Computational Study of Combustor-Turbine Interactions

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Acknowledgement: Christopher Heath, Thomas Wey, Tsan-Hsing Shih, Clarence Chang, Kumud Ajmani

Outline

- **Introduction**
  - Combustor-Turbine Interaction
    - ✓ Hot-streaks
    - ✓ Spatial and temporal thermal variations
  - Current Capability of OpenNCC
  - Energy Efficient Engine (E^3)
- **Problem Setup**
  - Geometry (clocking)
  - Mesh
  - Numerical Setting
  - Boundary Condition and Operating Condition
- **Results**
- **Conclusions**

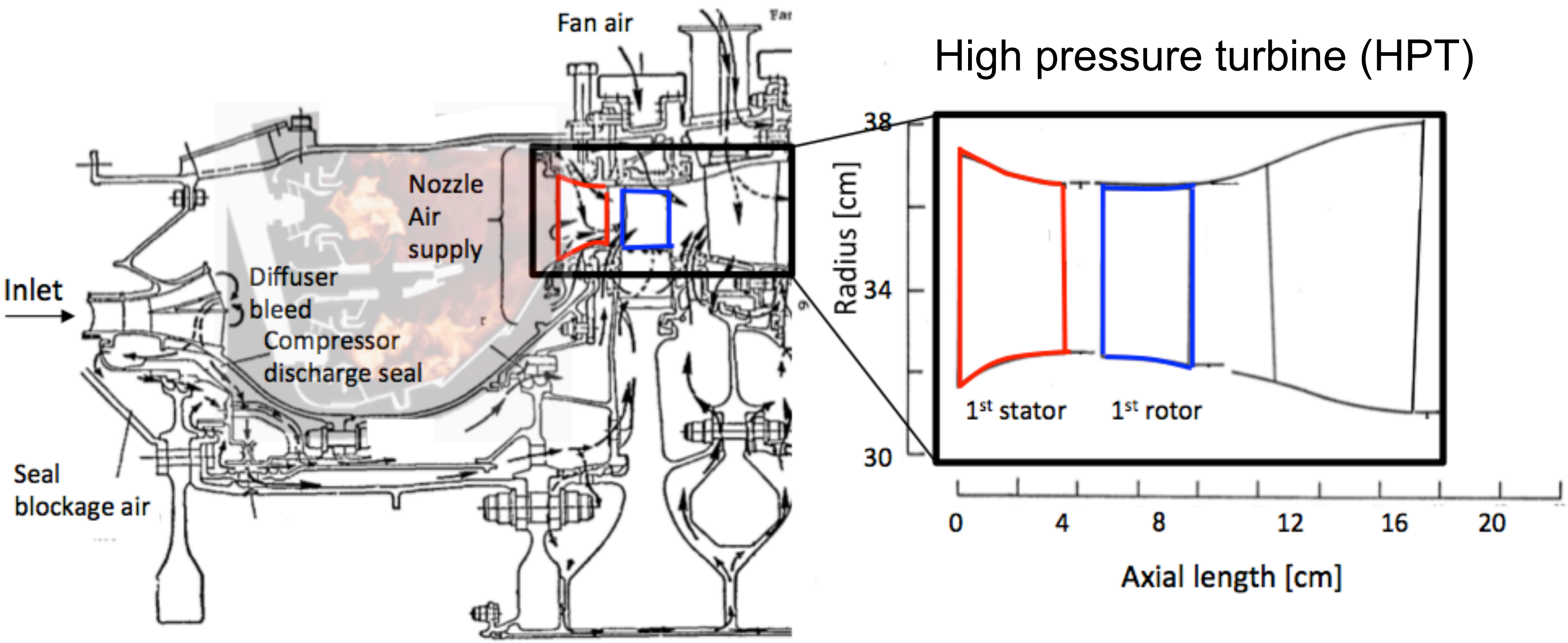
Motivations

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)

- Designing high-pressure turbines (HPTs) for *peak* temperatures at the combustor exit ➔ More cooling air ➔Less cycle efficiency
- Designing HPTs for the *mean* exit-temperature at the combustor exit ➔ More local hot spots (hot streaks) ➔ Less gas turbine durability
- CFD should give some design guidelines

Important to understand core engine component interactions, such as combustor-turbine interactions

Energy Efficient Engine– GE design, 80s -



- E³ is a double-annular and compact combustor, intensively investigated in the mid-1970s and 1980s and set a historically important milestone toward more fuel efficient jet engines (and now geometry is publically available!)
- HPT for the GE E³ is a two-stage, low thru-flow design for moderate loading.
- Relative position of the stator with respect to the fuel nozzle, so-called ``clocking'', is critical.

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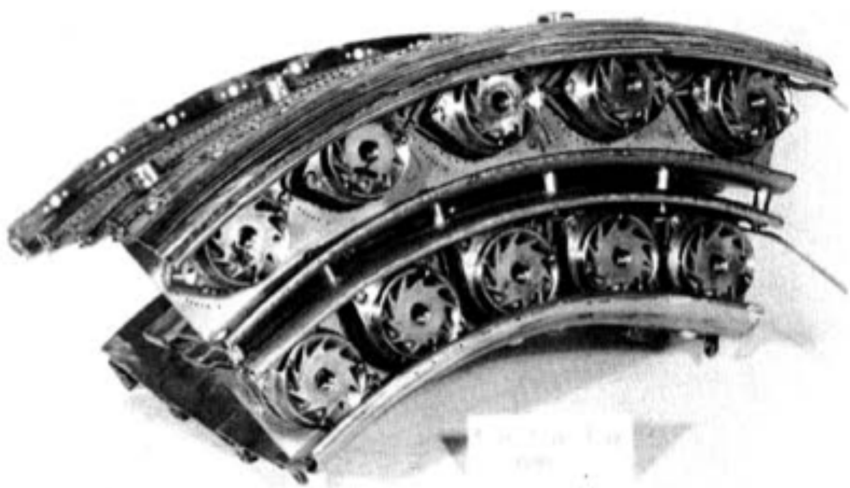
Features of Open National Combustion Code (OpenNCC)

- 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 and Roe's upwind scheme, and Advection Upstream Splitting Method (AUSM)[1-3,11]
  - ✓ Turbulence: Cubic non-linear k-ε[4] model with the wall function, Low-Re model
  - ✓ Combustion: Finite Rate Chemistry, low dimensional manifold with EBU, PDF, Linear Eddy Model (LEM)[5]
  - ✓ Spray: Lagrangian liquid phase model[6-8]
  - ✓ Other features: Low-Mach preconditioning, transition model[9], unstructured mesh, adaptive mesh refinement (AMR)[10], massively parallel computing (with almost perfectly linear scalability achieved for non-spray cases up to 4000 central processing units)

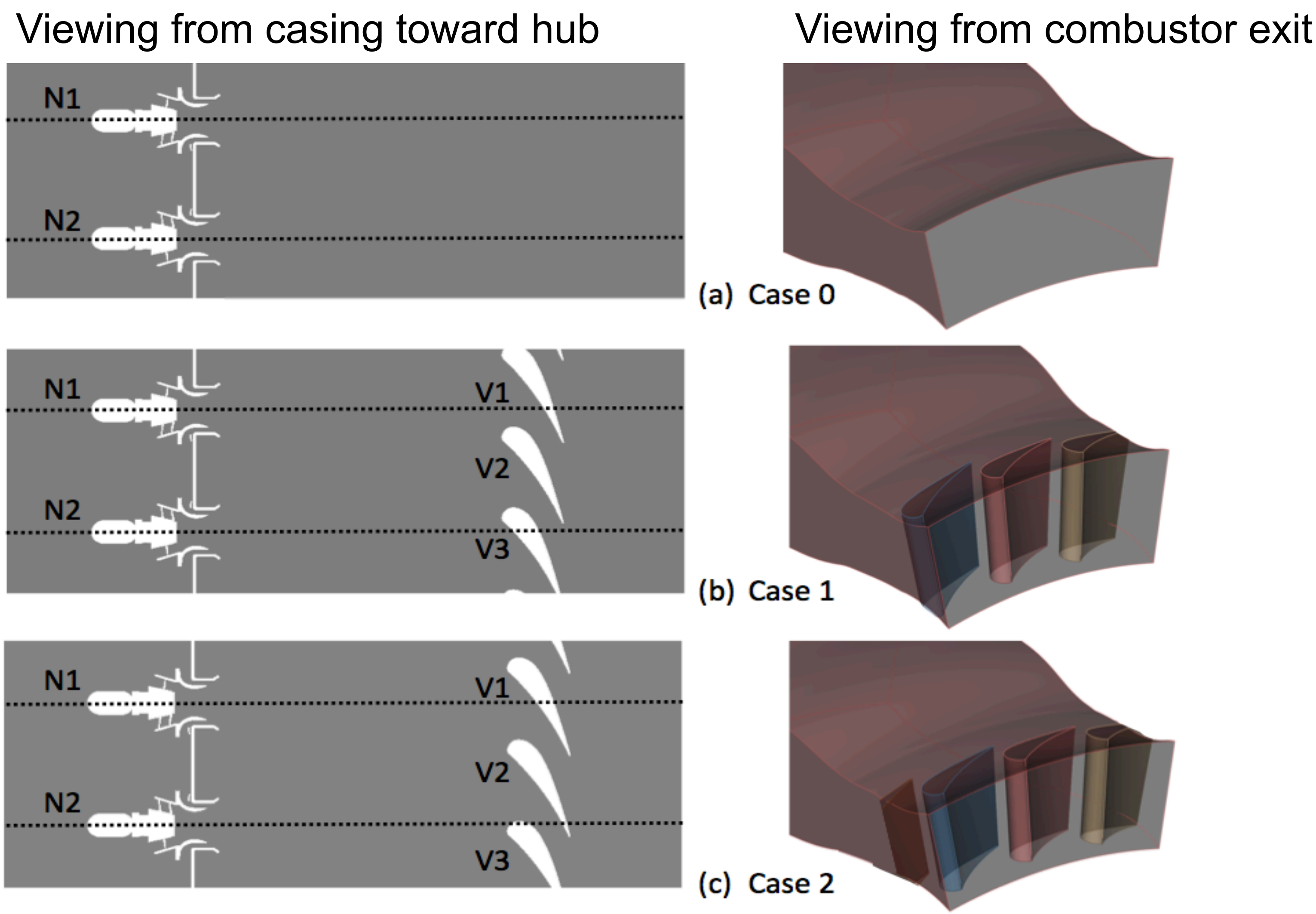
Selected referece
(1) Liou, M.-S. and Steen, C. J., Journal of Computational Physics, Vol. 107, (1993)
(2-3) Liou, M.-S., Journal of Computational Physics, Vol. 129, 1996) and (2006)
(4) Shih, T.-H., Chen, K.-H., and Liu, N.-S., AIAA 1998-35684 (1998).
(5) Alan R. Kerstein, Combustion Science and Technology, Vol 60 (1988)
(6-8) Raju, M., NASA/CR97-206240 (1997), NASA/CR1998-20401 (1998) and NASA/CR2004-212958 (2004).
(9) Liou, W. and Shih, T.-H., No. NASA/CR-2000-209923 (2000).
(10) Wey, T. and Liu, N.-S., AIAA 2014-1385 (2014).
(11) Miki, K., Moder, J., and Liou, M.-S. Journal of Propulsion and Power (2017)

