Enhancement of the Open National Combustion Code (OpenNCC) and Initial Simulation of Energy Efficient Engine Combustor

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

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  - Current Capability of OpenNCC
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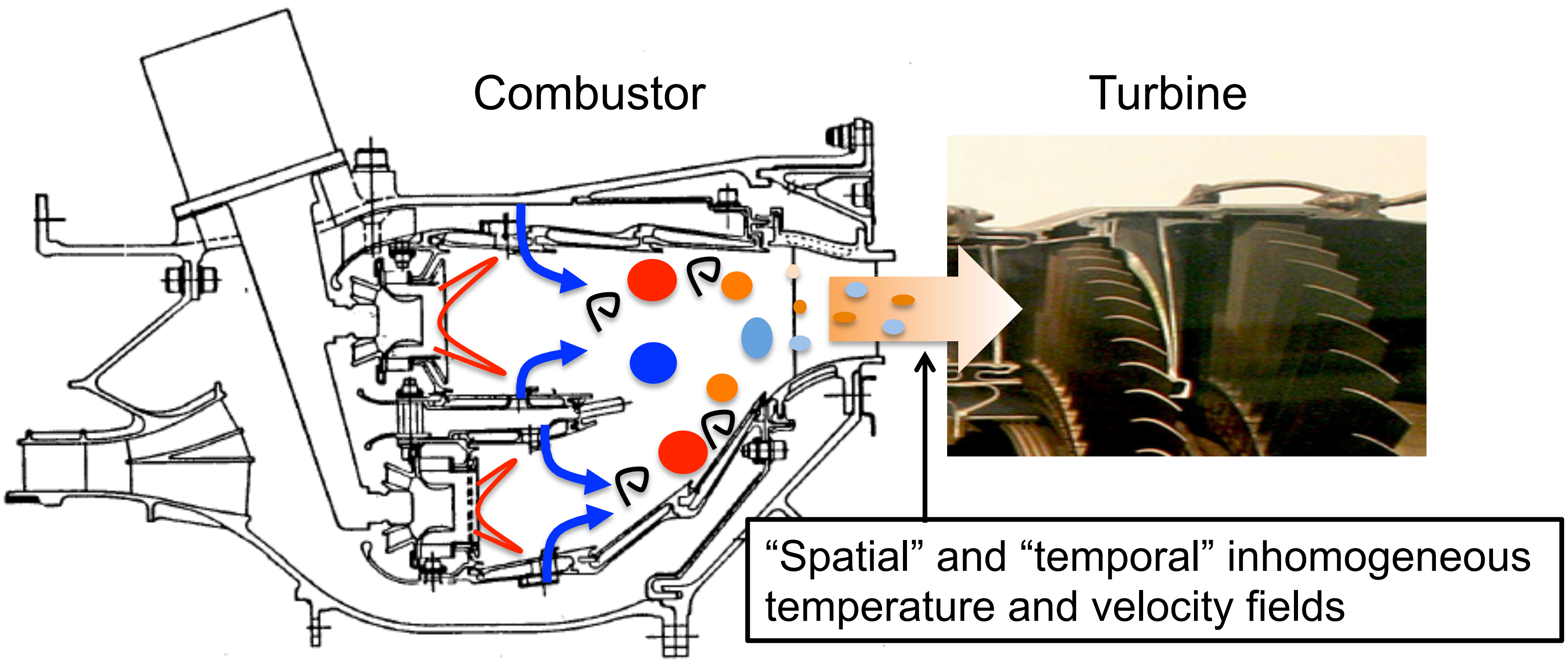
  - Turbulent Flow Over Flat Plate (skin friction)
  - Highly-Loaded Turbine Guide Vane (heat flux)
  - Non-Swirling Coaxial Jet Combustor (temperature and velocity)
- **Energy Efficient Engine (E^3)**
  - Cold Flow (RANS)
  - Reacting Flow (RANS)
- **Conclusions**

Motivation

- Future propulsion systems will be of increasingly higher bypass ratio from larger fans combined with much smaller cores
- Important to understand core engine component interactions, such as <u>combustor-turbine interactions</u>



Hot Streaks

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

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)
  - ✓ Turbulence: Cubic non-linear k-ε(4) model with the wall function, Low-Re model
  - ✓ Combustion: Reduced chemical kinetic, low dimensional manifold, 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)

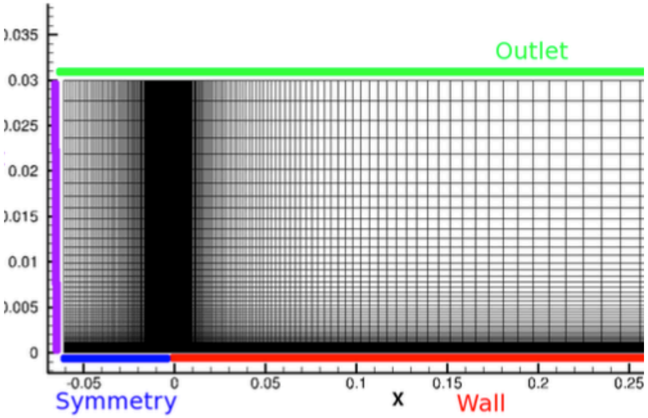
Selected referece

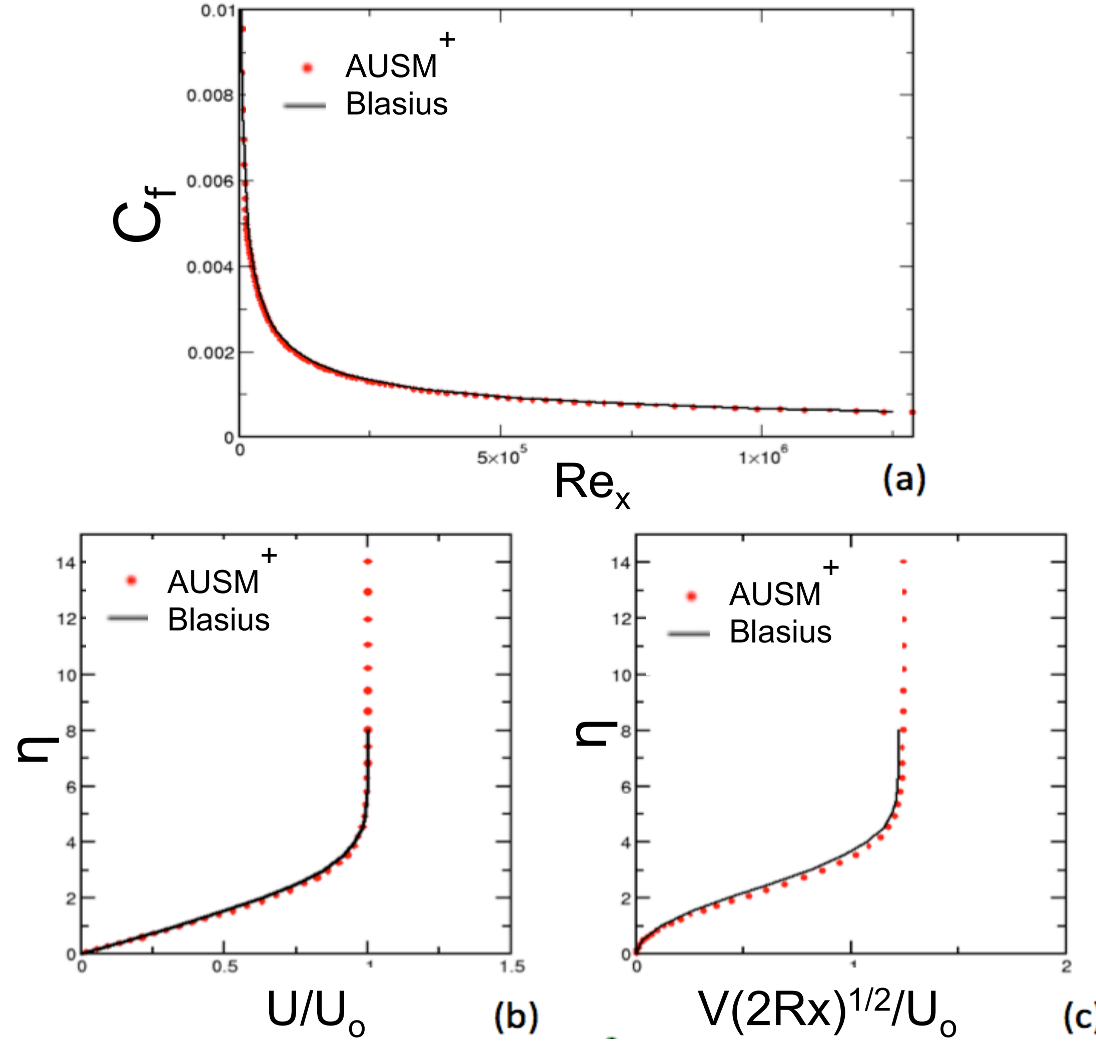
(1) Liou, M.-S. and Steen, C. J., Journal of Computational Physics, Vol. 107, (1993)
(2-3) Liou, M.-S., Journal of Computational Physics, Vol. 129, 1996) and (2006)
(4) Shih, T.-H., Chen, K.-H., and Liu, N.-S., AIAA 1998-35684 (1998).
(5) Alan R. Kerstein, Combustion Science and Technology, Vol 60 (1988)
(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).

