LES Simulation of Cooling Airflow of High-Pressure Turbine using the Source Term Approach

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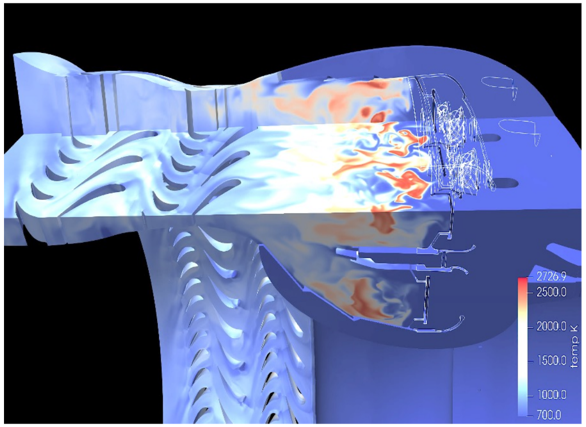
Outline

- **Introduction**
  - Combustor-Turbine Interaction (CTI)
    - ✓ Hot-streaks
    - ✓ Spatial and temporal thermal variations
  - Energy Efficient Engine (E^3) and Cooling Airflow Distribution
  - NASA GRC Sequential Approach for CTIs
- **Source Team Approach**
- **Results**
  - **Validation Case**: E^3 High-Pressure Turbine (HPT) under the rig condition
  - **Preliminary result**: Fully coupled E^3 combustor + HPT under the engine condition
- **Conclusions**



Thanks to R. Rinehart for post-processing

Introduction

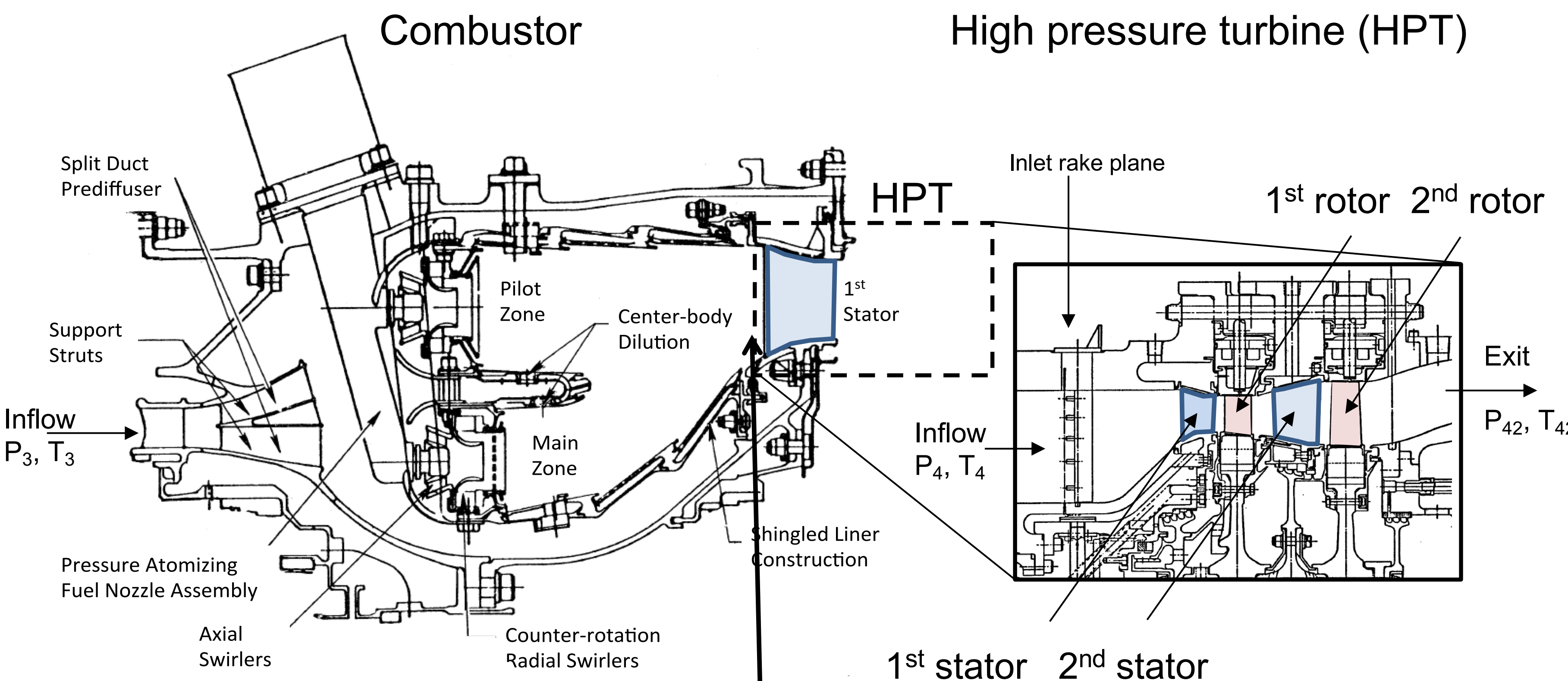
Temperature non-uniformities are evidenced by the ash deposition pattern.

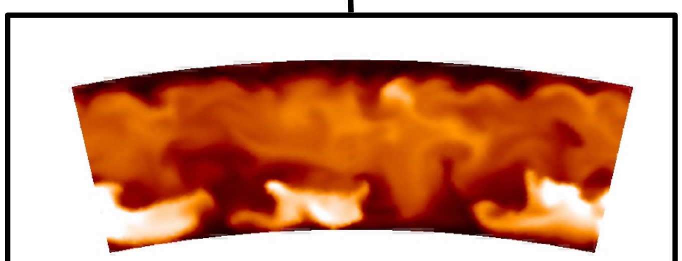
From "**Deposition With Hot Streaks in an Uncooled Turbine Vane Passage**", B. Casaday, R. Prenter, C. Bonilla, M. Lawrence, C. Clum, A. Ameri and J. Bons., J. Turbomach, 2013 Vol. 136 (Permission from Prof. Bons and Dr. Mike Dunn @ OSU)

- To improve jet engine efficiency, it is desirable to increase temperature and pressure entering a high-pressure turbine (HPT), and as a result, the inlet temperature approaches the metal's melting point.
- It requires the careful introduction of cooling air to protect the metal surface.
- Modeling hundreds of cooling airflows is not feasible due to computational cost (and griding).

It is required to develop an engineering approach to mimic cooling airflows without losing accuracy much and significant increase in computational time.

Energy Efficient Engine– GE design, 80s -





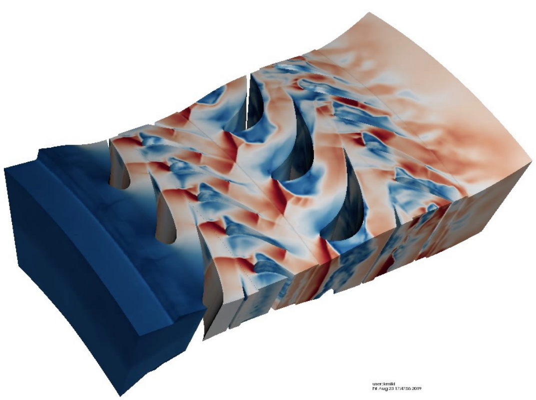
Predicted temperature contour at the combustor exit (T_{40})

The detailed information of the geometries of E3 combustor and high-pressure turbine are publicly available.

Open National Combustion Code (OpenNCC)

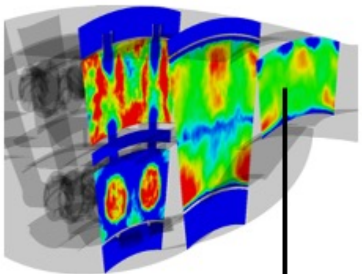
Decided on single code for combustor-turbine simulations (versus code coupling)

- OpenNCC is the releasable version of the National Combustion Code (NCC), which has been continuously updated for more than two decades at NASA Glenn Research Center (GRC)
- Main Features
  - ✓ Numerics: Jameson-Schmidt-Turkel (JST) scheme, Roe's upwind scheme, and AUSM [1]
  - ✓ Turbulence: Cubic non-linear k-ε model with the wall function, Low-Re model, local dynamic k-model (LDKM) [2]
  - ✓ Combustion: Finite Rate Chemistry, EBU [3] , PDF [13] , Linear Eddy Model (LEM) [4], Dynamic Thickened Flame Model (DTF) [5]
  - ✓ Spray: Lagrangian liquid phase model [6]
  - ✓ Other features: Low-Mach preconditioning, transition model, unstructured mesh, adaptive mesh refinement (AMR), moving mesh, massively parallel computing



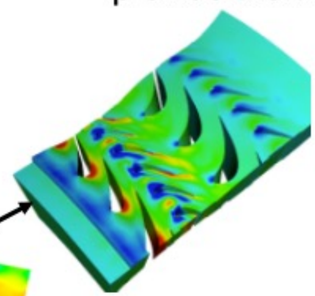
Mach number of HPT

Histories of Our Work



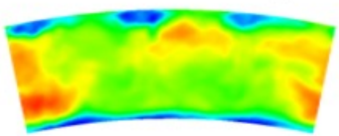
STEP 1

Combustor + 1st Stator of HPT (no moving rotor)
- provide the time-averaged non-uniform inflow BC for Step 2



STEP 2

Two stage HPT (stators/moving rotors)
- provide the exit pressure ($P_{S,42}$) for Step 3



Time-averaged flow fields at ($T_{T,40}$, $P_{T,40}$, etc.)

STEP 3

Combustor + Two stage (stator/rotor) of HPT

2014-2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021-Present

STEP 1 : [Ref. 1-3]
Adding necessary modules (AUSM, turb-comb. models) & validations

STEP 2 [Ref.4]
Speedup the rotating interface

STEP 3 [Ref.5]

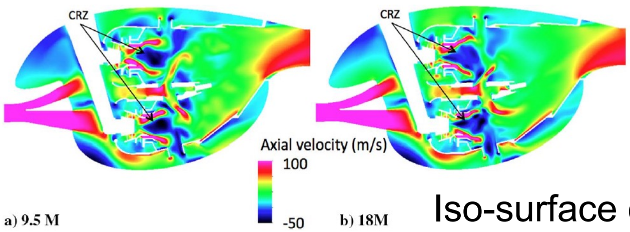
Simulated Take-Off Con. Completed (2atm)

Realistic Take-Off Con. (30atm)
STEP 1 → STEP 2 → STEP 3

Cooling Airflow

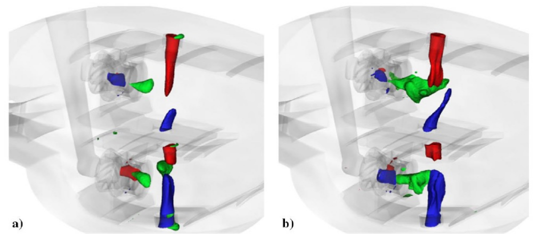
[1] Miki, K., Moder, J., and Liou, M.-S., Journal of Propulsion and Power, Vol. 34, 2018, pp. 415{- 427. [2] Miki, K., Moder, J., and Liou, M.-S Journal of Propulsion and Power, Vol. 34, 2018, pp. 1529-1534. [3] Miki, K., Moder, J., and Liou, M. Shock Waves, Vol. 29, 2019, pp. 1009-1021. [4] Miki, K., Wey, T., and Moder, J Proceedings of the International Society for Air Breathing Engines, Canberra, Australia, Sept. 2019, ISABE-2019., [5] Miki, K., Wey, T., and Moder, Journal of Propulsion and Power (2023)

Snapshot of What We Have Done



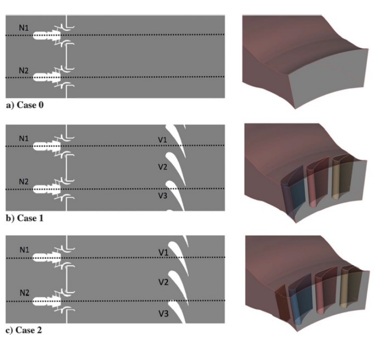
Axial velocity

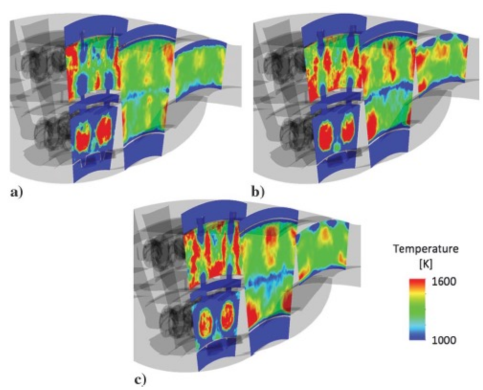
Iso-surface of U and V



- Performed RANS for a Grid Sensitivity using JST vs. AUSM (AIAA 2016, JPP,2017a)

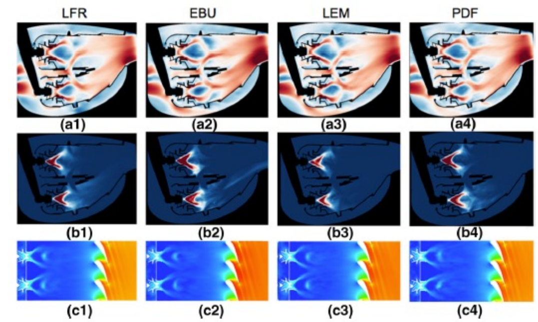
Time-averaged temp.