Problem Setup

- ✓ Geometry (clocking)
- ✓ Mesh
- ✓ Numerical Setting
- ✓ Boundary Condition and Operating Condition

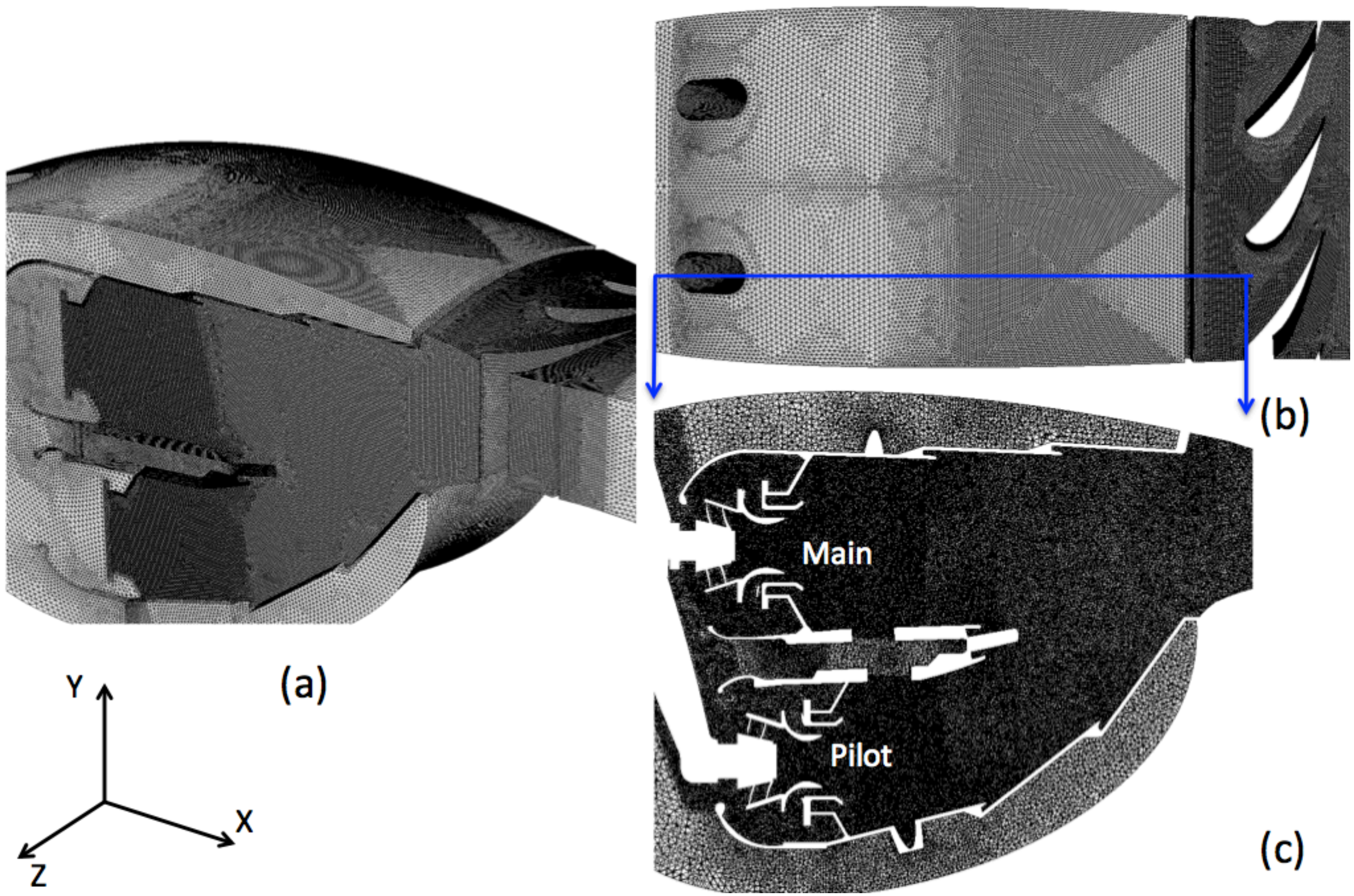


24 Degrees of Full Annular E^3 Combustor



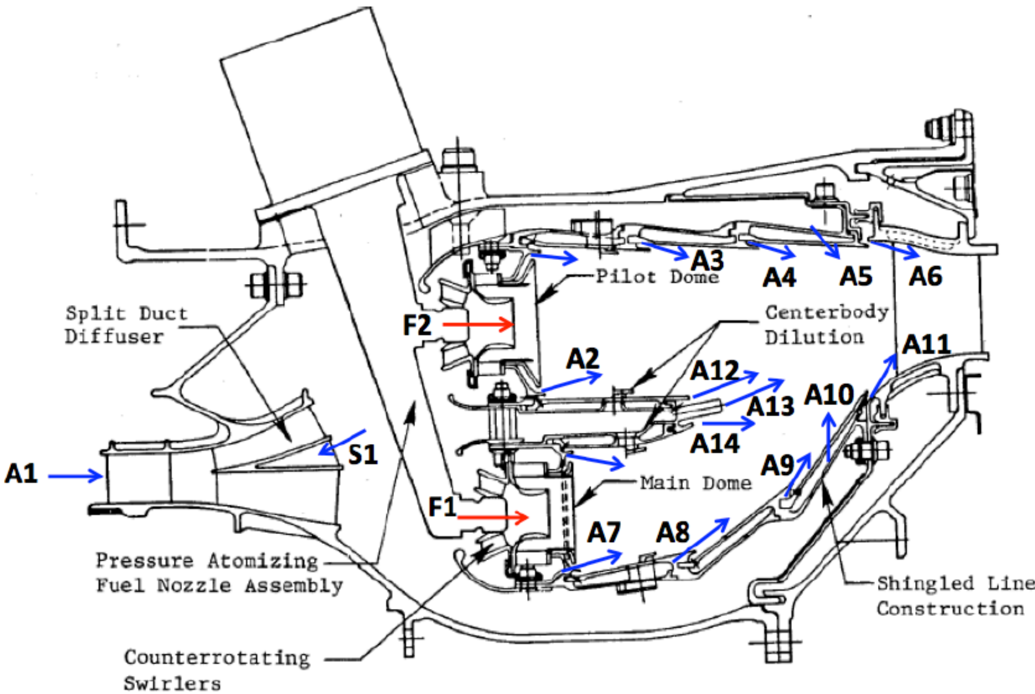
- One without a vane, two others with vanes set at different relative positions in relation to the fuel nozzle, ``**clocking**''.
- The difference of clocking between Case 1 and Case 2 is two degrees.

Mesh for 24 Degrees E^3 Sector Model



- Tetrahedral mesh is generated by Cubit, and the total mesh count is approximately 50 million elements for all cases (AMR is off).
- Very uniform and fine mesh (~0.5 [mm]) inside the combustor and vane.

