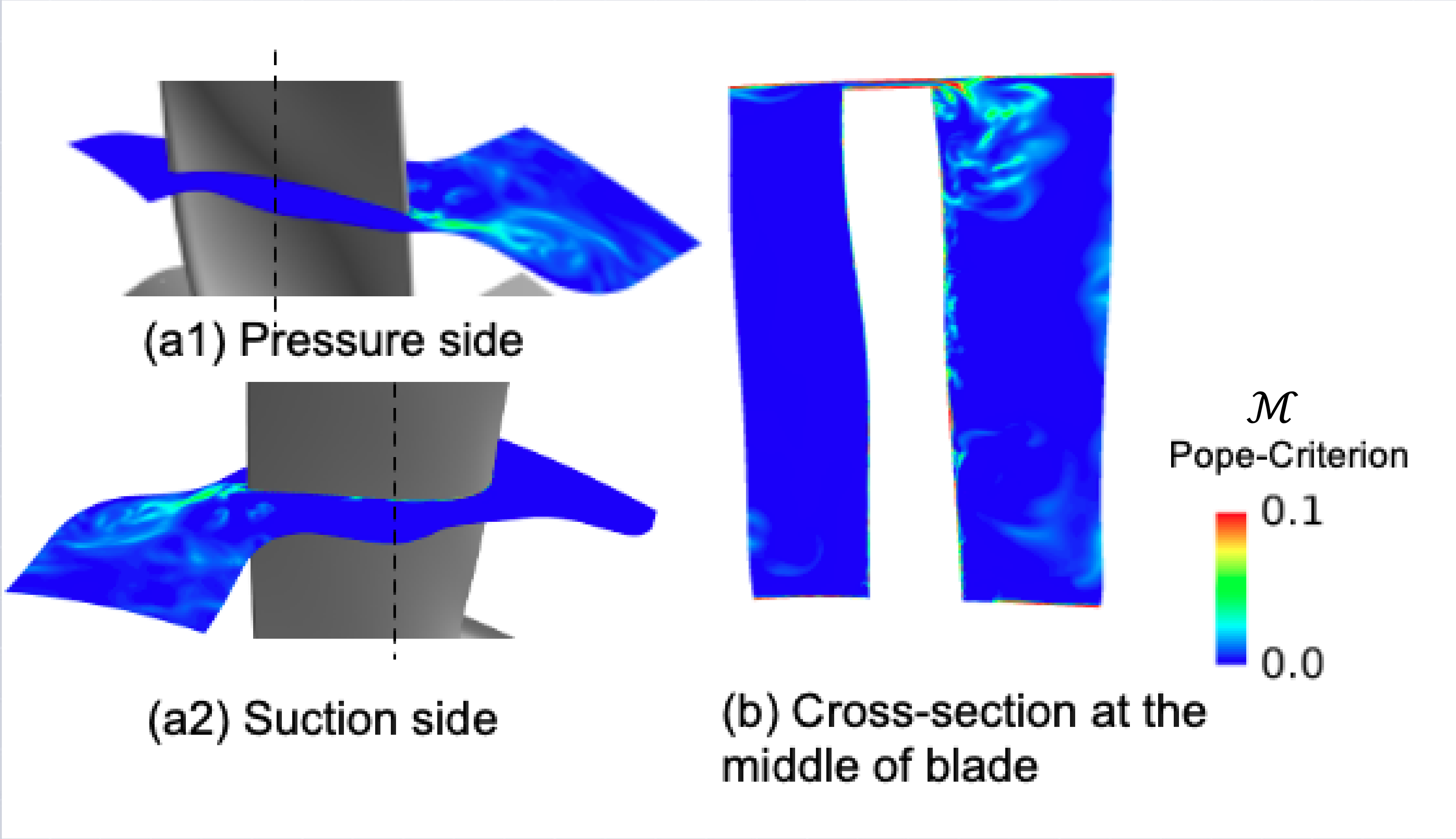
Computing $T_{aw\_nocooling}$

- Applying adiabatic wall condition to a blade without any cooling streams yields the $T_{aw\_nocooling}$.

