Numerical Study of Combustor-Turbine Interactions Using Open-National Combustion Code (OpenNCC)

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NASA Glenn Research Center

RTRC Full-Engine Simulation Workshop

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Outline

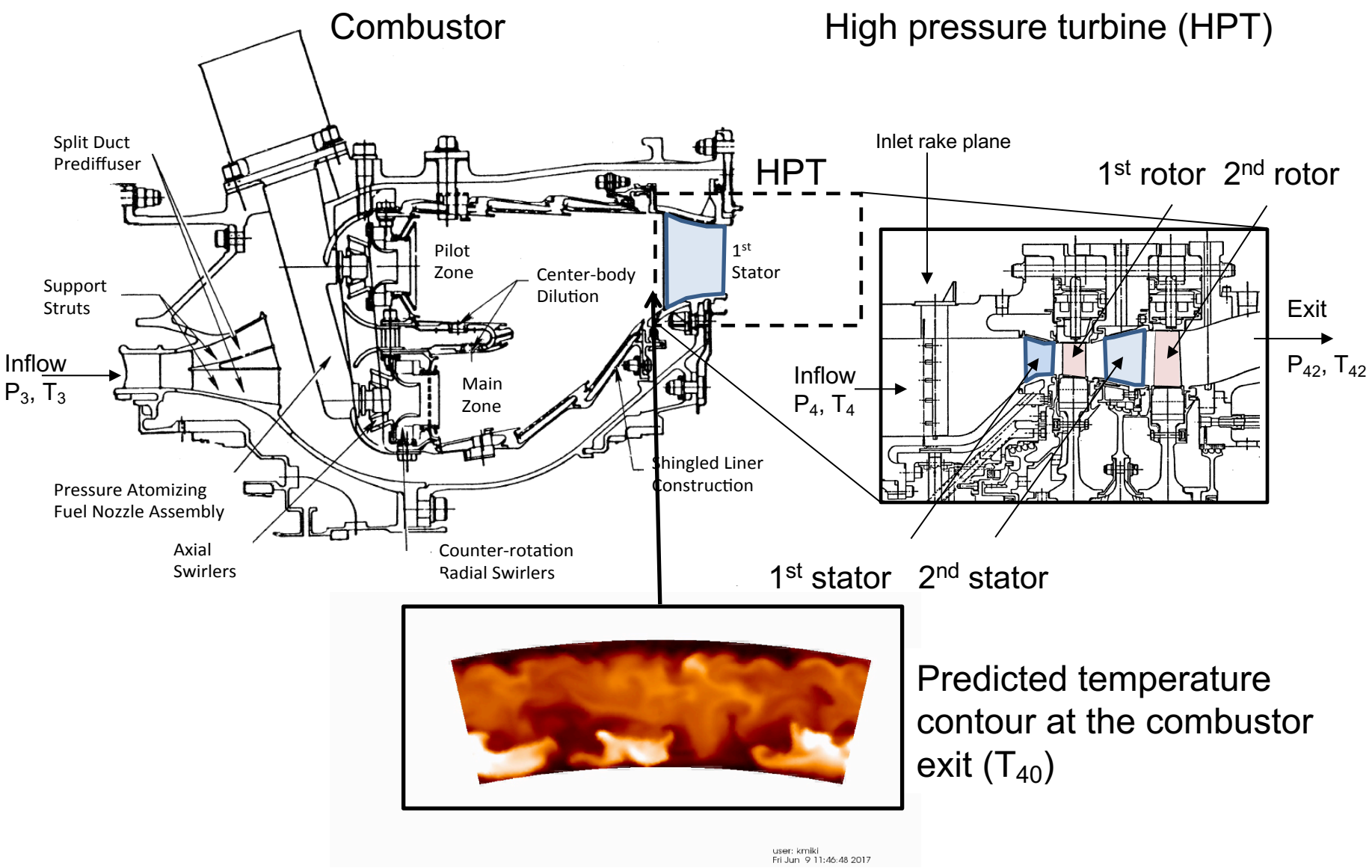
- **Introduction**
  - ❑ **Energy Efficient Engine (GE-E^3)**
  - ❑ **NASA GRC Plan for CTI**
- **Numerical Setting**
- **Results**
  - ❑ **STEP1: Combustor + 1st stage stator**
    - ✓ Clocking
    - ✓ Turbulence-combustion interaction
  - ❑ **STEP2: HPT(1st and 2nd stages stators/rotors)**
  - ❑ **STEP3: Combustor + HPT (1st and 2nd stages stators/rotors)**
- **Conclusions**

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



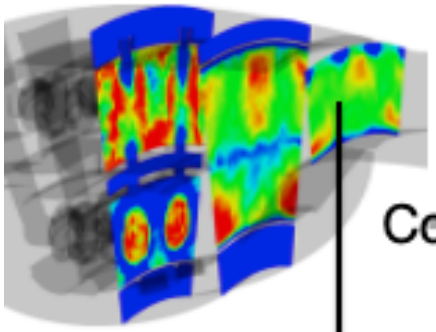
From "**Deposition With Hot Streaks in an Uncooled Turbine Vane Passage**", B. Casaday, R. Prenter, C. Bonilla, M. Lawrence, C. Clum, A. Ameri and J. Bons., J. Turbomach, 2013 Vol. 136 (Permission from Prof. Bons and Dr. Mike Dunn @ OSU)

Energy Efficient Engine– GE design, 80s -



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

Toward Fully-Coupled Combustor-HPT Simulation



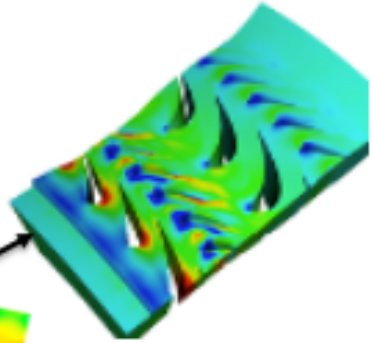
STEP 1 (2016-2018)[1-3]



- In 2011, demonstrated a single-element LDI + HPT using moving mesh (RANS, 1.8M mesh)

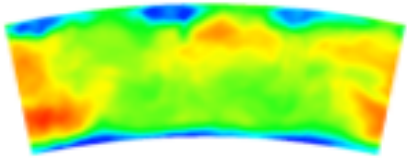
Wey, T. and Liu, N.-S., AIAA (2011)

Combustor + 1st Stator of HPT (no moving rotor)



STEP 2 (2018-2019) [4]

Two stage (stator/moving rotor) of HPT



Time-averaged flow fields at P_4



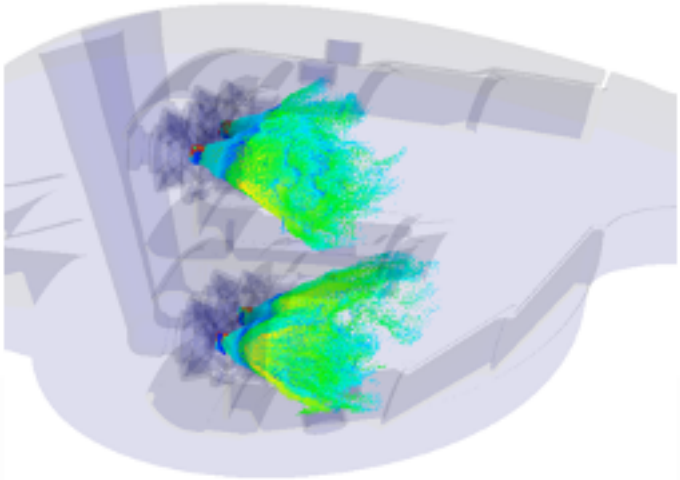
STEP 3 (present in AIAA P&E 2020)

Combustor + Two stage (stator/rotor) of HPT

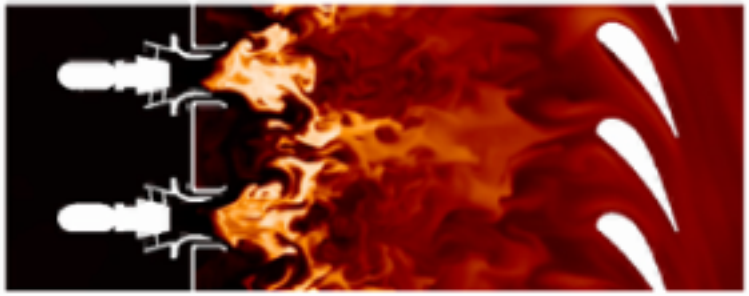
Assess importance of fully-coupled combustor-turbine simulations relative to sequential (combustor, then turbine) simulations.

[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. S., Shock Waves, Vol. 29, 2019, pp. 1009-1021. [4] Miki, K., Wey, T., and Moder, JProceedings of the International Society for Air Breathing Engines, Canberra, Australia, Sept. 2019. ISABE- 2019

Numerical Setup



Droplets colored by size



T (black:700, white: 2700)

- 50M (step1), 24M (Step2),70 M(Step3) Mesh
- Subgrid Scale: non-linear k-ε model with the wall function.
- Liquid droplets (C11H21) are stochastically injected from the main and pilot domes with 70^{o} cone angle (hollow cone, SMD=8.8)
- Finite-rate chemistry (2-step mechanism[1]):