Validation Test

1. Laminar Flow Over Flat Plate
2. Turbulent Flow Over Flat Plate
3. Highly-Loaded Turbine Guide Vane
4. Non-Swirling Coaxial Jet Combustor

Laminar Flow Over Flat Plate





Numerical Setting

- 2D Flat Plate, Laminar
- Mesh size: 256x64
- Inflow Condition:
  Mach=0.2 (69m/s), 300K, Air

- Excellent agreement with Blasius solution is achieved.

Validation Test

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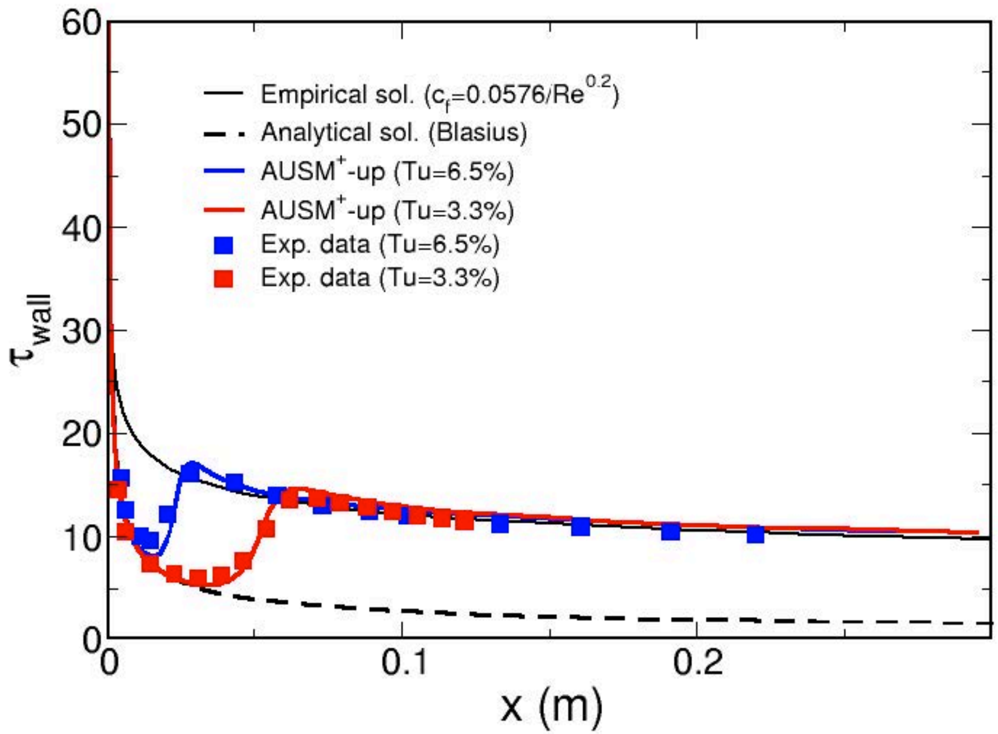
Turbulent Flow Over Flat Plate



Numerical Setting

- 2D Flat Plate, RANS
- Turbulent Model: nonlinear k-ε model(1)
- Transition Model(2)
- Mesh size: 256x128 and 512 x 256
- Inflow Condition:

  Mach=0.2 (69m/s), 300K, Air

  Turbulent intensity (T_U) : 6.5% and 3.3%

- One model parameter associated with the transition model is fixed for both Tu = 6.5 % and 3.3 %.
- Shear stress and transition locations agree with the experimental data and analytical solution.

(1) Shih, T.-H., Chen, K.-H., and Liu, N.-S., \A Non-linear k-epsilon Model for Turbulent Shear Flows," 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, No. AIAA 1998-35684, Cleveland, OH, July 13-15 1998.
(2) Liou, W. and Shih, T.-H., “Bypass Transitional Flow Calculation using a Navier-Stokes solver and Two-equation models,” No. NASA/CR-2000-209923, 2000

Validation Test

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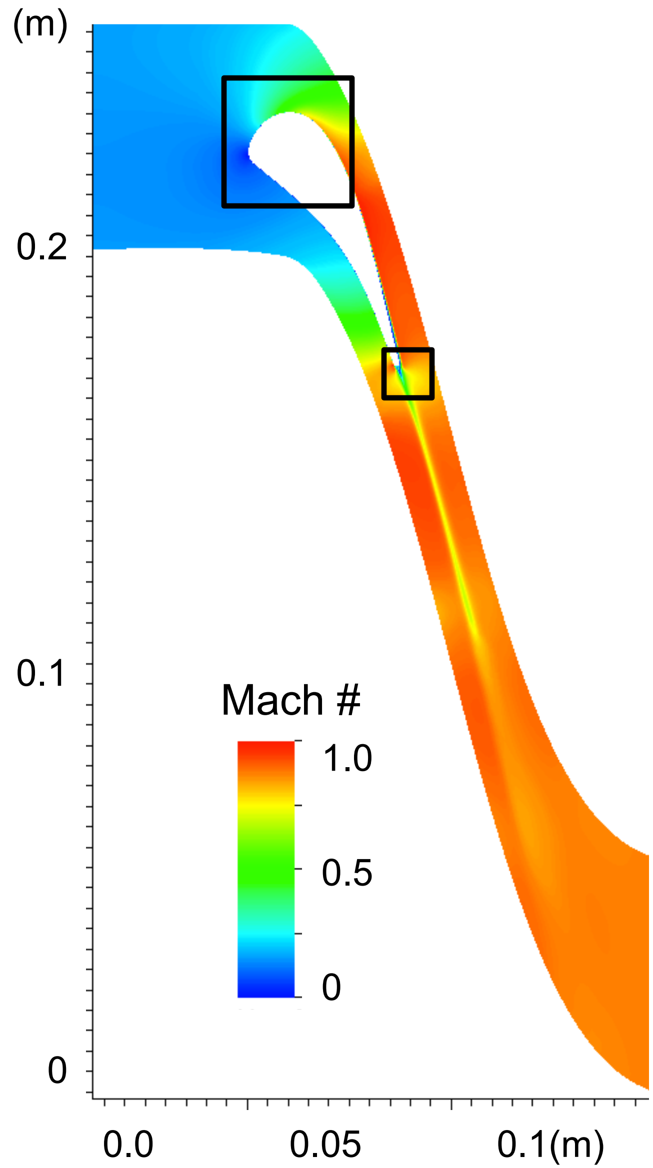
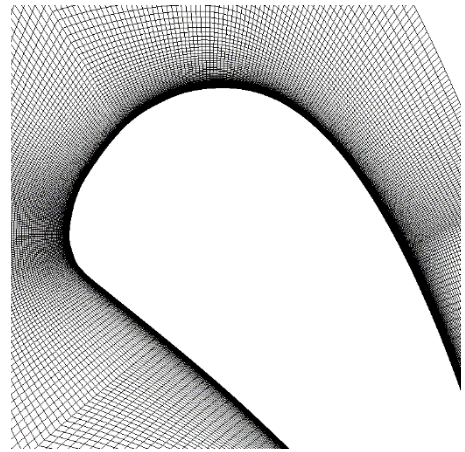
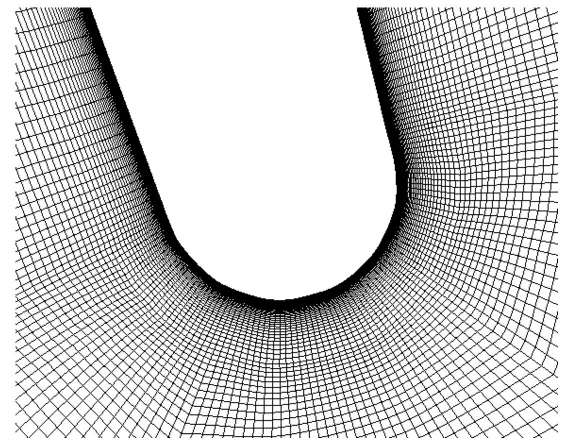
Highly-Loaded Turbine Guide Vane





