# NASA's Turbulent Heat Flux (THX) Experiments


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**Transformational Tools and Technologies (TTT) Project**
**Transformative Aeronautical Concepts Program (TACP)**

**TTT-RCA High-Fidelity CFD Workshop**
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*Note: several individuals contributed to the experimental and computational efforts documented herein. See the references at the end of this slide package for these authors/contributors.*

# Motivation

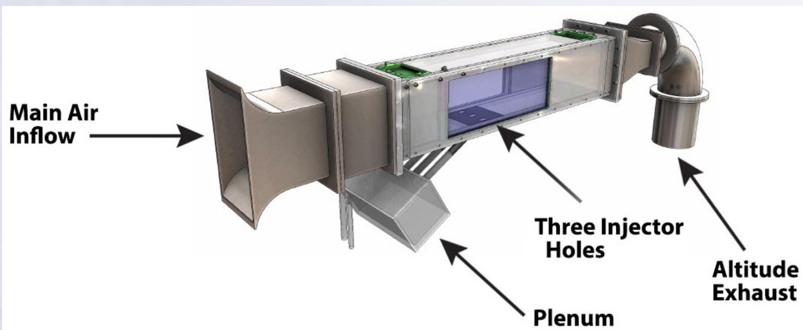
- **In CFD, turbulent temperature variations & heat flux haven't received as much attention as traditional aerodynamic turbulence, yet are important to many flows.**
- **Examples include: (1) high Mach number applications, (2) propulsion systems, (3) systems requiring active cooling – just to name a few**
- **The turbulent heat flux (THX) experiments were designed to make detailed turbulent measurements of velocities and temperatures – with the goal of obtaining data to:**
  1) **improve understanding of turbulence in flows where turbulent thermal transport is important.**
  2) **develop and validate better computational models for simulation of flows involving turbulent heat flux**
- **Alongside experiments, CFD efforts were undertaken to provide a baseline of RANS and scale-resolving (WRLES, WMLES, HRLES) techniques for these flows.**

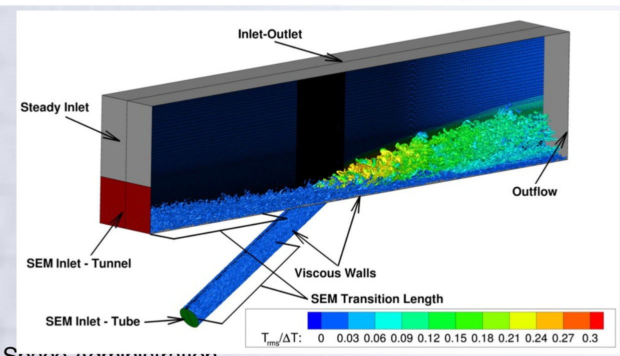
# Turbulent Heat Flux (THX) Experiments Phases

1. **Low speed / temperature cooling hole experiments in GRC SW6.**
2. **Subsonic jet temperature measurements: using Raman in GRC Aeroacoustic Propulsion Laboratory (AAPL).**
3. **Subsonic Square nozzle flow over plate with single cooling hole, PIV and Raman temperature measurements in AAPL.**
4. **Subsonic Square nozzle flow over perforated plate film cooling, PIV & Raman temperature measurements in AAPL.** ***Data used in 5th AIAA Propulsion Aerodynamics Workshop (PAW5).***
5. **Supersonic round nozzles replicating experiments of Seiner et al., 1992. BOS, Raman and PIV measurements were obtained in AAPL.** ***Data used in AIAA PAW6 and NASA TMR.***

# THX – Phase 1

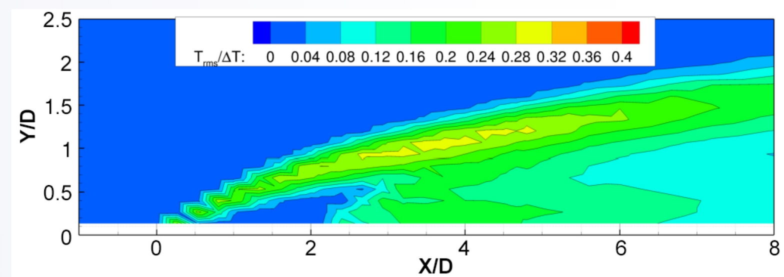
- **Low speed / temperature cooling hole experiments in GRC Fundamental Film Cooling and Heat Transfer Facility (SW6).**
- **Hotwire measurements of velocities, temperature, and turbulent heat flux (u'T'), also PIV for velocities.**