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

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

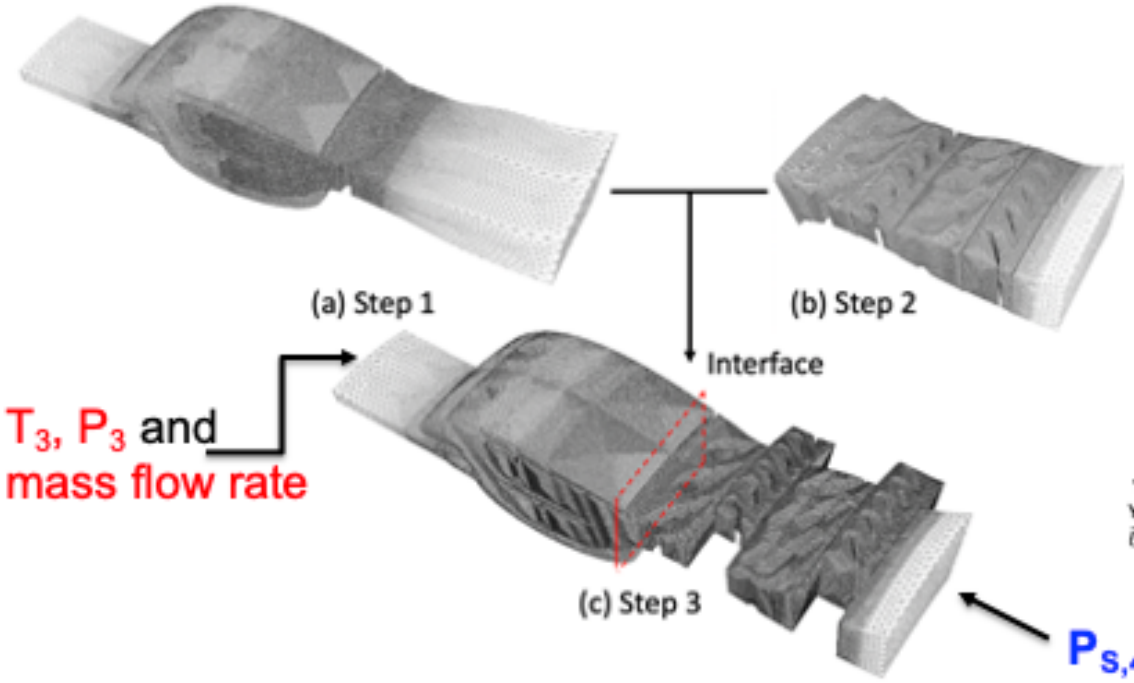
$$k_{f,1} = A_1 f_1(\phi) e^{(-E_{a,1}/RT)} [\mathrm{KERO}]^{n_{\mathrm{KERO}}} [O_2]^{n_{O_2,1}},$$

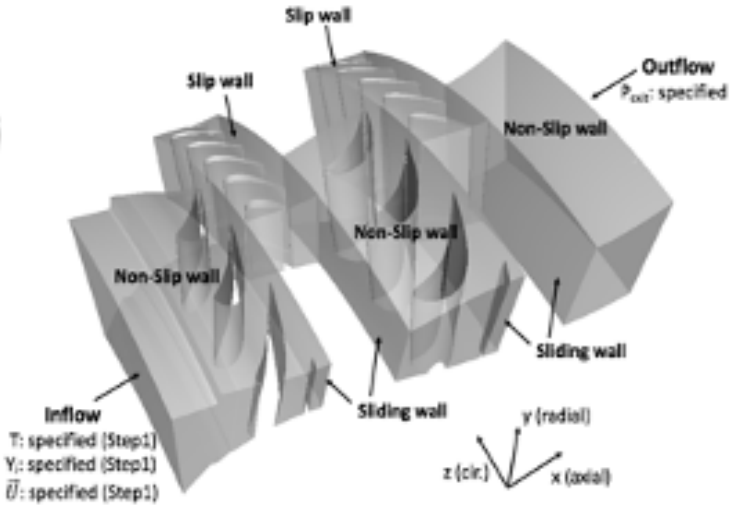
$$k_{f,2} = A_2 f_2(\phi) e^{(-E_{a,2}/RT)} [CO]^{n_{CO}} [O_2]^{n_{O_2,2}},$$

- Turb.- chem. int. (DTF)
- ~1.5 million CPU-hours (initial transients and sufficient time to get meaningful time-averaged and time-history results) for Step 3.

[1] Franzelli, *et al*., Combustion and Flame, Vol. 157, (2010)

Mesh and Boundary Conditions



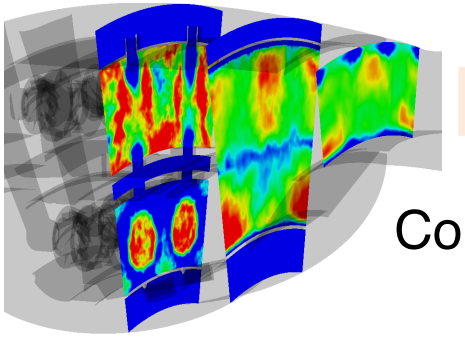


	P_3 [atm]	T_3 [K]	W_3 [kg/s]	Wf_{total} [kg/s]	f/a	Wf_{pilot}/Wf_{total}	T_{fuel} [K]	RPM
SLTO	2.52	720	0.26	0.00364	0.014	0.5	520	8313

Step 1: Combustor inflow (T_3, P_3, mass flow rate); Combustor exit pressure, $P_{S,41}$

Step 2: HTP inflow = time-averaged plane from Step 1;
HTP exit pressure, **$P_{S,42}$** which requires calibration with specified RPM

Step 3: Combustor inflow (T_3, P_3, mass flow rate); HPT exit pressure, **$P_{S,42}$** from Step 2.



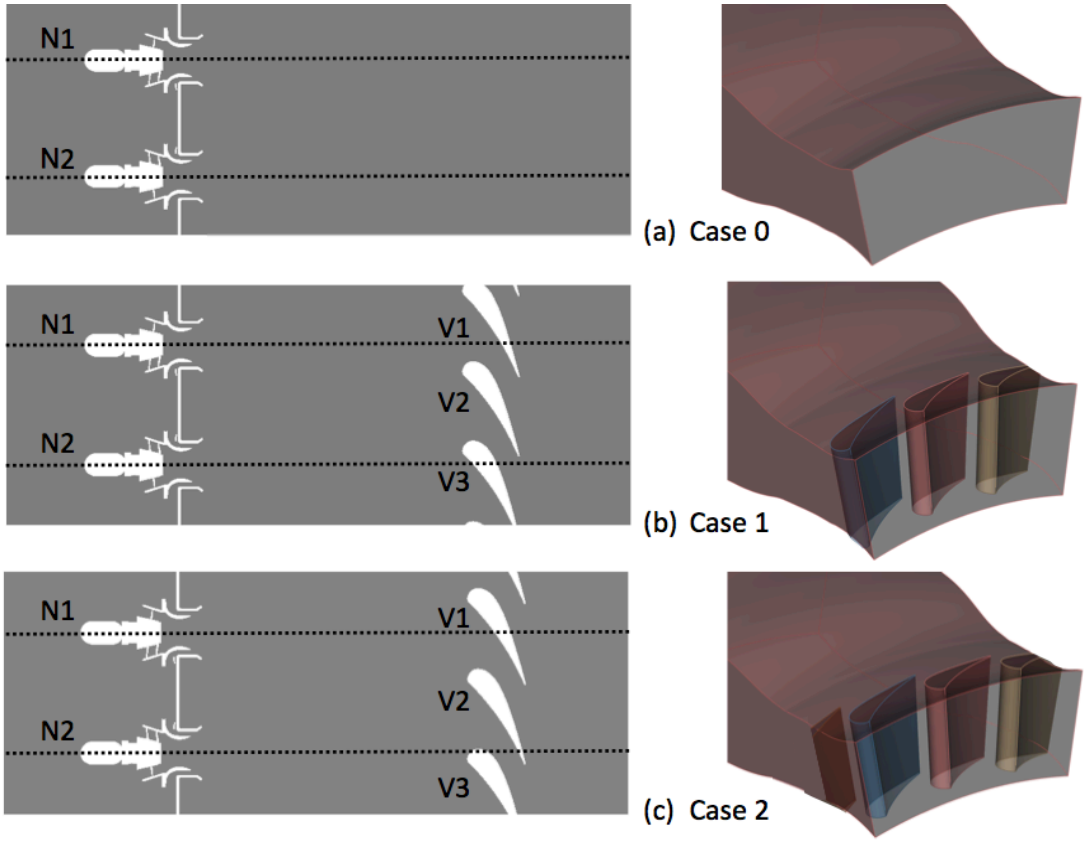
STEP 1 (2016-2018)[1-3]

Combustor + 1st Stator of HPT (no moving rotor)

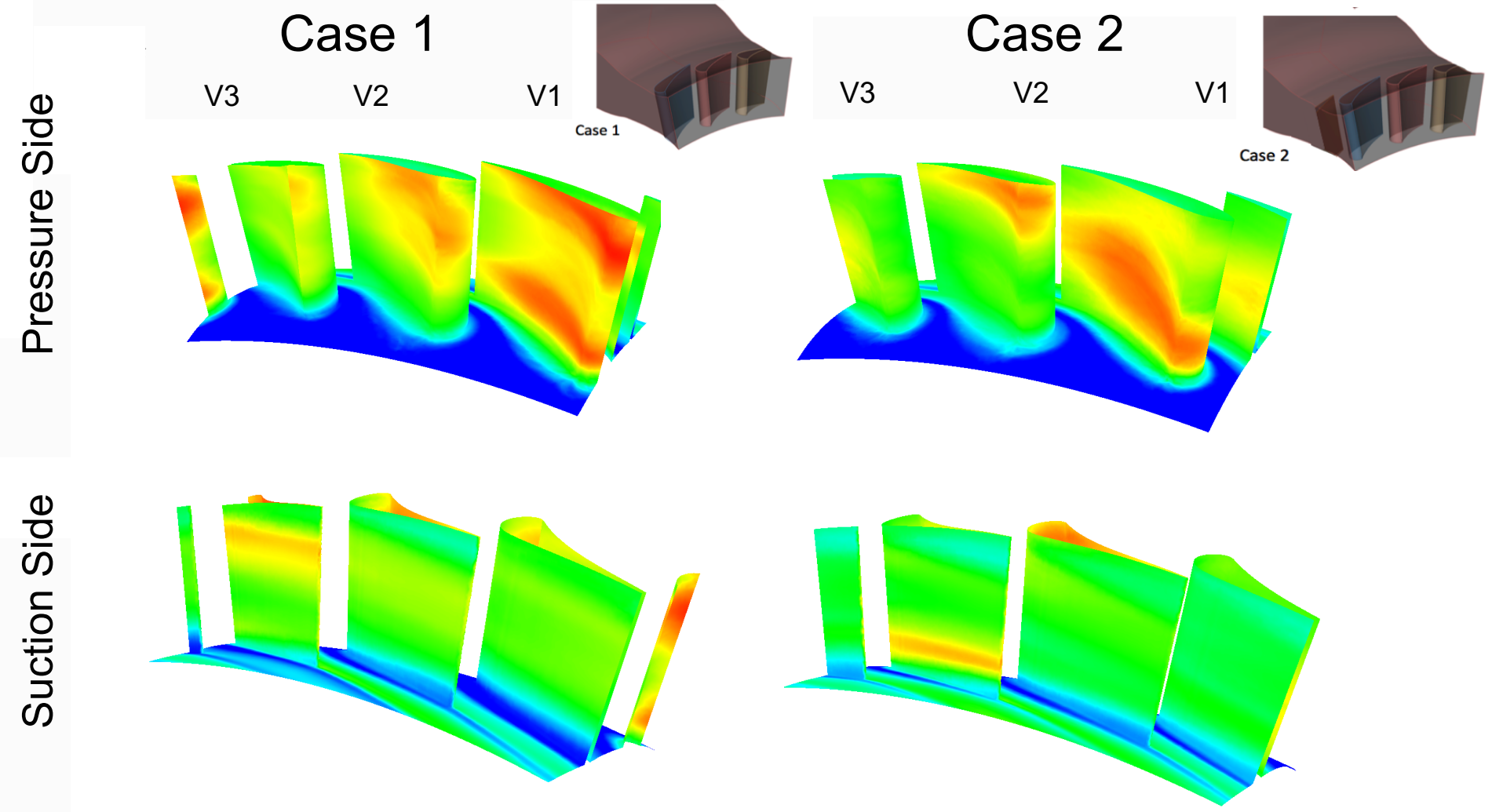
[1] Miki, K., Moder, J., and Liou, M.-S., Journal of Propulsion and Power, Vol. 34, 2018, pp. 415{- 427. [2] Miki, K., Moder, J., and Liou, M.-S Journal of Propulsion and Power, Vol. 34, 2018, pp. 1529-1534. [3] Miki, K., Moder, J., and Liou, M. S., Shock Waves, Vol. 29, 2019, pp. 1009-1021.