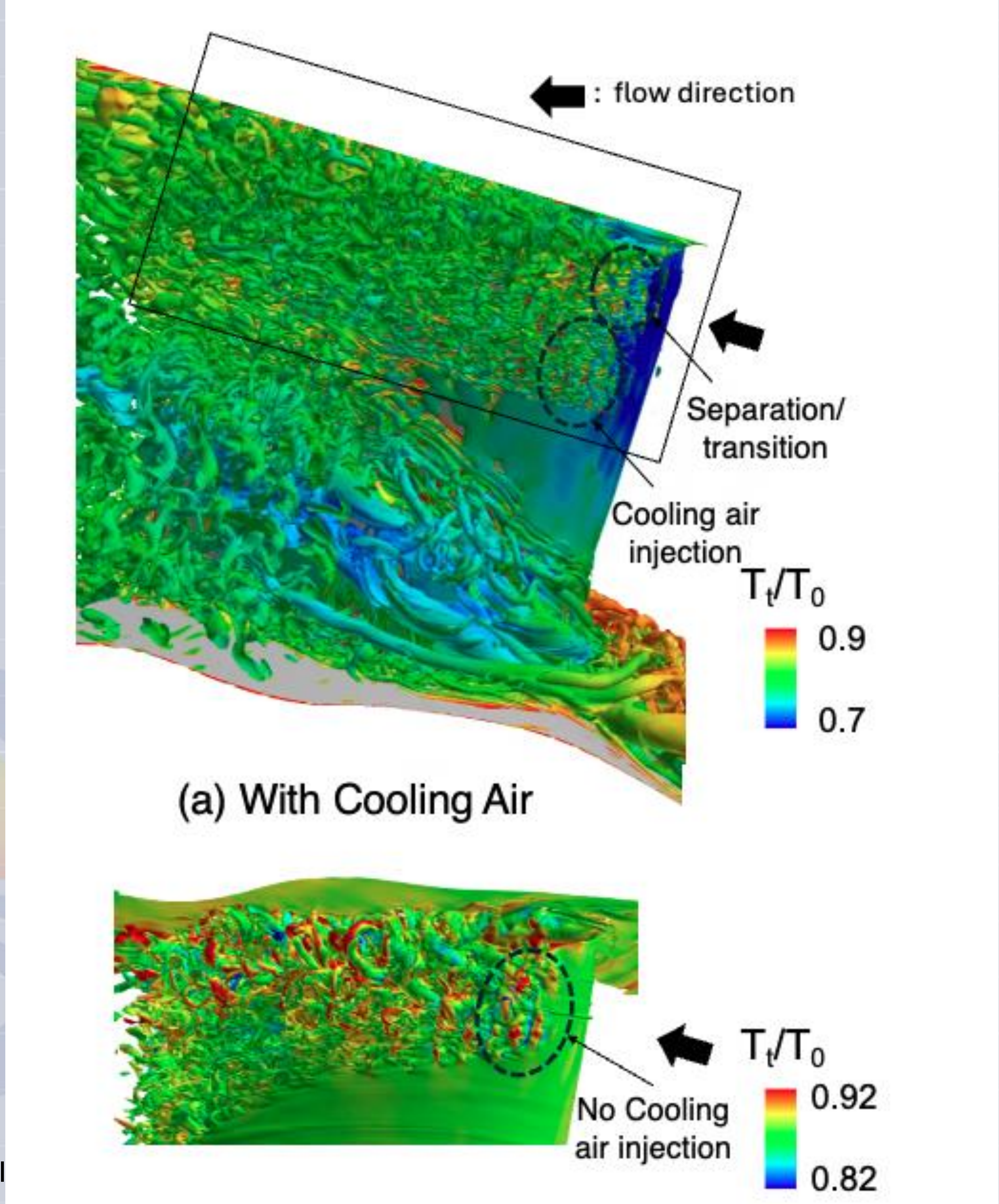
Computational Results

- Grid Resolution
- 3D Flow Fields
- Heat Flux

