A GPU-based Approach for Turbomachinery Application

Ali A Ameri[1,2], Azab Mohammad[2], David Rigby[1,2] ,
Erlendur Steinthorsson[1,2],
Gabriele Jost1[1,3], Kenji Miki[1], Paht Juangphanich[1]

1) **NASA Glenn Research Center**
Turbomachinery and Turboelectric Branch
2) **HX5 LLC**
3) HX5 LLC / Supersmith, a California Corporation

Overview of NASA Glenn-HT Team

NASA

Kenji: PI

Mohammad: Technical lead

Erlendur: GlennHT code modification for GPU

Gabriele: GPU-code test/developer

Ali: Adviser for GlennHT code and application

Paht: Consultant test/developer

Dave: Adviser for GlennHT code/connectivity etc.

This work is supported by the Subsonic Vehicle Technologies and Tools Project (SVTT) at NASA under KM/Joseph Connolly and KM/Laura Evans.

Introduction: Team Members

PI

Dr. Kenji Miki

- Ph.D. in Aerospace Engineering from Georgia Institute of Technology (Aerospace Engineering)
- CFD experience: 20 years
- ~90 technical papers
- Proficient at Fortran/MPI programming and experts in CFD (turbomachinery and combustion)
- AIAA Associate Fellow

Introduction: Team Members

POC (tentative)

Dr. Mohammad Azab

-Ph.D. From The university of British Columbia, Vancouver, Canada

- Industrial CFD experience: 15 years
- Proficient in C++/C/Fotran/CUDA/MPI programming, experience with the following areas of finite volume CFD simulations (numerics, turbulence, multiphase, reacting, pressure based, and density based techniques)

Introduction: Team Members

Main Architect of GlennHT

Dr. Erlendur Steinthorsson

-Ph.D. in Mechanical Engineering from Carnegie Mellon University
- CFD experience: 30 years
- ~20 technical papers and patents
- Proficient at Fortran/MPI programming and expert in CFD (turbomachinery and combustion)

Introduction: Team Members

GPU-code Test/Developer

Dr. Gabriele Jost

-Ph.D in Mathematics from the University of Goettingen

- Working in Computer Science 20+ years in industry and academia (former NASA HPC technical support member and organizer of the NASA Hackathon)

- Proficient in Fortran, compiler technology, performance optimization: single core (Intel, Arm, Sparc, AMD Epic, etc.), shared memory multi-core (OpenMP, OpenACC, SHMEM), distributed memory (MPI), GPU accelerators (OpenMP, OpenACC, CUDA, HIP, vendor provided GPU libraries

Introduction: Team Members

Adviser for GlennHT and Application

Dr. Ali Ameri

- Ph.D. in Aerospace Engineering from Cleveland State University
- Proficient at Fortran/MPI programming and experts in CFD (turbomachinery, turbulence modeling, heat transfer).
- More than ~150 papers
- ASME Fellow

Introduction: Team Members

Adviser for GlennHT and Application

Dr. David L Rigby

- *Ph.D* in Mechanical Engineering from the State University of New York at Buffalo
- *E*xtensive research in the area of fluid flow and heat transfer for 30 years at NASA Glenn.
- ~ 80 technical papers and has been invited to lecture internationally

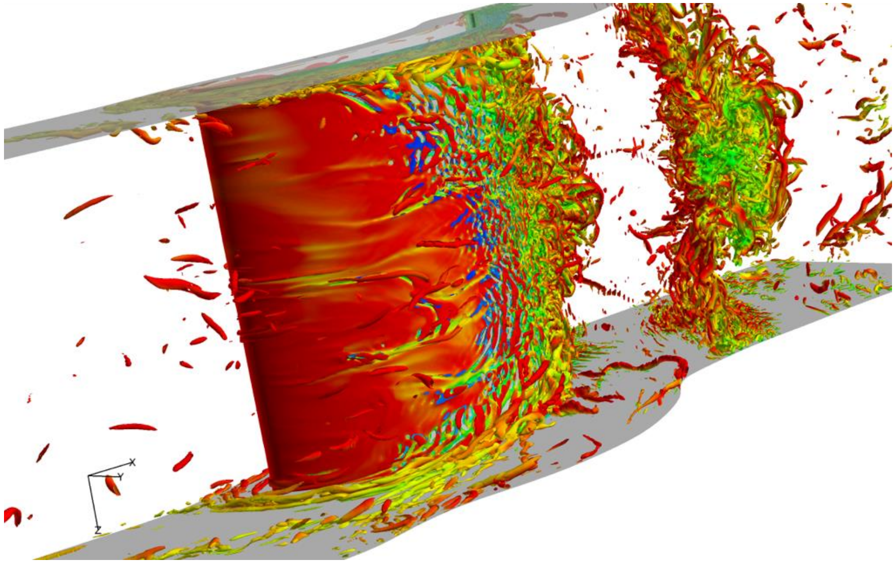
Introduction: Team Members

Consultant

Dr. Paht Juangphanich

- Ph.D. in Aerospace engineering from Purdue University (Aerospace Engineering)
- Proficient in Python, C#, Rust, likes to share with the public: https://github.com/pjuangph/landing_page

Overview of GlennHT Code



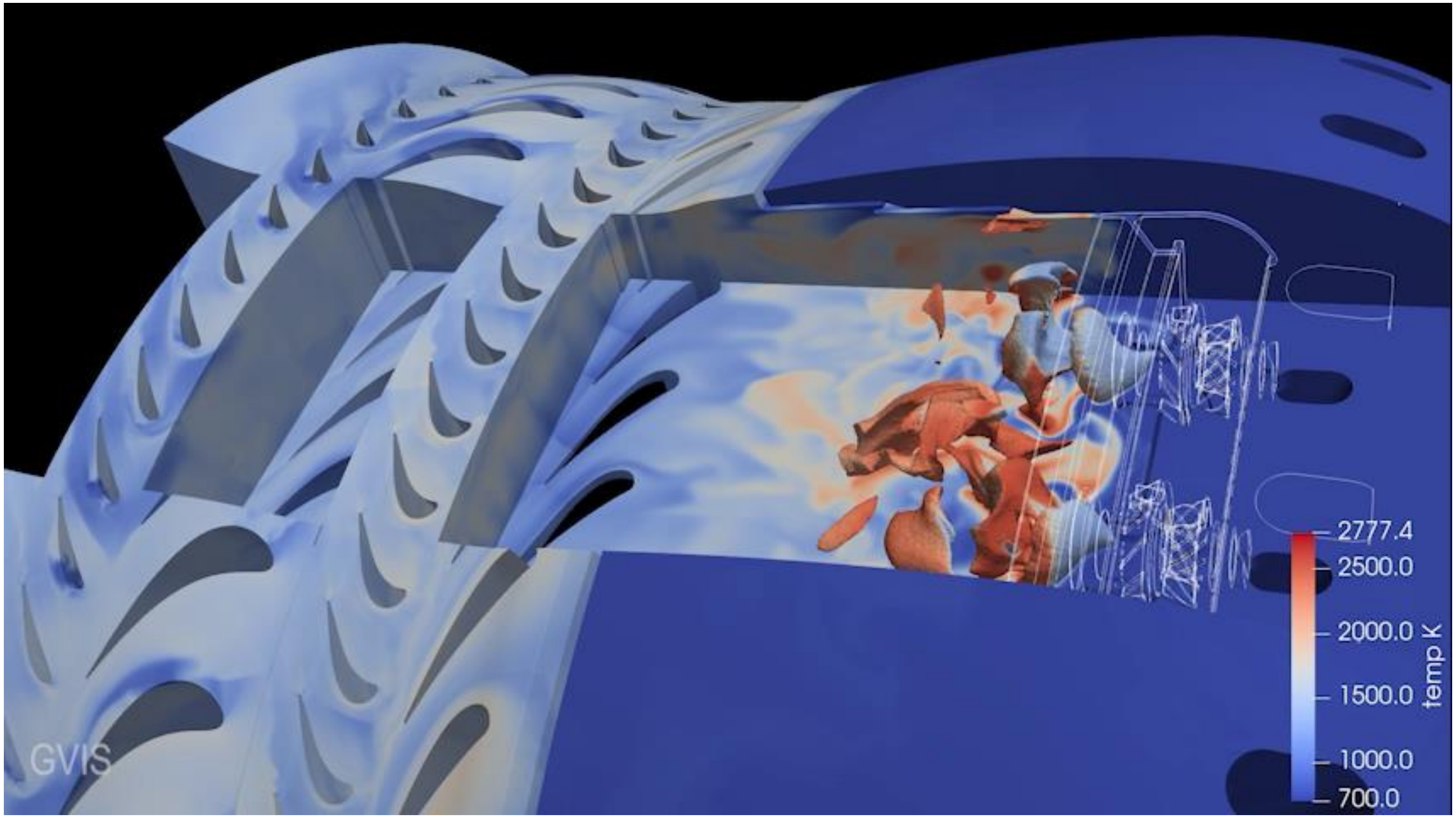
- Glenn-HT is a CFD code that has been in continuous use and development at NASA GRC.
- It has been extensively used for calculations of heat transfer in turbomachinery.

Mean Features of GlennHT

- Written in Fortran 2003+. (and beyond), MPI (excellent scalability on CPU for NAS)
- 100K+ lines with multiple turbulence models (RANS, URANS, LES) and BCs
- Parallel computing by domain decomposition, Explicit Runge-Kutta algorithm
- Alternating-direction implicit solver for linear system of equations
- Red-black Gauss-Seidel solver for linear systems of equations
- Multigrid algorithm for convergence acceleration for nonlinear PDE equations.
- General interface (sliding mesh, mixing plane model, etc.)

Challenge Problem and Its Impact on the Field

Introduction: Turbine is HOT!



High-pressure turbine stator/rotor surface are subject to hot products coming out of a combustor -> Cooling Air needs to be “carefully” introduced.

If Cooling Air Flows are Carelessly Introduced…

From "**Deposition With Hot Streaks in an Uncooled Turbine Vane Passage**", B. Casaday, et al J. Turbomach, 2013 Vol. 136 (Permission from Prof. Bons and thanks to Dr. Mike Dunn @ OSU)

This significantly affects durability and maintenance cost of Jet Engine!

Our Challenging Problem

Gas turbines will over time suffer gradual but continuous deterioration of efficiency that impacts overall performance and fuel consumption.

For every 1% drop in turbine efficiency, the added fuel cost to the global aircraft fleet in 2025–2026 is estimated to be $2.46 billion* USD!