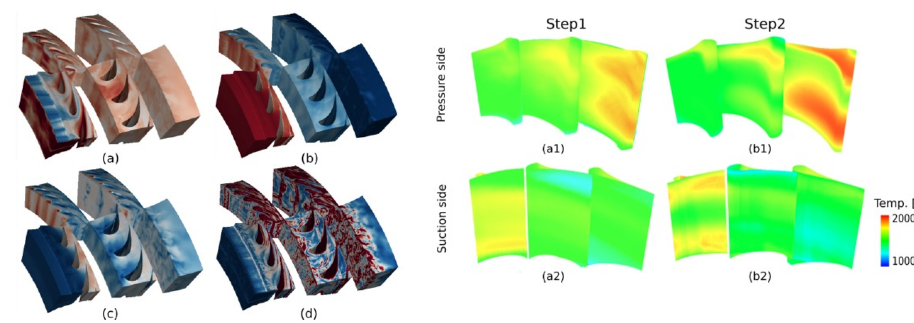


clocking

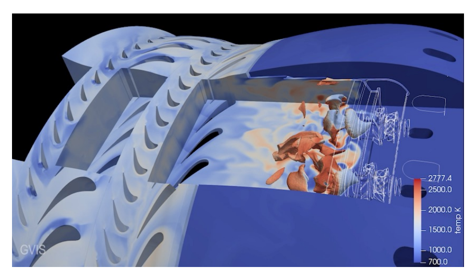
- Performed LES for investigating the clocking effect of Step 1 (AIAA 2017, JPP,2017b)

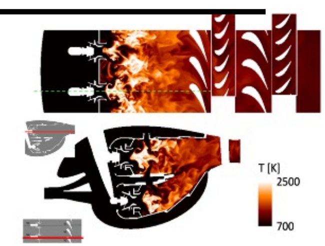


- Performed a sensitivity analysis of comb-turb int model using Step 1 (Shock wave, 2019)



- Performed Step 1vs. Step 2 (ISABE, 2019)





Temperature

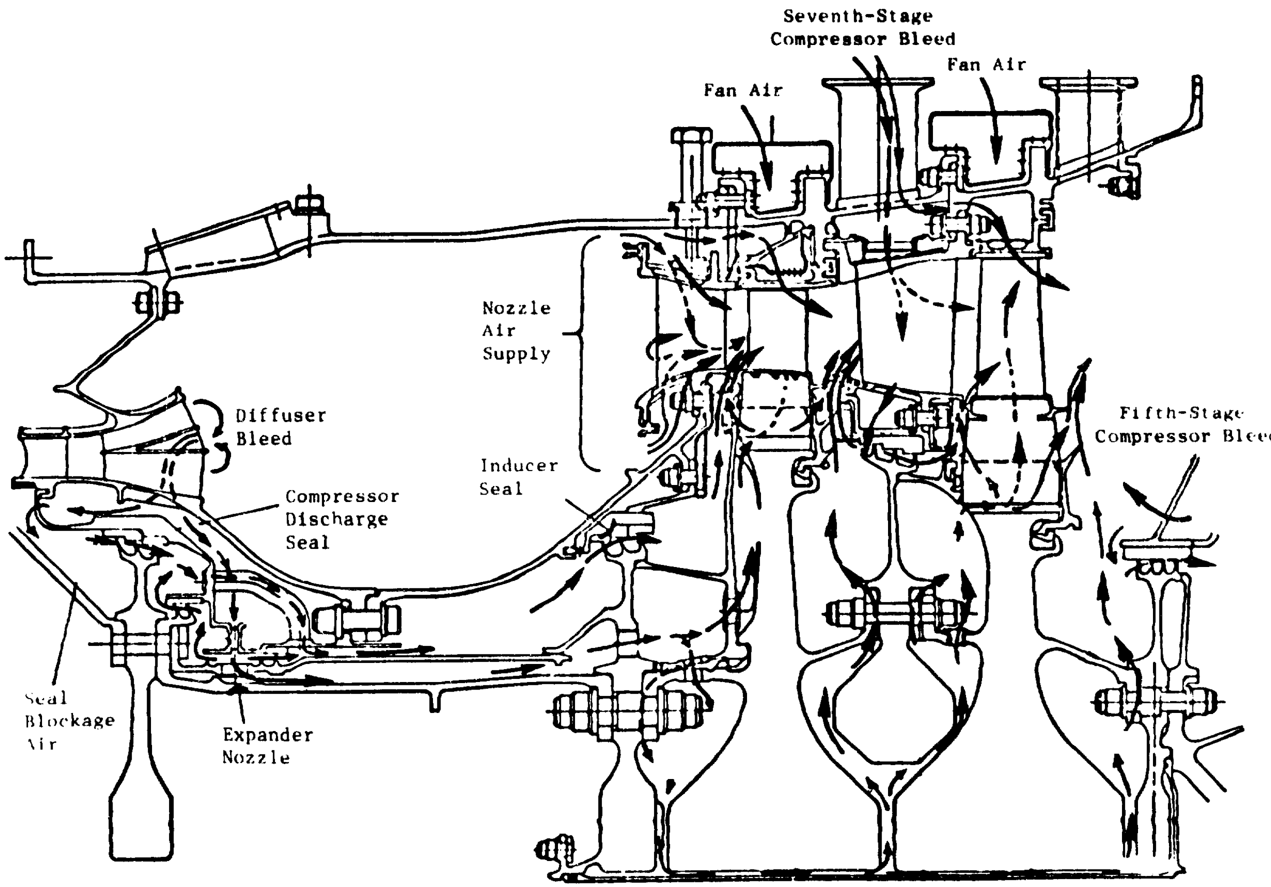
- Performed Step 1, Step 2, Step 3 (AIAA-2020, submitted to JPP 2021, ISABE-2022, JPP 2023)

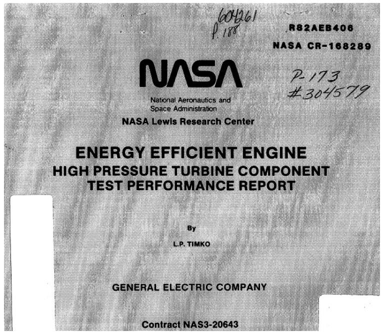
Cooling airflows were not included for these studies.

Cooling Airflow

Cooling Airflow

From GE E^3 Reports (1982, 1984)





R82AEB406
NASA CR-168289

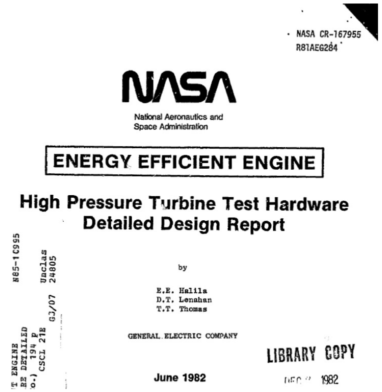
NASA
National Aeronautics and
Space Administration
NASA Lewis Research Center

ENERGY EFFICIENT ENGINE
HIGH PRESSURE TURBINE COMPONENT
TEST PERFORMANCE REPORT

By
L.P. TIMKO

GENERAL ELECTRIC COMPANY

Contract NAS3-20643



NASA CR-167955
R81AEG284

NASA
National Aeronautics and
Space Administration

ENERGY EFFICIENT ENGINE

High Pressure Turbine Test Hardware
Detailed Design Report

by

E.E. Halila
D.T. Lenahan
T.T. Thomas

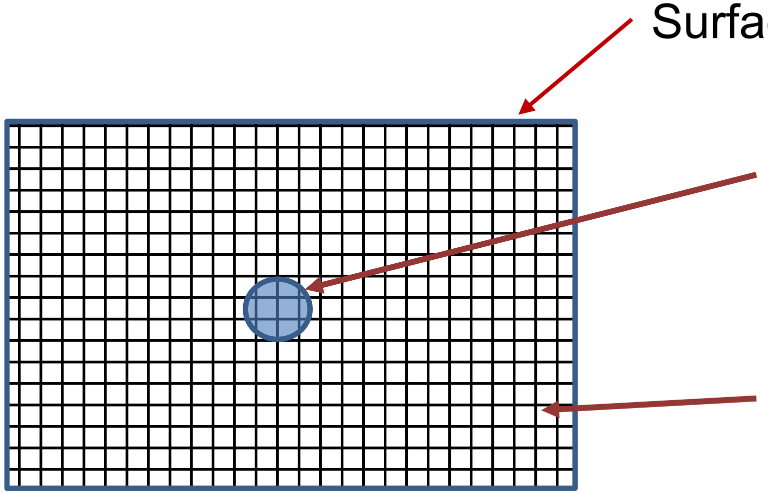
GENERAL ELECTRIC COMPANY

June 1982

Rotor and Casing Cooling-Supply System

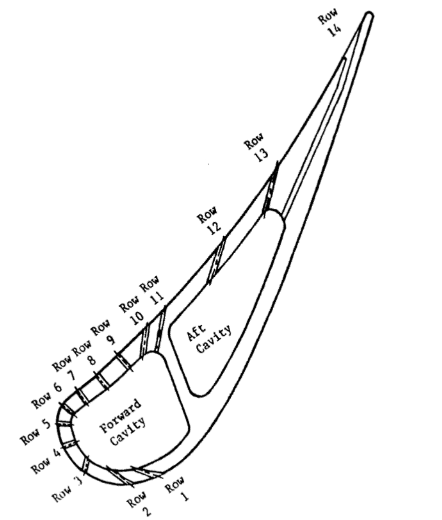
Source Term Approach

- Instead of grids hundreds of cooling airflow holes, the *source term approach is proposed [XXXX]*.



Main Feature of Source Term Approach:

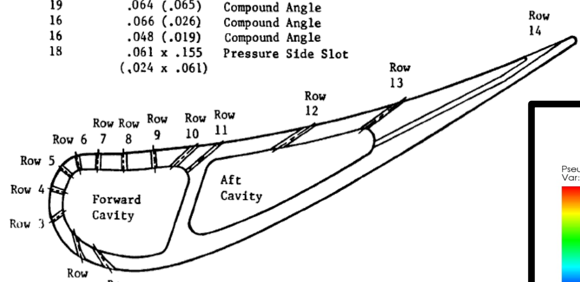
- Simulates injection of cooling flows through solid walls (no change to mesh)
- Identify the surface grid faces and specify the injection angle, mass flow rate, temperature, turbulence intensity (Tu), etc.
- Lots of information of geometries, locations, etc. available at NASA E^3 reports, but we still need to digitalize all information.