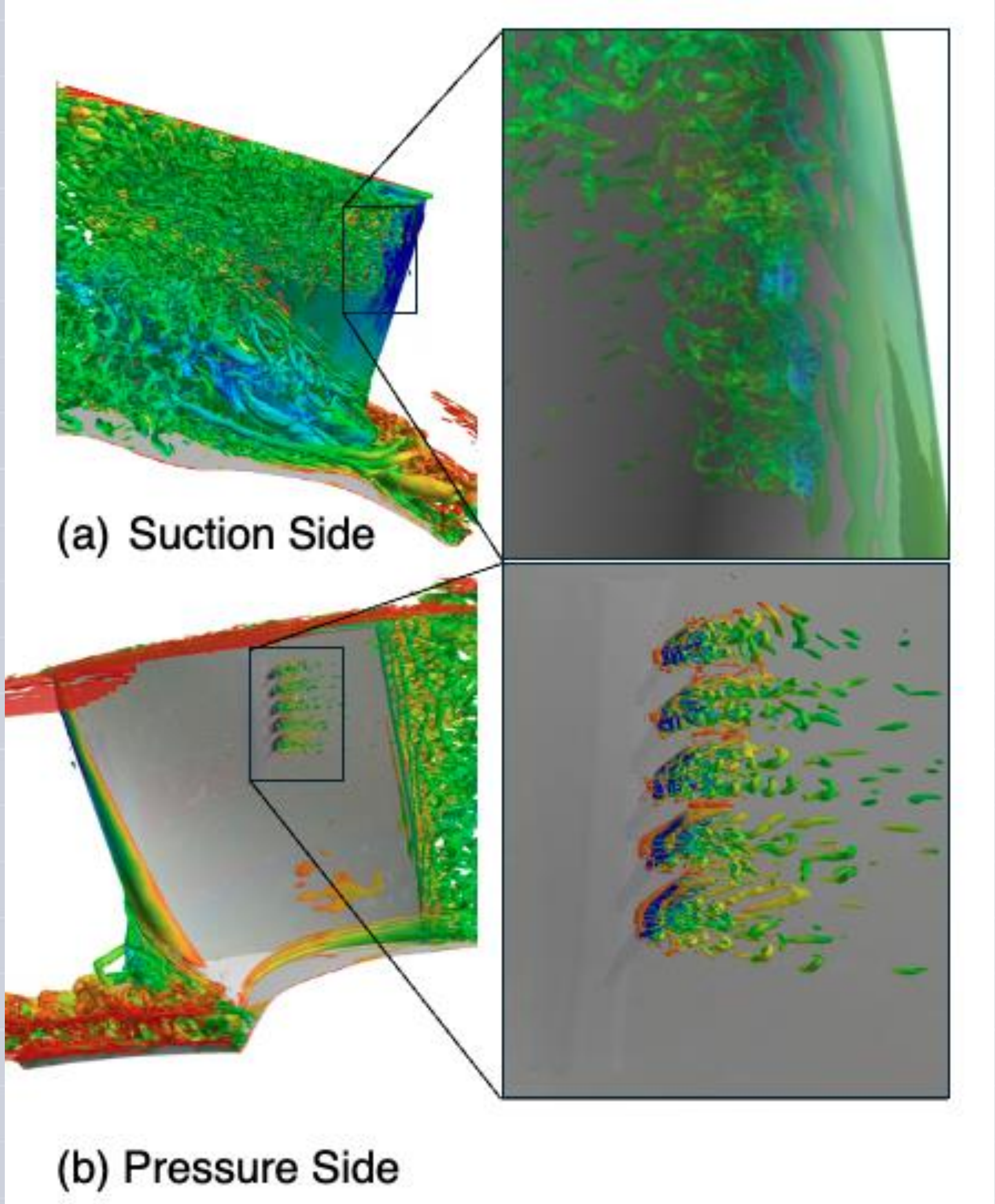


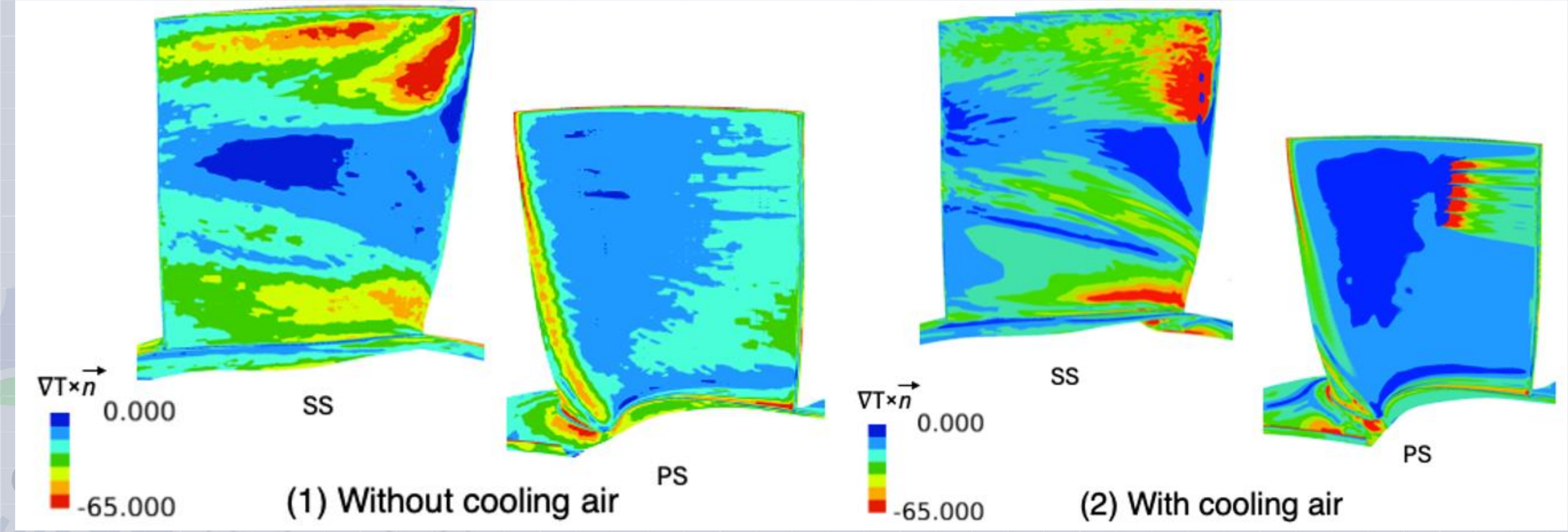


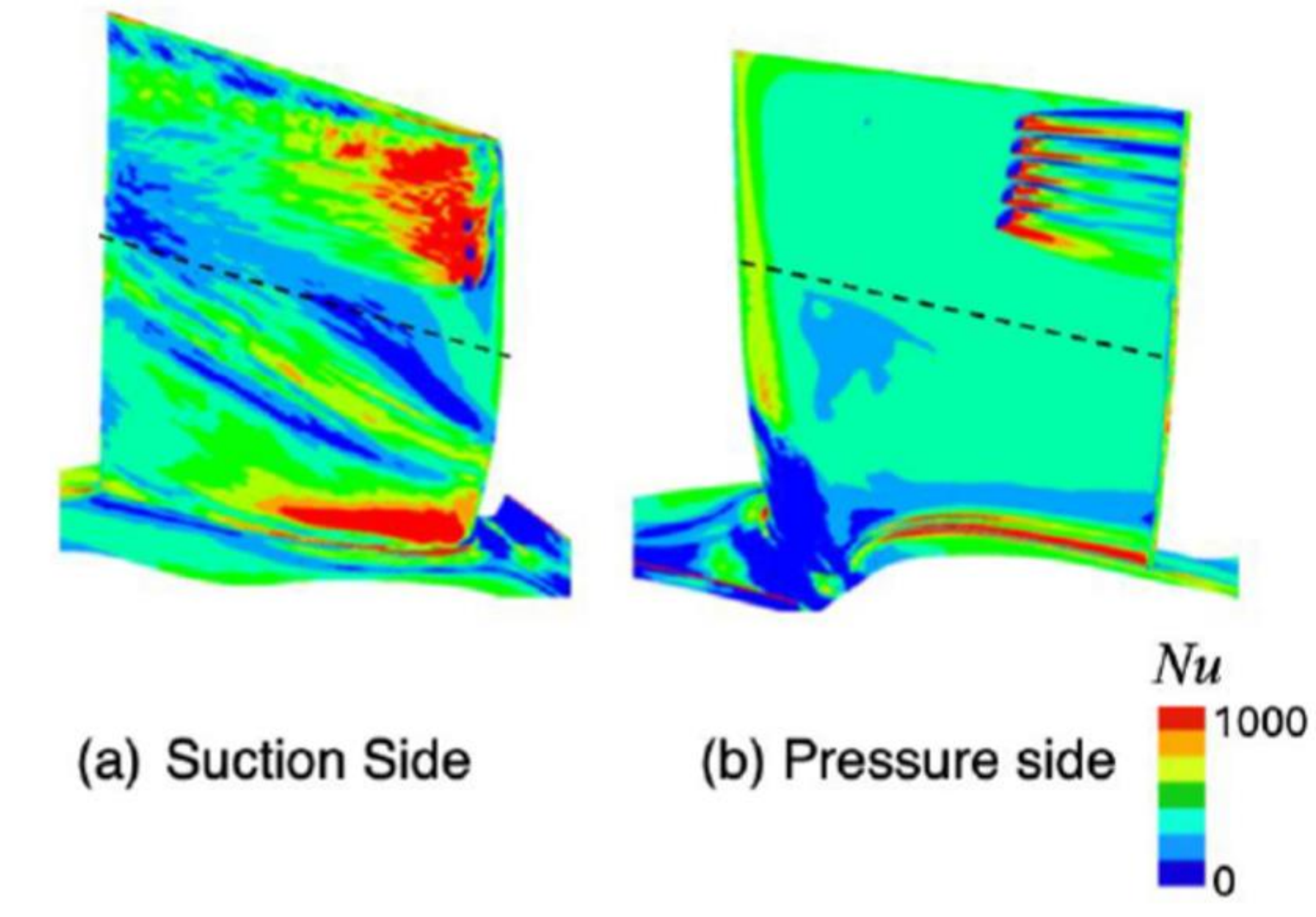
$\mathcal{M}$ is mostly below ~0.1 near the wall and in the freestream region, indicating that the mesh was fine enough to resolve FST.