Leading Edge



Trailing Edge

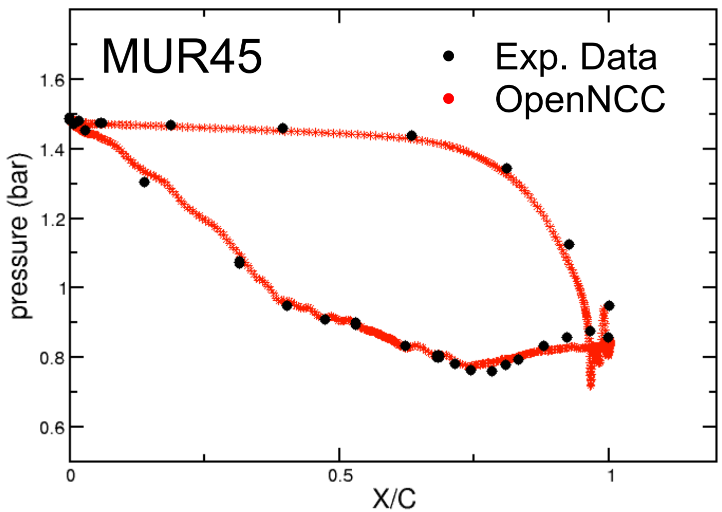
Test number #	p_{total} (bar)	T_{total}[K]	Mis_{out}	Re_{out}	Free stream turb. [%]
MUR45	1.475	-	0.875	10^6	-
MUR129	1.849	409.20	0.840	1.1352×10^6	0.8
MUR235	1.828	413.3	0.927	1.1521×10^6	6.0

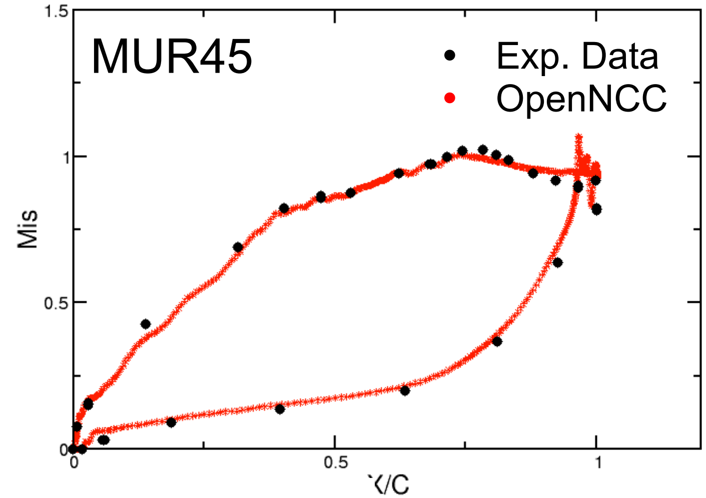
Test Conditions

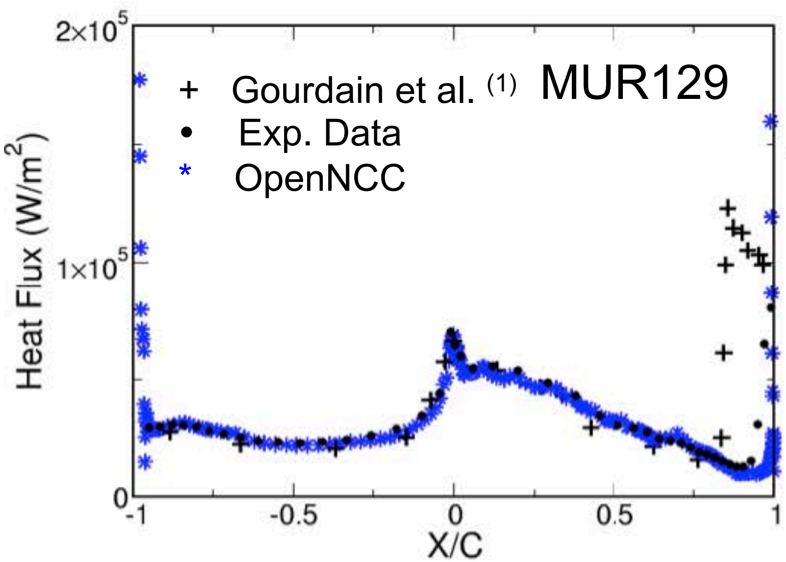
- Towards our ultimate goal of understanding combustor-turbine interactions, the validation test of turbine heat transfer is essential.
- High-quality mesh (80,000 grids) is generated by Cubit
- Pressure, M_{is} and heat flux are compared with the data[(1)] for three test conditions

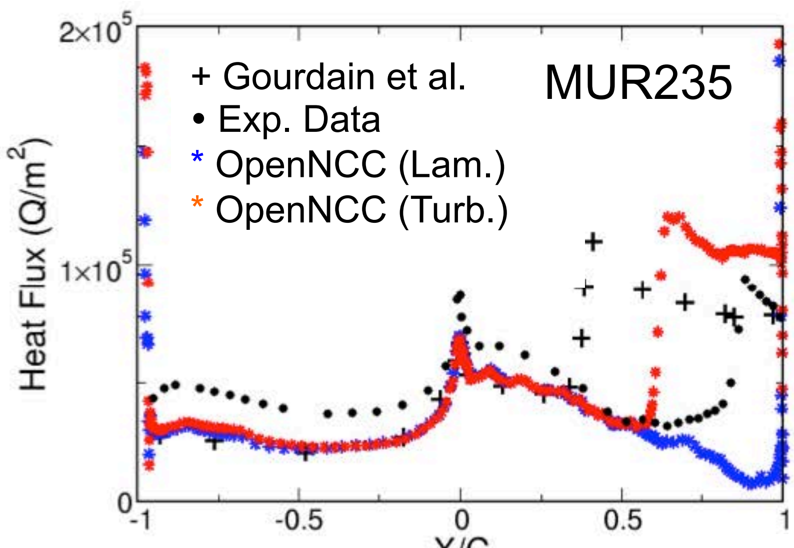
(1) Arts, T., Lambert de Rouvroit, M., and Rutherford, A., \Aero-thermal investigation of a highly loaded transonic linear turbine guide vane cascade," VKI Technocal Note, Vol. 174, 1990.

Highly-Loaded Turbine Guide Vane (cont.)









- MUR235 is the most challenging case, where subsonic-supersonic & laminar-turbulence transition take place

(1) Gourdain, E., et al., ASME Turbo Expo 2010, No. GT2010-22793, (2010)

Validation Test

1. Laminar Flow Over Flat Plate
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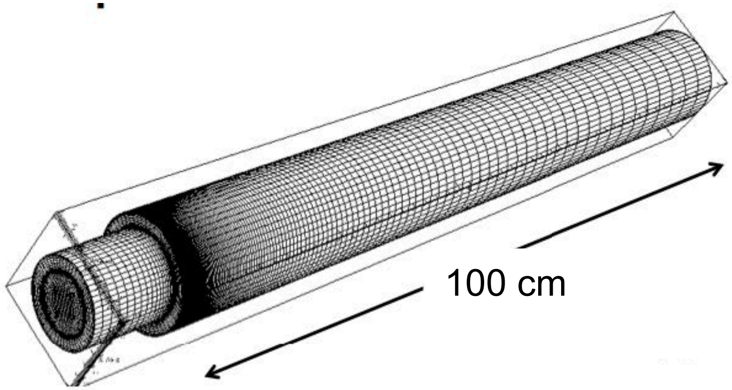
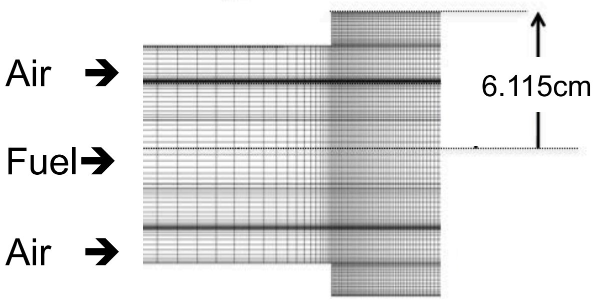
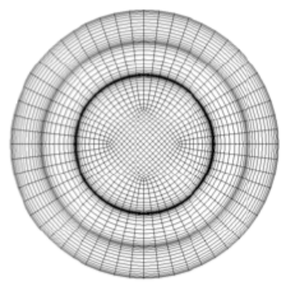
4. Non-Swirling Coaxial Jet Combustor