- There are further impacts in terms of maintenance and CO_2 emissions.

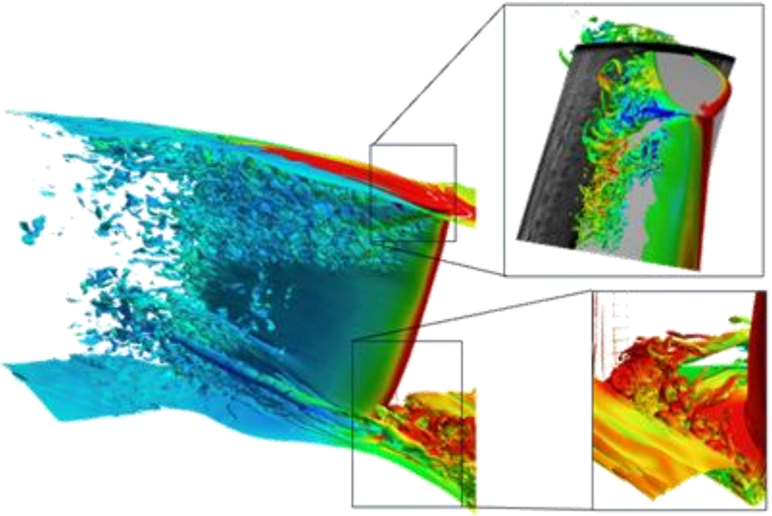
Therefore, studying blade deterioration and developing simulations of such conditions can provide valuable insights and indicate pathways to reducing these costs.

How can we simulate *the blade deterioration in a realistic sense?*

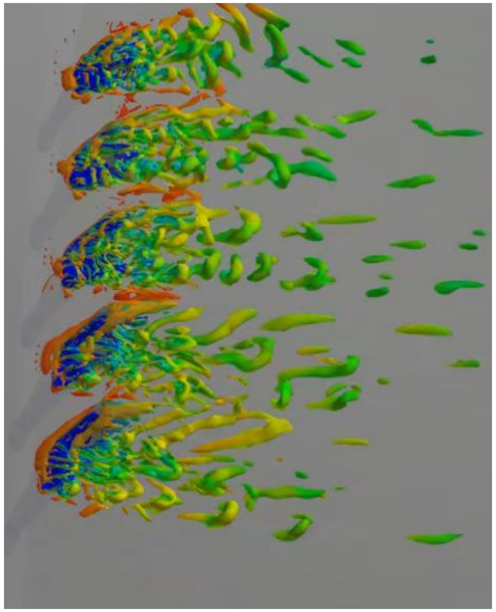
*In aviation, a 1% decrease in engine efficiency (thermodynamic or propulsive) generally results in a direct 1% increase in fuel burn to maintain the same thrust and mission profile.

Objective

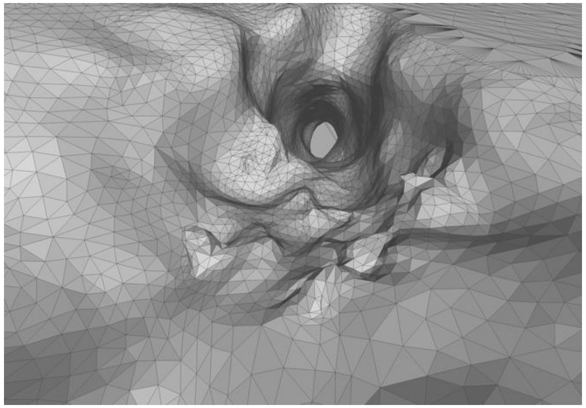
To use high fidelity computations to compare the performance of as-designed, film cooled and deteriorated film cooling holes…..



High fidelity LES

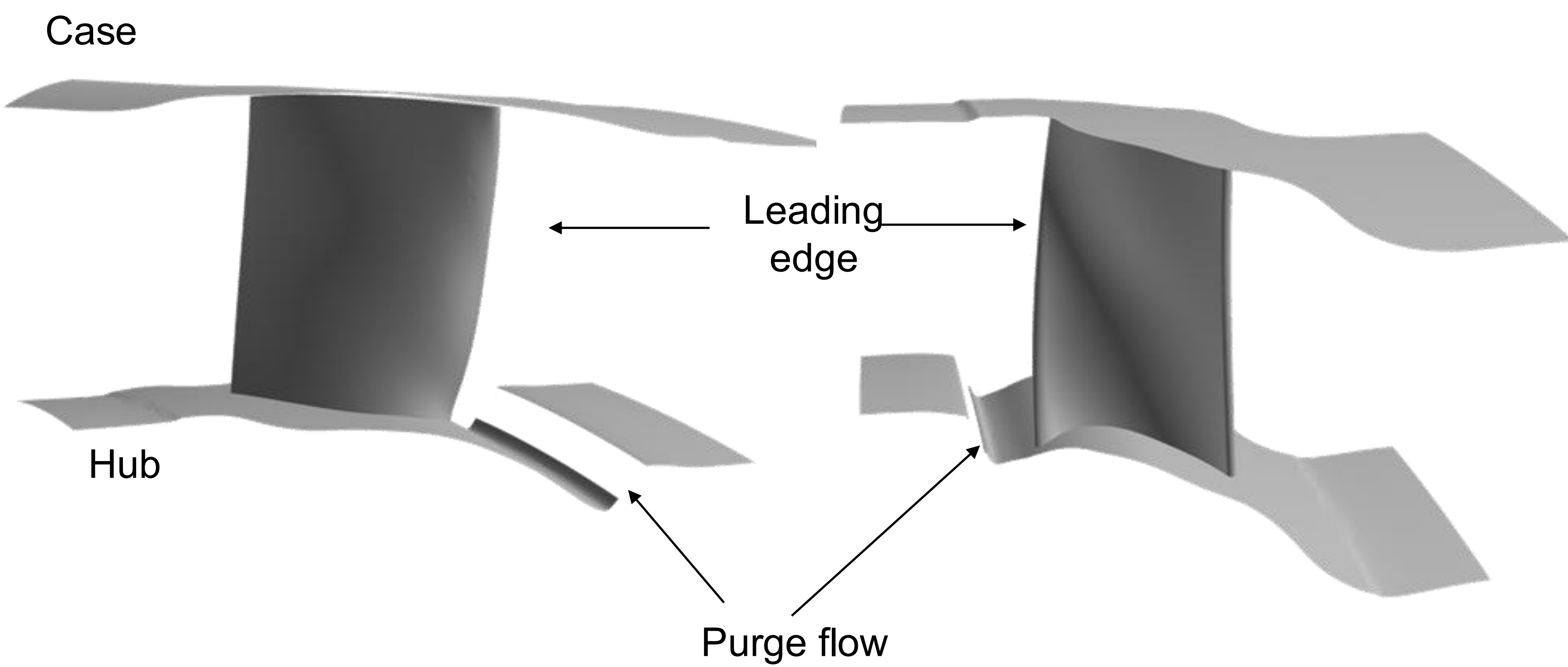


Cooling Air injection



Highly complex "deteriorated" cooling hole

3D View of Computational Domain (clean surface)

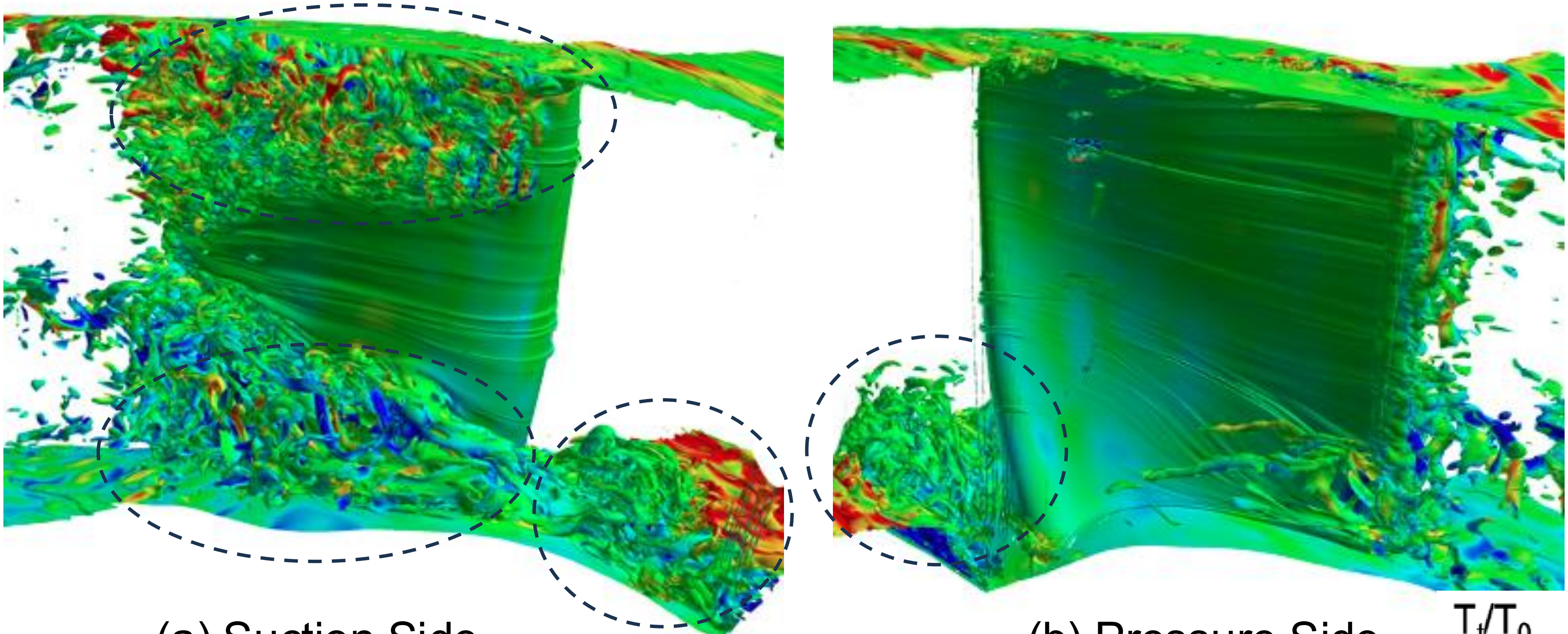


(a) Suction Side

(b) Pressure Side

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

Iso-Surface of Vorticity Magnitude



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(b) Pressure Side

- Active vortical motion exist at the case & hub and in the vicinity of the purge.