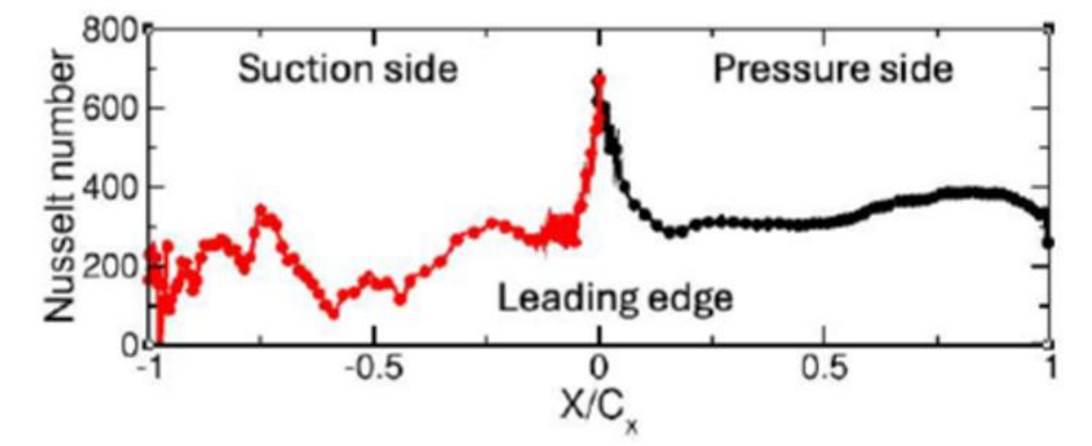


(a) With Cooling Air


(a) Suction Side
(b) Pressure Side

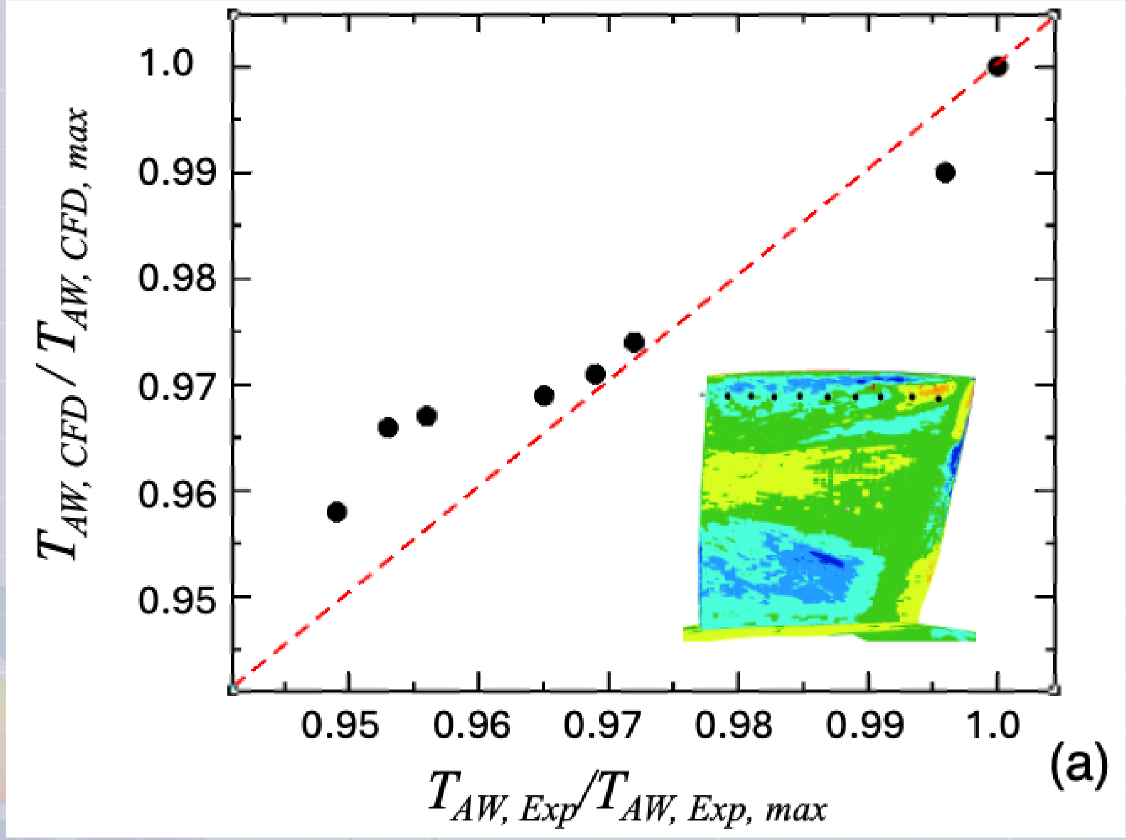

∇T×n
0.000
-65.000
SS
PS
(1) Without cooling air
∇T×n
0.000
-65.000
SS
PS
(2) With cooling air