STEP1 Combustor + HPT (1st Stator)

1. Clocking Effects
2. Sensitivity of Turbulent Combustion Model

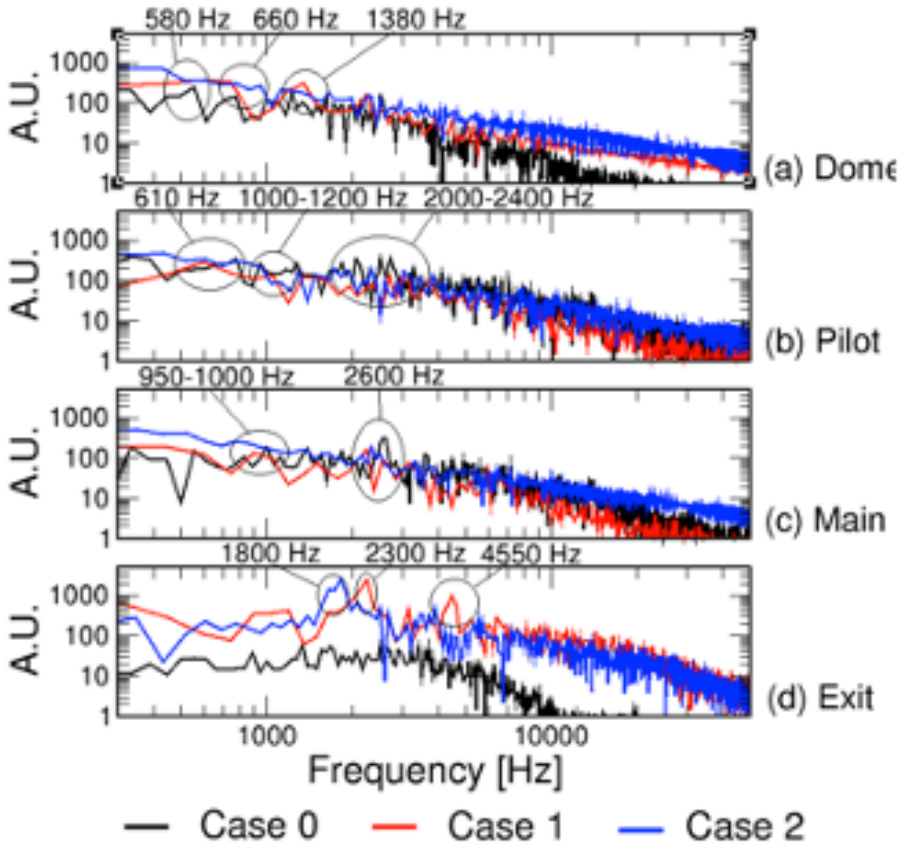


Unsteady Temperature Fields @ Vane



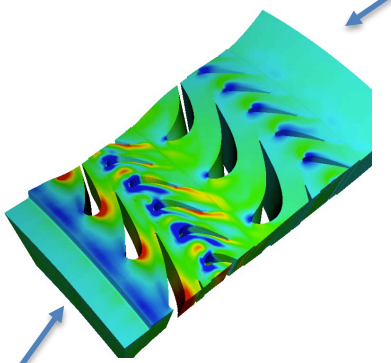
- Adiabatic condition is used and any cooling holes on the surface are not included.
- Locally hot (1600 [K]) and cool (900-1000 [K]) spots co-exist, which can cause the severe thermal stress on the vane, especially on the pressure side.

Turbulent Combustion Model and Dynamics



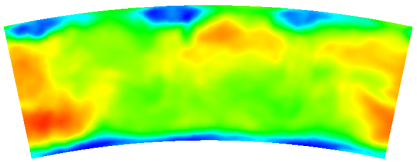
- Choice of turb. chem. int. model affects distributions of hot-streaks (i.e., physical model uncertainty).
- Clocking could significantly change characteristics of combustion (e.g., combustion dynamics).

$P_{S,42} = ?$



STEP 2 (2018-2019) [4]

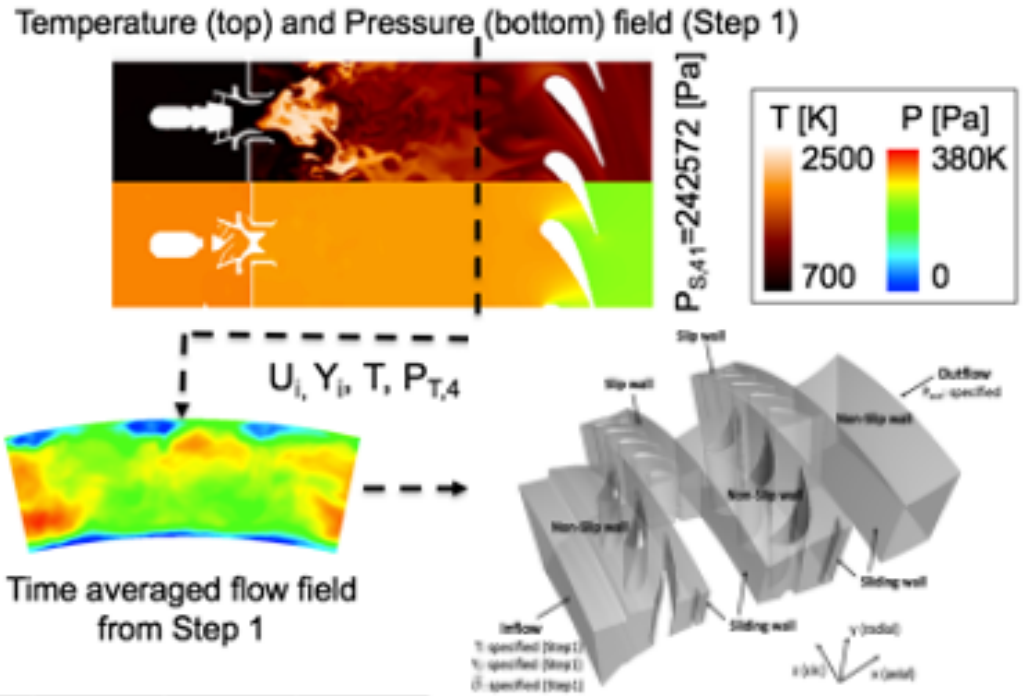
Two stage (stator/moving rotor) of HPT

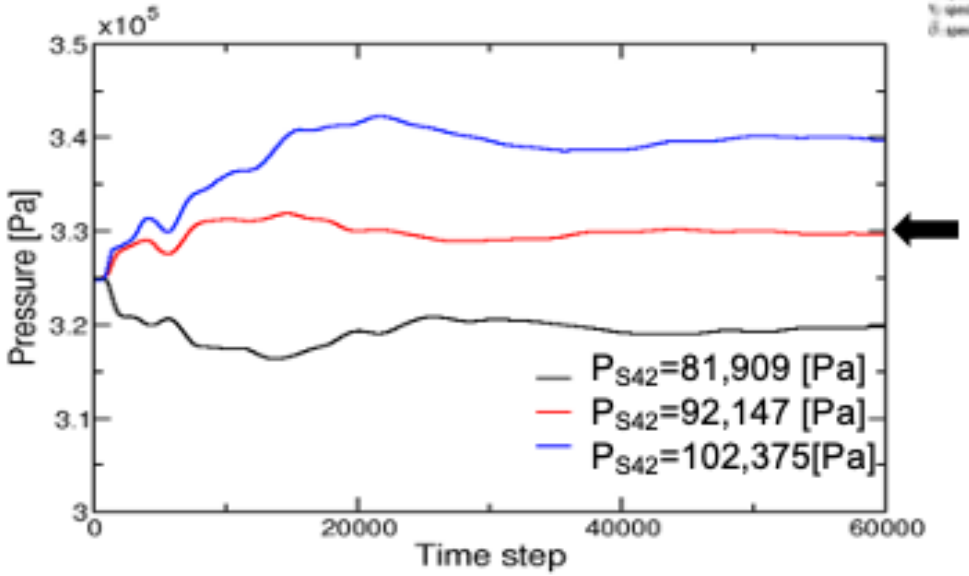


Time-averaged flow fields at P_4 from Step 1

[4] Miki, K., Wey, T., and Moder, JProceedings of the International Society for Air Breathing Engines, Canberra, Australia, Sept. 2019, ISABE- 2019.