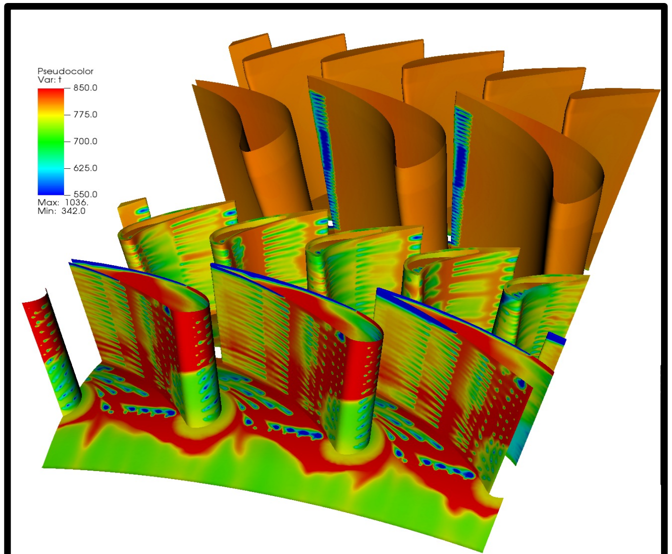


Information of Cooling Hole Geometries

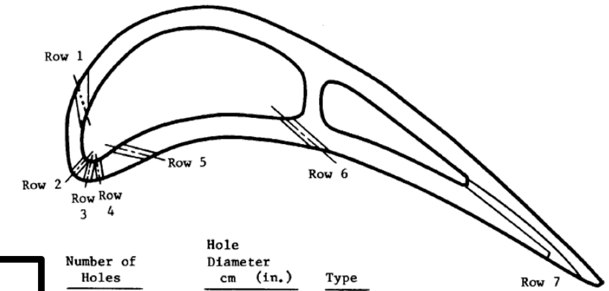
1st stage stator

Row	Number of Holes	Hole Diameter cm (in.)	Type
1	22	.058 (.023)	Axial, Shaped
2	23	.058 (.023)	Axial, Shaped
3	12	.048 (.019)	Radial
4	11	.048 (.019)	Radial
5	12	.048 (.019)	Radial
6	11	.048 (.019)	Radial
7	12	.048 (.019)	Radial
8	11	.048 (.019)	Radial
9	12	.048 (.019)	Radial
10	20	.036 (.014)	Compound Angle
11	19	.064 (.065)	Compound Angle
12	16	.066 (.026)	Compound Angle
13	16	.048 (.019)	Compound Angle
14	18	.061 x .155 (.024 x .061)	Pressure Side Slot





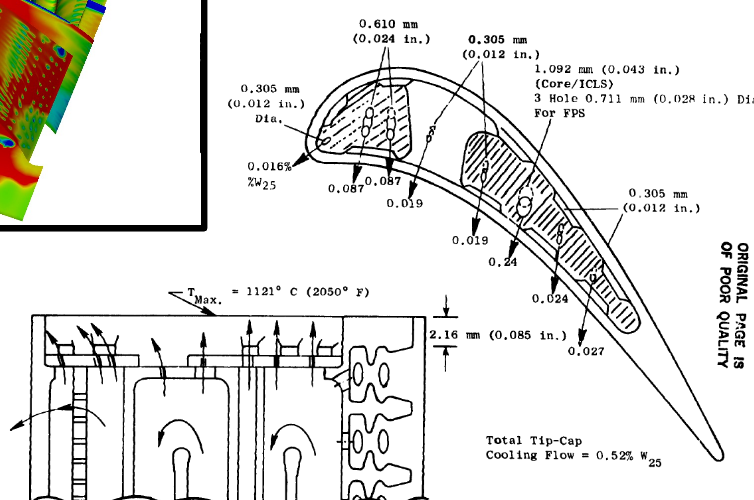
1st stage rotor



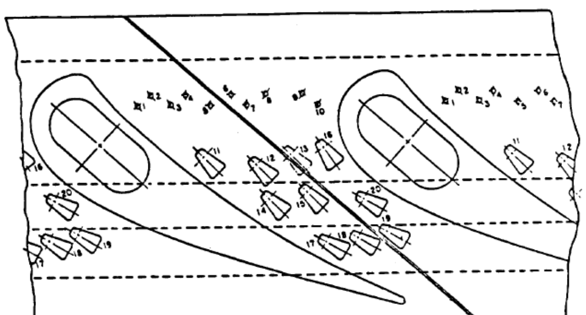
Number of Holes	Hole Diameter cm (in.)	Type
25	.036 (.014)	Axial, Shaped
11	.036 (.014)	Radial
10	.036 (.014)	Radial
11	.036 (.014)	Radial
22	.036 (.014)	Axial
17	.036 (.014)	Compound Angle
11	.048 x .152 (.019 x .060)	Pressure Side Slot

Figure 10. Stage 1 Blade Cooling Hole Definition.

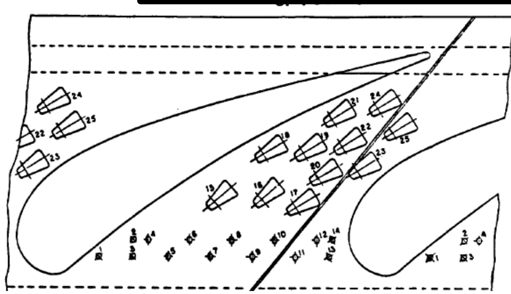
1st stage rotor tip



Hub/case

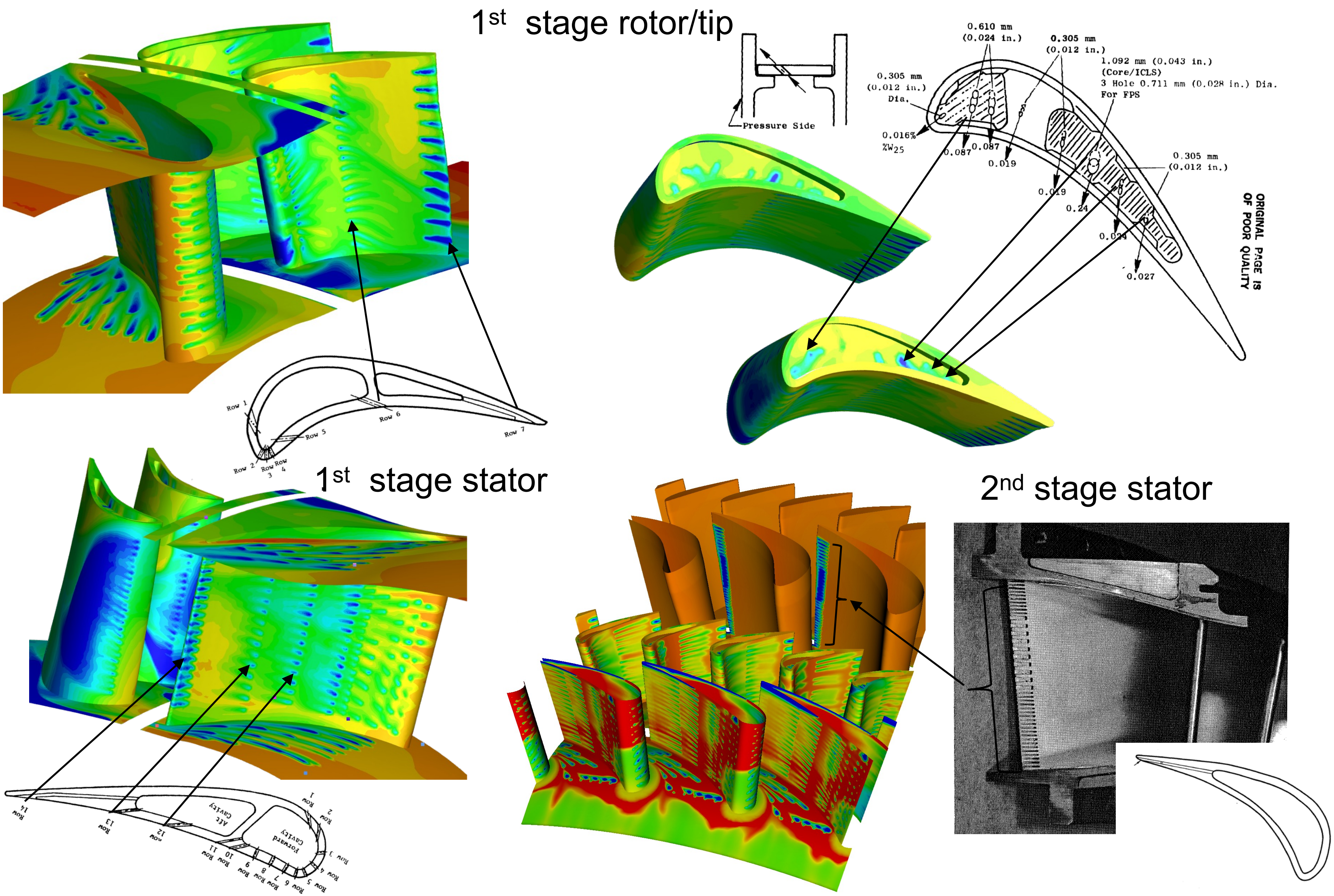


All holes are 0.089 cm (0.035 in) diameter
Hole Number 13 omitted in channels with saw cut.
a) Base



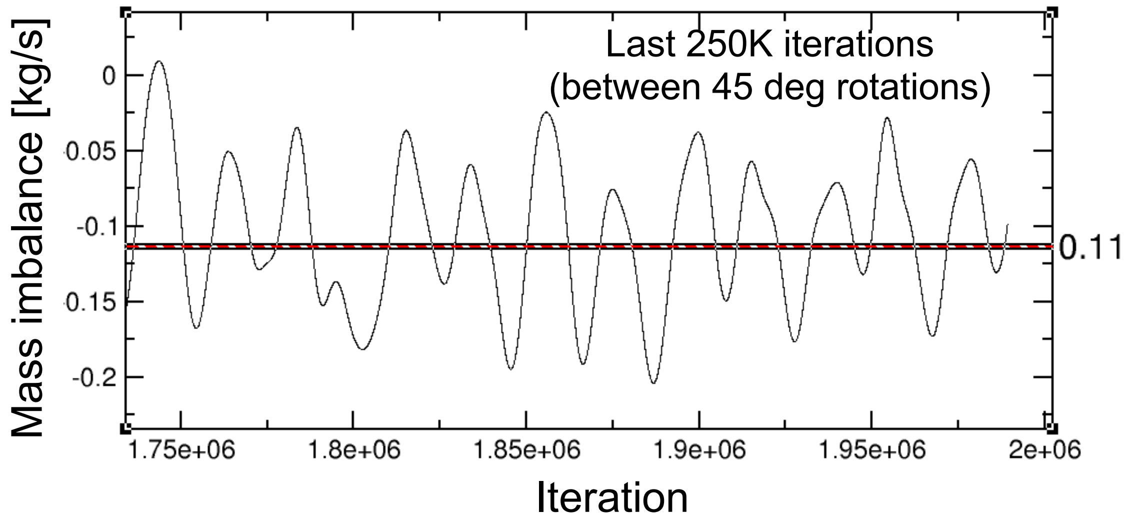
All information (shape, locations, injection angles, etc.) needs to be digitalized