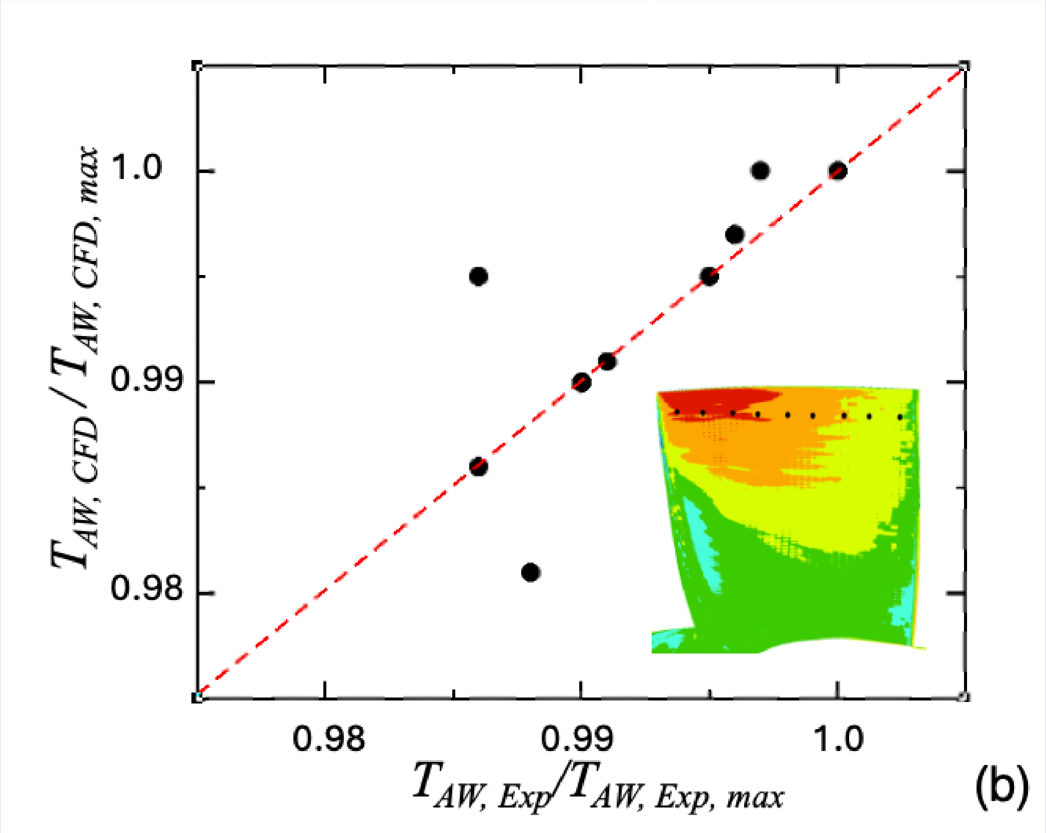


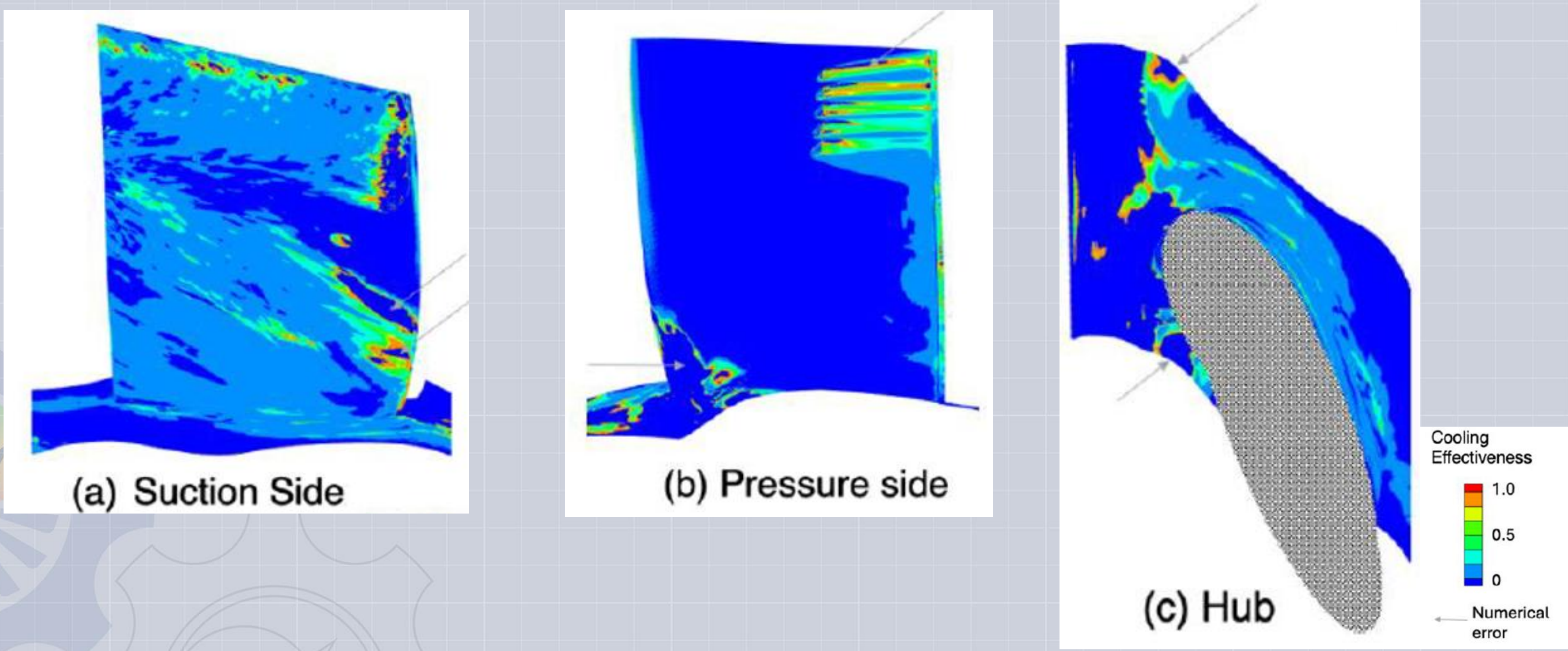


Nu at the midspan