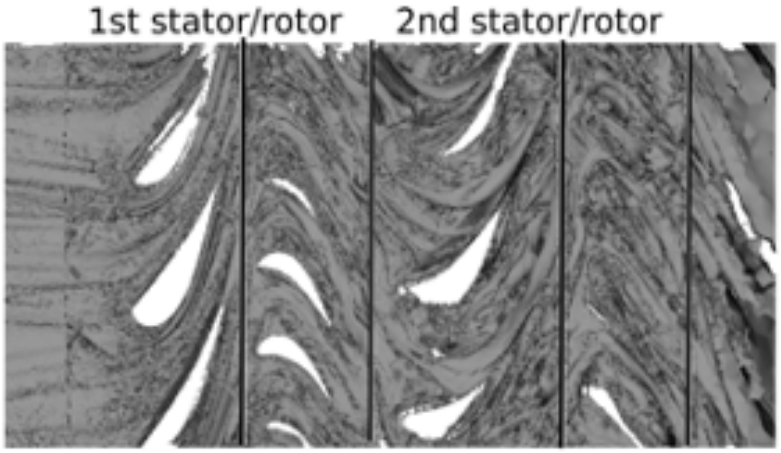
Estimation of HPT Exit Pressure (P_{S42})



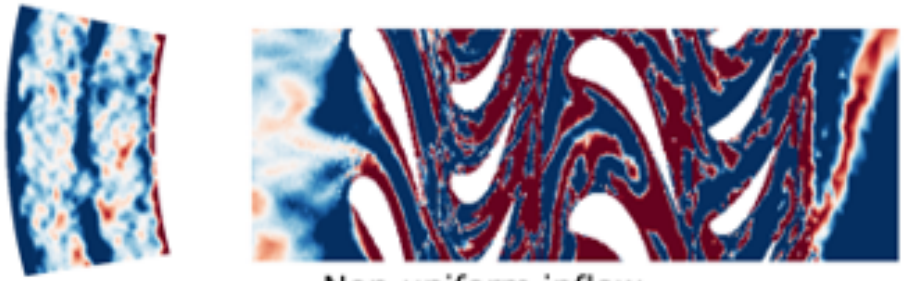


- Three values of P_{S42} (81,909, 92,147, and 102,375) are tested.
- P_{S42} =92,147 [Pa] gives the excellent agreement of P_{S4} from Step 1
- Since the total-to-total pressure ratio is a weak function of RPM, we keep RPM (= 8,313) constant for the rest of this study.

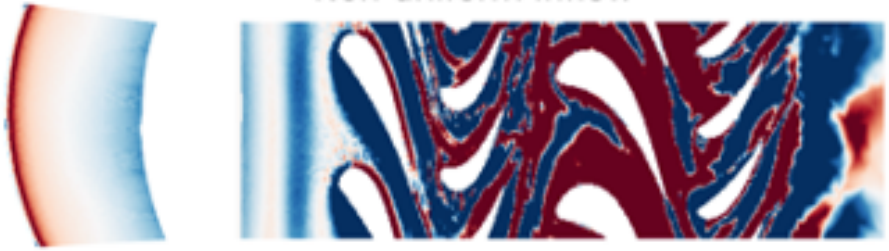
Effect of Non-Uniform Inflow from STEP1



(a) iso-surface of w-vorticity (non-uniform inflow)

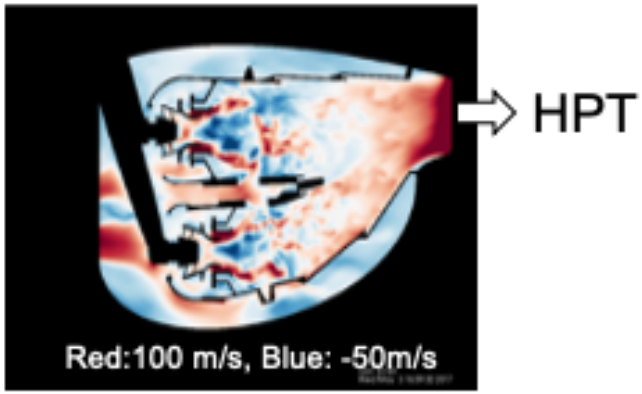


Non-uniform inflow



Uniform inflow

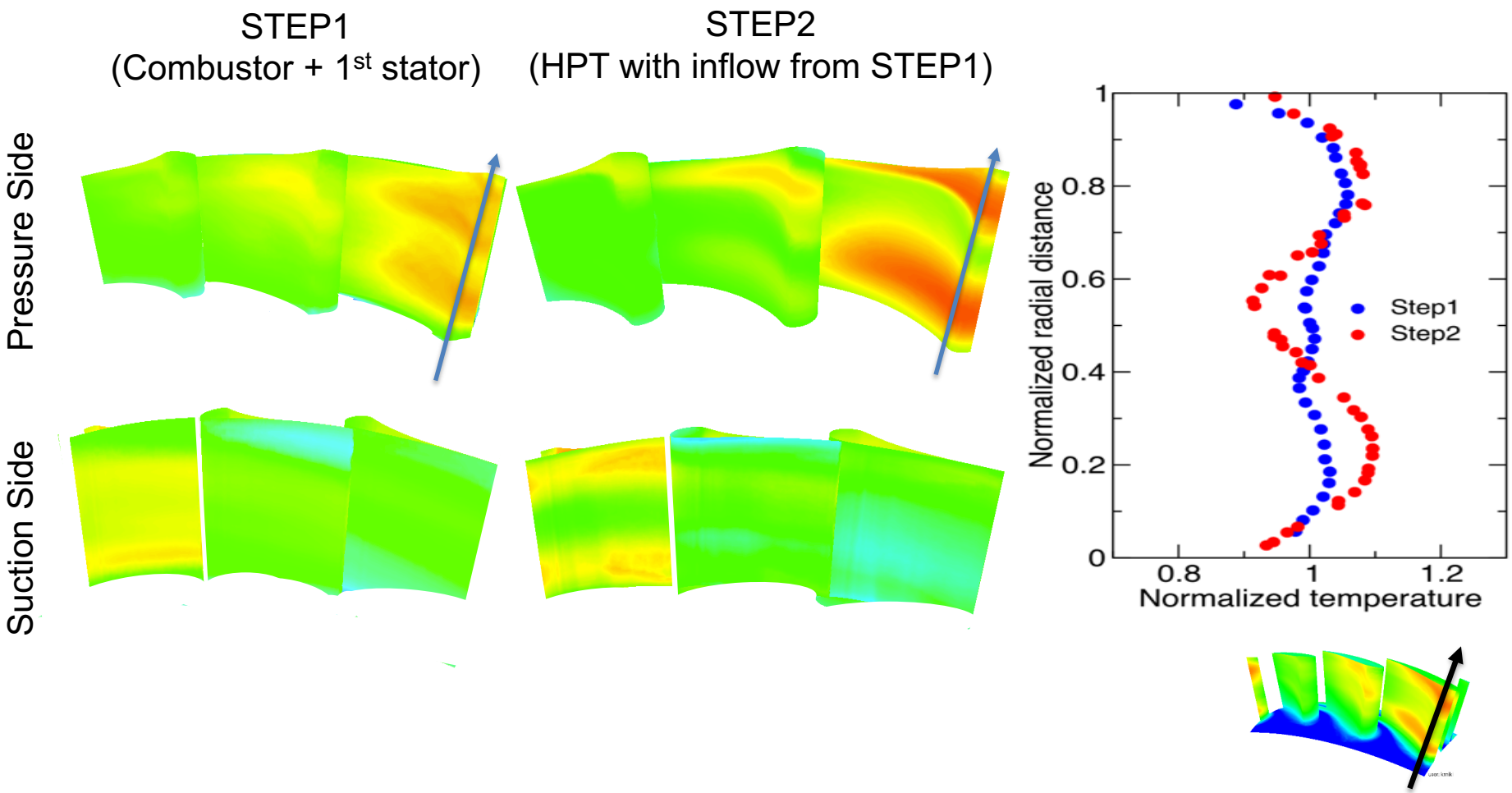
(b) contour of w-vorticity at x=0.29 [m] (left) y=0.345 [m] (right)



Axial velocity from STEP1

- Compare two test cases:
  - ✓ Non-uniform inflow from STEP1
  - ✓ Uniform inflow (conventional)
- There are long vorticity structures across the stators/rotors.
- Since vorticity structures from inlet remains and could affect flow fields inside HPT, it is important to take into account the “history” of flow coming from a combustor.