UTRC: Coaxial Jet-Flame



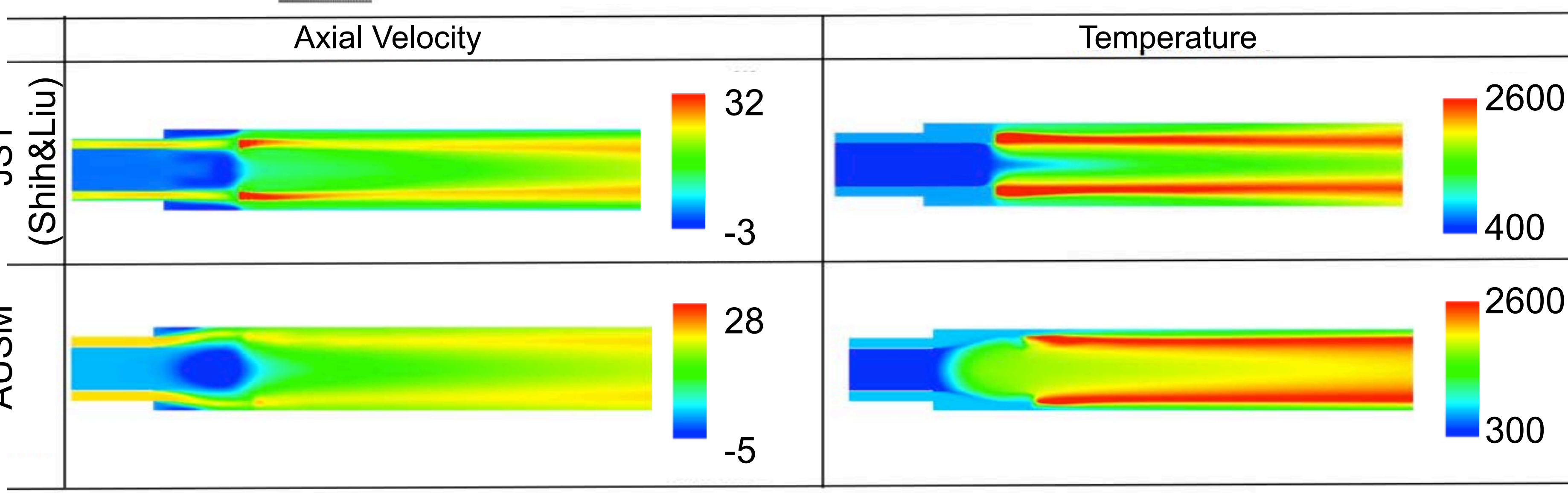




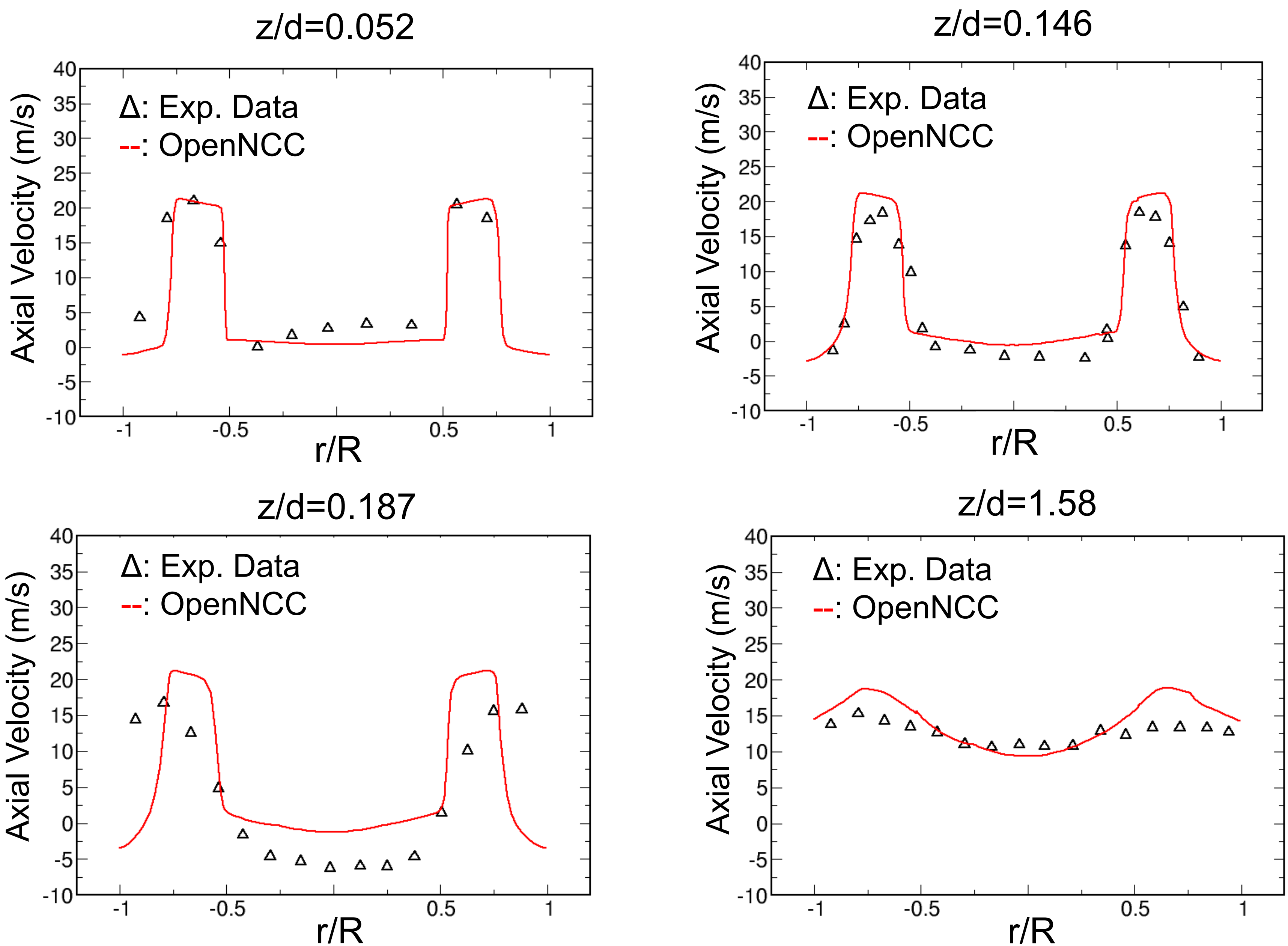
Numerical Setting

- Numerical scheme: AUSM$^+$-up
- Steady flow calculation (RANS)
- Turbulence model: Cubic non-linear k-ε with the wall function
- Mesh: 366,656 grids
- Chemistry: 1-step mechanism

gas	Temperature [K]	Mass flow rate [kg/s]	Velocity [m/s]
Air	750	0.137	29
Fuel (CH_4)	300	0.0072	0.9