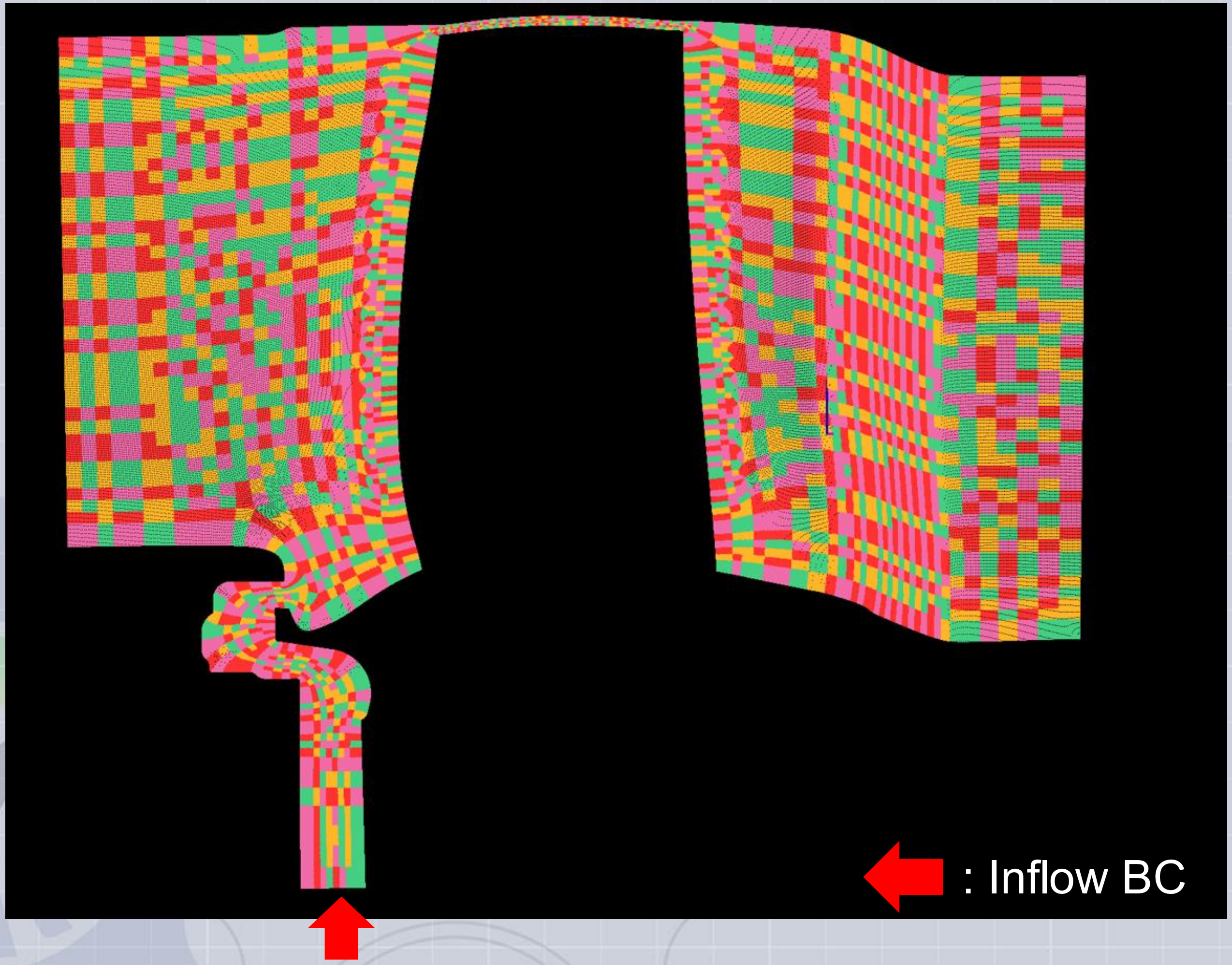
Validation with Experimental Data (no cooling)