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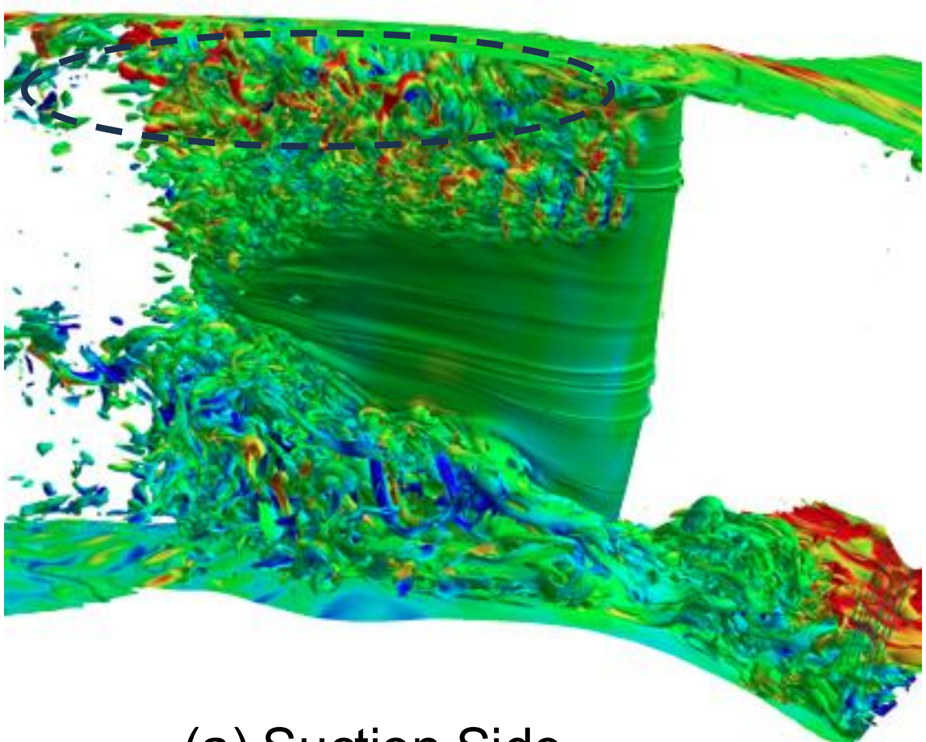

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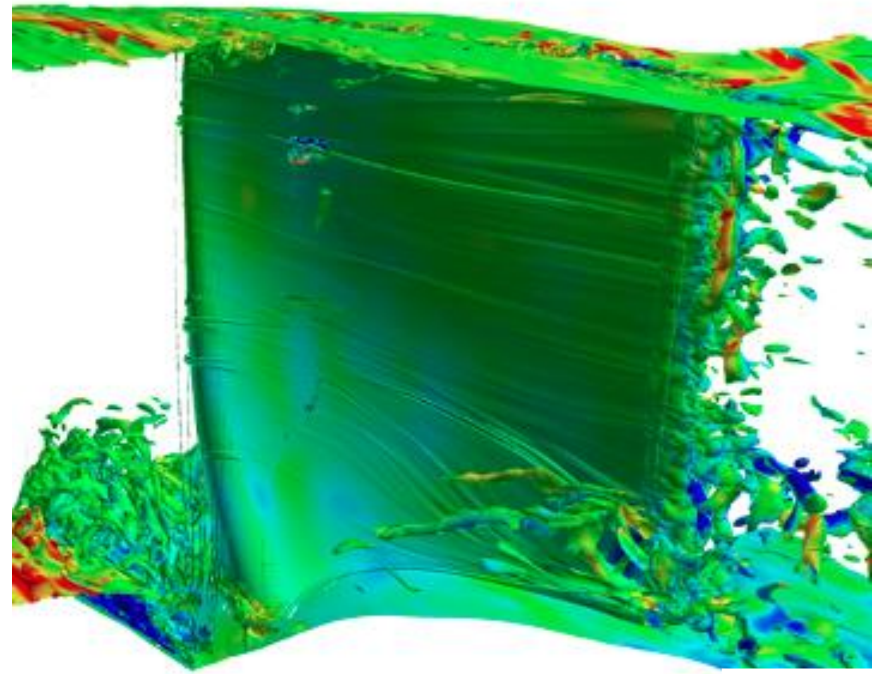
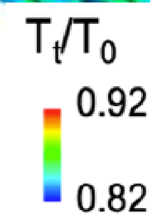


(b) Pressure Side



- Active vortical motion exist at the case & hub and in the vicinity of the purge.
- Near the tip region, a leakage vortex, is formed.

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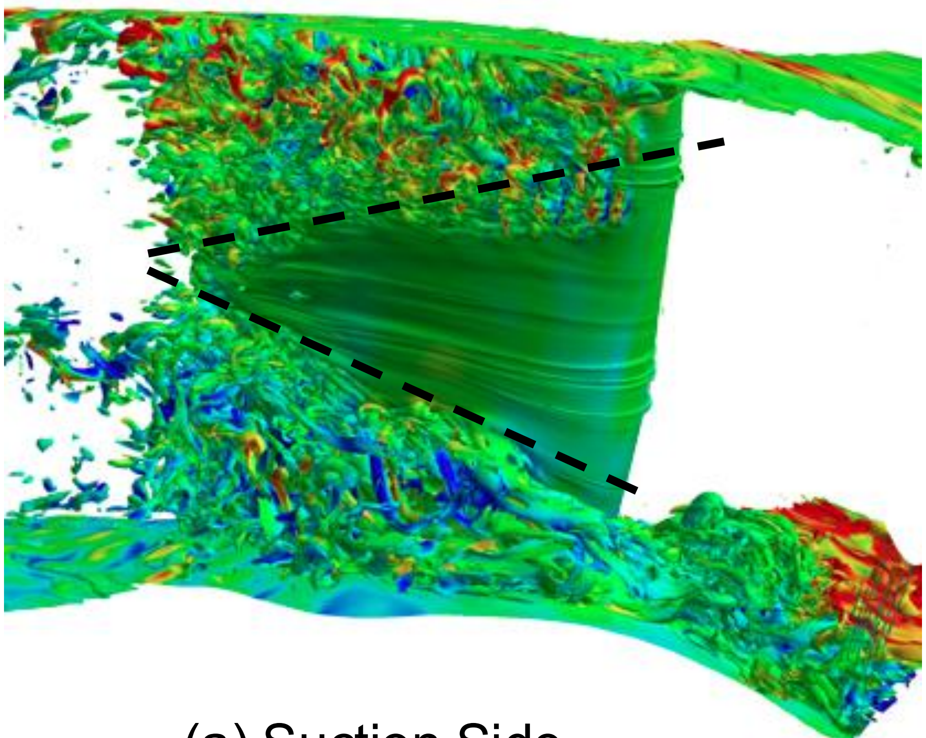

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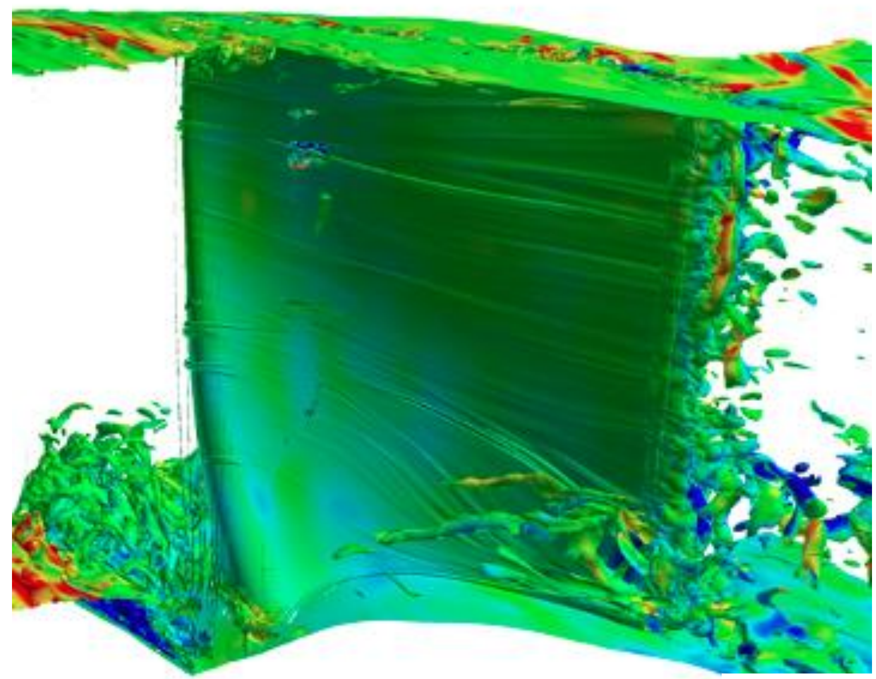