Boundary Condition

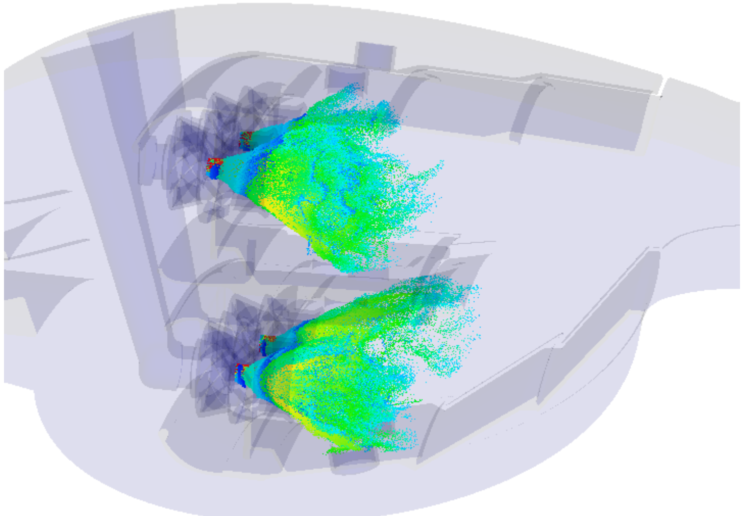


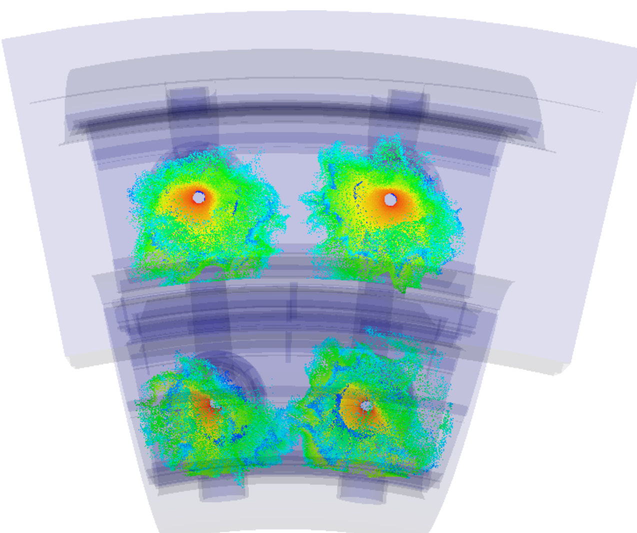
Aame	Index	Gas	Mass flow rate [kg/s]
Inflow	A1	Air	0.26
Main dome	F1	Fuel	0.00182*
Pilot dome	F2	Fuel	0.00182*
Diffuser Bleed	S1	Air	- 0.018
Pilot splash plate cooling	A2	Air	0.0104
Outer liner cooling 1	A3	Air	0.0053
Outer liner cooling 2	A4	Air	0.0053
Outer liner trim cooling	A5	Air	0.0018
Outer liner cooling 3	A6	Air	0.0024
Main splash plate cooling	A7	Air	0.0116
Inner liner cooling 1	A8	Air	0.0096
Inner liner cooling 2	A9	Air	0.0056
Inner liner trim cooling	A10	Air	0.0018
Outer liner cooling 3	A11	Air	0.0024
Centerbody outer cooling	A12	Air	0.0018
Centerbody mid cooling	A13	Air	0.0024
Centerbody Inner cooling	A14	Air	0.0024

	P3 [atm]	T3 [K]	W3 [kg/s]	Wf_{total} [kg/s]	f/a	Wf_{pilot}/Wf_{total}	T_{fuel} [K]
SLTO	2.52	720	0.26	0.00364	0.014	0.5	520

- Taken into consideration is the simulated sea level takeoff condition (SLTO), which is the most severe condition during the engine operation cycle.
- Cooling air is treated as source/sink terms on the surface

Numerical Setup





- LES-AUSM$^+$-up
- Liquid droplets (C12H21) are stochastically injected from the main and pilot domes with 70^o cone angle (hollow cone)
- Finite-rate chemistry (2step-mechanism[1]):

$$\mathrm{KERO} + 17.25\ O_2 \rightarrow 12CO_2 + 10.5\ H_2O$$
$$CO + 0.5\ O_2 \rightarrow CO_2$$
$$k_{f,1} = A_1 f_1(\phi) e^{(-E_{a,1}/RT)} [\mathrm{KERO}]^{n_{\mathrm{KERO}}} [O_2]^{n_{O_2,1}},$$
$$k_{f,2} = A_2 f_2(\phi) e^{(-E_{a,2}/RT)} [CO]^{n_{CO}} [O_2]^{n_{O_2,2}},$$

- Chemical integration: KIVA scheme.
- Turbulence mode: non-linear k-ε model with the wall function.

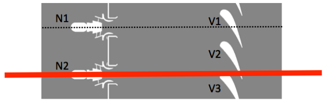
About CPU

- Used 1080 processors of Pleiades at NASA Advanced Supercomputing facility.
- ~ 3 weeks to get statistics of unsteady calculations.

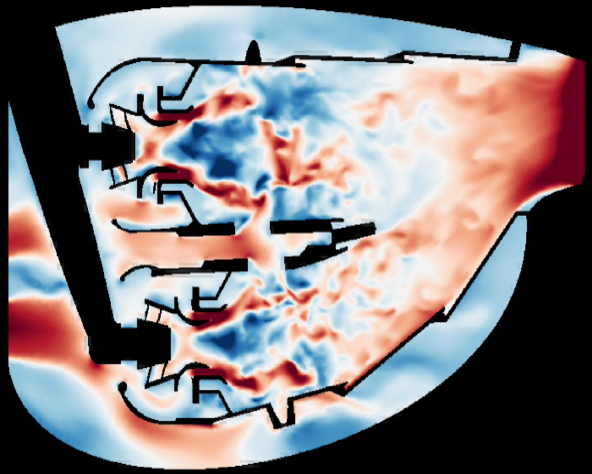
[1] Franzelli, *et al.*, Combustion and Flame, Vol. 157, (2010)

Numerical Results

Unsteady Flow Fields (Case2)