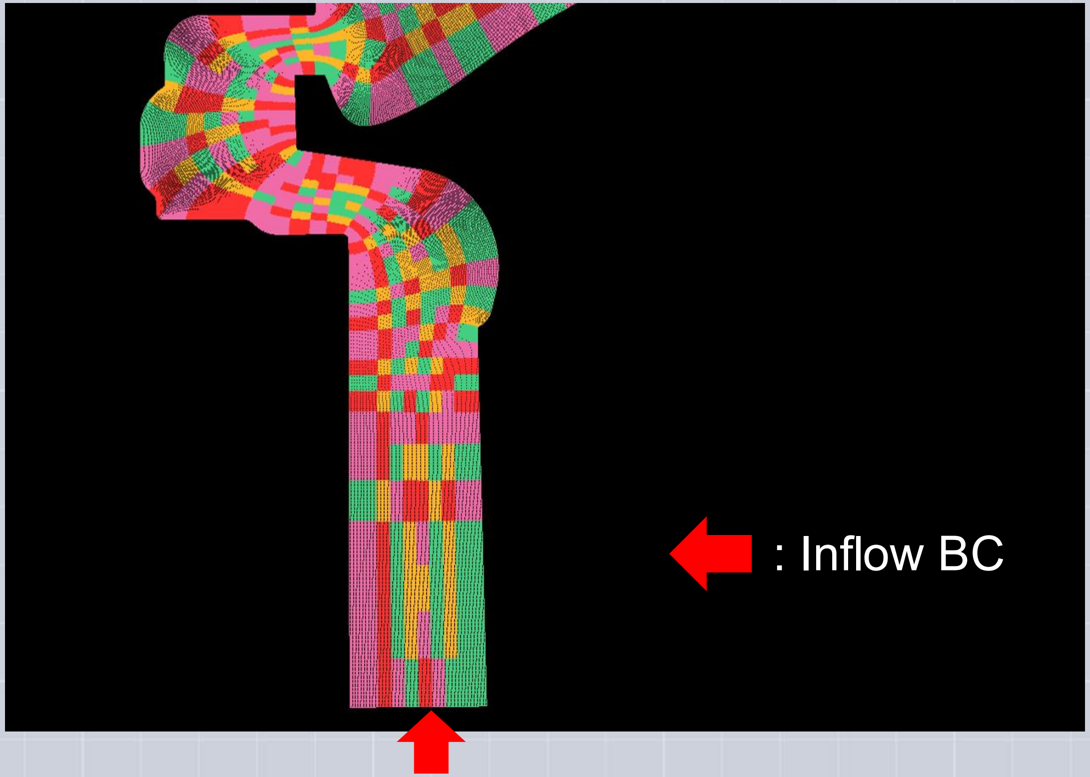


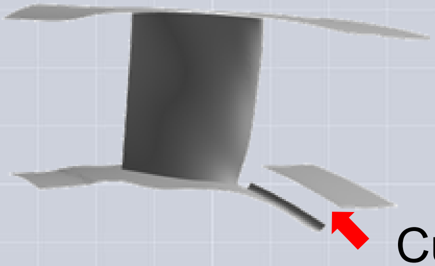



(a) Suction Side
(b) Pressure side
(c) Hub
Cooling Effectiveness
1.0
0.5
0
Numerical error

Truncated Purge Cavity (on-going)







A more realistic purge flow modeling is necessary for accurate exit profile of purge.

Summary

- A refined multiblock grid with nearly 800 million cells was used to simulate the hot gas path over a rotating blade, capturing the flow field, purge flow, tip leakage, and film cooling effects.
- Specific aspects of purge and film cooling were examined, including the interaction and mixing of purge flow with the secondary flow system within the passage. The simulations also captured the complex interactions between the purge flow, mainstream, tip leakage, and film cooling jets.
- A two temperature method was used to extract the effectiveness and heat transfer coefficient which appears to have not been successful in all regions.
- A lesson learned from this work is that separate computations of the adiabatic wall temperature and the wall heat flux may have been more appropriate which will be attempted in the future.

Thank you!

Questions?

Acknowledgement

- This work was supported by the HyTEC (Hybrid Thermally Efficient Core) project managed by Ms. Laura Evans.
- Simulations conducted on NASA Advanced Supercomputing (NAS) Pleiades computers.
- Dr. David Rigby, Dr. Paul Giel, and Dr. Paht Juangphanich for assistance in preparing and running the simulations.

NASA