Sanity Check:
Location of Injectors at Stator/Rotor Surfaces

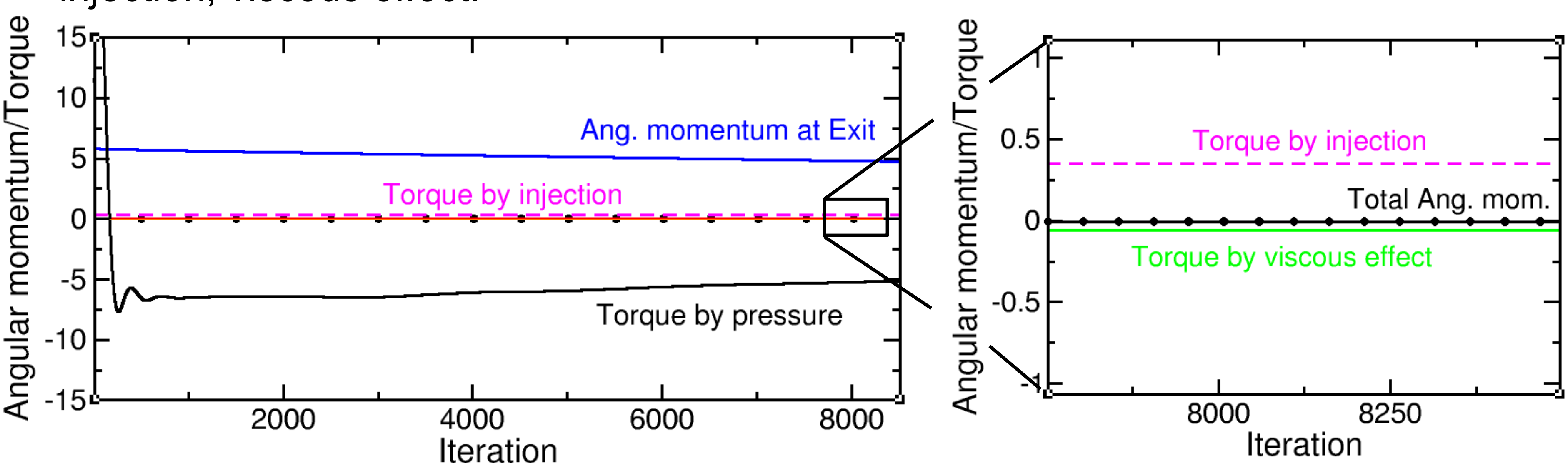


Sanity Check:
Mass Flux/Angular Momentum Conservation

- Total mass flux of all cooling airflow is 0.11 [kg/s]

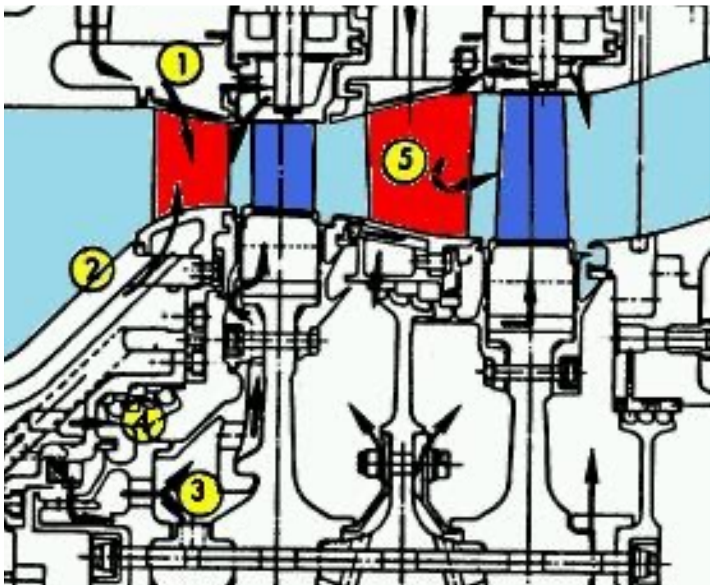


- Difference in ang. mom between inlet and exit is sum of torques by pressure, injection, viscous effect.



Validation Test

Validation Test Condition (RDG10)



Inflow Condition (reported)

Model Input Data	
Nozzle 1 inlet T_o (^oR)	1280.95
Nozzle 1 inlet P_o (psia)	50.163
Nozzle 1 inlet W (lbm/sec) (RDG 10)	24.015

Coolant Flows (reported)

Model Coolant Location	W_c (lbm/sec)	$P_{o,c}$ (psia)	$T_{o,c}$ ($^\circ R$)	Coolant Circuit	
Nozzle 1 Aft Vane	1.14936	50.0749	629.647	Nozzle 1 Outer	1
Gap 1A Casing	0.128881				
Nozzle 1 Fwd Vane	0.849162	51.0625	586.256	Nozzle 1 Inner	2
Gap 1A Hub	0.302624	40.0012	592.917	CDP	4
Rotor 1	1.3320	49.6262	619.715	Inducer	3
Rotor 2	0.3068				
Gap 2B Hub	0.0605				
Gap 1B Hub	0.04064	23.472	641.632	Nozzle 2 Outer	5
Nozzle 2 Casing	0.50127				
Gap 2B Casing	0.03522				

More Info is available

Proceedings of GT2005 ASME Turbo Expo 2005: Power for Land, Sea and Air June 6-9, 2005, Reno-Tahoe, Nevada, USA

GT2005-68608

AN ENTROPY LOSS APPROACH FOR A MEANLINE BLADEROW MODEL WITH COUPLING TO TEST DATA AND 3D CFD RESULTS

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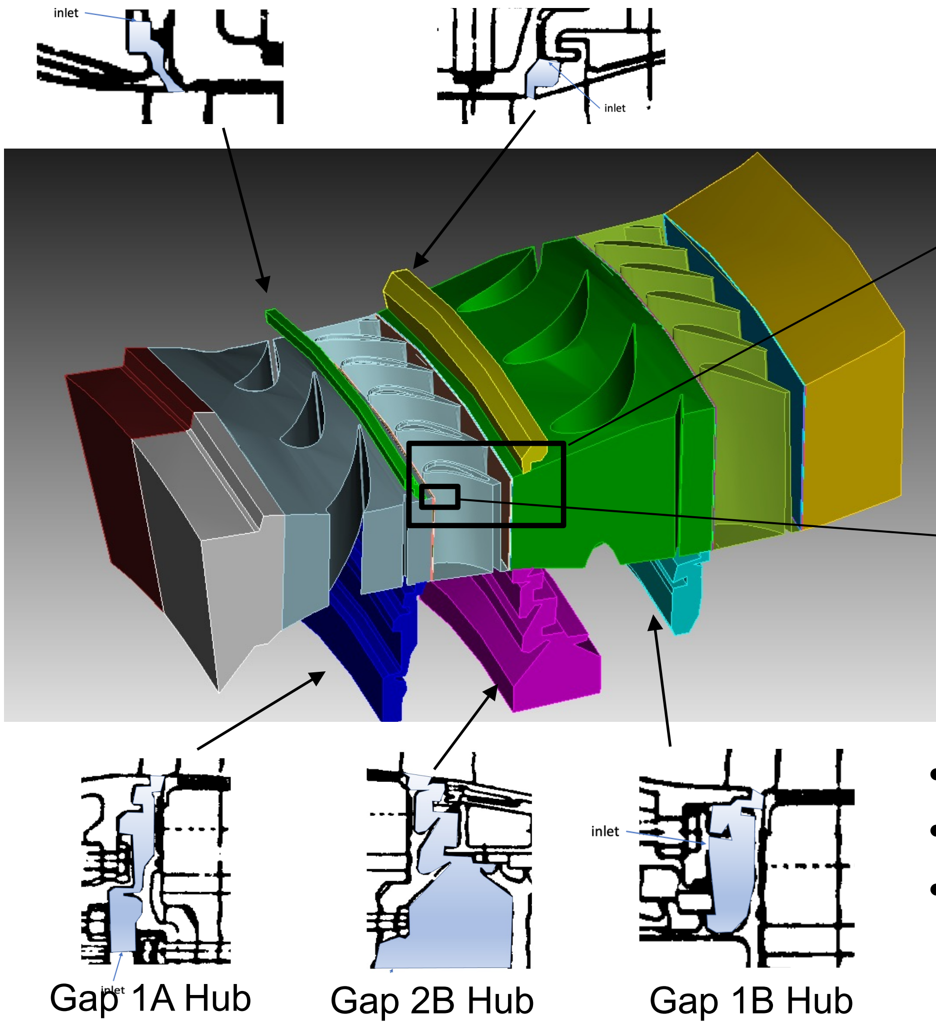
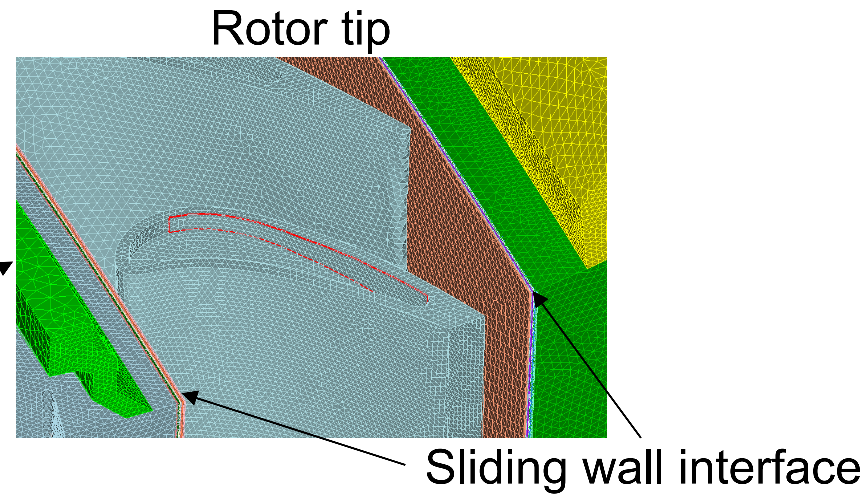
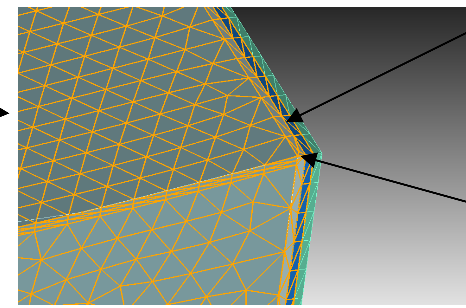
Table represents the circuits that are metered during a test. The total in a circuit is measured.

Numerical Setting and Boundary Condition



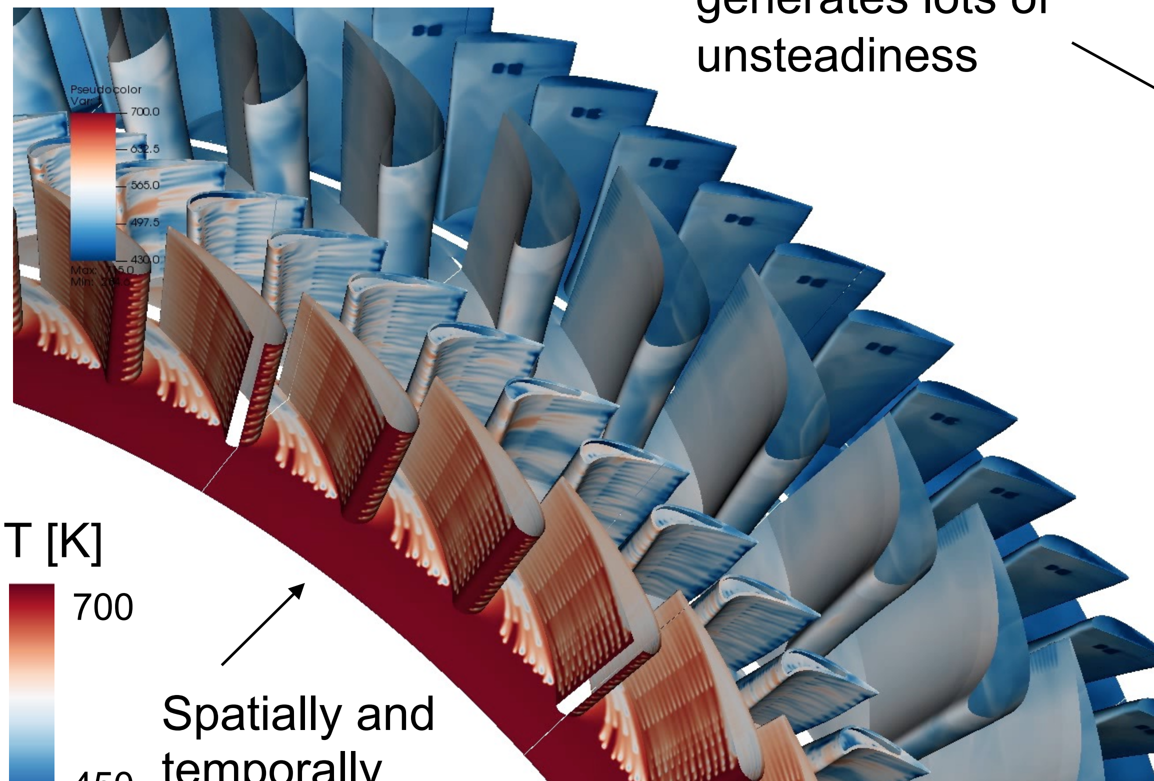




- ~50M tetrahedral elements
- Rotating speed: 8279.95 [RPM]
- Unsteady (TFNS [XXX], RCP=0.1, LES, JST), two-equations turbulence model with the wall function is used.