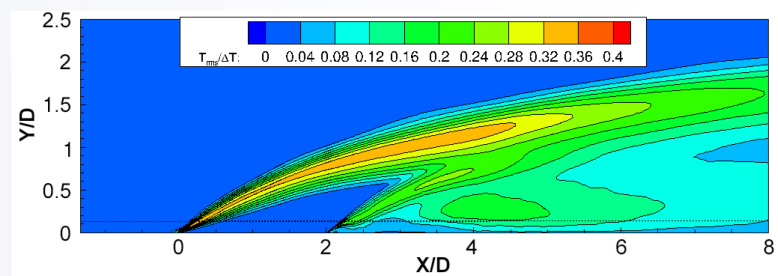




**T' / ΔT**

**Expt.**




**LES**

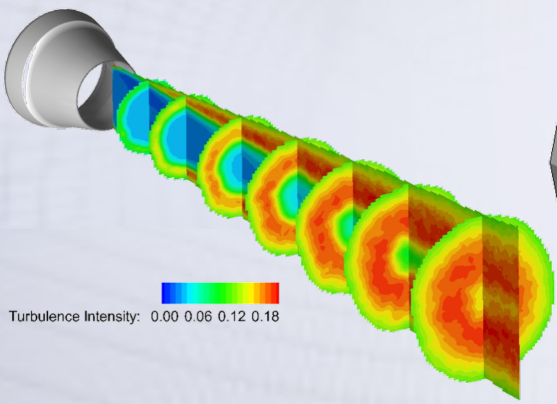


# THX Phases 2 - 5

**All experiments conducted in NASA GRC Aeroacoustic Propulsion Laboratory (AAPL) – using the Small Hot Jet Acoustic Rig (SHJAR) – having capability up to Mach 2 and 950 K conditions.**