(b) Pressure Side

T_t/T_0

0.92

0.82

- Active vortical motion exist at the case & hub and in the vicinity of the purge.
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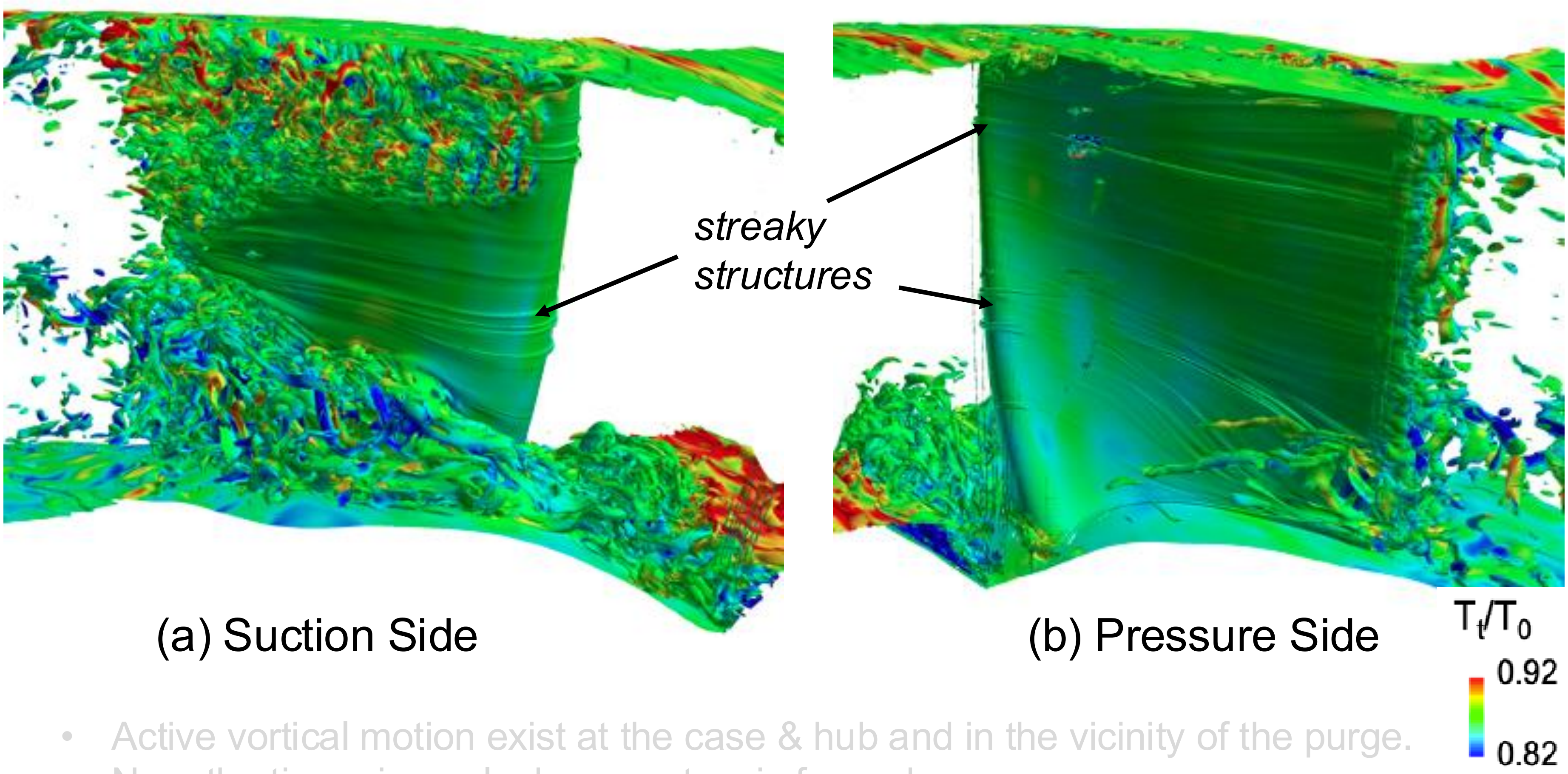
- A distinct "V"-shaped laminar region is evident in the midspan region.

Iso-Surface of Vorticity Magnitude



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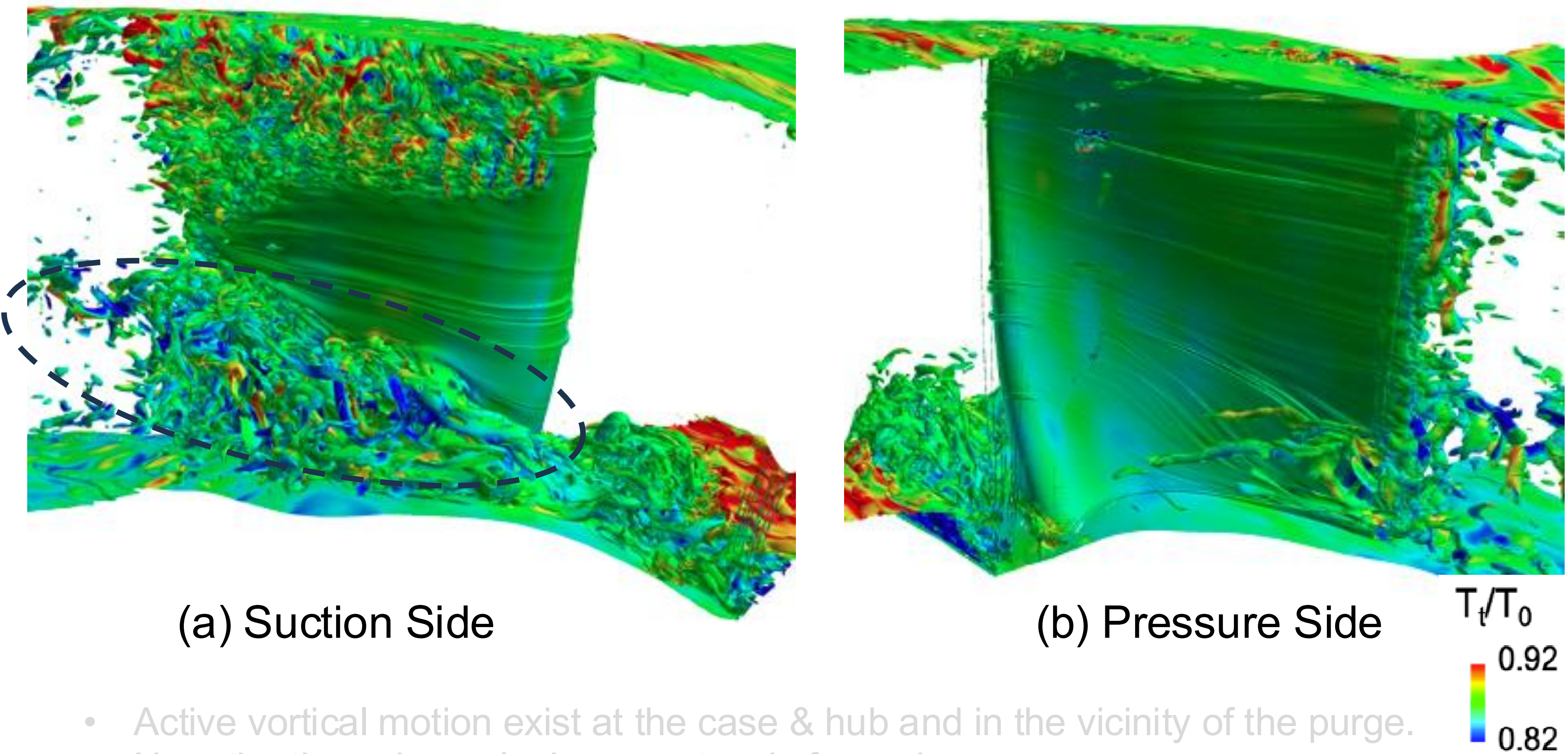
- The streamwise *streaky structures* [8,9] are generated due to variations in the free-stream velocity profile, enhancing local heat transfer.

Iso-Surface of Vorticity Magnitude



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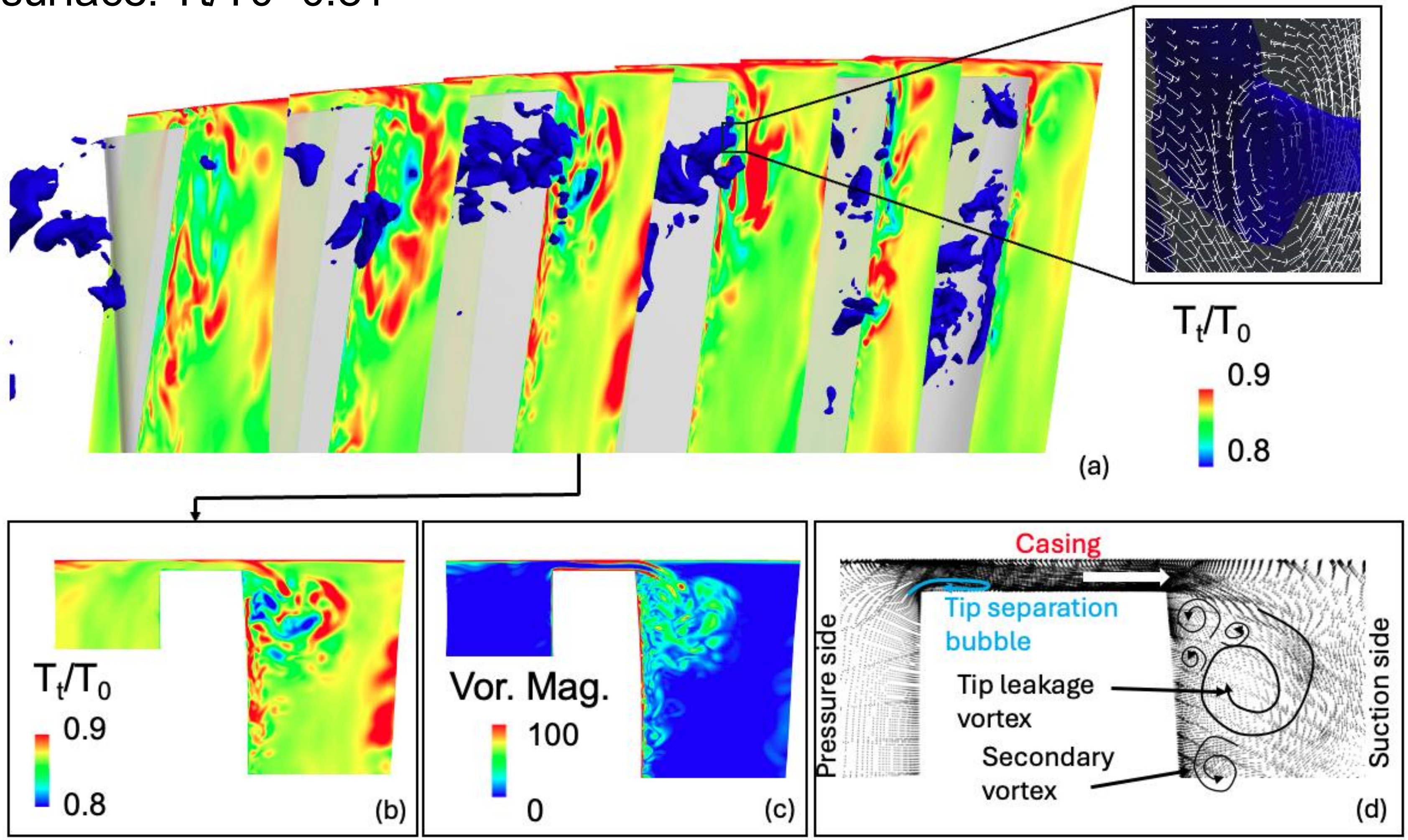
(b) Pressure Side

- Active vortical motion exist at the case & hub and in the vicinity of the purge.
- Near the tip region, a leakage vortex, is formed.
- A distinct "V"-shaped laminar region is evident in the midspan region.
- The streamwise *streaky structures* are generated due to variations in the free-stream velocity profile, enhancing local heat transfer.
- Near the endwall (hub), large-scale vorticity, known as the passage vortex, mixes with the cooling flow from the purge.