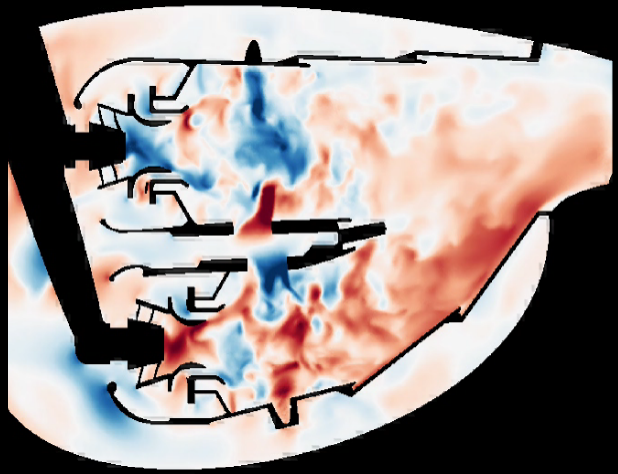


U-Velocity



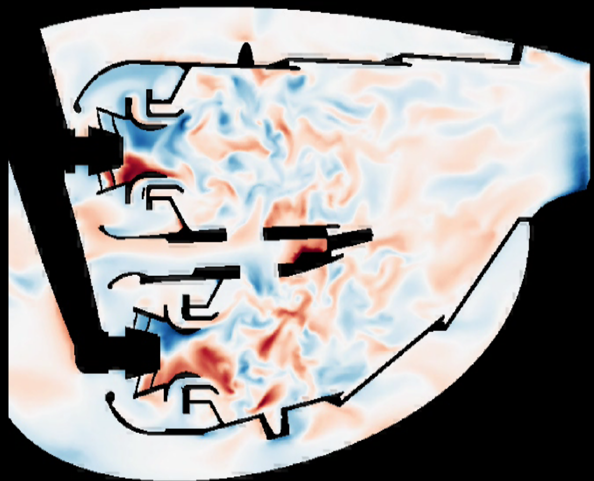
Red:100 m/s, Blue: -50m/s

V-Velocity



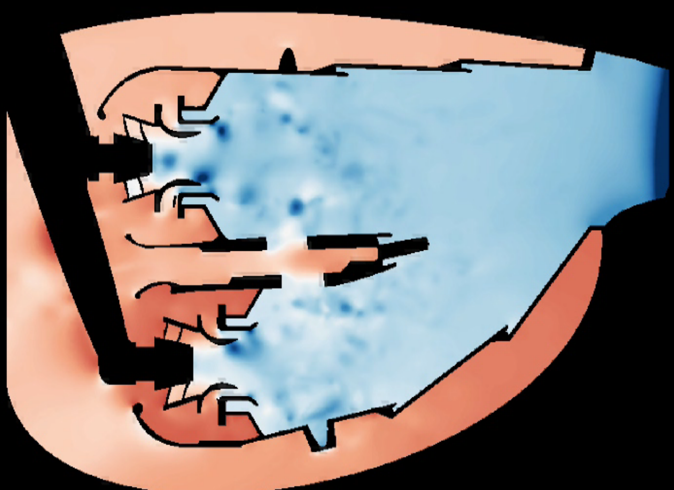
Red:100 m/s, Blue: -100m/s

W-Velocity



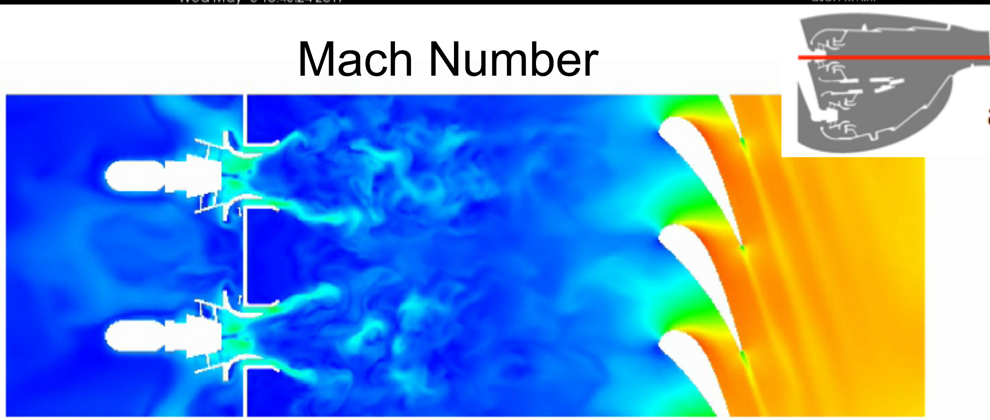
Red:100 m/s, Blue: -100m/s

Pressure



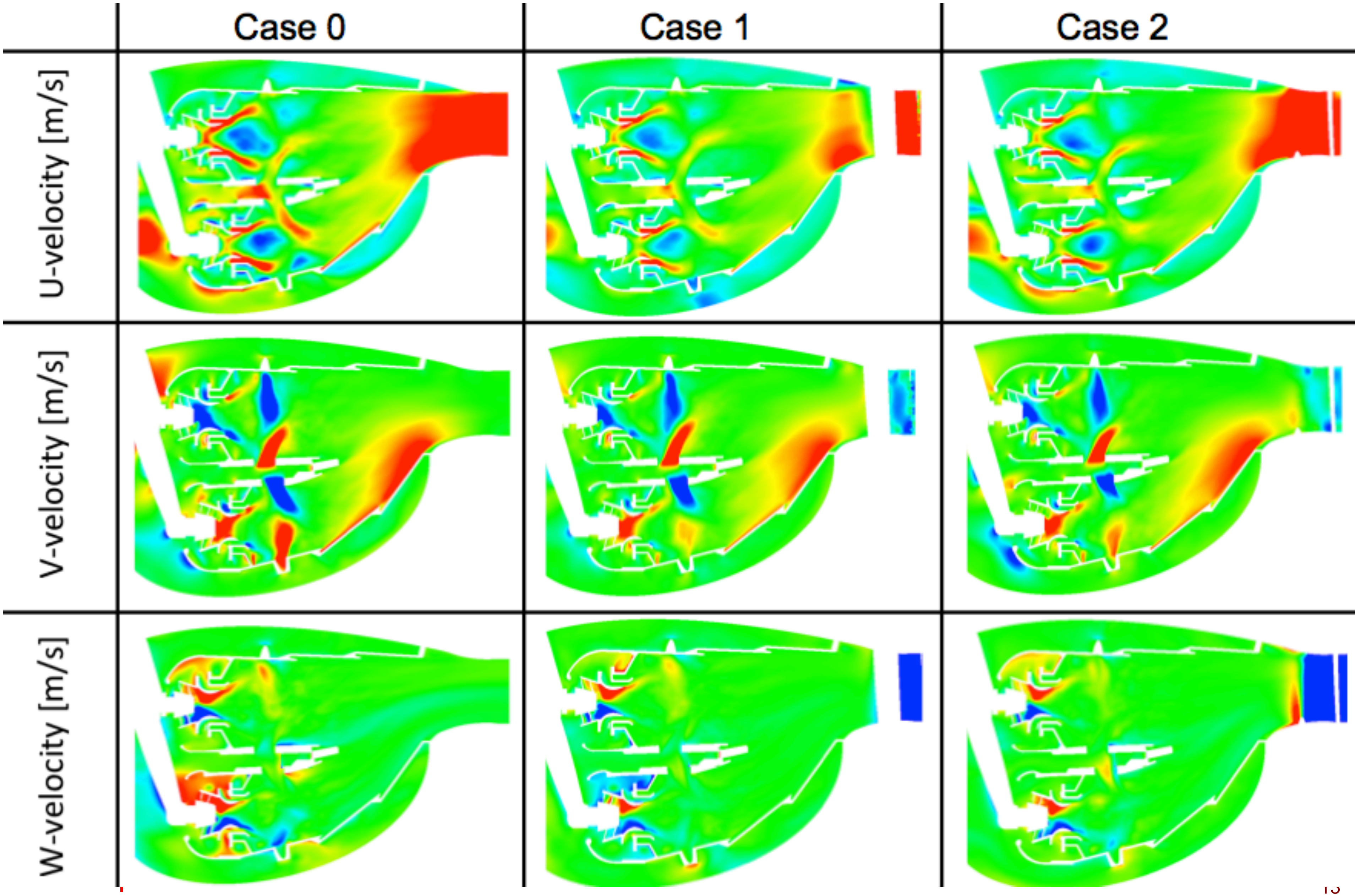
Red:315K Pa, Blue: 285K Pa

Mach Number

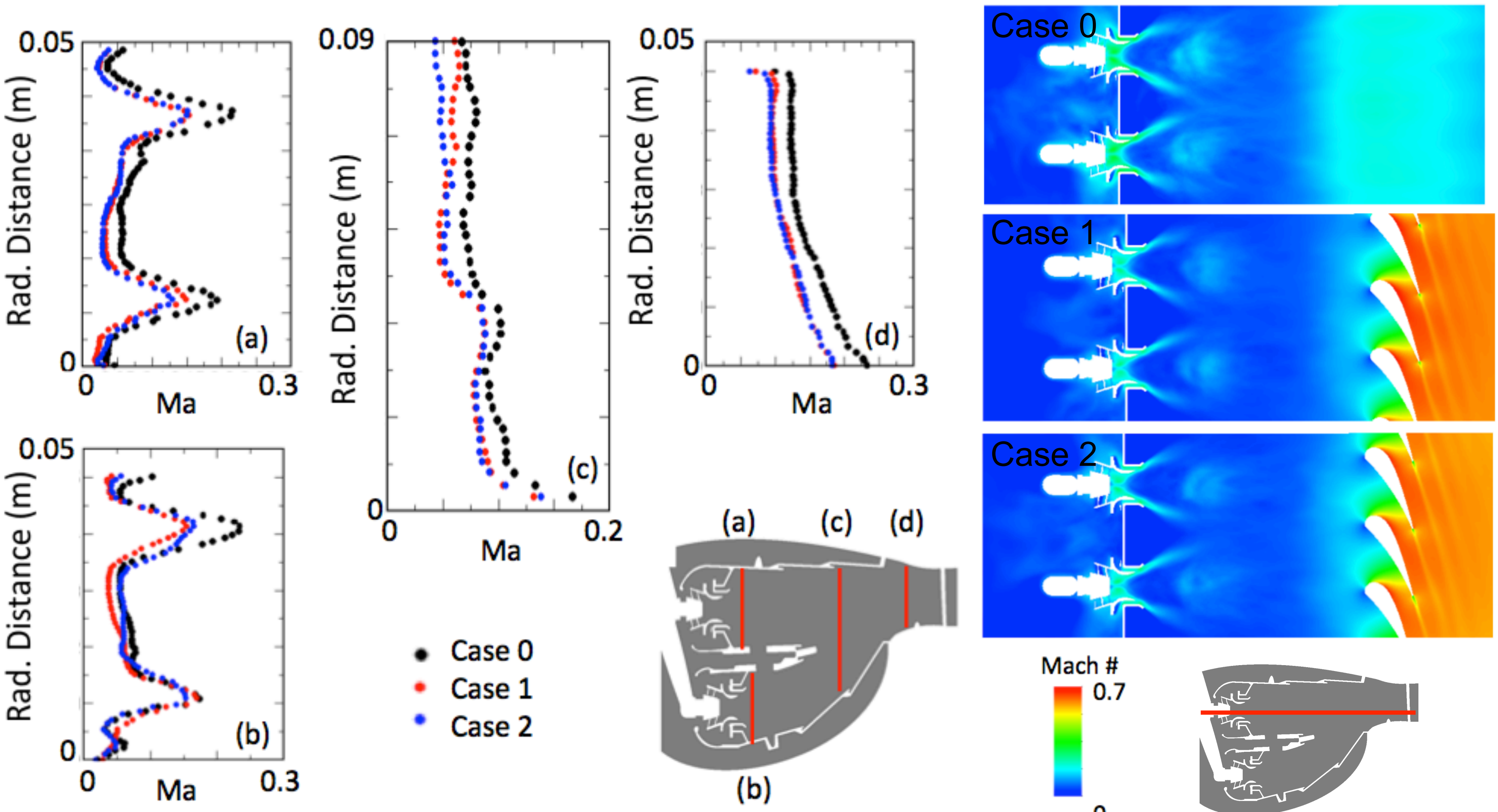


- Captured eddies of many different length scales, central recirculation zone (CRZ) and precessing vortex core (PVC).