	Gap 1B Casing	Gap 2B Casing	GAP 1A Hub	GAP 2B Hub	Gap 1BHub
MFX [kg/s]	0.0039	0.0011	0.0092	0.0018	0.0012
Total Temp [K]	349.8	356.4	329.4	344.2	356.4

Instantaneous Temperature Fields (3D movie)



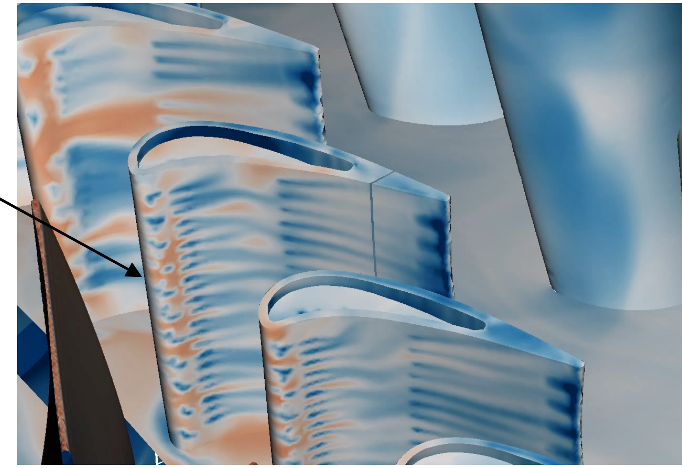
T [K]

700

450

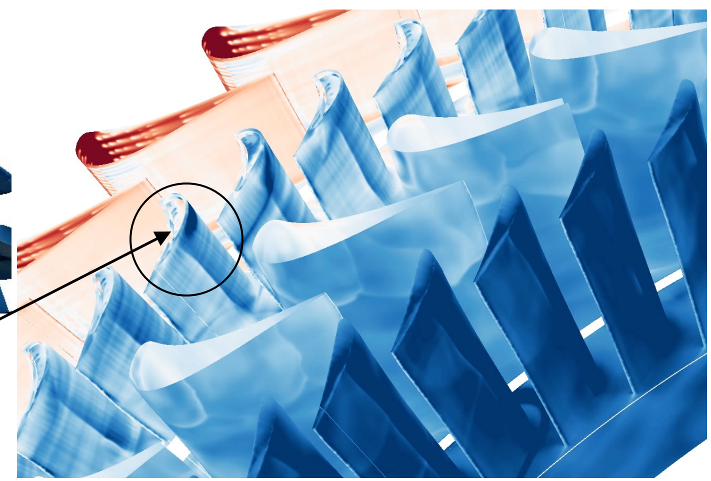
Spatially and temporally constant inlet BC

Interaction with wakes generates lots of unsteadiness



1^{st} stage rotor tip (pressure side)

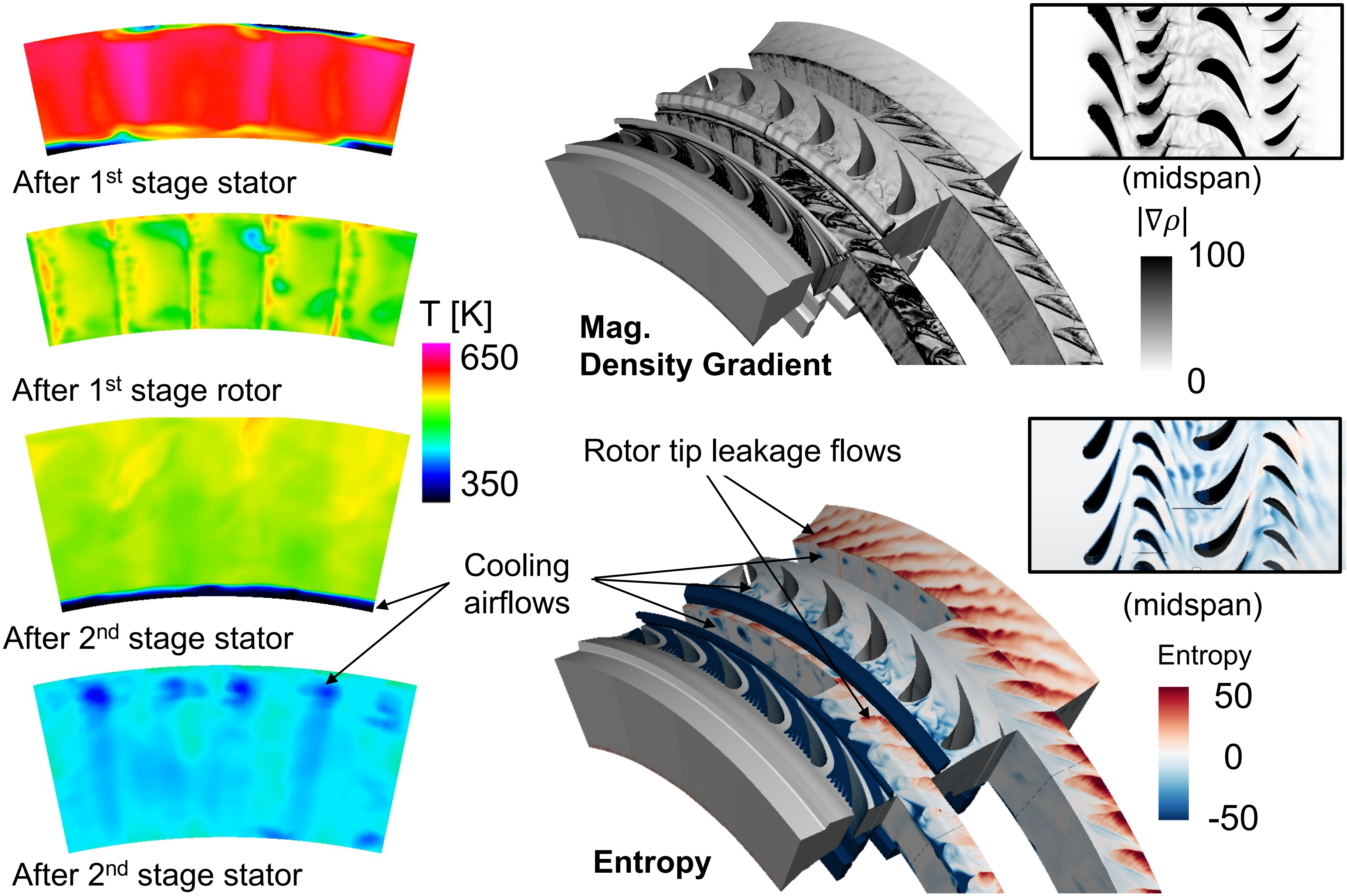
Purge flow occasionally gets in.



Suction side

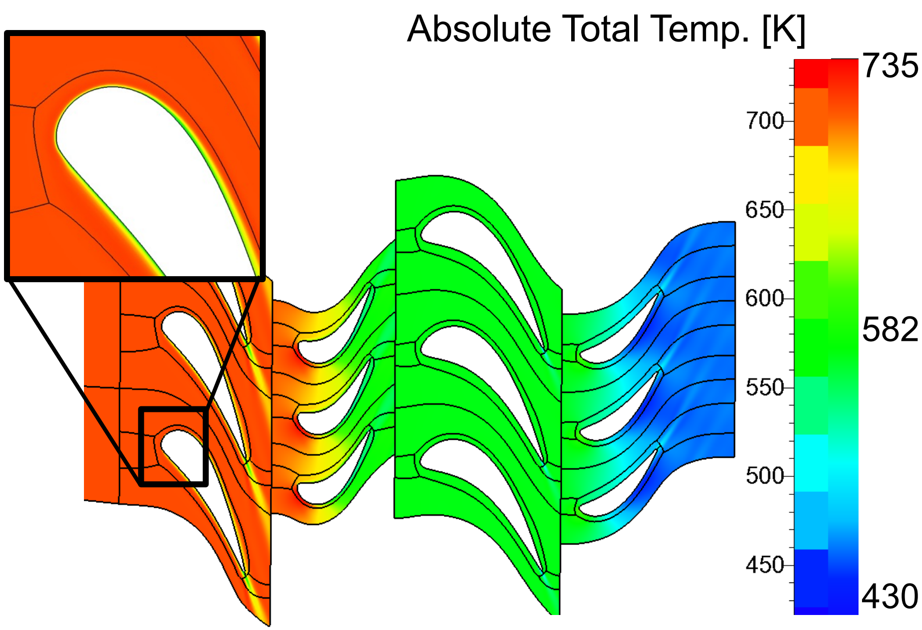
Although the inlet BC is stationary, there are lots of unsteadiness/mixing captured.