Total Temperature and Flow Fields Near the Tip

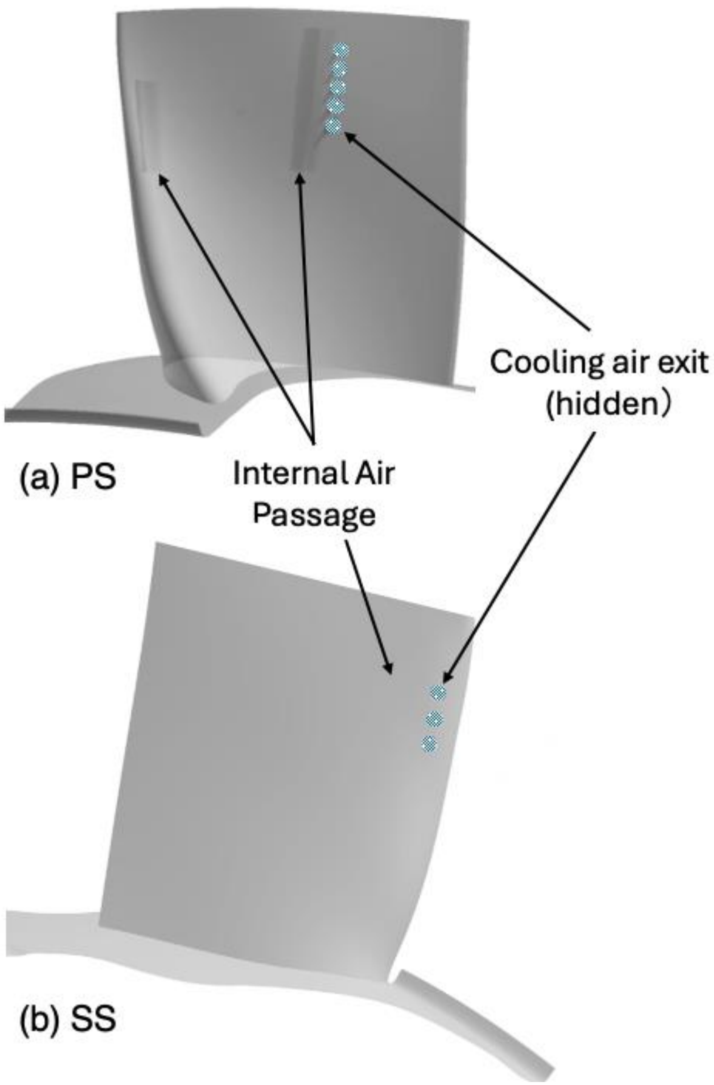
Iso-surface: Tt/T0=0.81

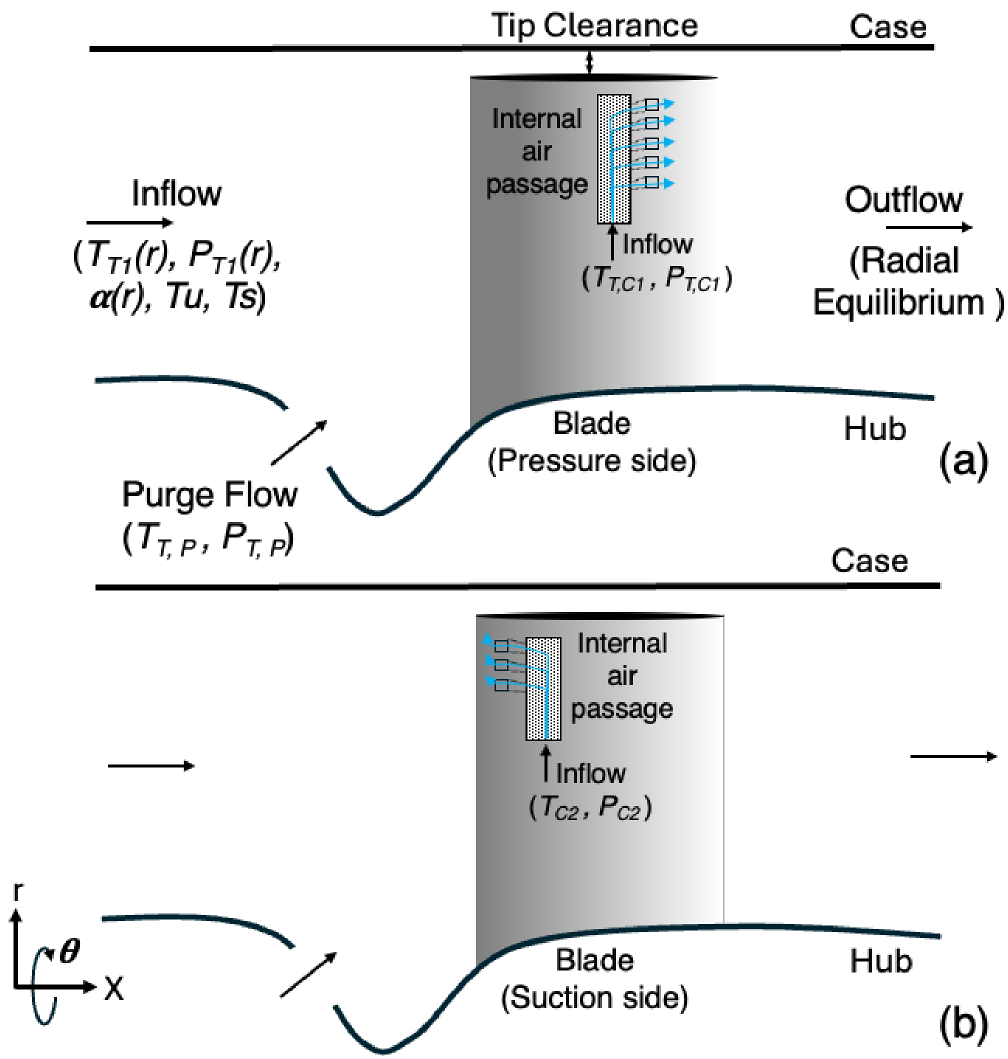


Notable cold regions are located at the core of these vortices → **Energy Separation**

(See a Ranque-Hilsch vortex tube as a reference)

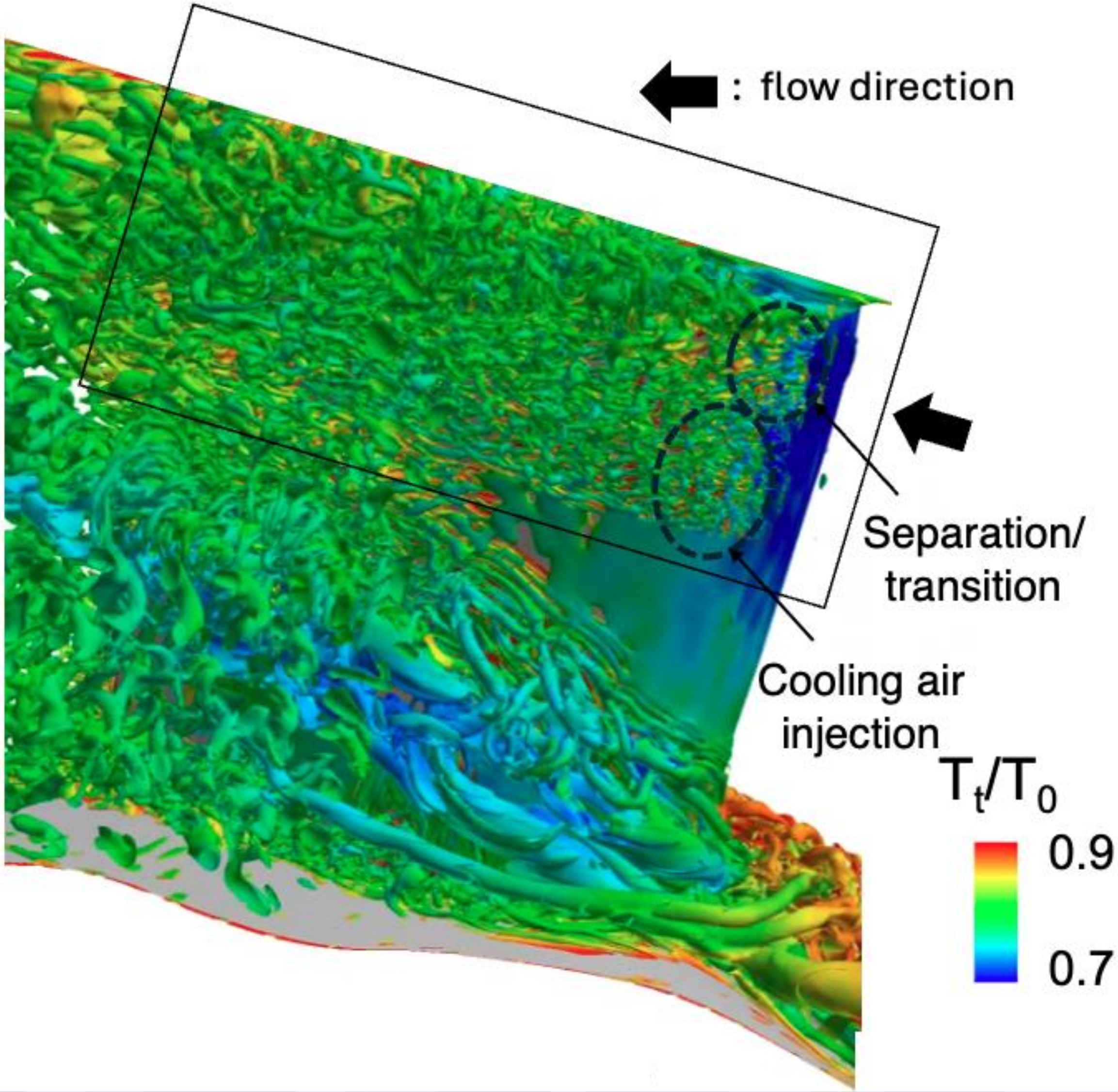
Computational Surface (designed cooling hole & plenum)

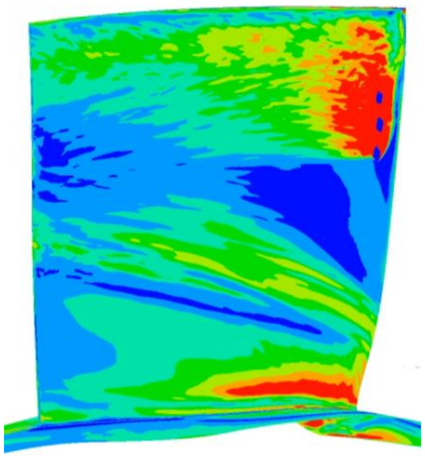




Internal air cooling passages are included.