Time-Averaged Flow Fields

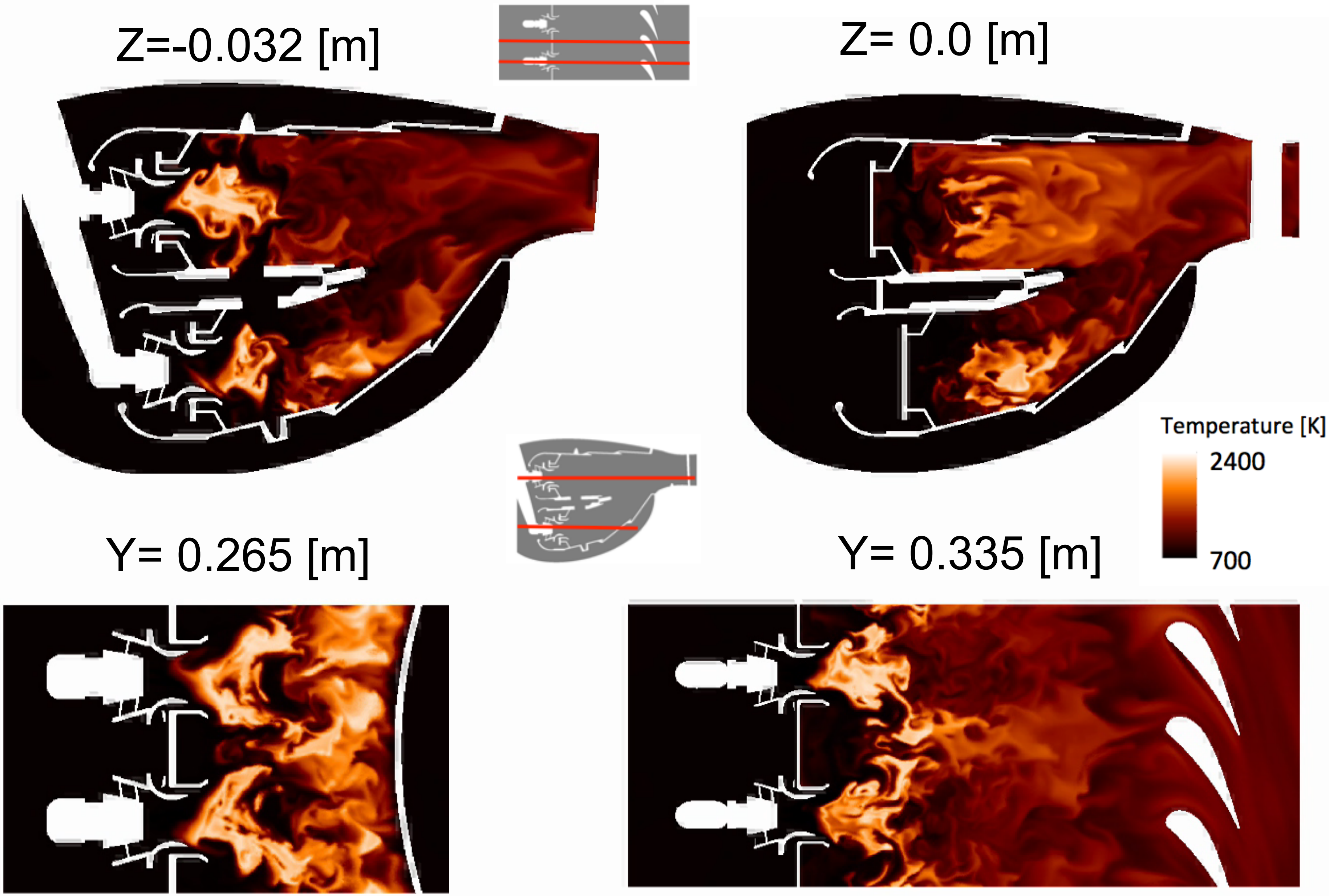


Blocking Effect: Mach Number



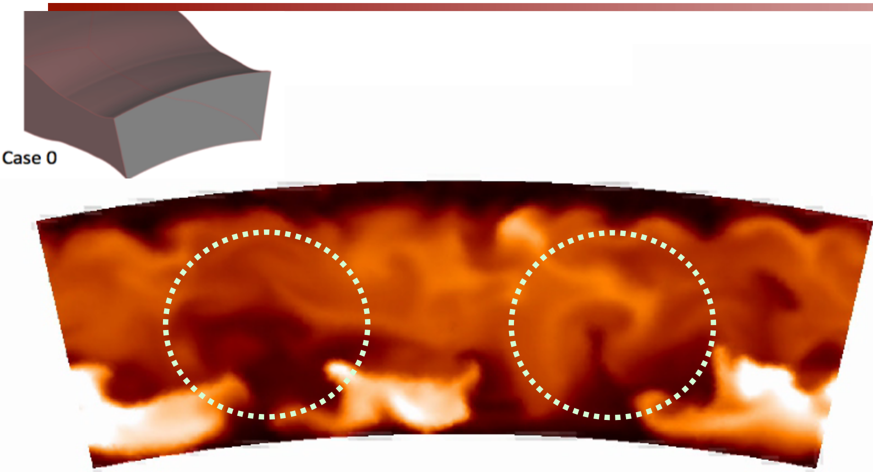
- Due to the blocking effect, there are up to 20% difference in Mach number throughout the combustor.

Unsteady Temperature Fields (Case2)

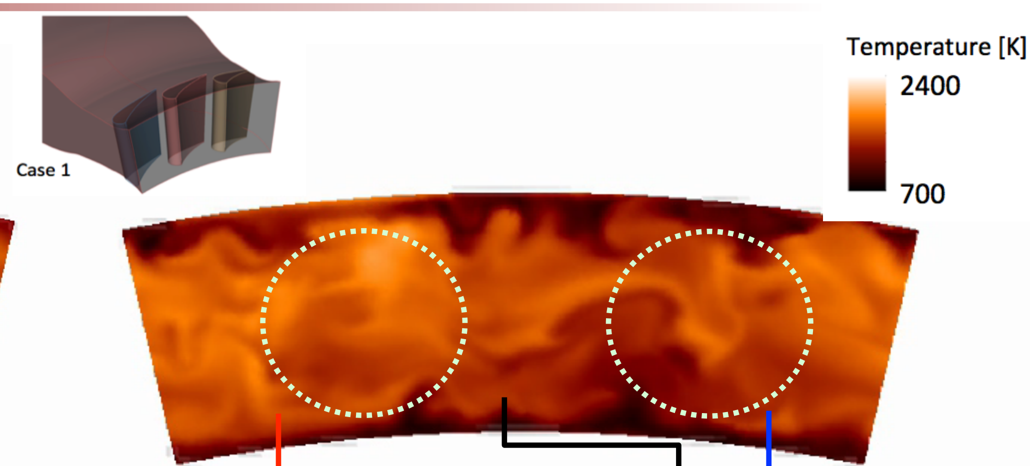


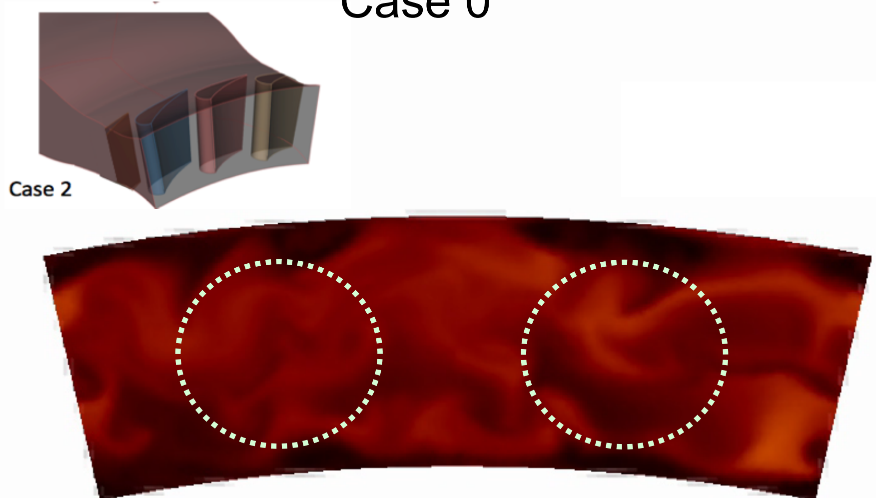
Unsteady Temperature Fields @ Exit (P40)

P40: X=0.32[m]