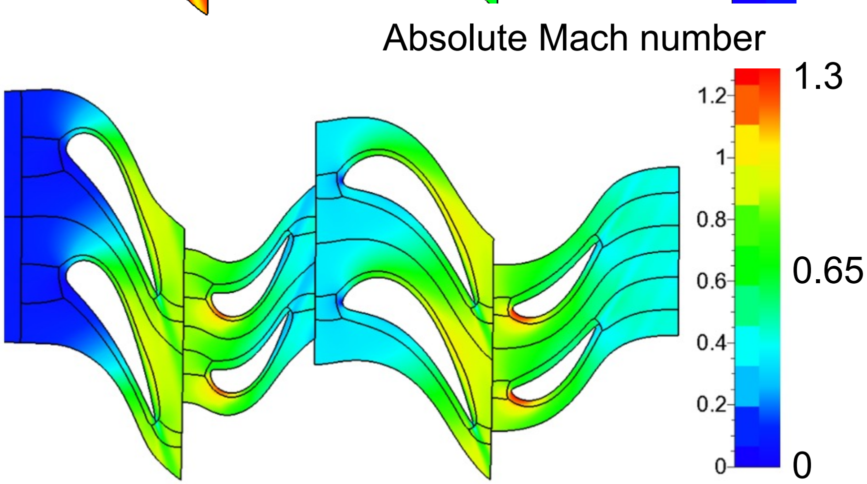
Instantaneous Flow Fields, con



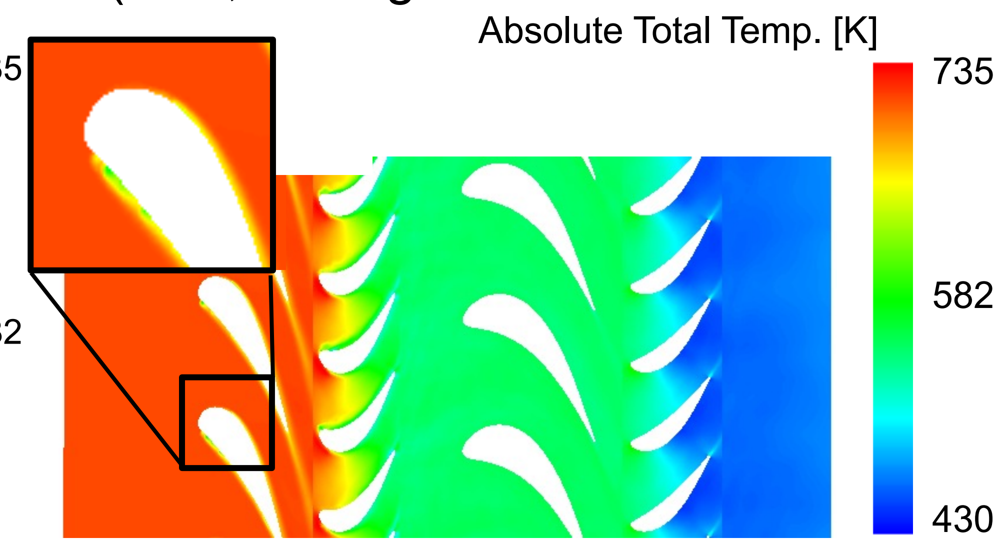
CFD Cross Validation: Total Temperature

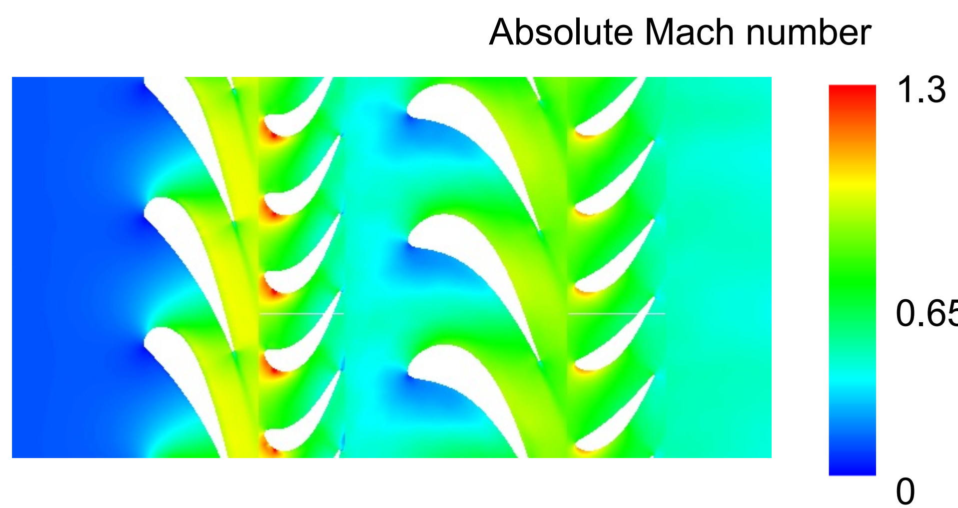
Fine/Turbo [XXX]
(RANS, Mixing plane, 1.1M mesh)



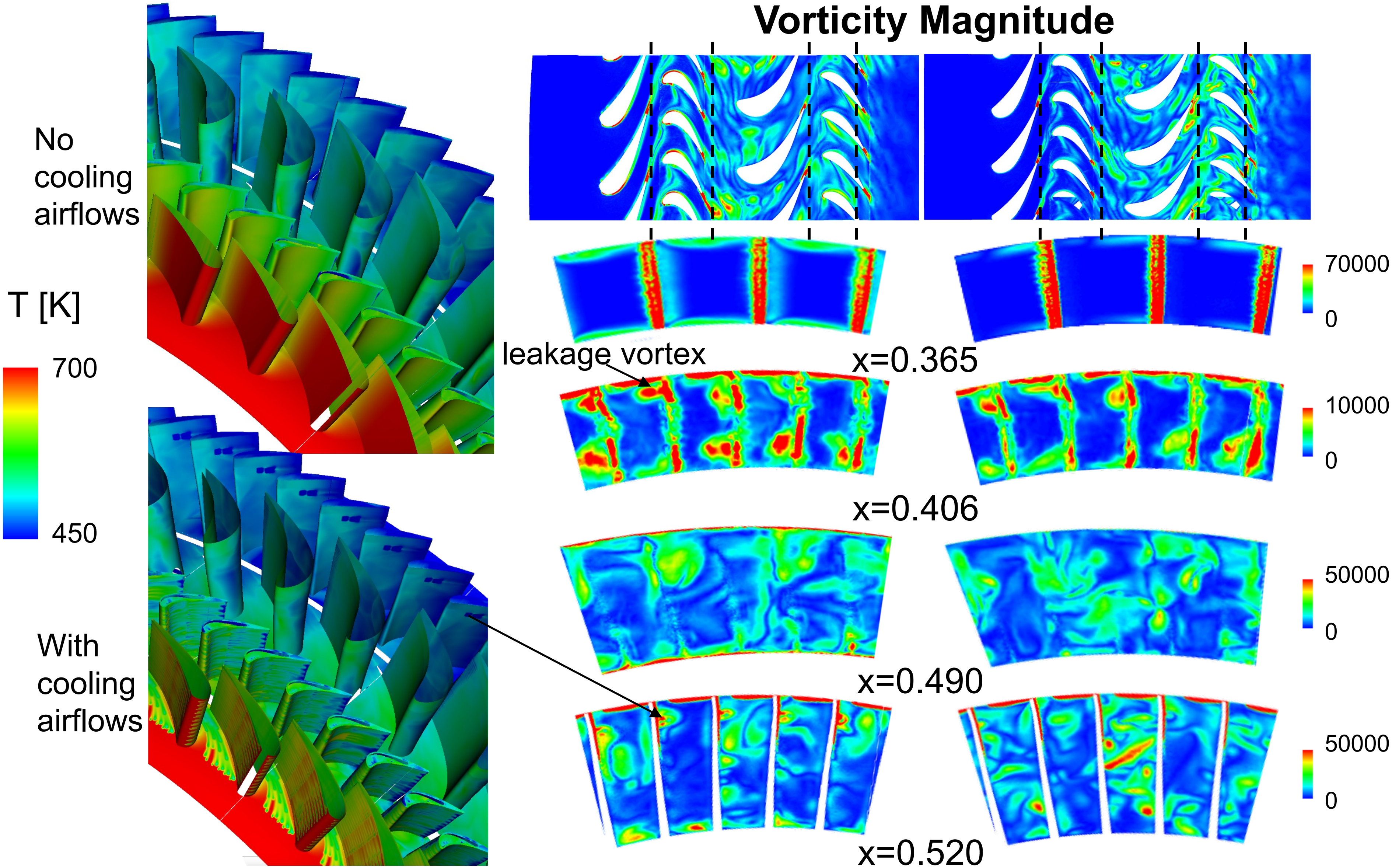


OpenNCC
(LES, Sliding mesh, 50M mesh)