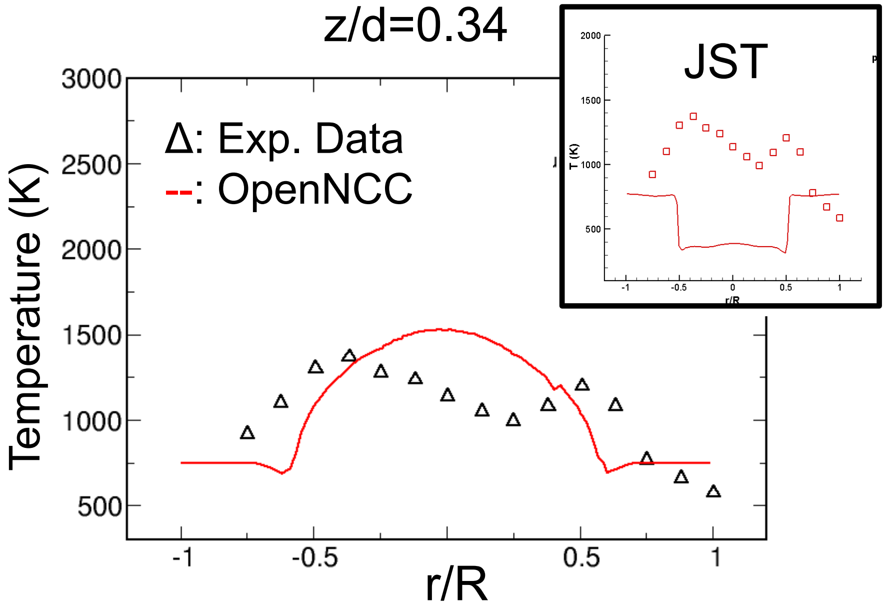


Axial Velocity Profiles

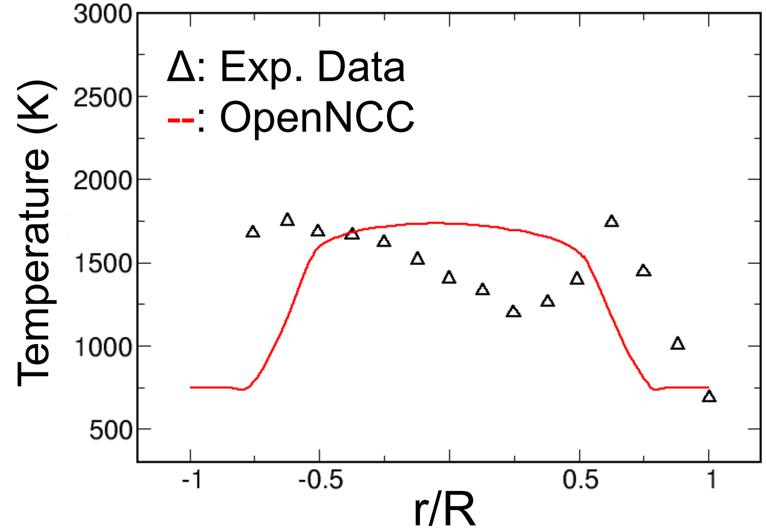


Temperature Profiles

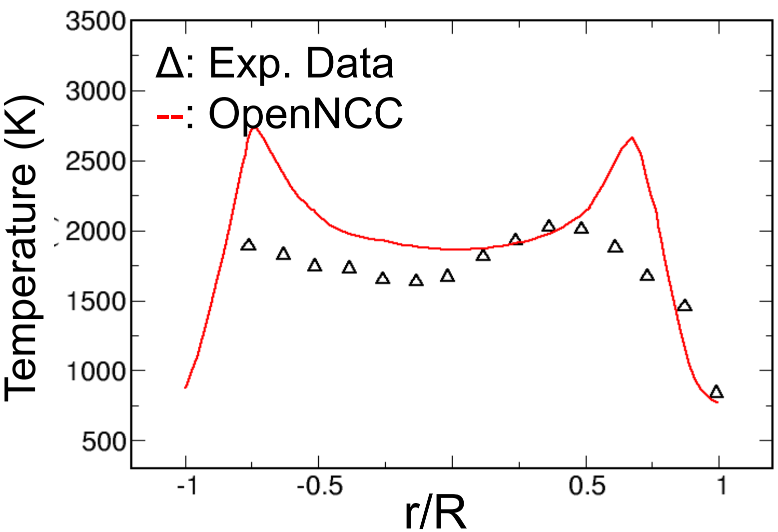
z/d=0.34



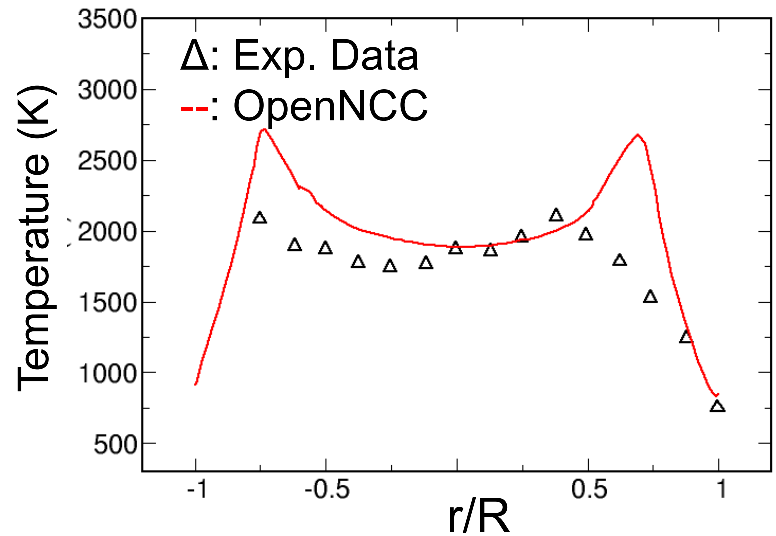
z/d=0.6



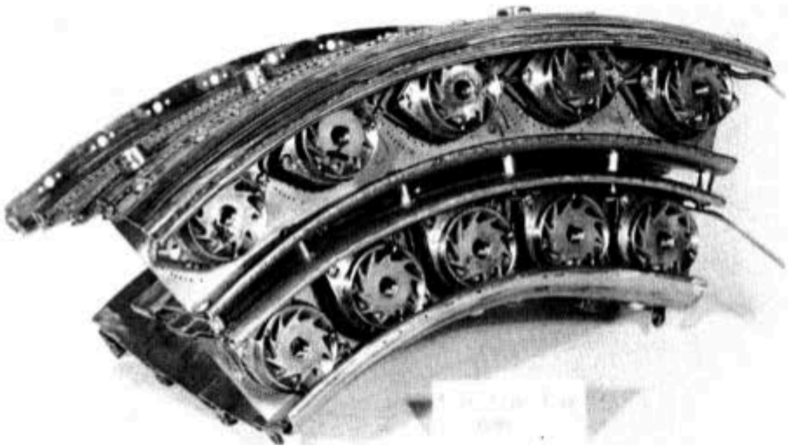
z/d=1.73



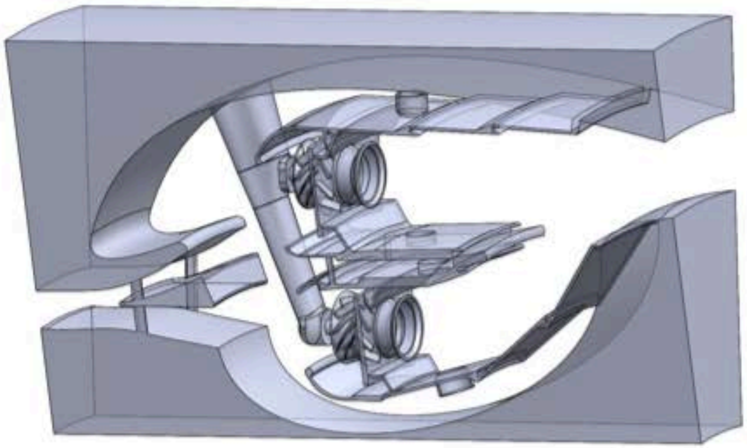
z/d=1.99



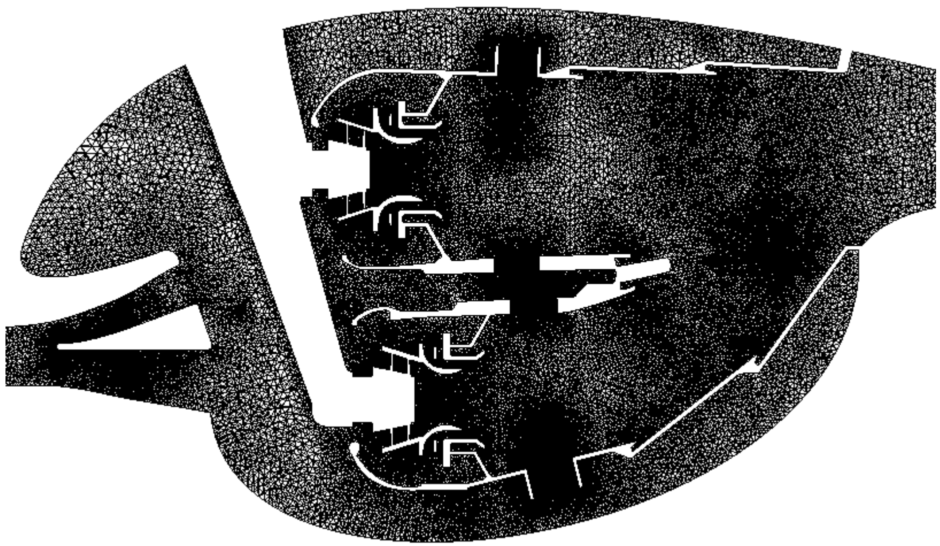
Energy Efficient Engine (E^3) – GE design, 80s -



Five-cups EEE sector test hardware (1)



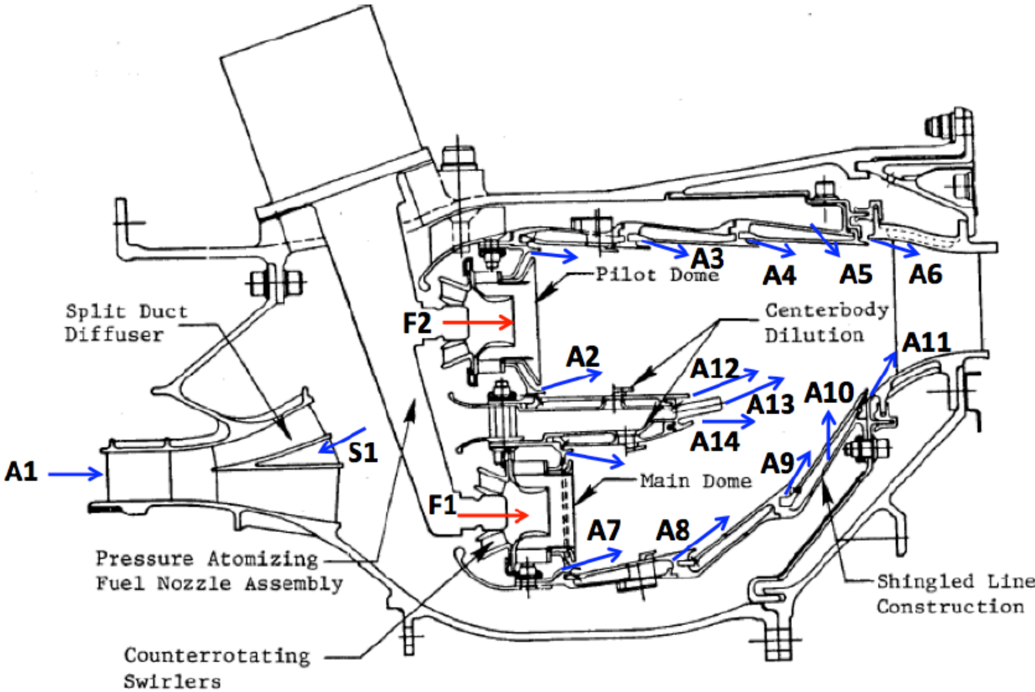
One-cup CAD geometry



- One-cup (12 degree) E^3 geometry is considered to demonstrate the predictive capability of OpenNCC
- Tetrahedral mesh (~9.5M) is generated by Cubit (AMR is off)
- Used 960 processors of Pleiades at NASA Advanced Supercomputing facility
- RANS (non-linear k-ε(4) model) with low-Mach preconditioning
- ~160,000 iterations (cold flow) and additionally ~340,000 iterations (rec. flow)