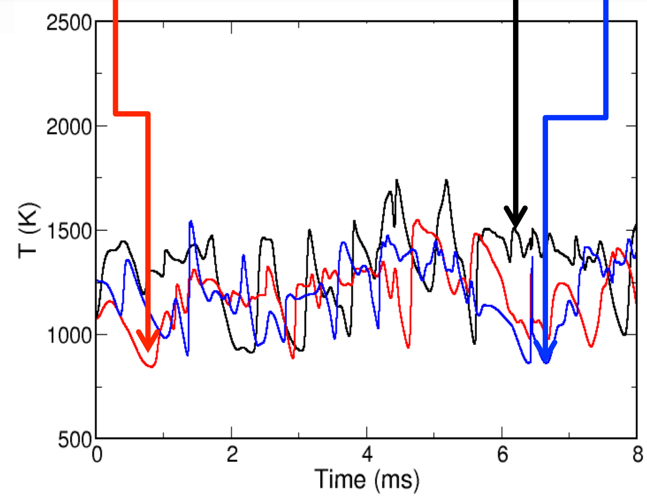


Case 0





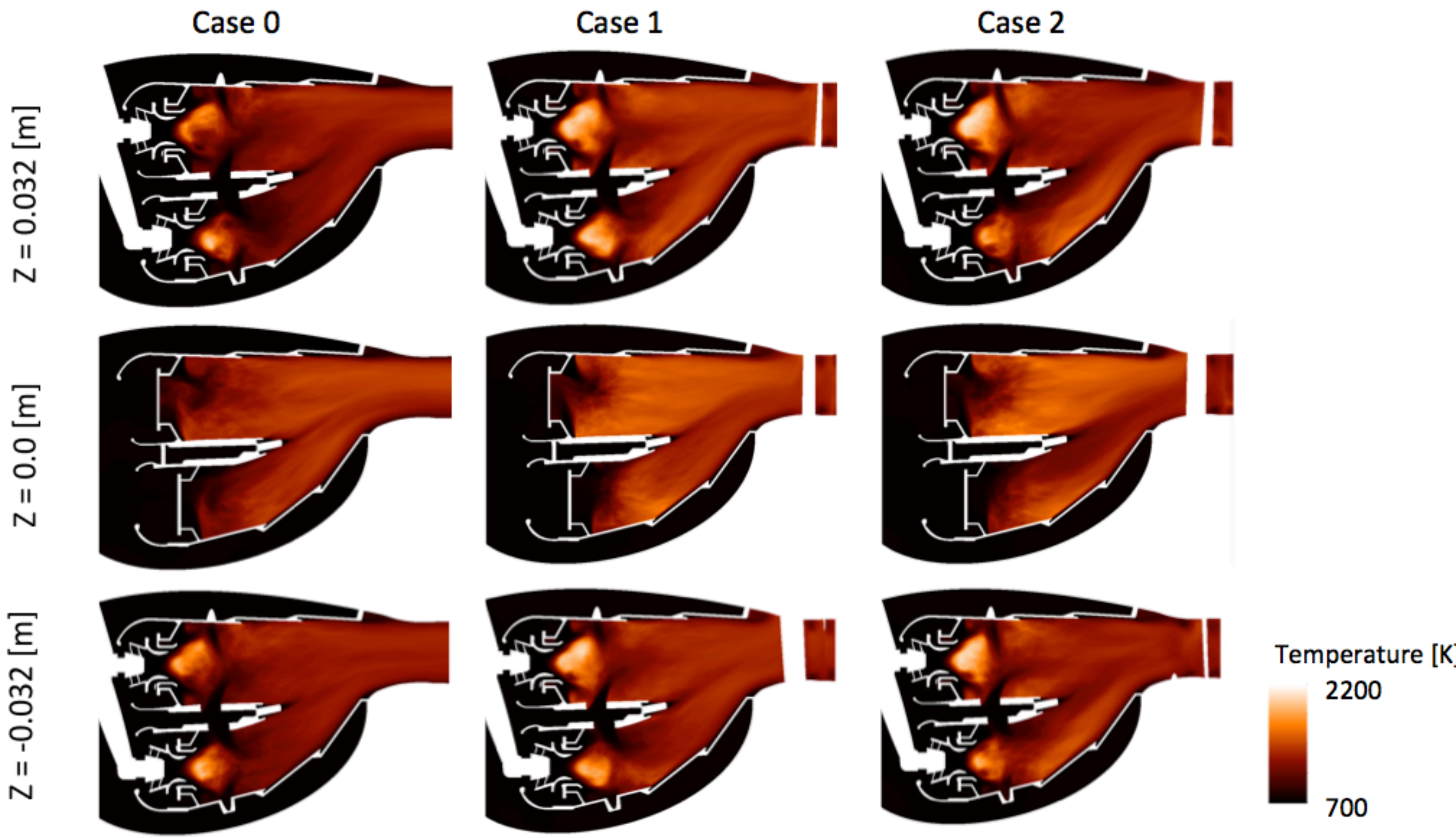
Case 2

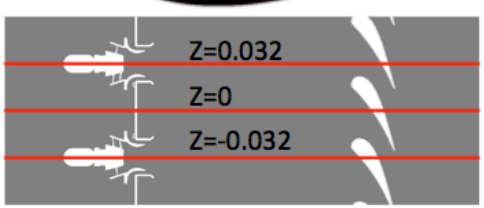


Example of Time-history T profile

- Temperature profile is not uniform in the circumferential & radial directions.
- Hot products are locally present, and the cooling air stays close to both the hub and the case.

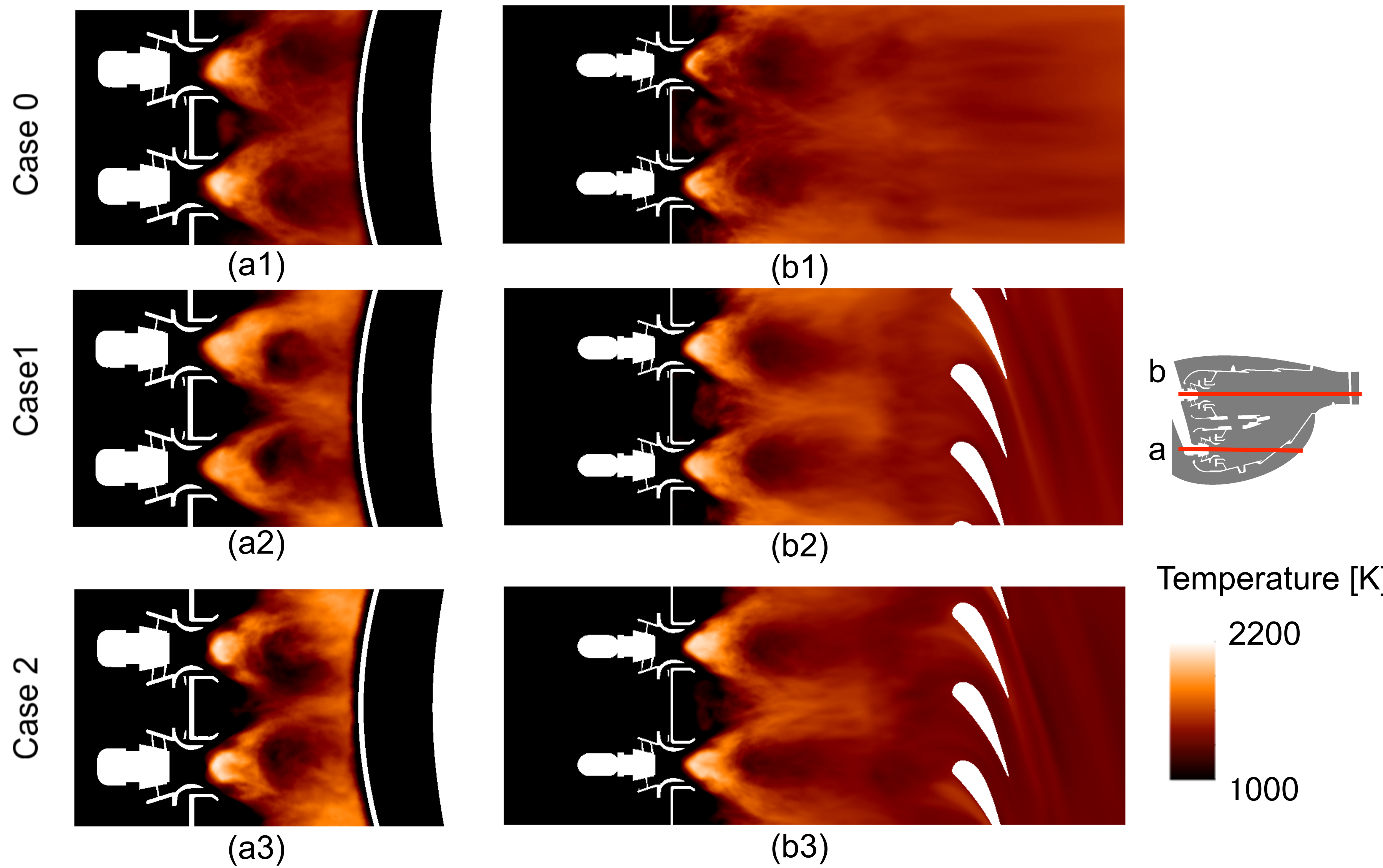
Time-Averaged Temperature Profiles





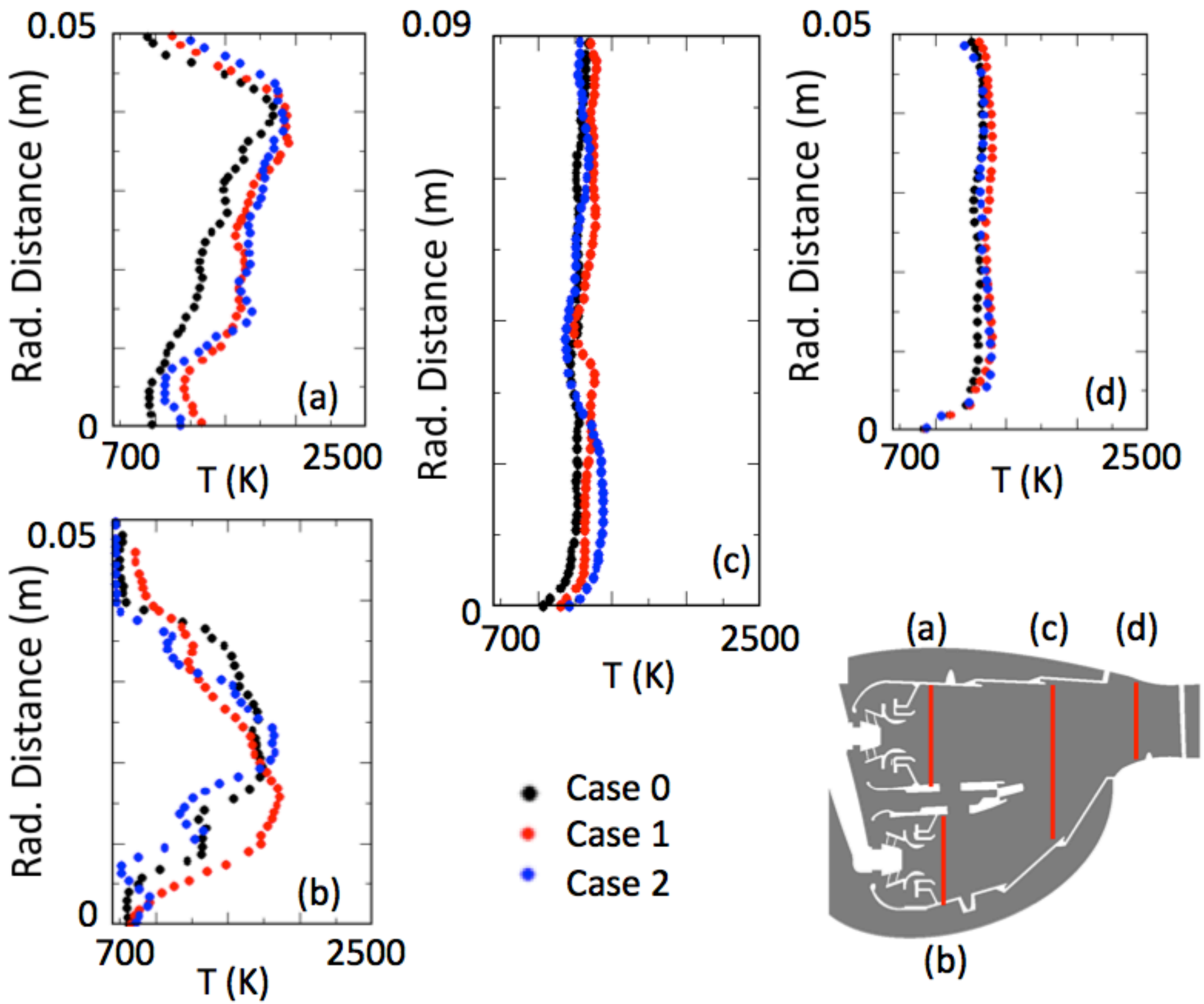
- Case 0 shows slightly lower temperature than that of Case1 and Case 2.
- Not much effects from clocking