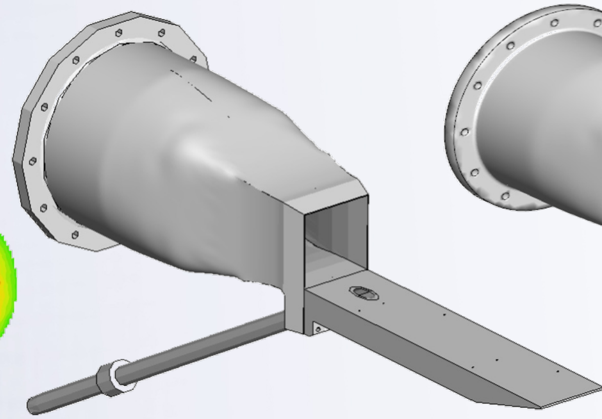
## THX 2

**SMC000**



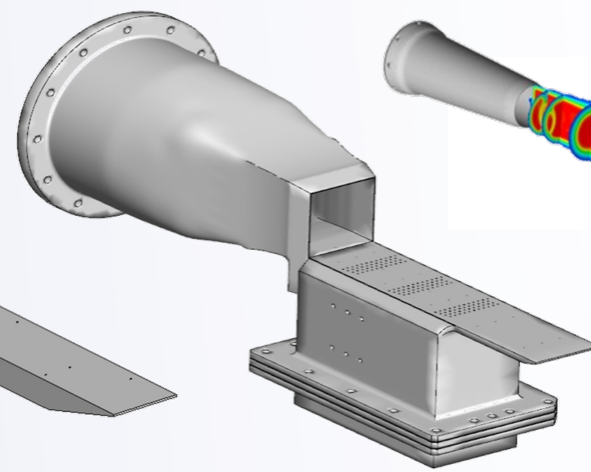

## THX 3

**Single Hole Plate**



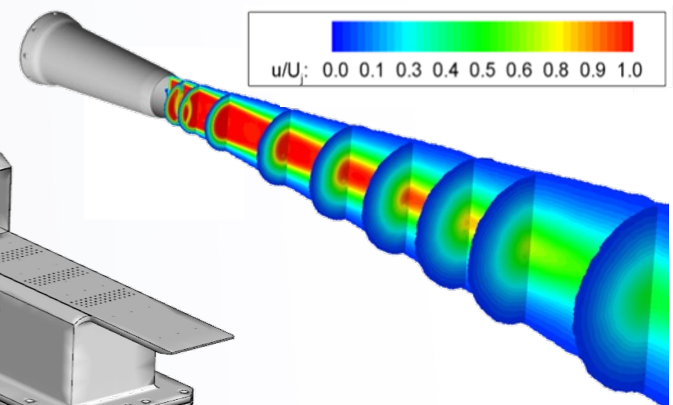
## THX 4

**Multi-Hole Plate**



## THX 5

**Supersonic Jets**

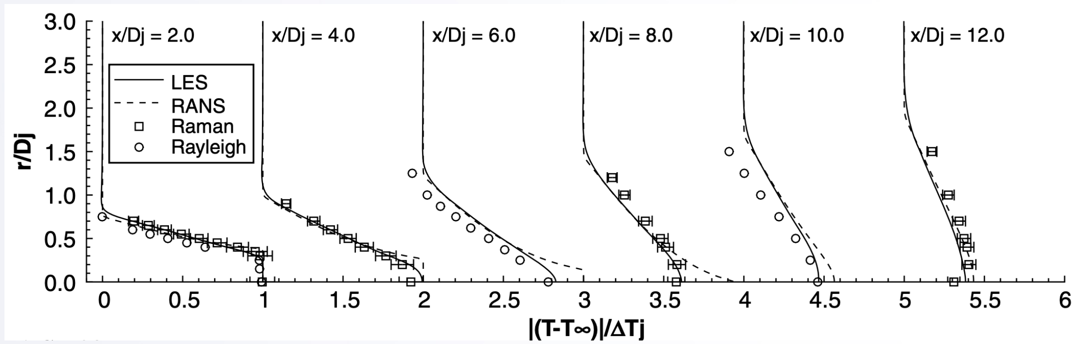


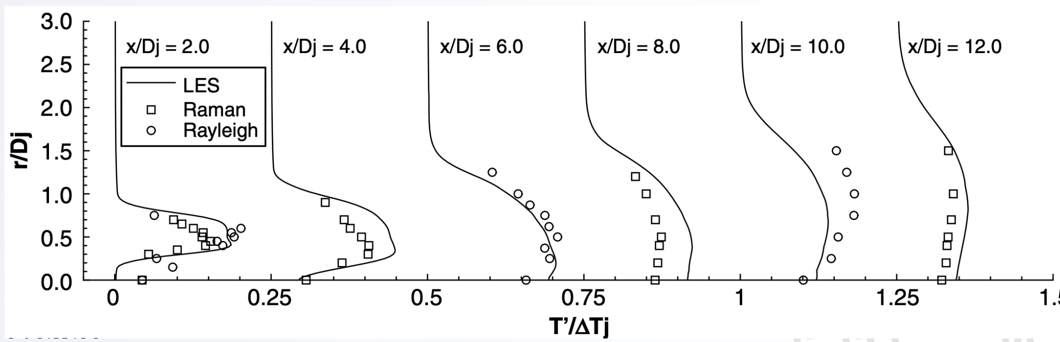
# THX 2 – Subsonic Jets Tested at GRC AAPL

- **Raman Scattering technique implemented and demonstrated using this phase.**
- **Examined the "SMC000" convergent nozzle, for many of the same points as the Bridges and Wernet Consensus Data (AIAA Paper 2010-3751) – also taken in GRC AAPL, data used on NASA TMR**

- Comparisons of temperature measurements and LES for consensus data SP23, Mach 0.38, $\Delta T$ = 233K.

- Raman Measurements: Locke, R. J., Wernet, M. P., and Anderson, R. C., "Rotational Raman-Based Temperature Measurements in a High-Velocity Turbulent Jet," ***Measurement Science and Technology***, Vol. 29, No. 1, Dec. 2017.
- Rayleigh Measurements: Mielke, A., Elam, K., and Sung, C.-J., "Multiproperty Measurements at High Sampling Rates Using Rayleigh Scattering," ***AIAA Journal***, Vol. 47, No. 4, 2009, pp. 850–862.
- LES: Debonis, J.R., "Prediction of Turbulent Temperature Fluctuations in Hot Jets," ***AIAA Journal***, Vol. 56, No. 8, Aug. 2018, pp. 3097-3111.