(1) Burrus, D. L., et al, No. NASA/CR-1984-168301, (1984)

Boundary Condition

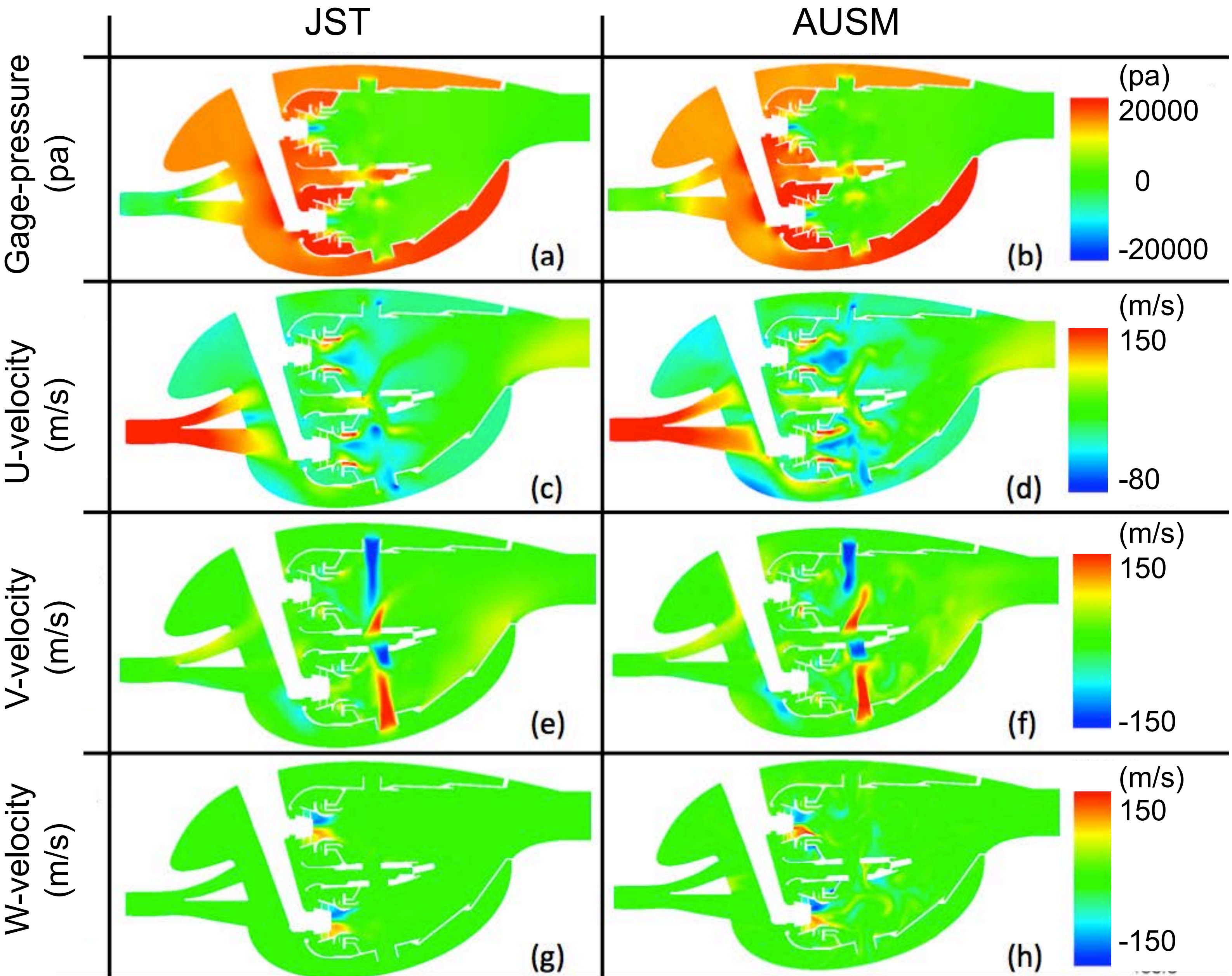


Aame	Index	Gas	Mass flow rate [kg/s]
Inflow	A1	Air	0.26
Main dome	F1	Fuel	0.00182*
Pilot dome	F2	Fuel	0.00182*
Diffuser Bleed	S1	Air	- 0.018
Pilot splash plate cooling	A2	Air	0.0104
Outer liner cooling 1	A3	Air	0.0053
Outer liner cooling 2	A4	Air	0.0053
Outer liner trim cooling	A5	Air	0.0018
Outer liner 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

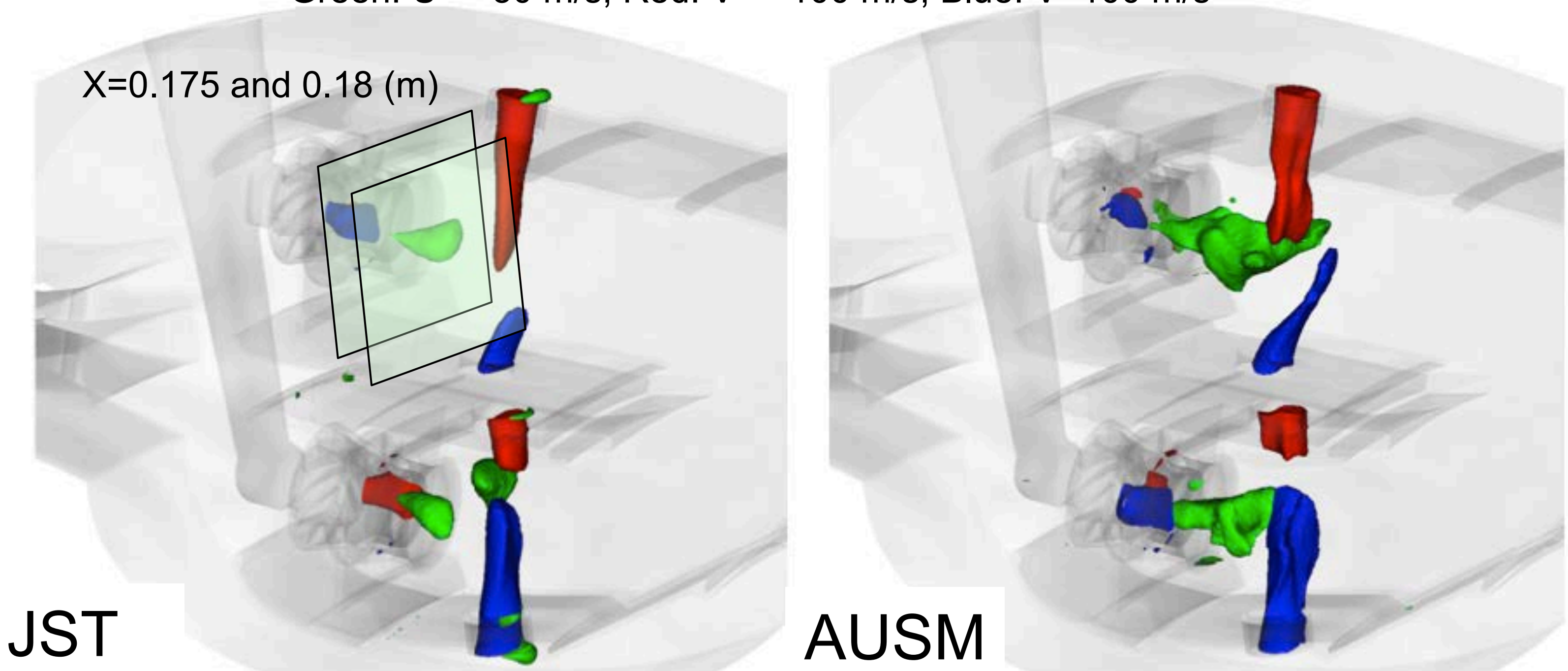
- Taken into consideration is the simulated sea level takeoff condition (SLTO), which is the most severe condition during the engine operation cycle
- Cooling air is treated as source/sink terms on the surface