Time-averaged Temperature fields @ 1st Stator from STEP1 & STEP2

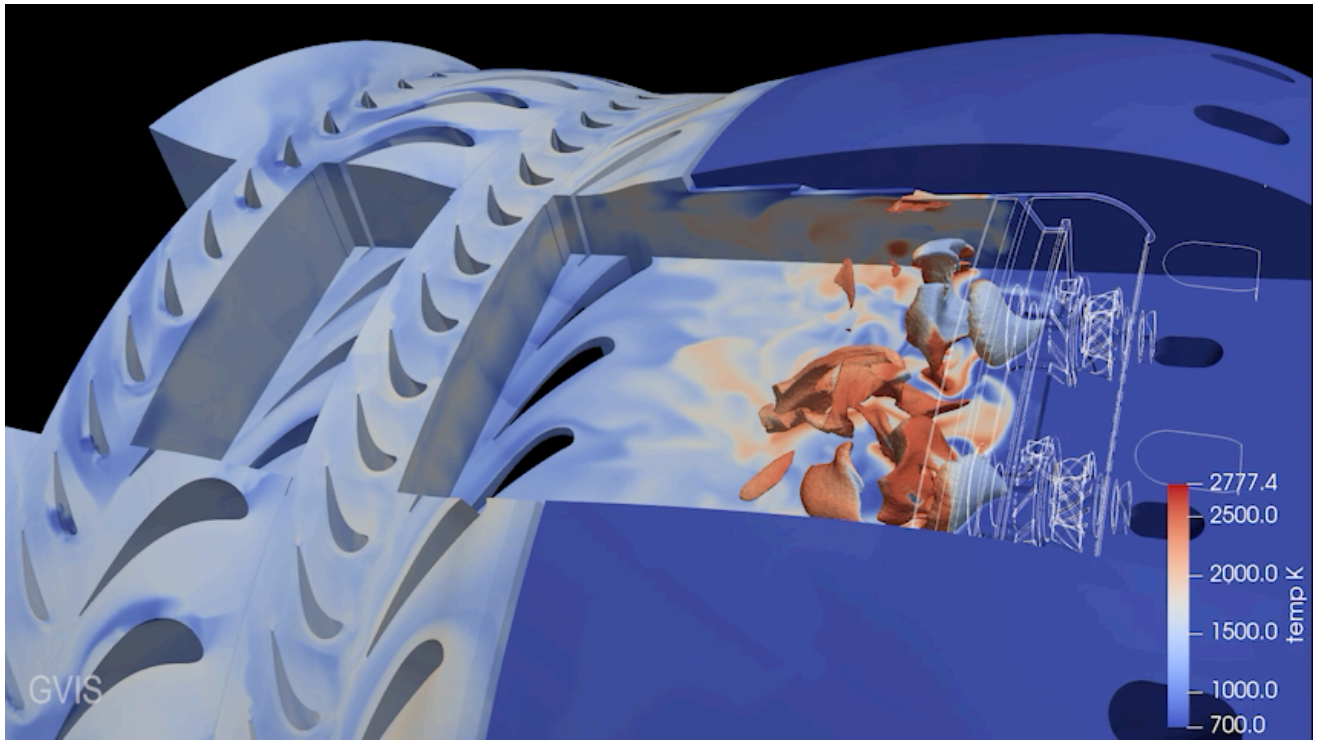


- STEP 2 shows a distinct hot region, and the temperature of these hot streaks is higher than the one of STEP 1
- Peak-to-peak variation is about 10% for STEP 2, which seems to be overestimated.



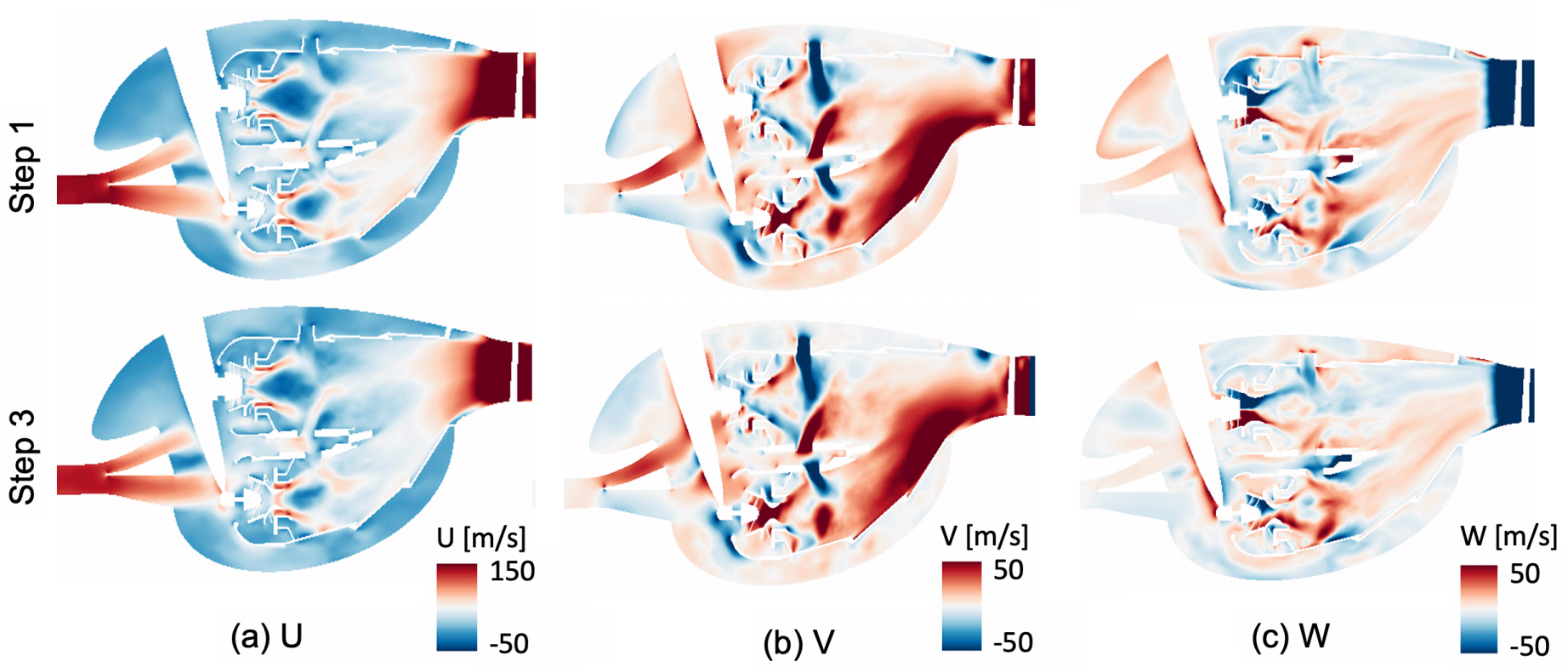
STEP 3 (present in AIAA P&E 2020)

Combustor + Two stage (stator/rotor) of HPT



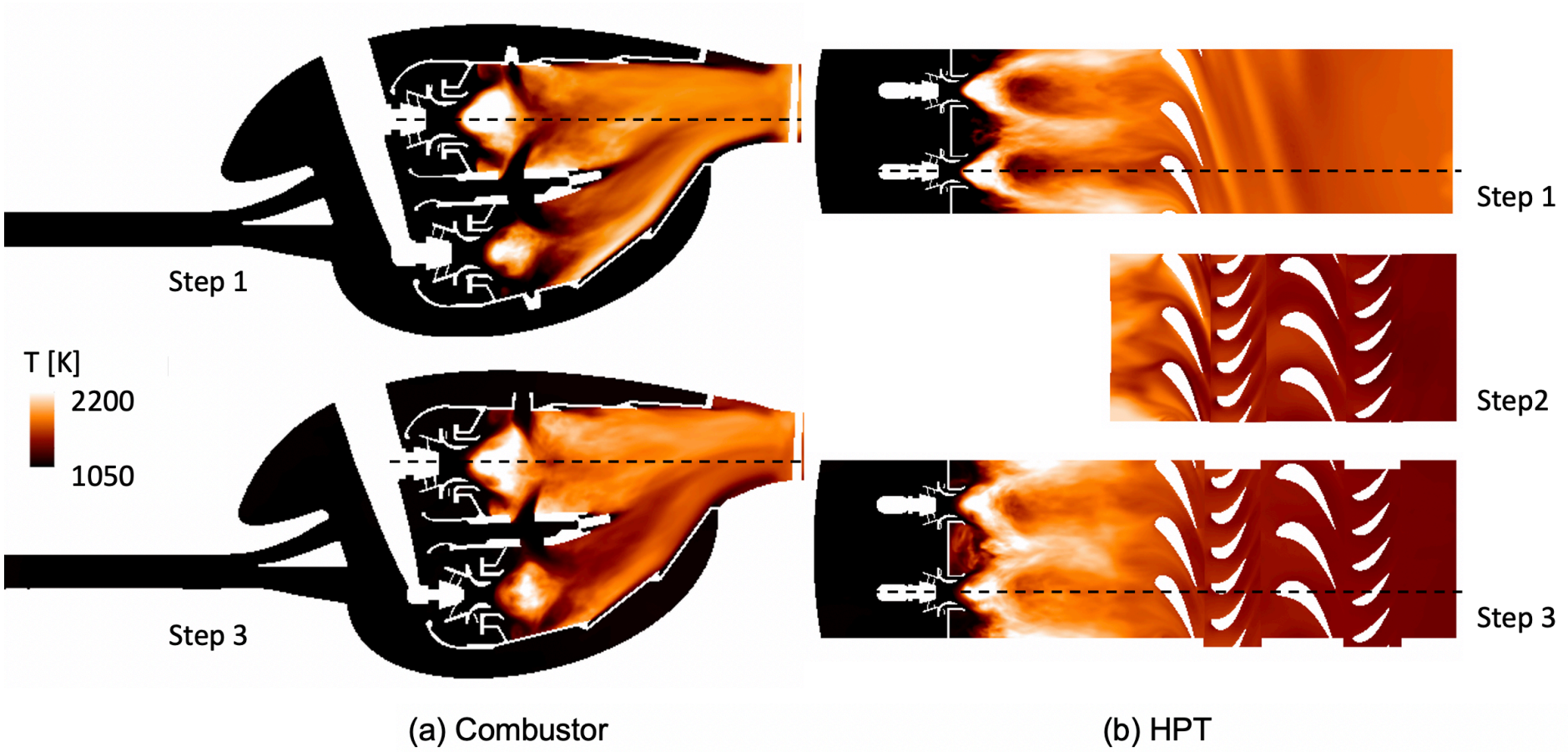
Thanks to R. Rinehart (GVIS) for post-processing

Time-Averaged Velocity Fields: Combustor



Overall mean velocity fields between Step 1 and Step 3 are very similar

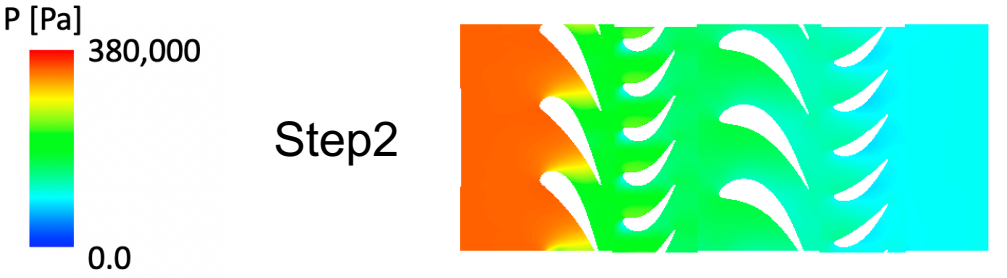
Time-Averaged Temperature Fields: Combustor