Time-Averaged Temperature Profiles, con



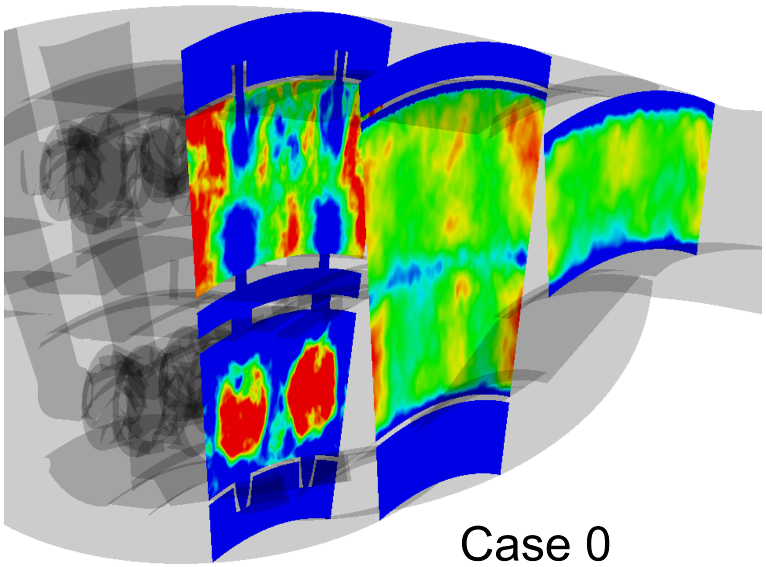
- Again, not much difference seen between Case 1 and Case 2

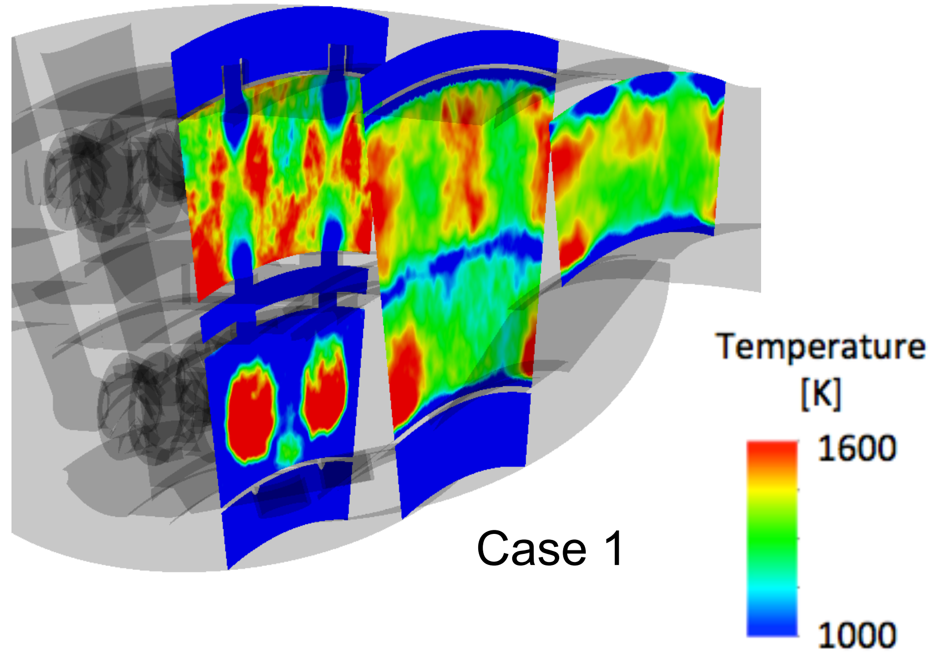
Blocking Effect: Temperature

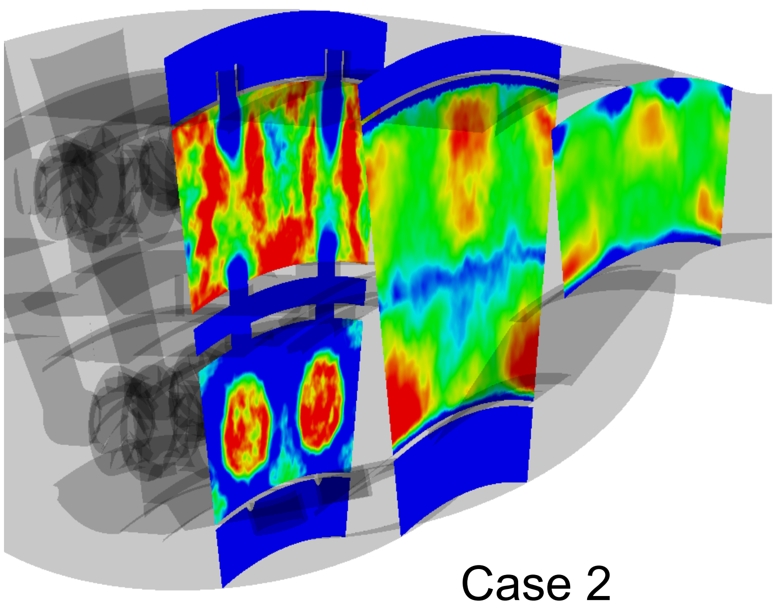


- Due to the blocking effect, Case 0 shows lower temperature, especially in the main, but Case 1 and Case 2 are similar to each other.