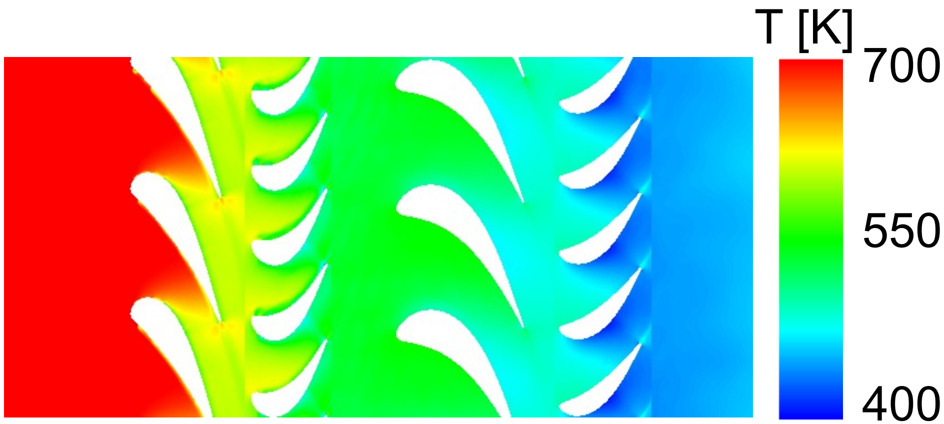


With/Without Cooling Airflows

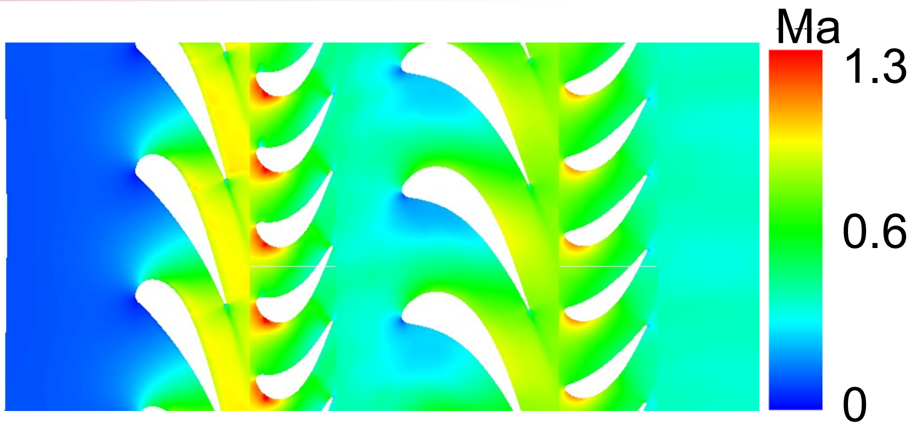


Cooling airflows significantly affect the vorticity fields

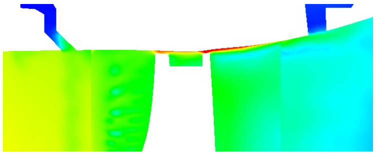
Time-Averaged Flow Fields

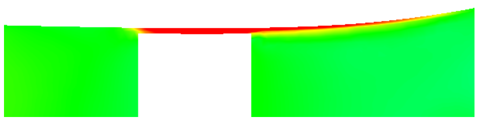


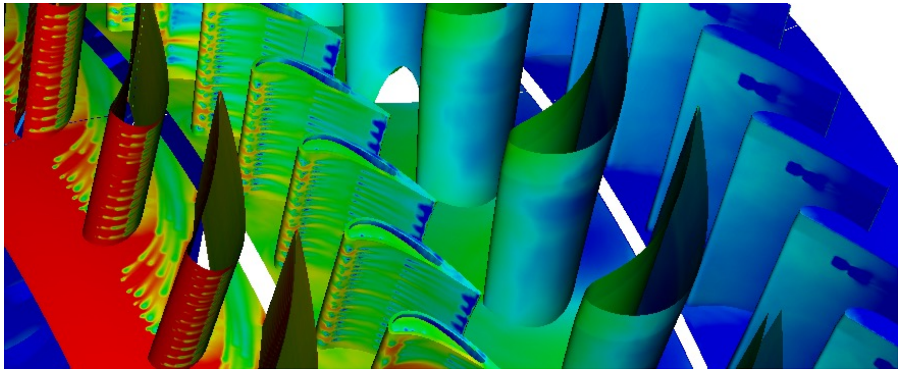
Temperature

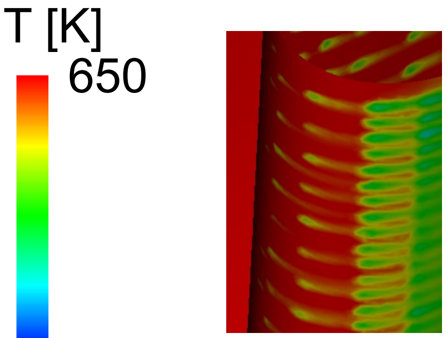


Mach

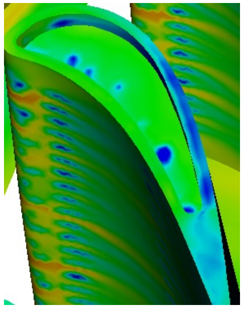

1st stage rotor tip

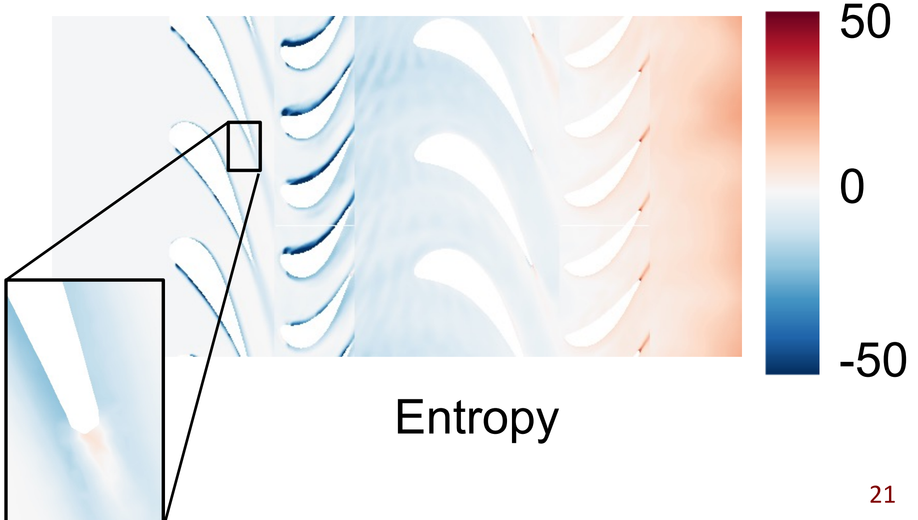

2nd stage rotor tip





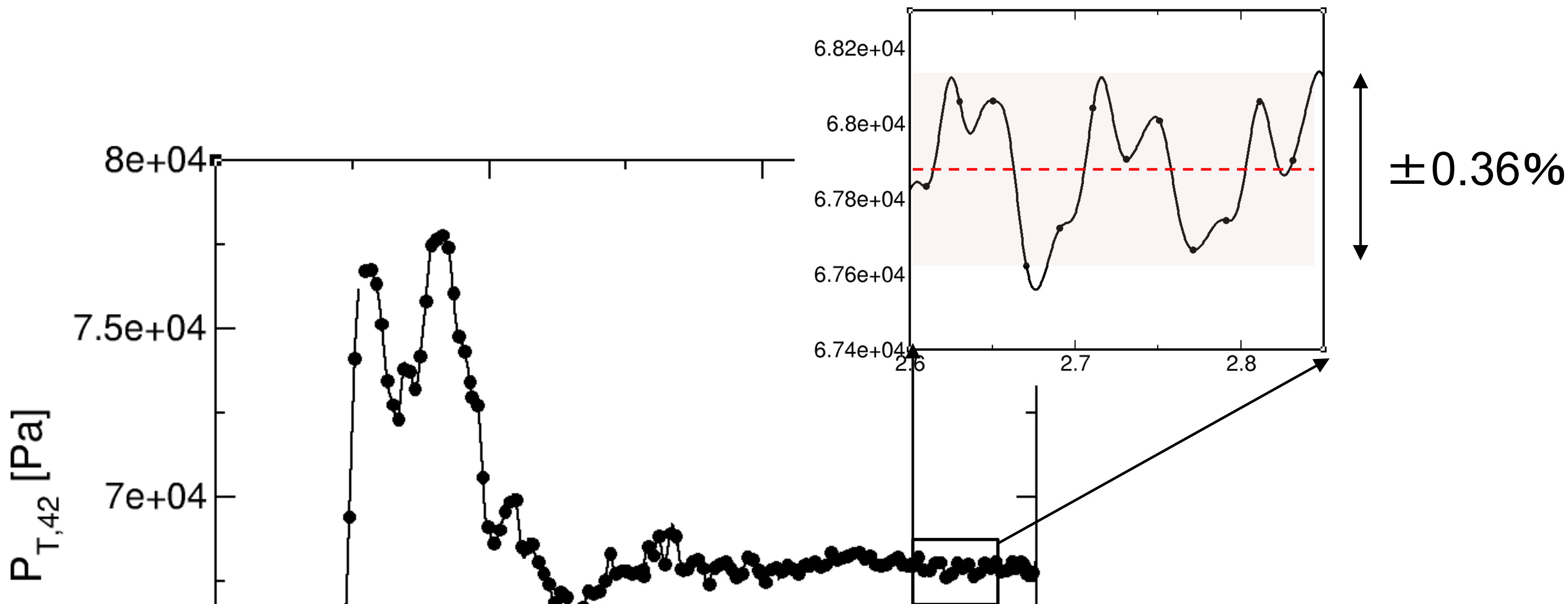
Suspect side

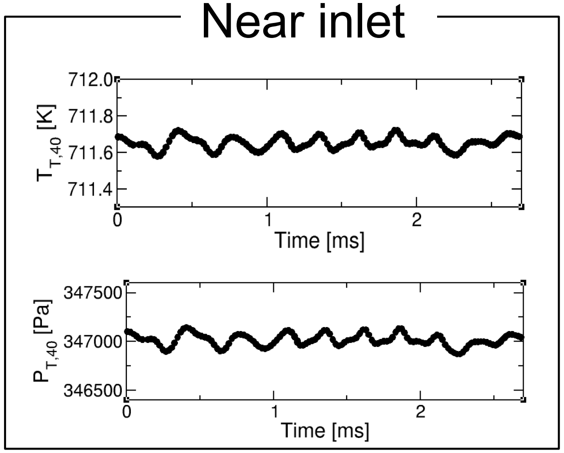

Rotor tip



Entropy

Time-History of Inlet/Exit Properties

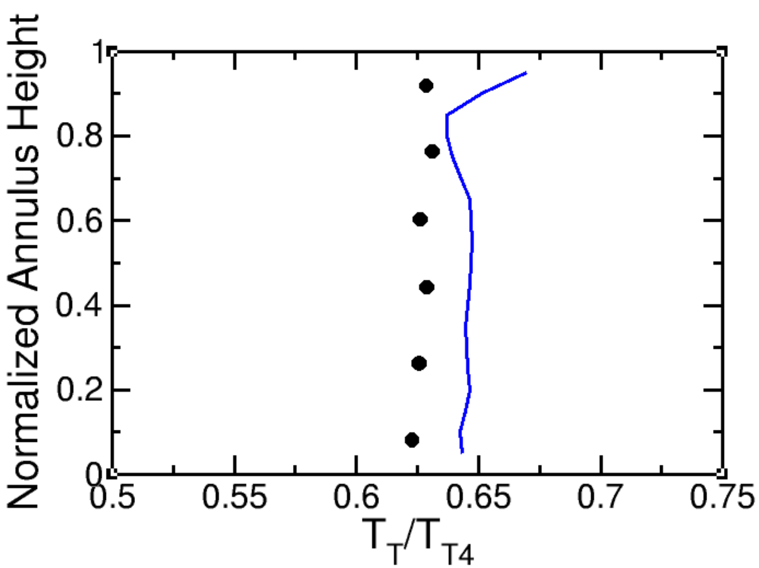


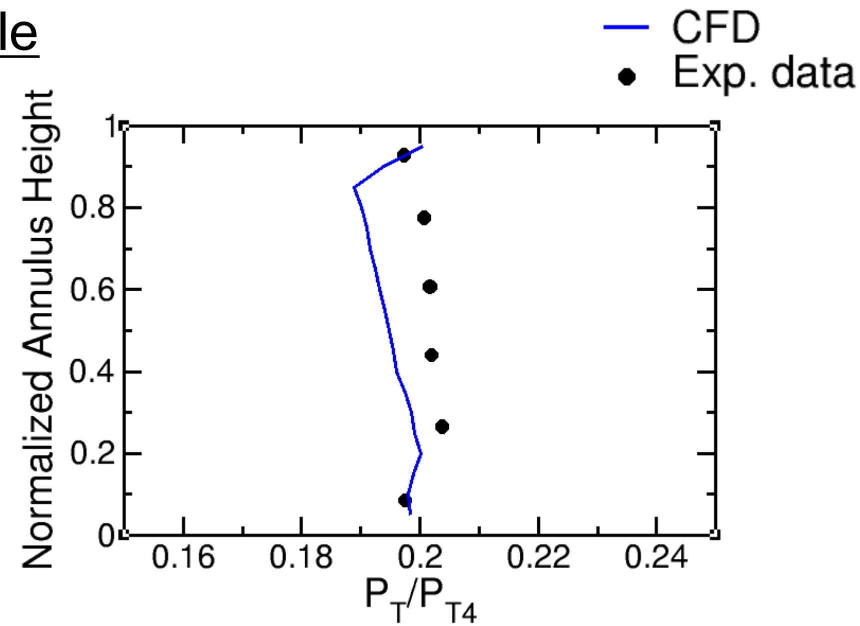


Even with the stationary inlet BC, the exit total pressure oscillates due to the rotor motion (~10K Hz). This could be much stronger through the combustion dynamics.

Comparison with the Experimental Data

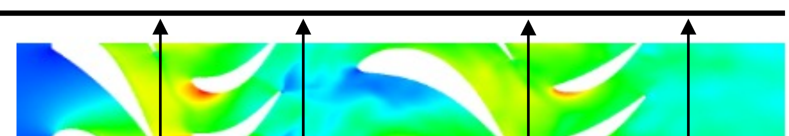
Exit Profile



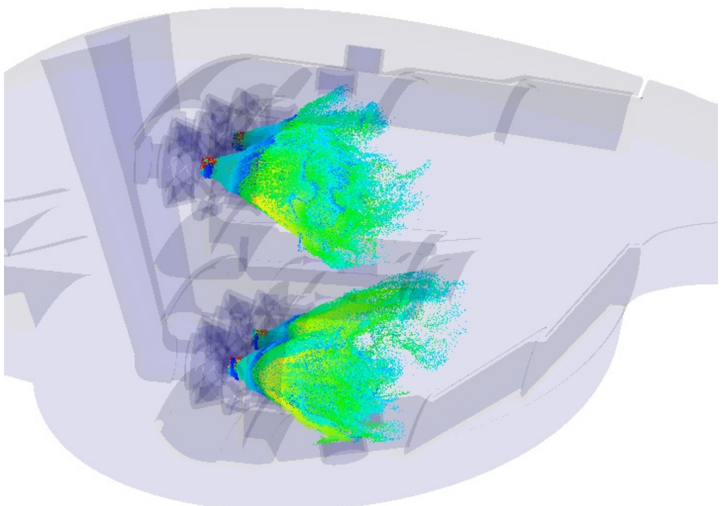


Other Key Properties

	$P_{T,4}/P_{42}$	$P_{T,4}/P_{T,42}$	Efficiency η_{GE}	Corrected speed	Mass flux [kg/s]	S1, exit P [psi]	R1, exit P [psi]	S2, exit P [psi]	R2, exit P [psi]
Exp. Data	5.59431	5.01834	0.9259	235.966	0.726	29.325	20.1111	12.9287	8.88196
LES	5.64	5.056	0.9202	235.66	0.730	29.56	20.08	12.97	8.87
Error [%]	0.840	0.76	0.611	0.128	0.59	0.820	0.154	0.334	0.112



Numerical Setup and Operating Condition



Spray distribution colored by the diameter.