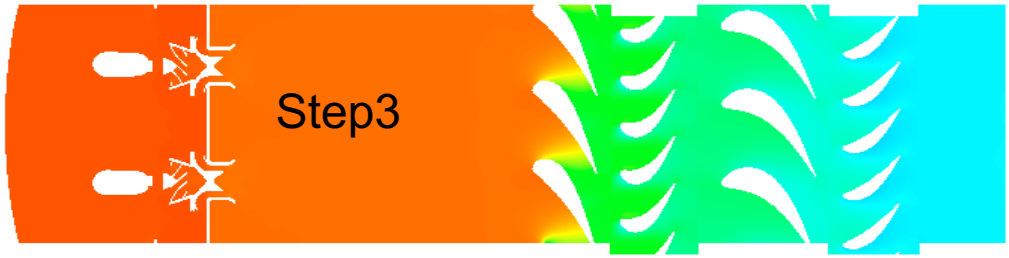


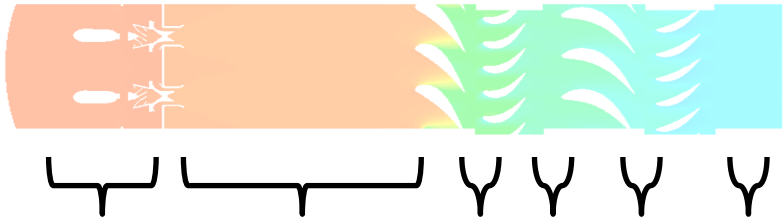
Overall mean temperature fields between Step 1 and Step 3 are very similar.

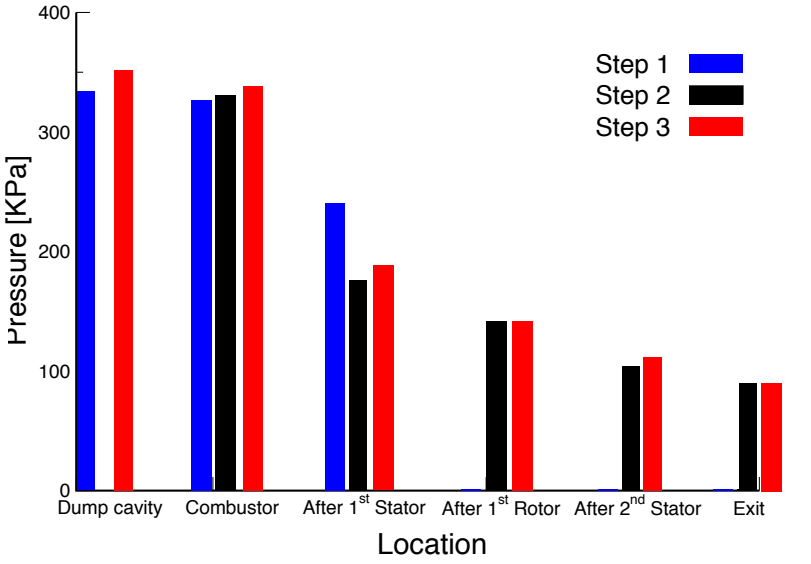
Time-Averaged Pressure Fields







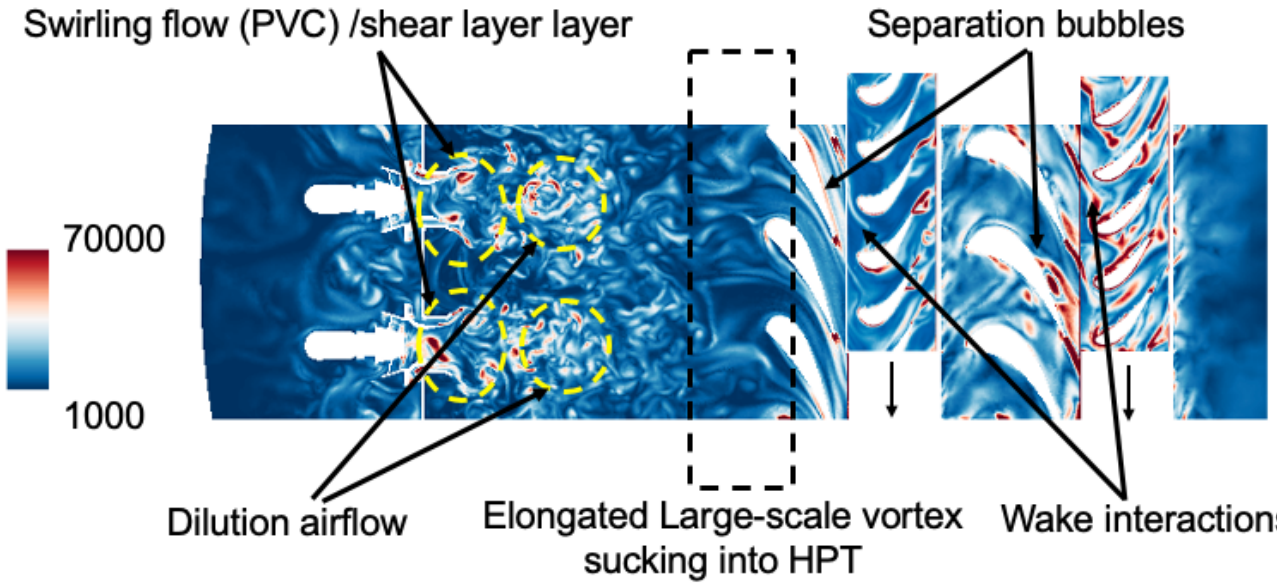


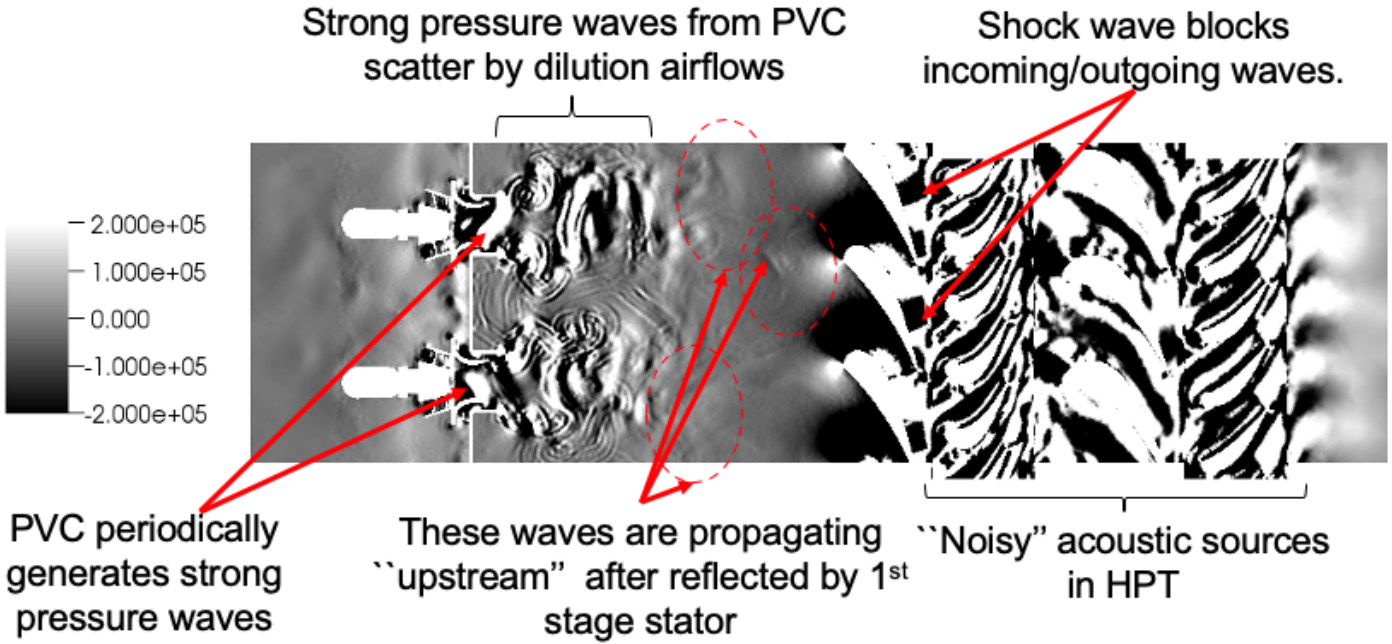


	Dumper	Combustor	1^{st} stator	1^{st} rotor	2^{nd} stator	Exit	Dp (Dumper-Combustor)
Step 1	334	325	242	242	242	242	3.9%
Step 2	-	330	177	142	107	92	
Step 3	348	338	187	142	112	92	4.3%