3D Flow Field with Cooling Air (Suction Side)

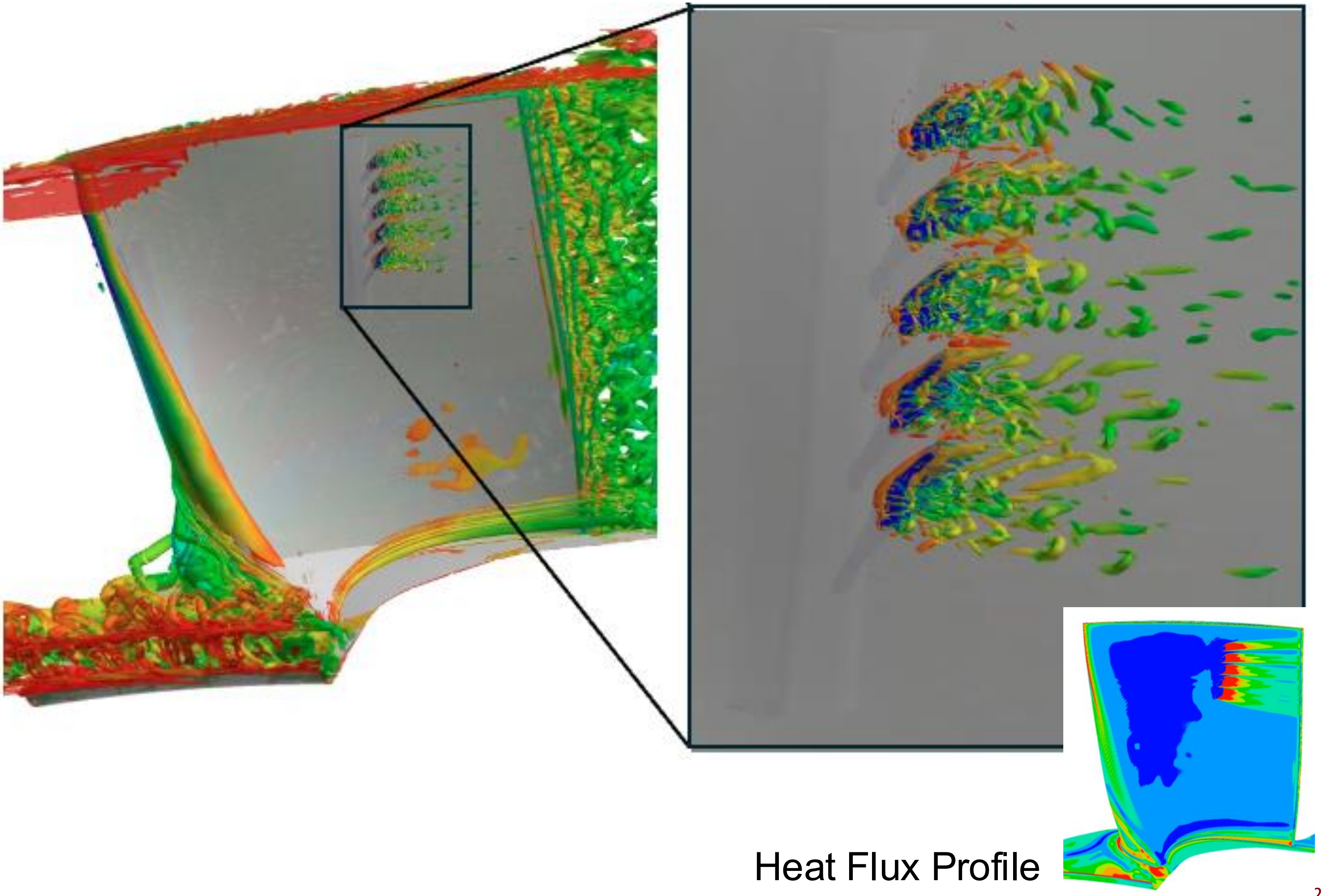




Heat Flux Profile

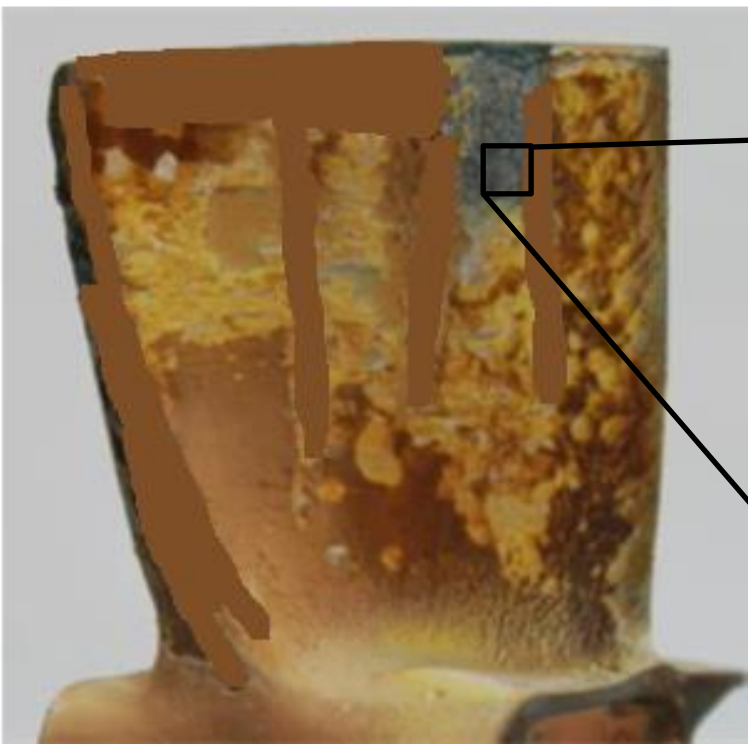
Air cooling injection promotes flow separation (e.g., more mixing -> large heat flux)

3D Flow Field with Cooling Air (Pressure side)