Clocking Effect on Temperature Fields

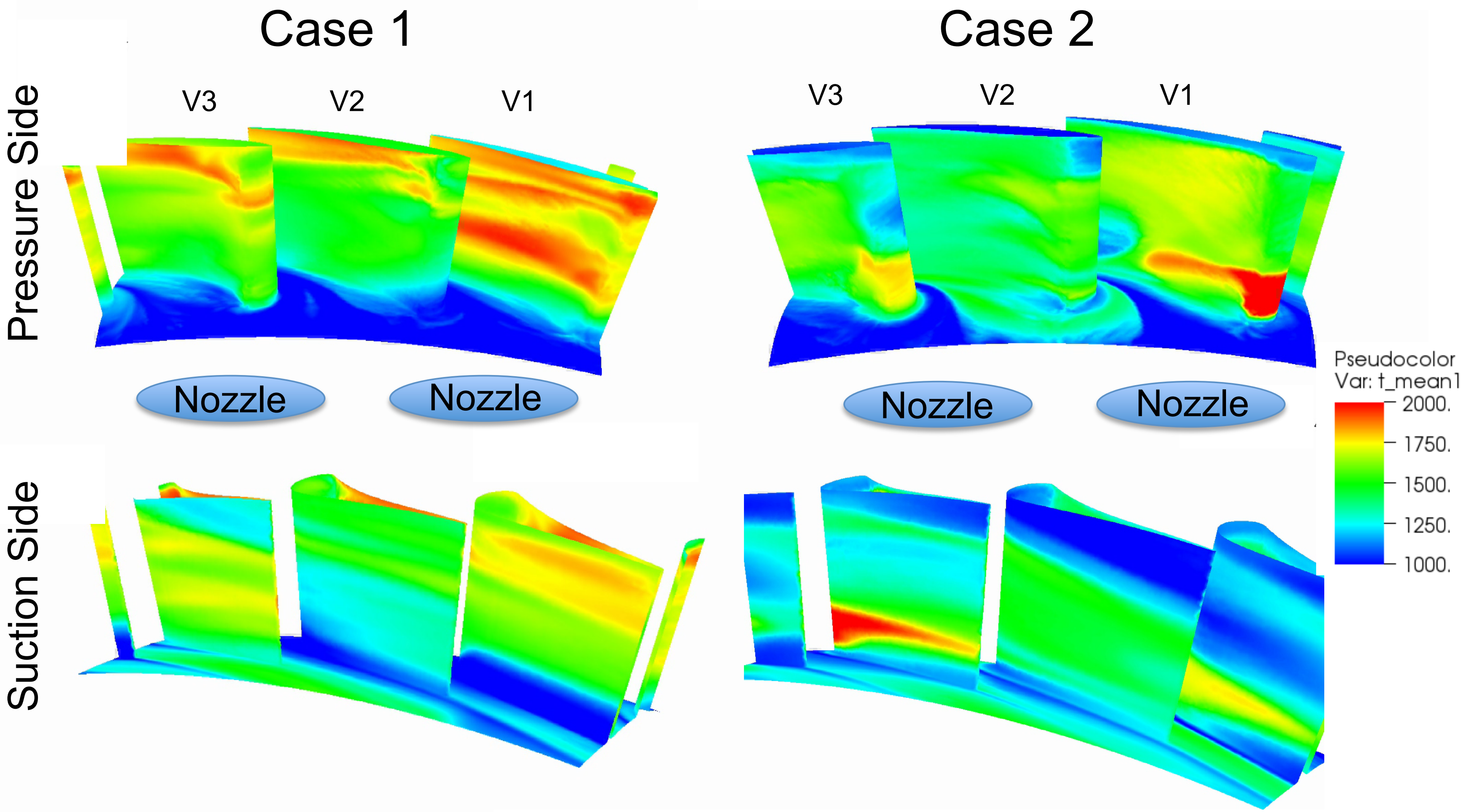






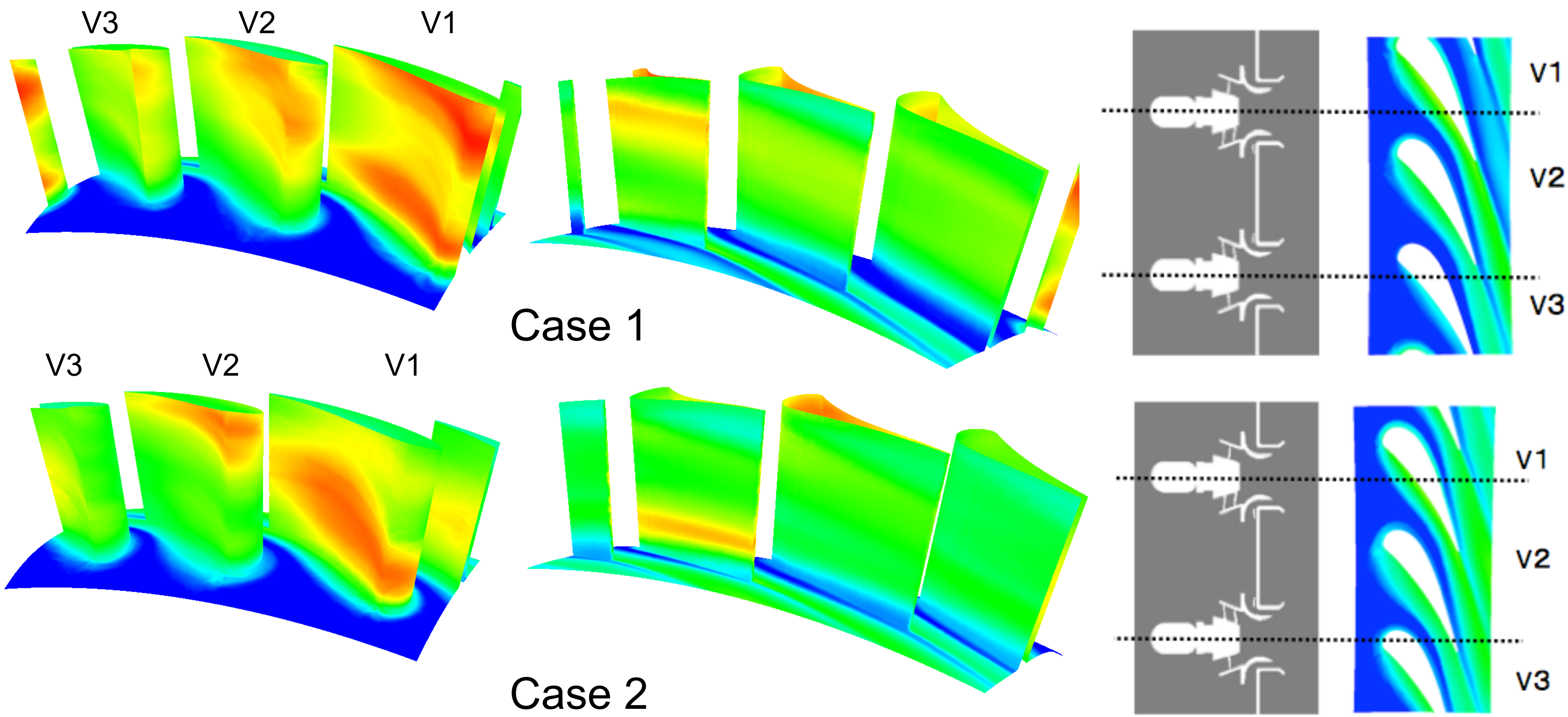
- At P40, there are some noticeable differences between Case 1 and Case 2.
- For Case 1, there are five distinct hot regions, but only three for Case 2.
- Also, the two hot regions in the top parts of Case 1 are slightly hotter than the ones in Case 2 (more mixing?)

Unsteady Temperature Fields @ Vane



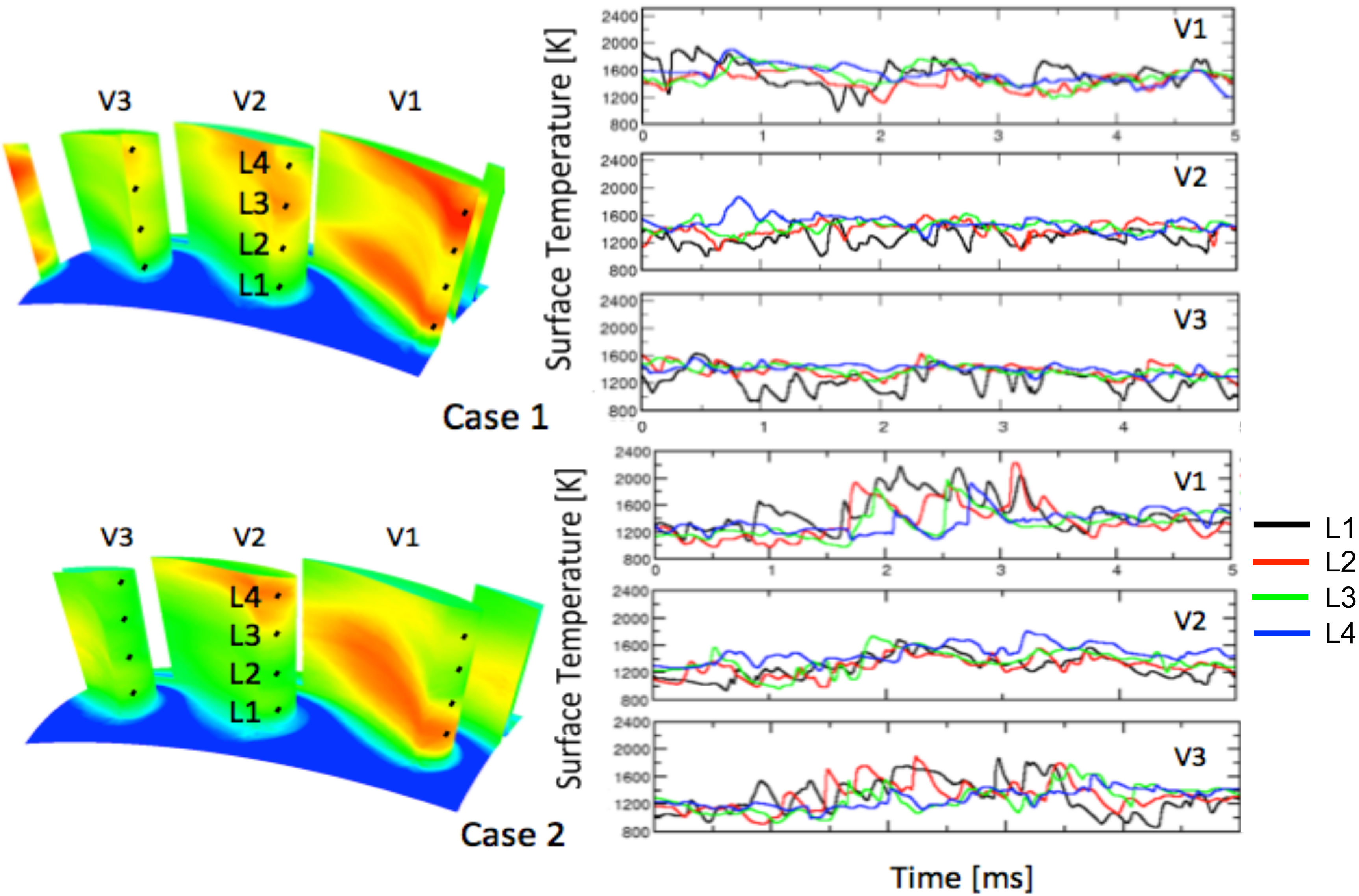
- Adiabatic condition is used and any cooling holes on the surface are not included.
- Locally hot (1600 [K]) and cool (900-1000 [K]) spots co-exist, which can cause the severe thermal stress on the vane, especially on the pressure side.

Time-Averaged Temperature Profiles @ Vane



- For Case 1 (top), hot streaks (1600 [K]) located at the far-right vane (V1), and these spots elongate on the pressure side.
- For Case 2 (bot.), only one hot streak on V1. Also, the temperature of these hot streaks (1450 [K]) is not as high as the ones in Case 1.

Histories of Temperature Profiles @ Vane



- Case 2 shows stronger temperature variation, with lower mean temperatures.

(Standard deviation of temperature of v1: Case1 176 [k], Case2 200 [K])

Conclusions and Future Work

- In this paper, we have investigated the E^3 combustor using the OpenNCC developed at NASA Glenn Research Center.
- The three different geometries, without the vane and with the vane of two different clockings, are considered.
- Our numerical results show:
  - ❑ Presence of the vane at the combustor exit increases the pressure inside the combustor, resulting in weaker swirling flows and dilution airflows. This blocking effect causes up to 20% difference in Mach number.
  - ❑ The effect of clocking is not significant in the flow fields inside the combustor and temperature fields in the primary zone. However, it indeed affects the distribution of the hot-streaks at the first stage vane surface as well as P40.
  - ❑ In addition, one case shows stronger temperature variation with time, but cooler. Also, our results show that the temperature field on the pressure side is much higher than on the suction side.
- Future works will focus on the comparison of turbulence chemistry interaction models and adding the rotor.

Thank you!

Questions?

Acknowledgement

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