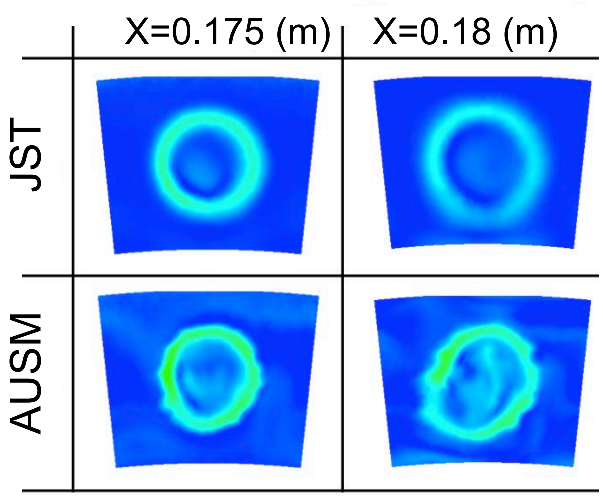
Pressure and Velocity Profiles (center-plane)



Dilution Airflow and Recirculation Zone

Green: U = -30 m/s, Red: V = -100 m/s, Blue: V=100 m/s

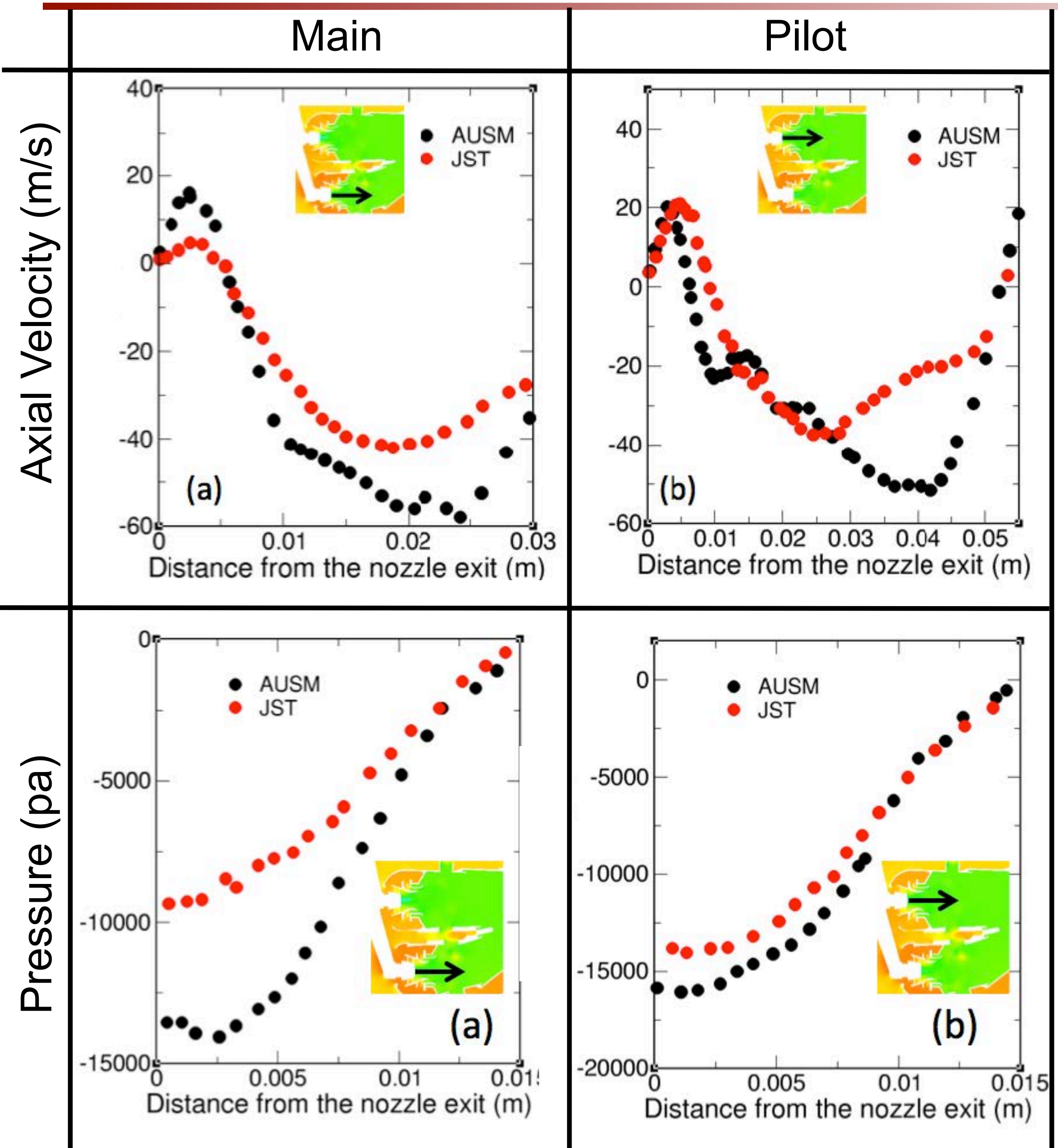




Mach Contour

- For AUSM scheme, the central-recirculation zone (CRZ), is much larger and extends up to the location where the dilution airflows meet
- In contrast, JST scheme predicts a much smaller CRZ, and CRZ and the dilution airflows are weakly interacted
- JST is more dissipative

Quantitative Comparison: Axial Velocity and Pressure

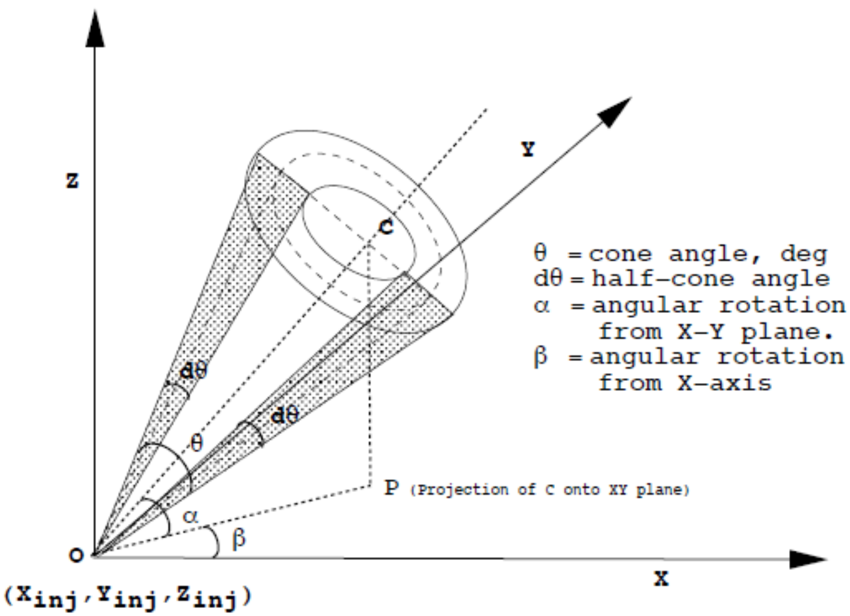


- AUSM scheme shows that the reverse flow is stronger than the JST scheme (i.e., larger CRZ)

- AUSM scheme shows the pressure is much lower than JST scheme, which indicates a stronger precessing vortex core (PVC)

Flame structures would be predicted in a different manner?