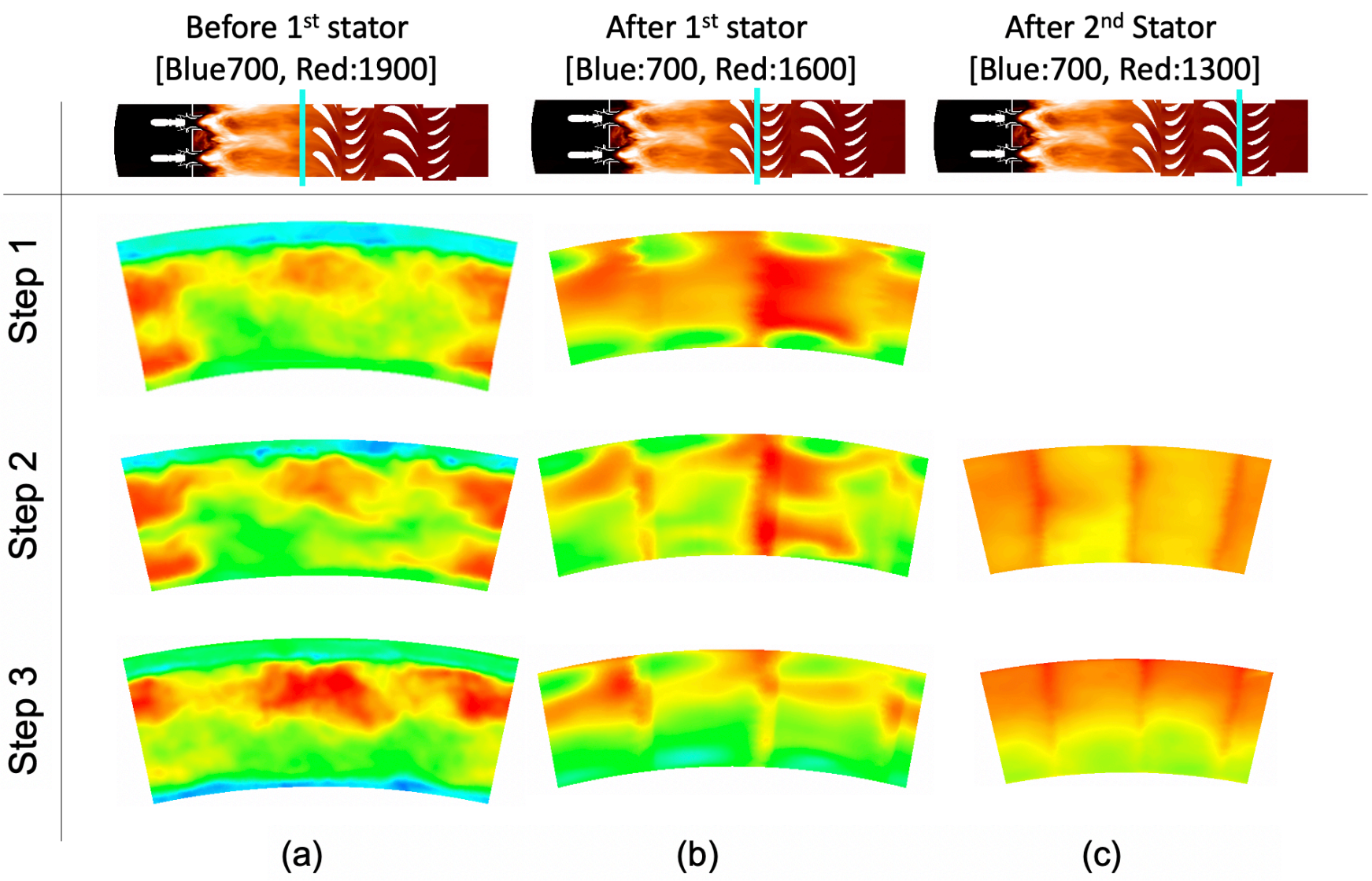
Step 1, Step 2, and Step 3 show very similar pressure inside the combustor!