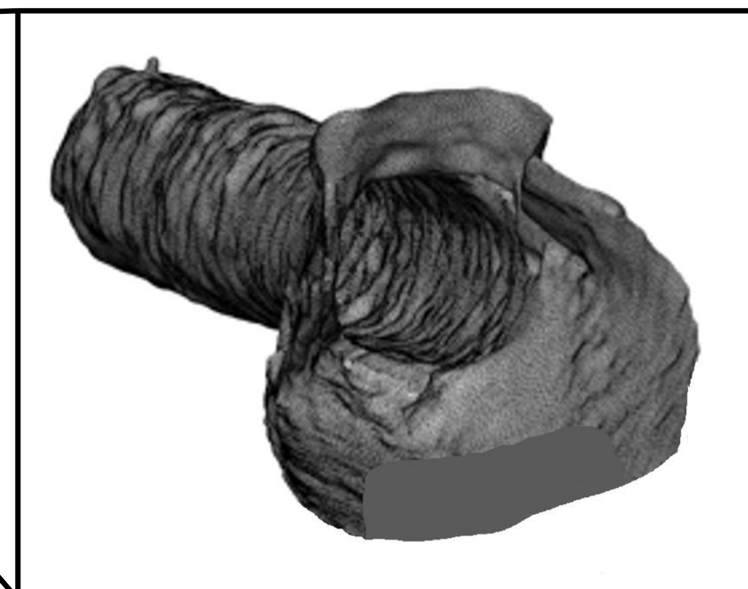


Heat Flux Profile

Preparation of High-Quality LES Grid for Deteriorated Cooling Holes

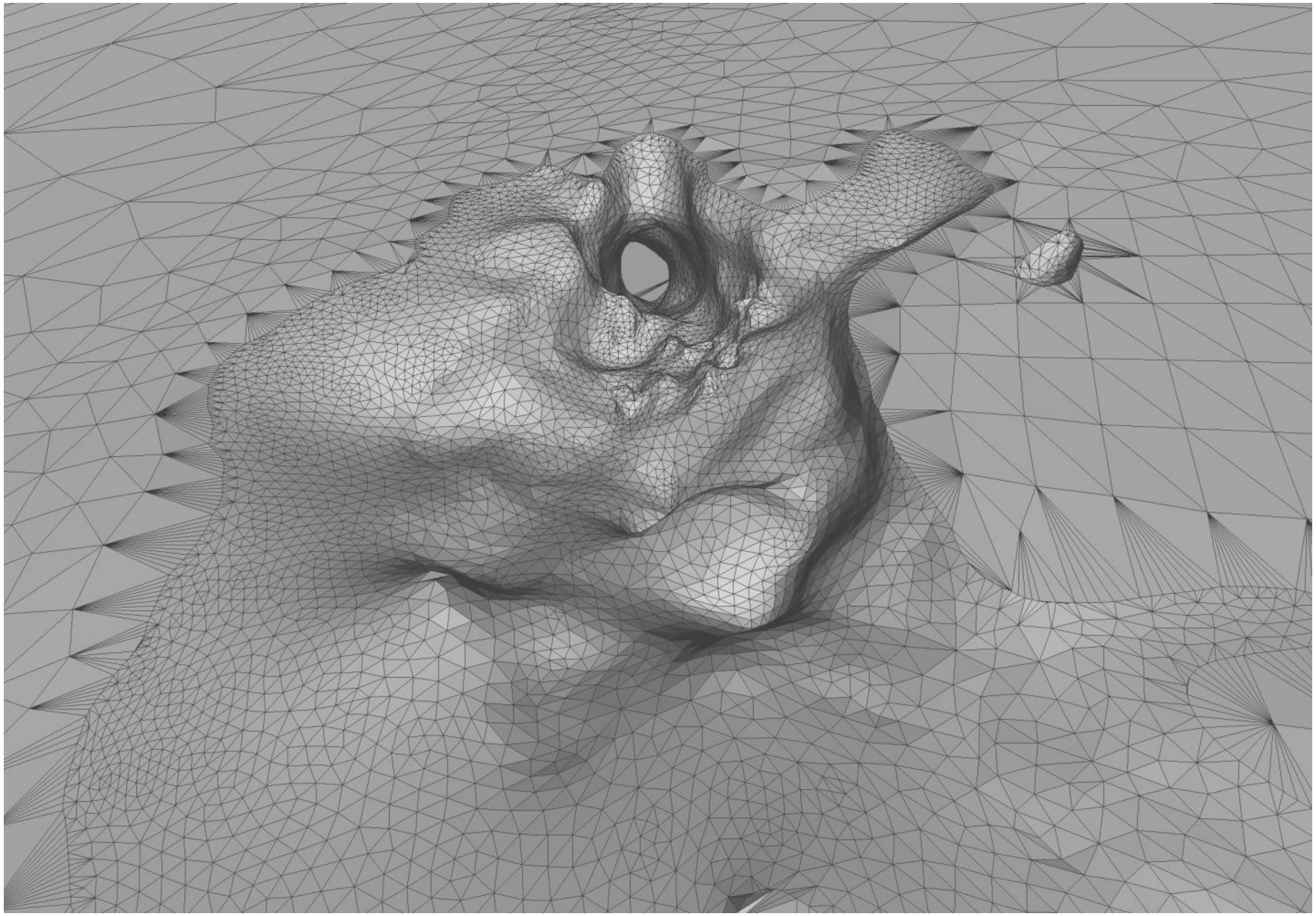


Example of deteriorated blade



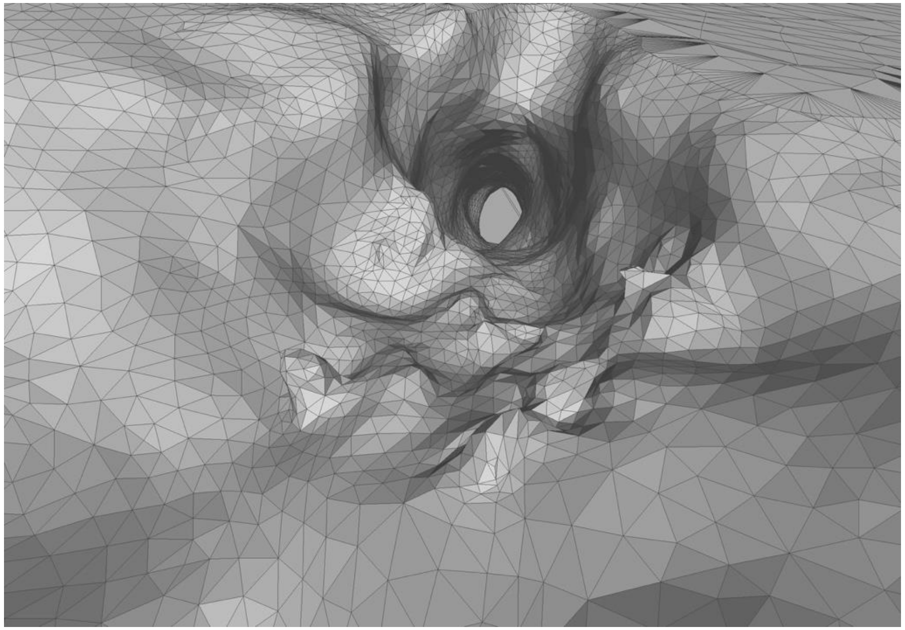
CT scan of deteriorated hole

CT-Scan Images



- After the hot test, the 3D detailed CT-scan deteriorated cooling hole was generated after the hot test.
- CT-Scan files are not ready for meshing. It requires a “smoothing” process.

Surface Data Provided/Refine and Smooth



Original Surface

Refine and Smoothed Surface

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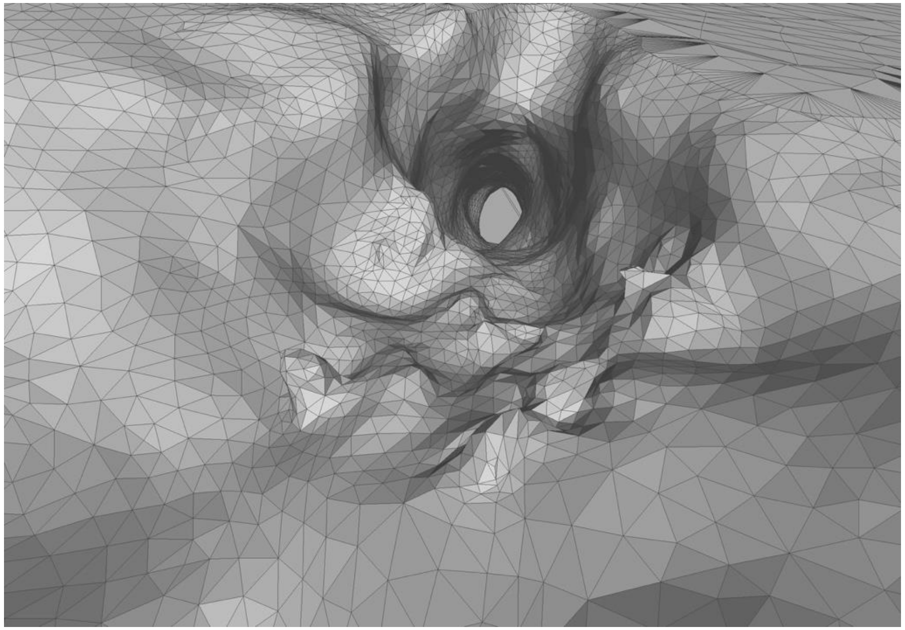

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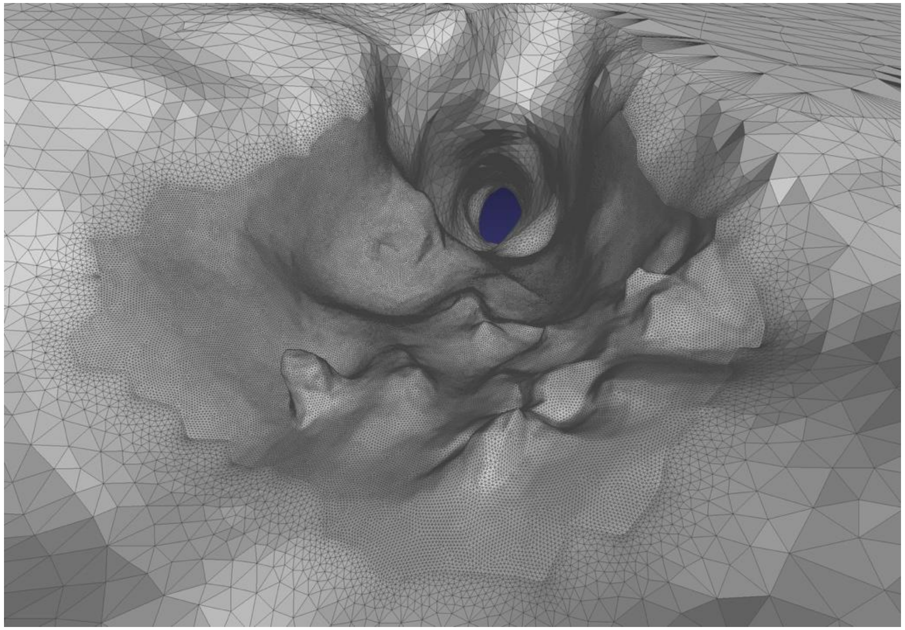
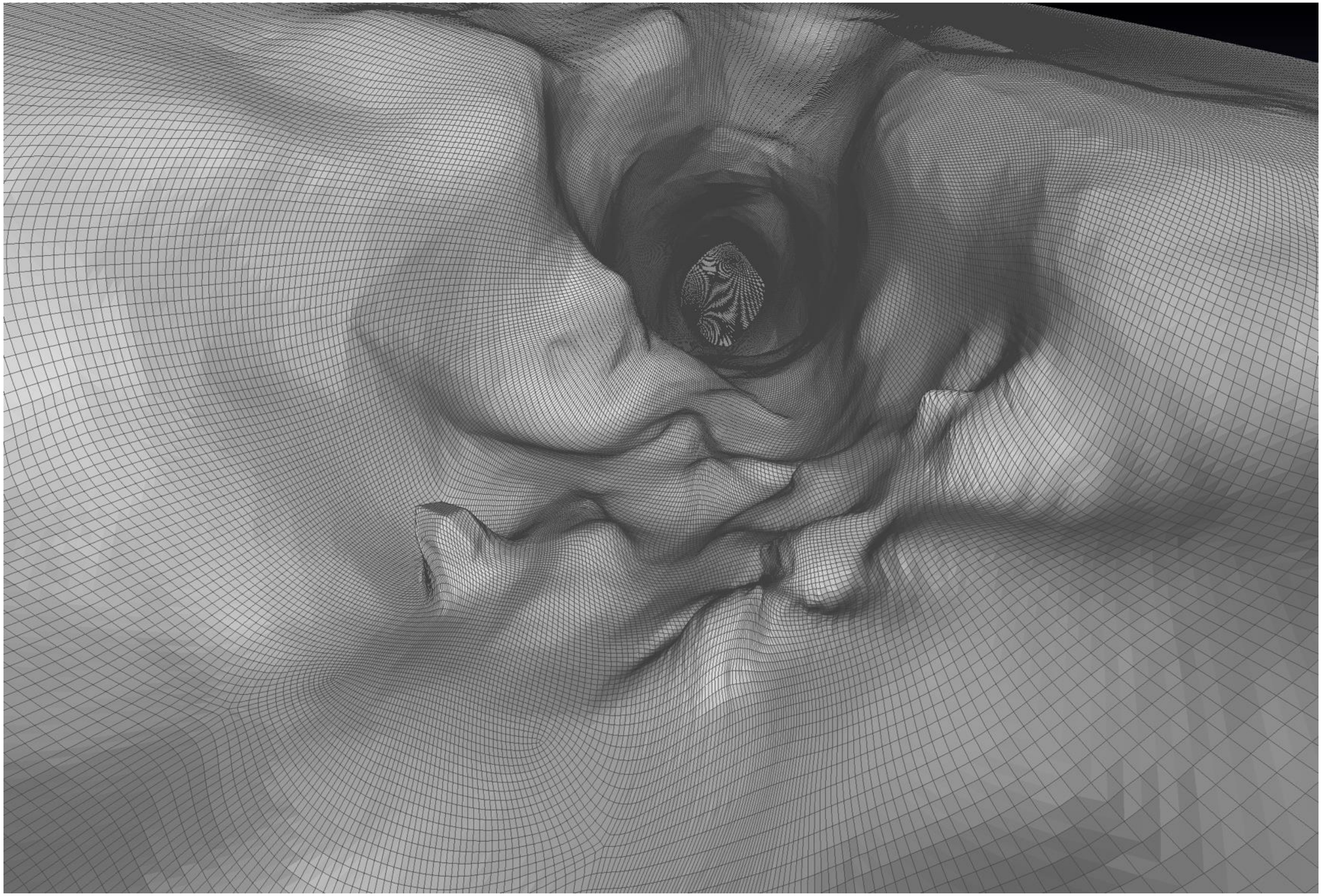