- Unsteady (TFNS, two-equations model) with RCP = 0.1 (LES)
- Liquid droplets (C11H21) are stochastically injected from the main and pilot domes with 70^o cone angle (hollow cone, SMD=8.8)
- Central Scheme (JST) is used for inviscid flux
- Finite-rate chemistry (2step-mechanism) [10]

$$KERO + 17.25\, O_2 \rightarrow 12CO_2 + 10.5\, H_2O$$

$$CO + 0.5\, O_2 \rightarrow CO_2$$

$$k_{f,1} = A_1 f_1(\phi) e^{(-E_{a,1}/RT)} [KERO]^{n_{KERO}} [O_2]^{n_{O_2,1}},$$

$$k_{f,2} = A_2 f_2(\phi) e^{(-E_{a,2}/RT)} [CO]^{n_{CO}} [O_2]^{n_{O_2,2}},$$

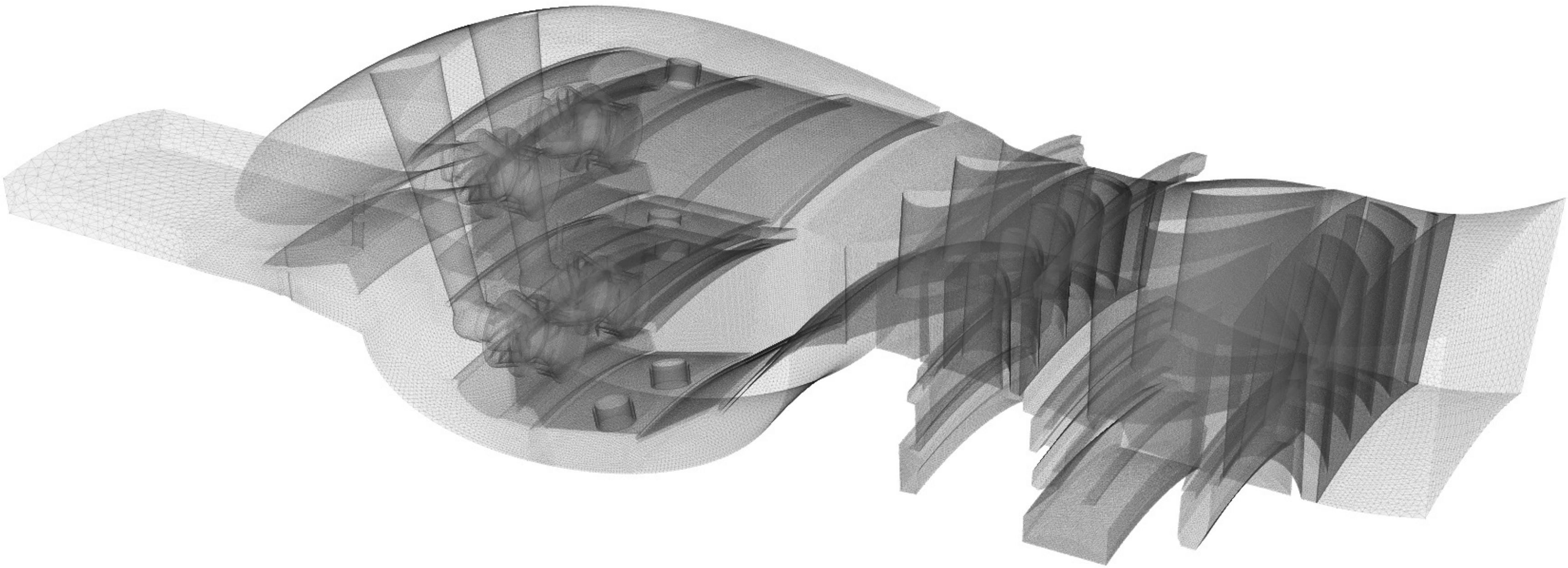
About CPU

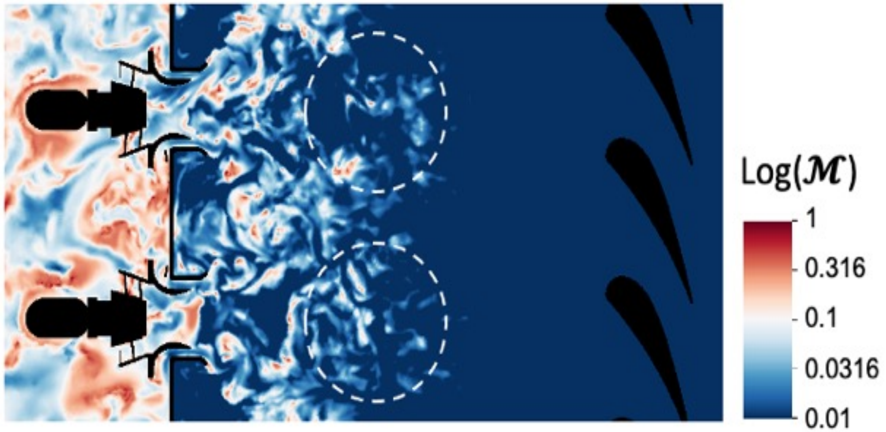
- Used 1680 processors of Pleiades at NASA Advanced Supercomputing facility.

Operating Condition

	$P_{S,41}$ [atm]	$P_{S,45}$ [atm]	T_3 [K]	W_3 [kg/s]	f/a	Wf_{pilot}/Wf_{total}
Test condition	27.4	8.2.	815	3.64	0.0245	0.5

Mesh



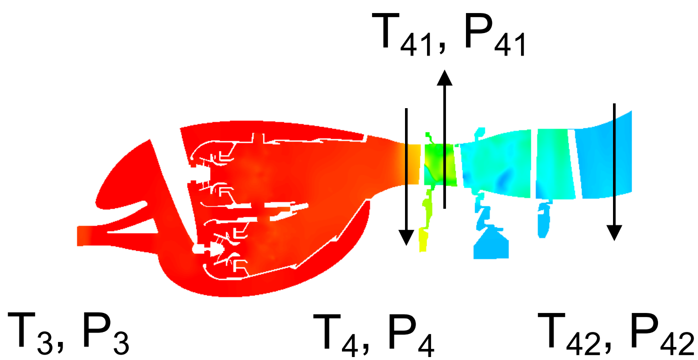


Instantaneous contour of Pope criterion inside the combustor

- ~100M tetrahedral elements for E^3 combustor and 2-stage stator/rotor of HPT are generated by Cubit.
- Mesh quality inside the combustor is checked, and most of turbulent motions were captured given the mesh resolution.
- Without any BL mesh inside HPT, the viscous effect might be overlooked.

Cooling Airflow for The Engine Condition

- Converting the rig condition (NASA test campaign) to the engine condition is critical.
- We need the mass flux and temperature information for all cooling airflow inputs.



Input

T_3: 820 [K], P_{S42} : 828,000 [Pa]

From the simulation

Mass flow rate into the HPT: 4.19 kg/s,
Corrected Rotating Speed: 243.3
$P_{T,4}/P_{S,42} = 3.82$
$P_{T4}/P_{T42} = 3.60$

NASA CR-168286 by L. P. Timko

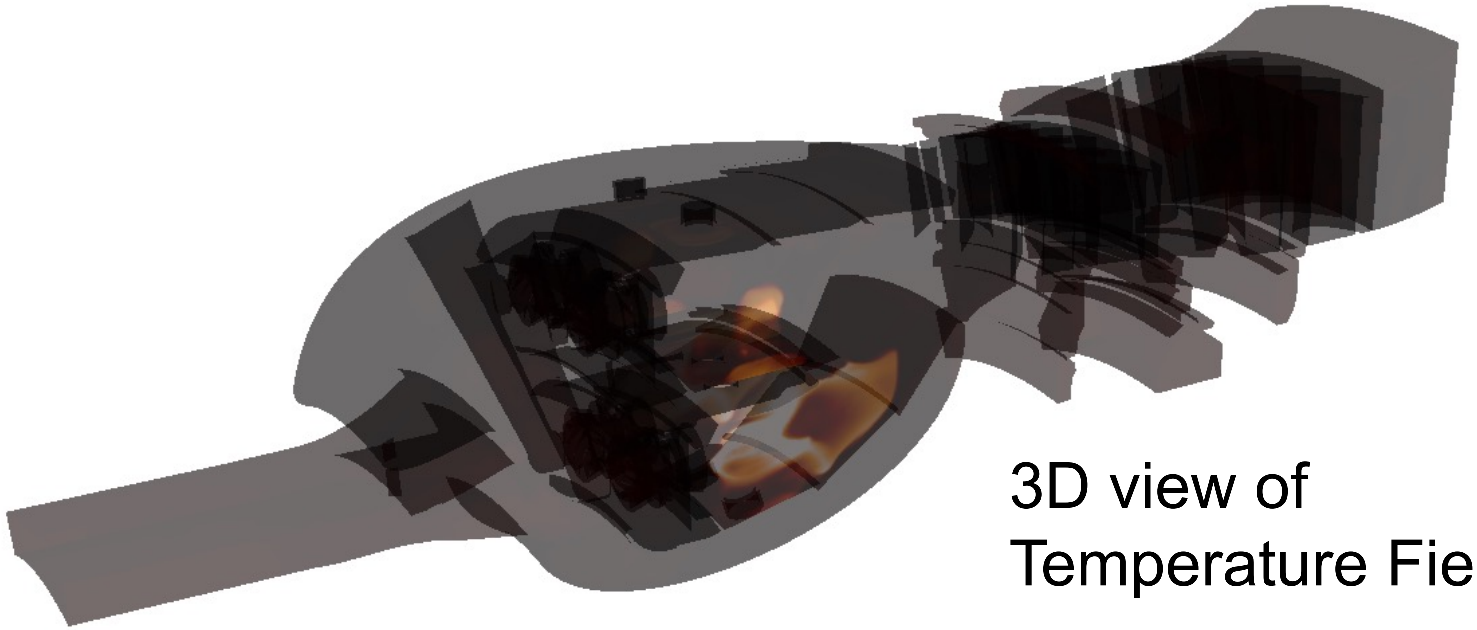
PERFORMANCE

RDG.	$P_{T,4}/P_{S,42}$	$P_{T,4}/P_{T,42}$	$N/\sqrt{T_{T,41}}$ rpm/$\sqrt{°R}$	U/C_o	$W_{41}\sqrt{T_{T,41}}/P_{T,4}$ $\frac{lbm\sqrt{°R}}{sec\ psia}$	$\Delta h/T_{T,41}$ Btu/(lbm °R) Measured	$\Delta h/T_{T,41}$ Btu/(lbm °R) w/Pumping
69	4.01473	3.66000	244.508	0.651476	18.1084	0.681370E-01	0.697495E-01
70	4.01036	3.66000	244.856	0.652720	18.1011	0.680861E-01	0.696990E-01

- Mass flux rate is re-scaled based on the mass flow rate into the HPT.
- All cooling airflow temperatures are assumed to be T_3 .
- Injection angle, locations and Tu are assumed to be the same as the rig condition.

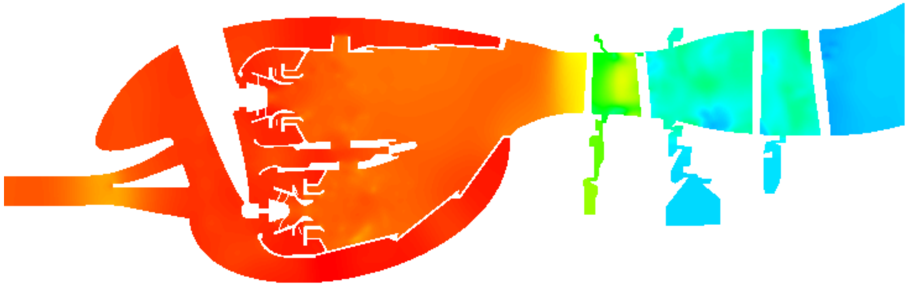
Our engine condition is close to RDG 69 or RDG70 Test Campaign.

Preliminary Results (without rotating)



3D view of
Temperature Field

Temperature



Pressure

Conclusion

- We implemented the source term approach into the NASA in-house combustion code, OpenNCC, in order to take into account the cooling airflows for the high-pressure turbine.
- The validation of the approach was performed by using the the Energy Efficient Engine program (GE version, 80s).
- The numerical results predicted by large eddy simulation were compared with the experimental data (Test campaign: RDG10) of the exit temperature and pressure profiles. The reasonable agreement is achieved.
- We also show the preliminary result of fully-coupled combustor and high-pressure turbine with cooling airflows for the engine condition.
- Although it is not trivial to digitalize all geometrical information of hundreds of cooling airflows from literature, it is shown that this engineering approach is capable of modeling the effect of the cooling airflows with satisfactory accuracy.

Thank you!

Questions?

Acknowledgement

- **Supported by NASA's Transformational Tools and Technologies project**
- **Simulations conducted NASA Advanced Supercomputing (NAS) Pleiades computers**
- **Grid Generation conducted with Cubit (Sandia National Labs)**
- **Flow Viz was conducted with Visit (Lawrence Livermore National Labs)**