Instantaneous Vorticity/Pressure Gradients



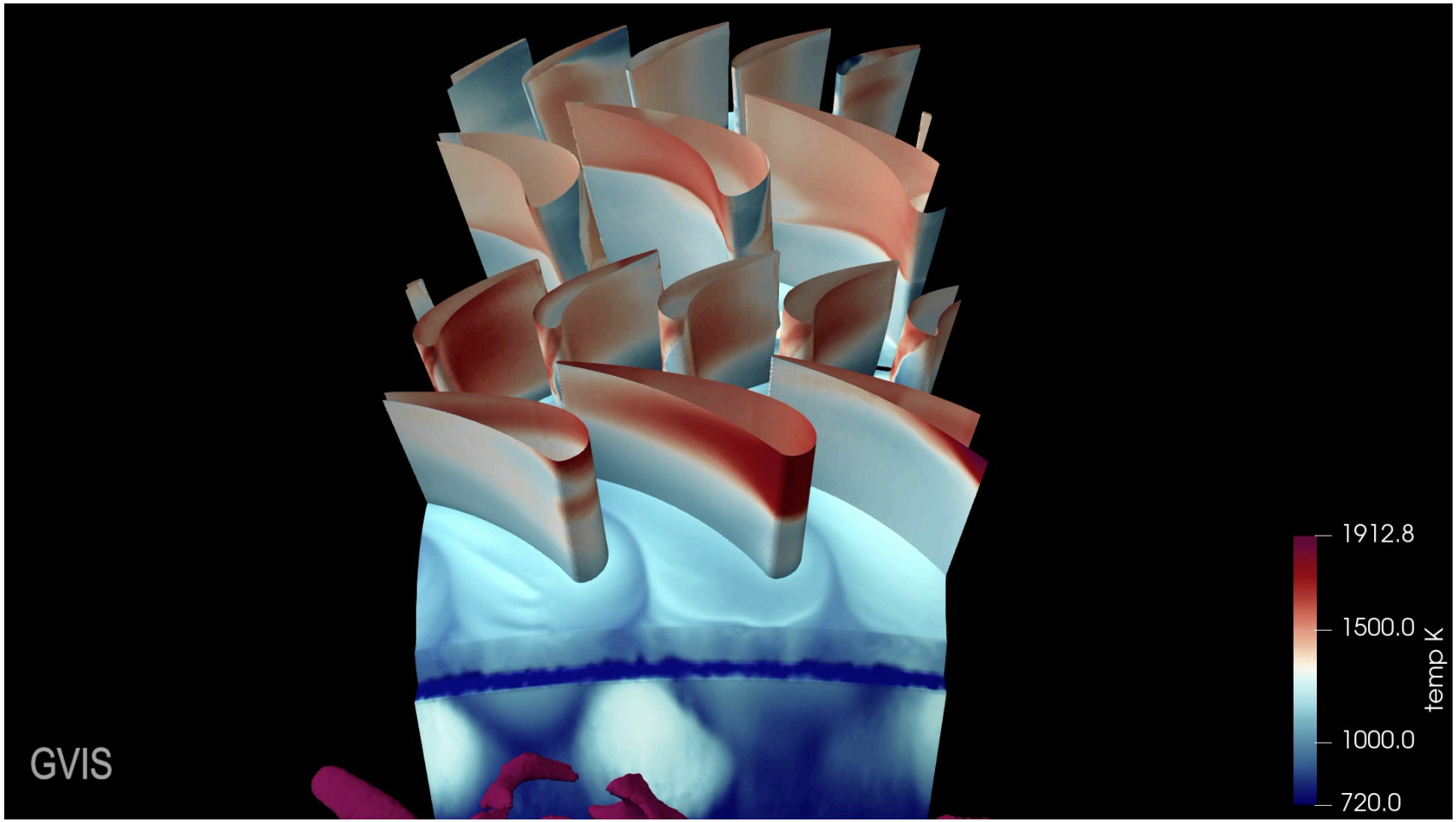


Time-Averaged Pressure Fields



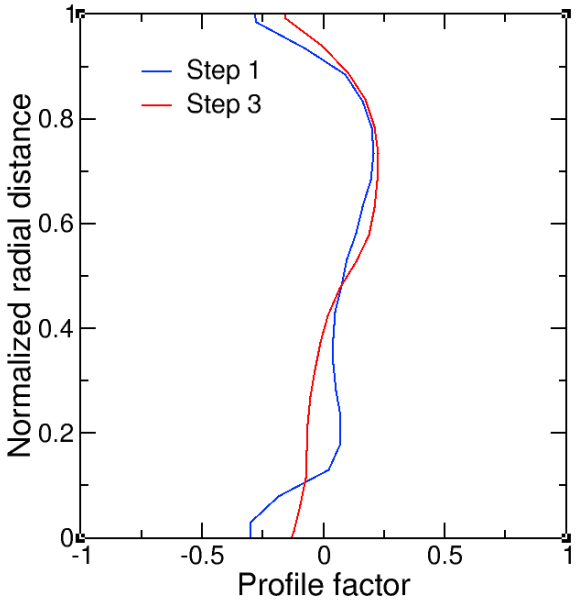
Hot-Streaks

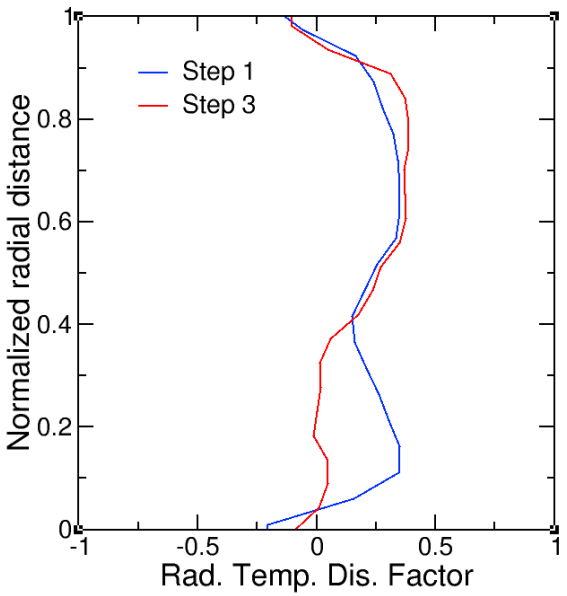
Adiabatic wall temperature

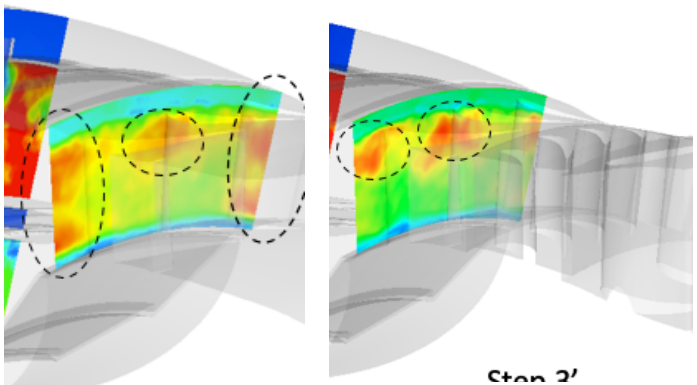


Thanks to R. Rinehart for post-processing

Profile/Pattern/Radial Temp Dis. Factor





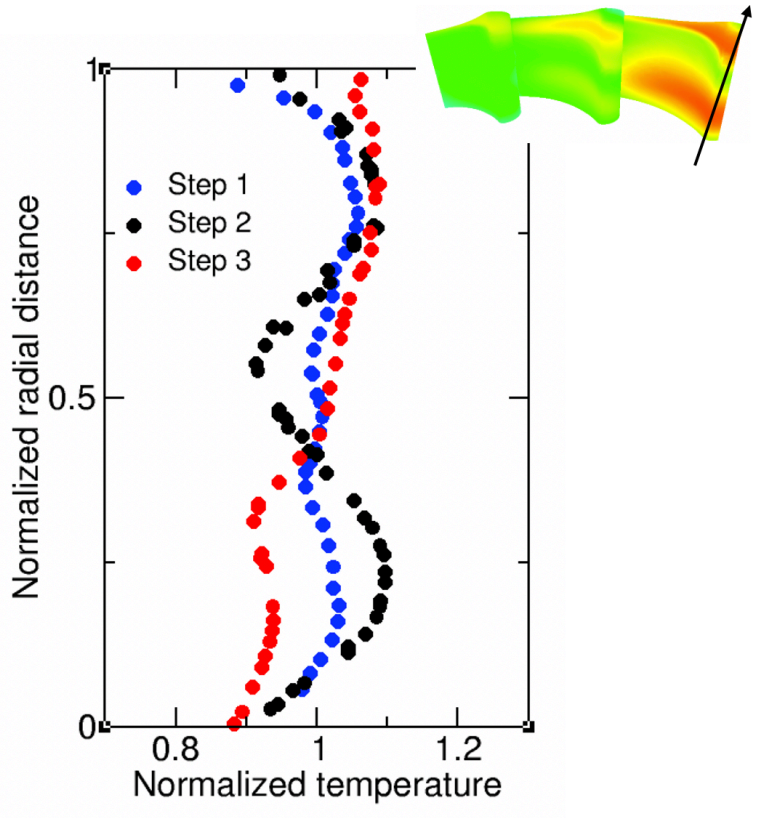


Step 1 Step 3

	Pattern factor
Step 1	0.348
Step 3	0.384

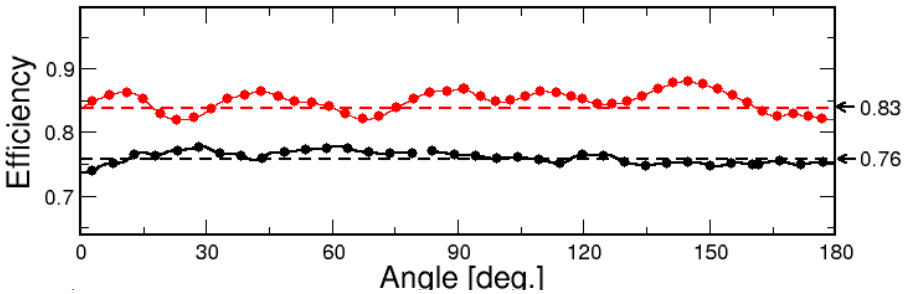
- Step 1 shows the bimodal distributions, and the peak-to-peak variation is 0.2 for the profile factor, and 0.35 for the radial temperature factor.
- Predicted pattern factors are larger than typical combustor design targets, and the relative difference between Step 1and Step 3 is ~10%.

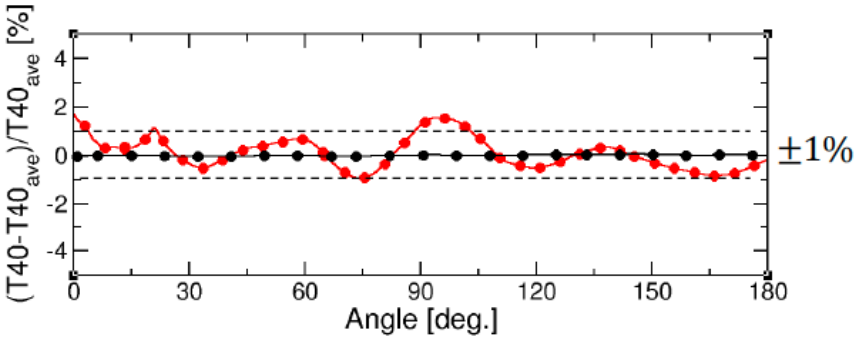
Adiabatic Wall Temperature at 1st Stage Vane

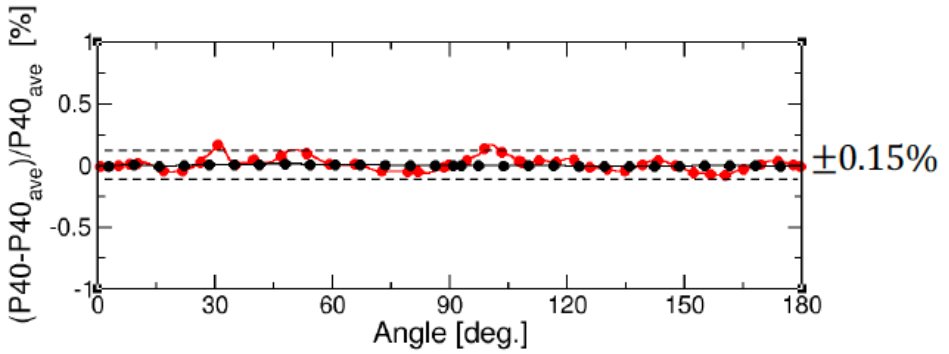


- Adiabatic condition is used and any cooling holes on the surface are not included.
- Locally hot and cool spots co-exist, which can cause the severe thermal stress on the vane, especially on the pressure side.
- At the far-right vane, peak-to-peak variations are 5 [%] for Step 1 and 10 [%] for Step 2 and Step 3.

Time-Histories of Efficiency, T40 and P40







- The mean values of efficiencies are 76 [%] for Step 2 and 83 [%] for Step 3.
- Modeling both the combustor and HPT seems to enhance the oscillation of efficiencies (± 2.5 [%] for Step 3)
- The variation of T_{40} for Step 3 is relatively larger than P_{40}

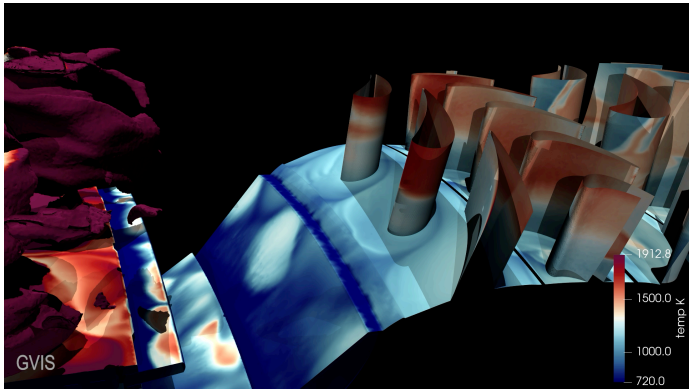
Conclusions and Future Work

Our numerical results show:

- ✓ Step 1 and Step 3 qualitatively show similar flow features inside the combustor.
- ✓ For Step 2 and Step 3 (where include moving rotors), shock wave appears on the suction side of the 1st stage stator.
- ✓ Hot-streak distributions among three cases differ from each other. The peak-to-peak variances are 5 [%] for Step 1 and 10 [%] for Step 2 and Step 3.
- ✓ The calculated mean values of the HPT efficiencies are 76 [%] for Step 2 and 83 [%] for Step3. Modeling both the combustor and HPT may enhance the oscillation through the temperature fluctuations.

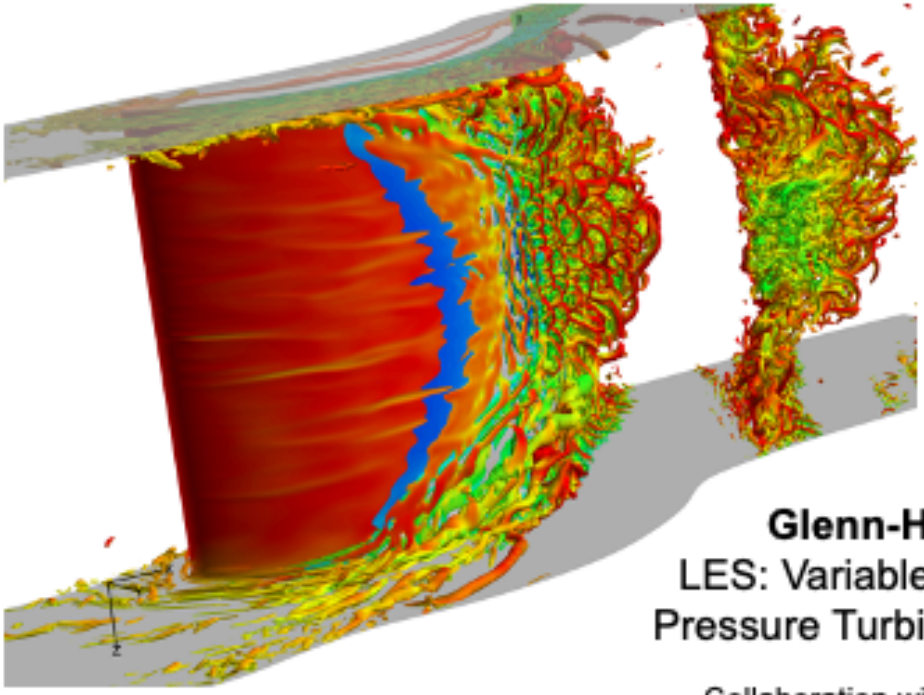
Future work

- Simulate the design Take-off condition (P3 ~30 [atm]) and compare fully coupled and sequential results
- Compare fully coupled and sequential results at two test points
- Include cooling air in HPT



Thanks to R. Rinehart for post-processing

“Tightly” Coupling OpenNCC and Glenn-HT



Glenn-HT code
LES: Variable Speed Low Pressure Turbine Simulation

Collaboration with Dr. A. Ameri
(present at IGTI 2020 and accepted for J of Turbomachinery 2020)

- Glenn-HT code is another in-house code developed at Turbomachinery Branch at NASA-GRC
- It is a compressible non-reacting flow solver (RANS w. transition model, LES), which is capable of modeling heat transfer and internal flow of turbine blades.



Thank you!

Questions?

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- **Flow Viz was conducted with Visit (Lawrence Livermore National Labs)**