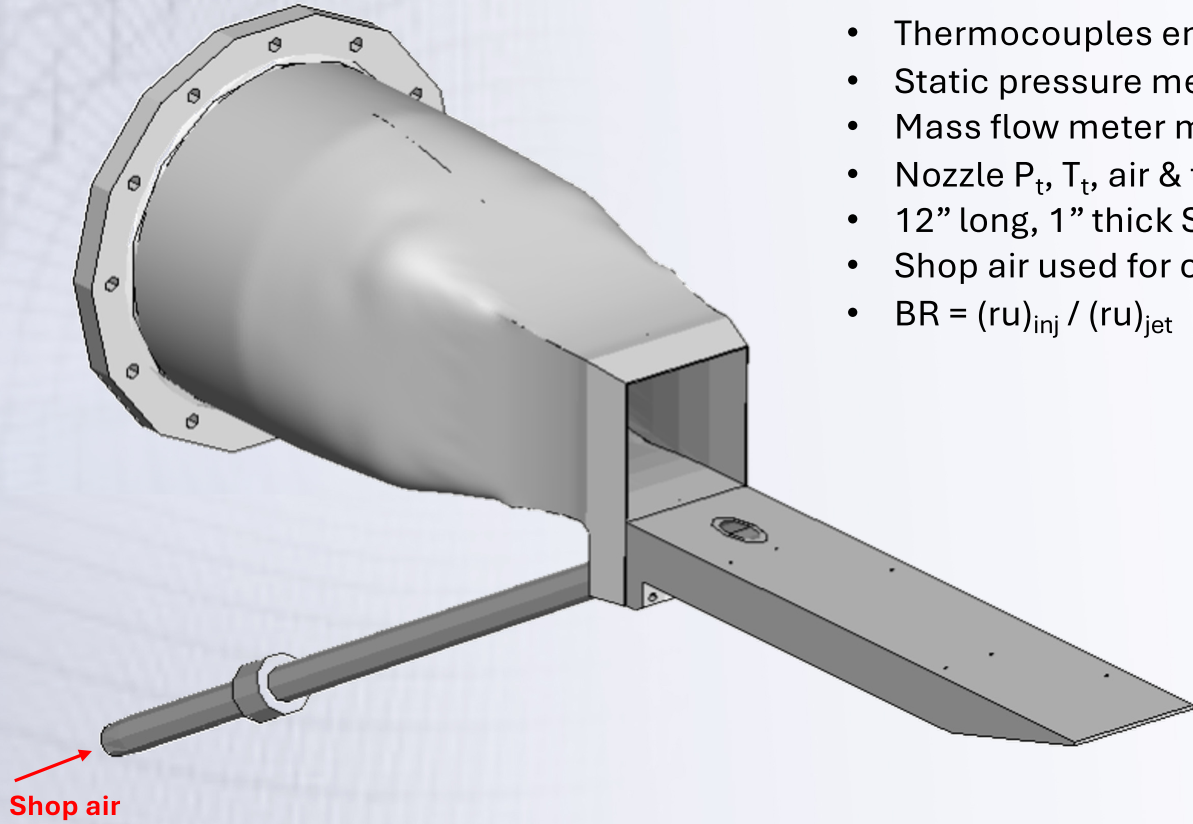


# Off-Body Measurements for THX Experiments

- Background Oriented Schlieren (BOS)
  - BOS measurements used to optimize the Raman measurement grid depending on cooling film thickness
- **Raman Scattering *(key new measurement technology developed & demonstrated)***
  - **Molecular scattering technique for measuring the gas temperature**
  - **Composition of the gas is known, only interested in temperature**
  - **Measure both the mean and rms temperature**
  - **Measurements at a single point**
  - **See the following publications for details of the technology development of this Raman scattering technique:** Locke, R. J., Wernet, M. P., Anderson, R. C., "Rotational Raman-Based Temperature Measurements in a High-Velocity Turbulent Jet," *Measurement Science Technology*, Vol. 29, No. 1, Dec. 2017, pp. 1-16, https://doi.org/10.1088/1361-6501/aa934d.
- Particle Image Velocimetry (PIV)
  - Streamwise plane of 2-component measurements
  - Cross-stream planes of 3-component measurements
  - Planar measurements