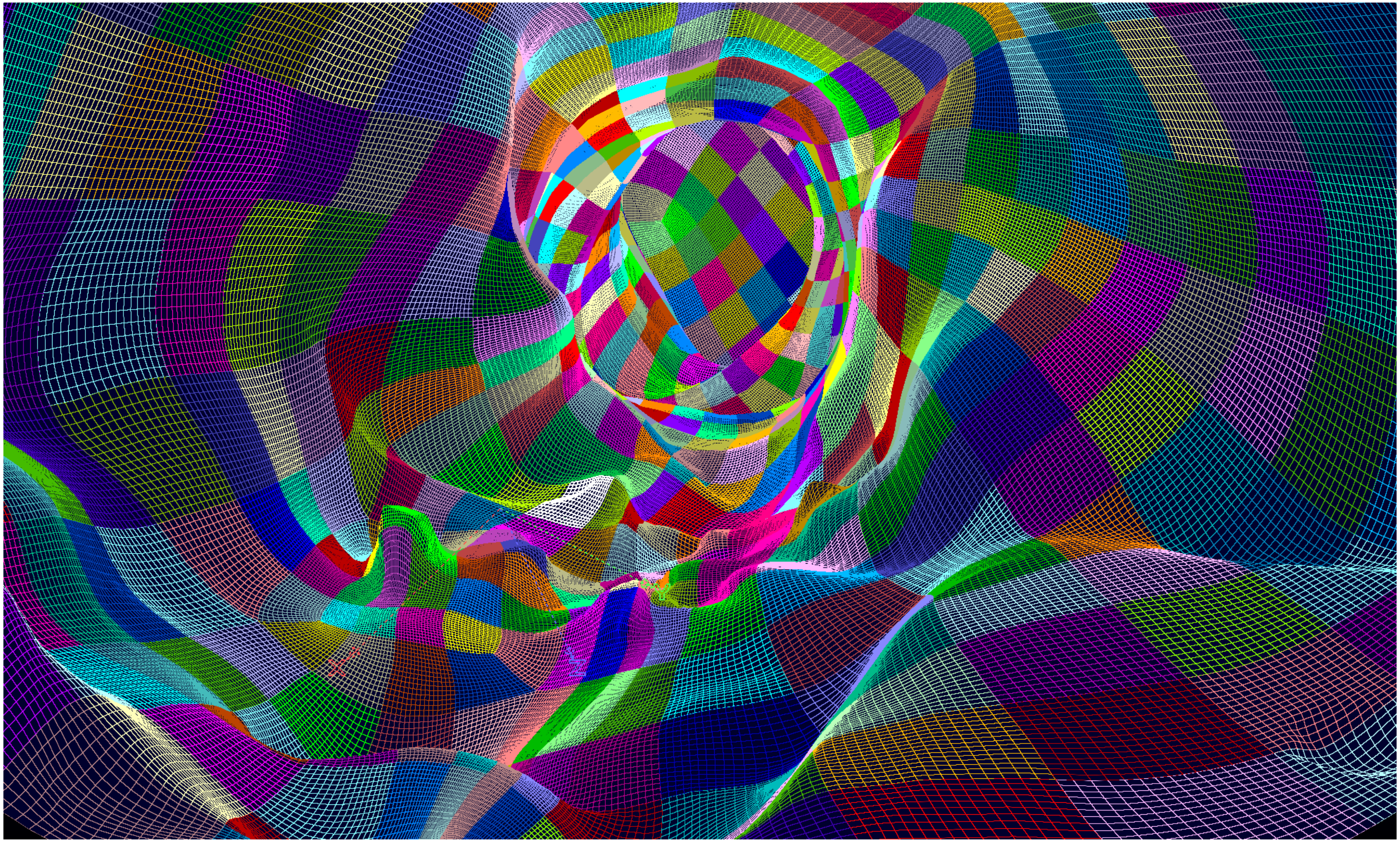
Refine and Smoothed Surface

Mesh for One Exit of a Cooling Hole



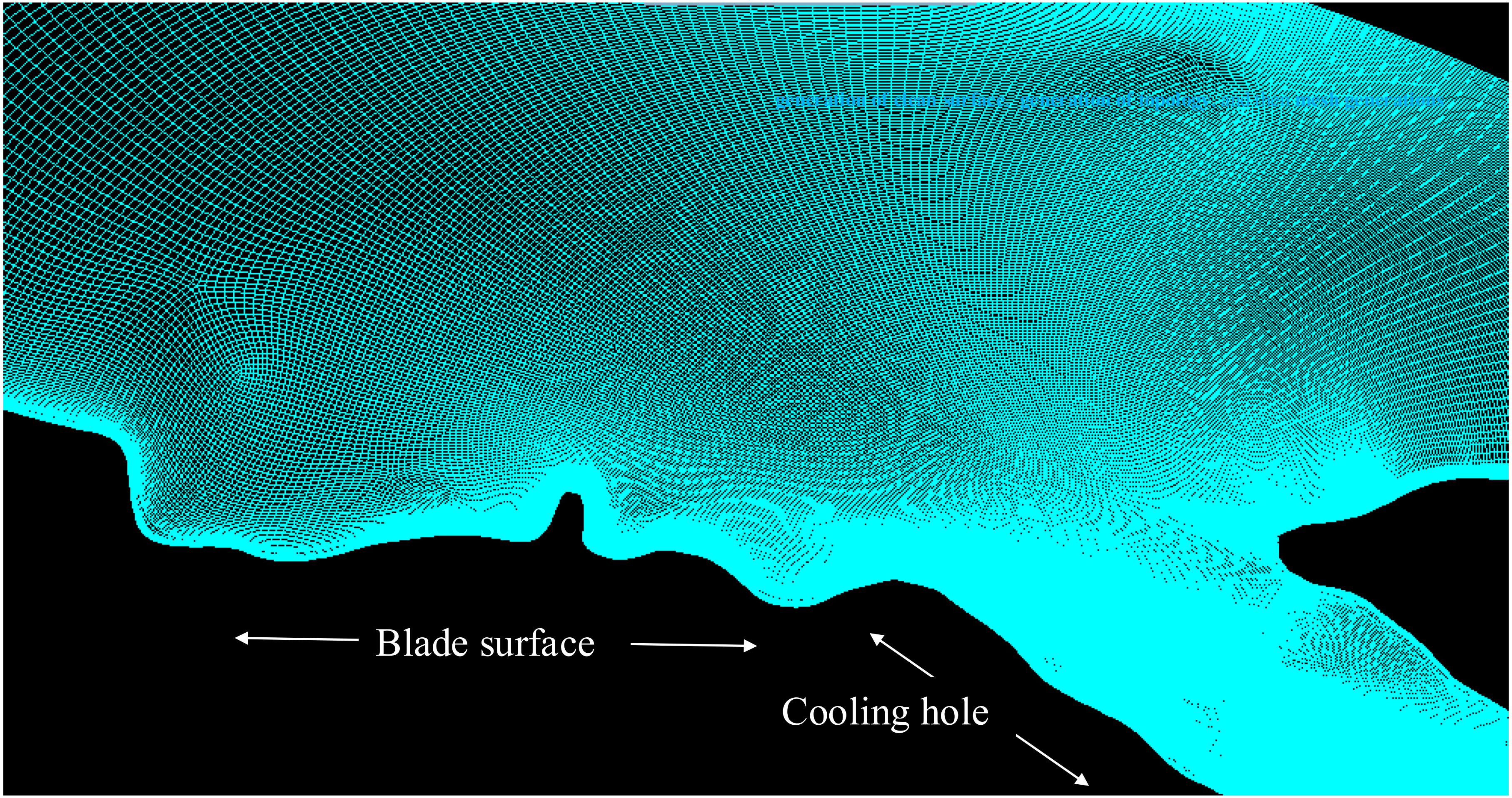
Concave and convex surfaces are challenging for BL mesh generation for high-quality LES

Mesh Inside a Cooling Hole



The mesh quality is extremely high, and it is indeed "state of art" !

Mesh for BLs for Concave and Convex Surfaces



Making a high-quality boundary layer mesh is extremely challenging!

Finally….

Generating topology for the deteriorated cooling holes significantly increases complexity of topology, which is absolutely "**one of the kind**" in the CFD community.

Final Mesh count is about ~ few billion, and this is our CAAR project!

Impact on Science/Engineering Fields

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- For our work, access to a highly optimized GPU-enabled version of our CFD code is a key enabler—it will allow the multiple LES runs to make it possible to incorporate additional physics relevant to **blade durability** in future turbine designs.

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- Realistic deteriorated-hole geometries were obtained experimentally through CT scanning of an actual damaged blade, performed at Penn State University. ***To the best of our knowledge, no CFD study—not even RANS—has attempted to analyze this type of highly challenging flow problem*.**

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- To advance the limits of CFD within the turbomachinery community, we seek to demonstrate that a highly optimized GPU-based CFD code equipped with LES can successfully analyze the aerodynamics of this extremely complex system.

Our Figure of Merit (FOM)

1. The FOM will be "Computational Work" / Wall Clock Time. For a given test case, the work shall be measured as (Number of Cells) (Total Number of Iterations), when running without transient output.
2. The focus would be on fluid domains only. Work on solid domains will be done separately after the conclusion of the project.
3. The FOM improvement will measured by asking the question: How much work can the code accomplish per hour of wall clock time when running on some given number of nodes, with the nodes at some optimal level of loading.
4. The runs would be with-or-without GPU acceleration. Some detail will need to be established at the outset.

Conclusion

- We are very honored to be selected for the highly competitive Discovery Center for Accelerated Application Readiness (CAAR) Program at Oak Ridge National Laboratory Leadership Computing Facility in Tennessee.

- With the highly optimized GPU-enabled version of our CFD code, GlennHT, we believe this work will ***set a new standard*** for turbine-blade design processes, with significant impact on aerospace research and industrial practice.

Thank you!

Questions?

Acknowledgement

- This work is supported by the Subsonic Vehicle Technologies and Tools Project (SVTT) at NASA under KM/Dr. Joseph Connolly and KM/Mrs. Laura Evans
- Dr. Kalyan Gottiparthi (ONRL) has been providing excellent technical instruction for last 1.5 years.
- Mr. Tim Beach spent more than a year to generate this LES mesh.
- Mr. Doug Thurman, Mr. Phil Poinsatte, and Dr. Paul Giel have been supporting the project.