Reacting Flow Calculation (Preliminary)



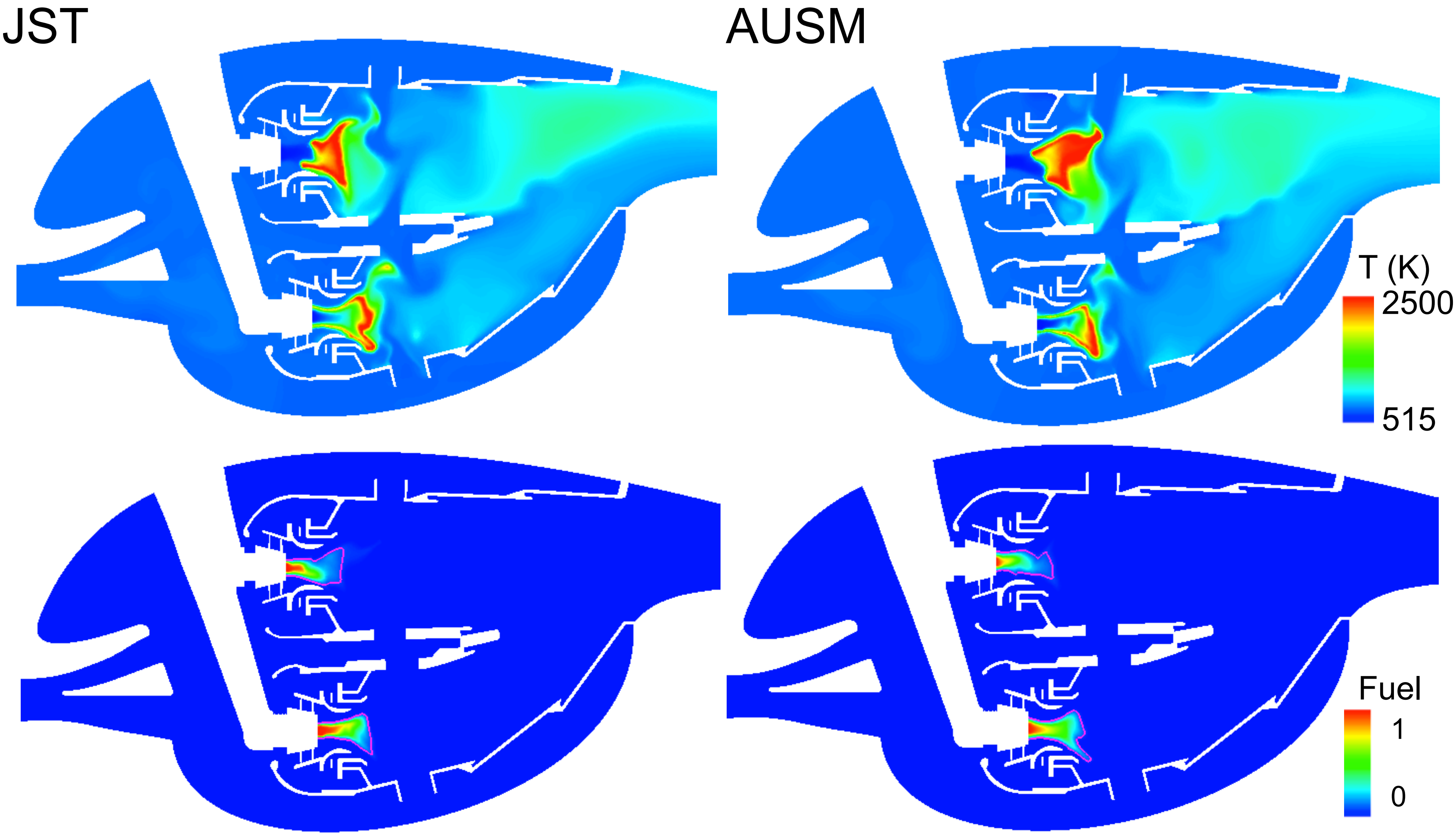
Geometrical details of fuel injection for a 3D solid or hollow cone spray

- "Gaseous" fuel (T_{fuel}=515K) is injected from the main and pilot domes with 70^o cone angle (hollow cone)
- Finite-rate chemistry:

$$4C_{12}H_{23} + 71O_2 \rightarrow 48CO_2 + 46\, H_2O$$

- The reaction rate is calculated in the Arrhenius form: $k=A\,T^n \exp(-E/RT)$ where A = 8.6E+11, n=0, E = 30000
- Chemical integration is done using the KIVA scheme.
- Turbulence mode: non-linear k-ε[4] model with the wall function

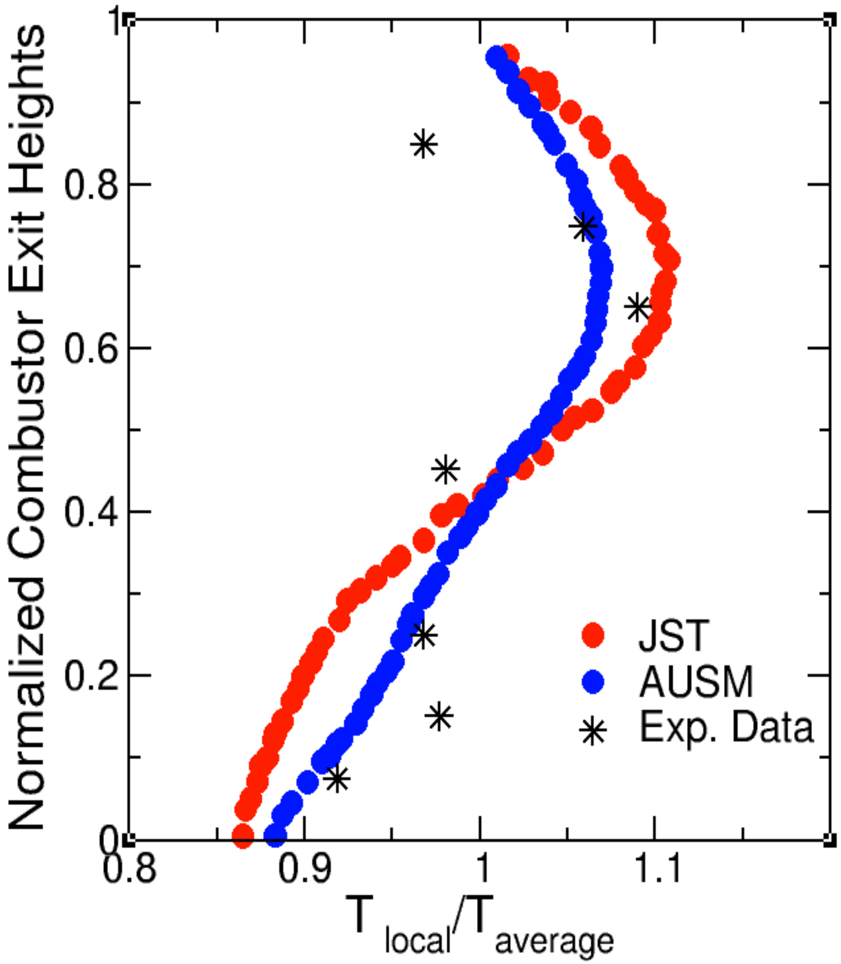
Temperature and Fuel Mass Fraction

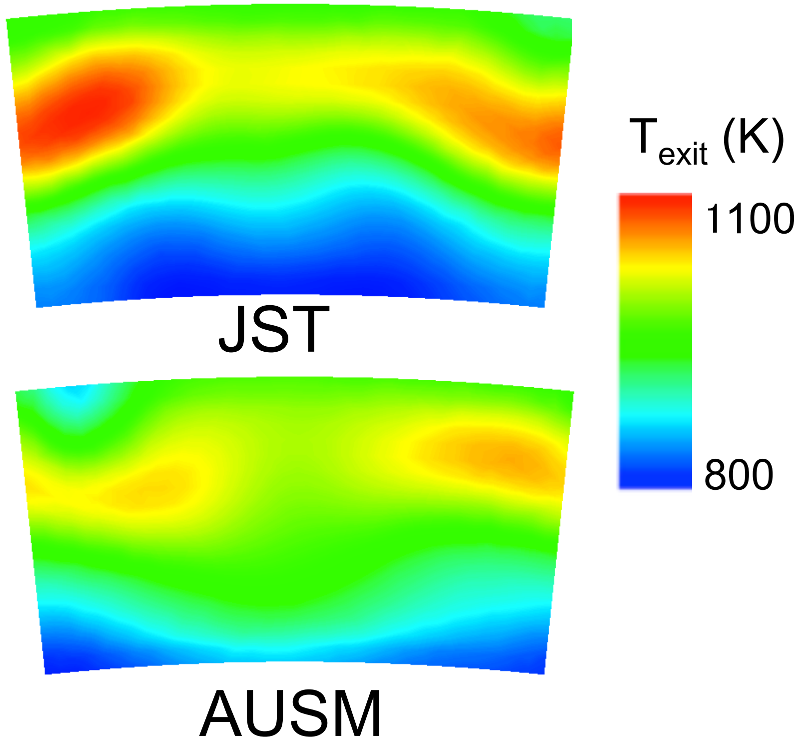


* Magenta indicate the stoichiometric mass ratio

- Both models predict the flame structures in a similar way.

Exit Temperature Profile





- Radially and circumferentially non-uniform temperature profile is observed
- AUSM scheme predicts more uniform profile than the one by JST scheme
- Relatively large discrepancy from the data is seen at the top/bottom wall

Conclusions and Future Work

- We have performed detailed validation studies of the newly implemented numerical schemes and applied them to the real combustor configuration, E^3 combustor
- The enhanced OpenNCC shows satisfactory performance through a series of validation tests
- In the study of E^3, we observe that the AUSM scheme is less dissipative and thus, seems to capture the swirling flow and the recirculation bubble more realistically than the JST scheme
- Even though the flame structures are similar between the two schemes, the exit temperature profiles differ from one another
- We are planning to turn on the adaptive mesh refinement, spay liquid injection and turbulence-chemistry interaction (e.g., LEM)

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)**