# THX Phase 3 – Single Cooling Hole

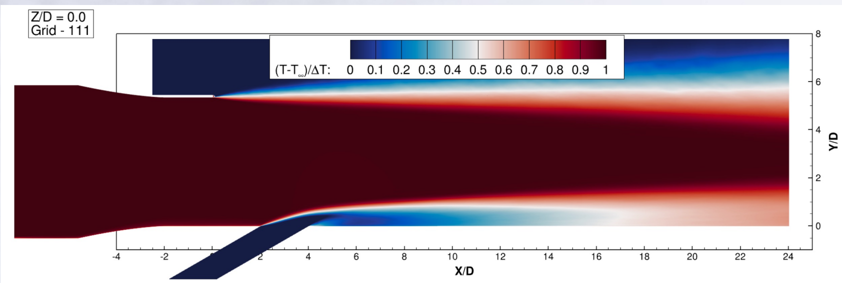



- Thermocouples embedded in plate surface
- Static pressure measured in cooling flow tube
- Mass flow meter measured injector flow
- Nozzle $P_t$, $T_t$, air & fuel flow rates measured upstream
- 12” long, 1” thick SS deck
- Shop air used for cooling flow
- $BR = (ru)_{inj} / (ru)_{jet}$

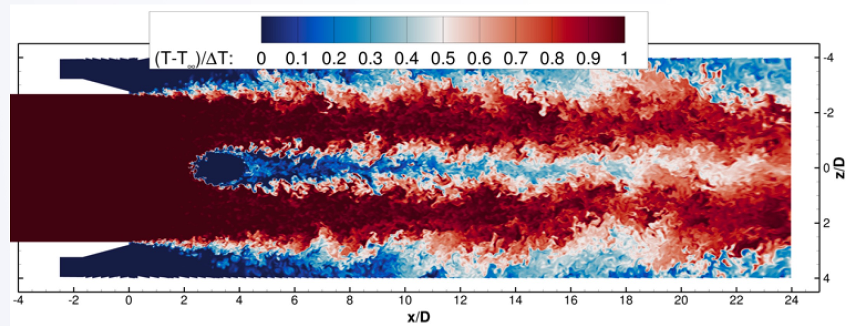
# THX Phase 3 – Single Cooling Hole

- Computational simulations obtained with GFR and FDL3DI, using WRLES; FUN3D using SSG-LRR RSM RANS.
- Comparisons of mean and RMS velocities and temperatures to experimental measurements.

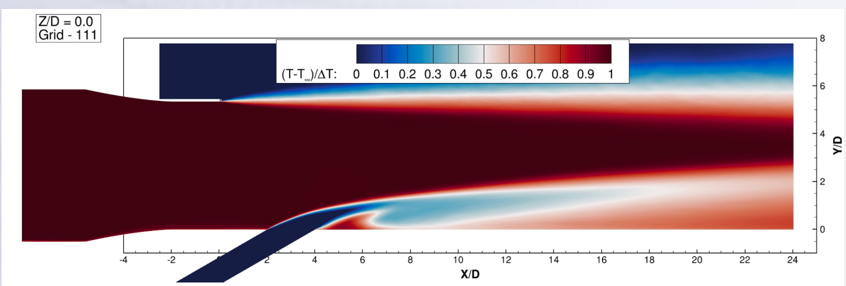
## FDL3DI, BR = 1



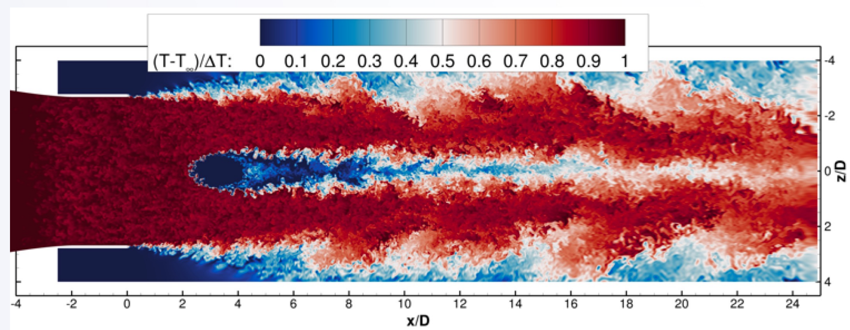

## GFR, BR = 1, y/D = 0.1



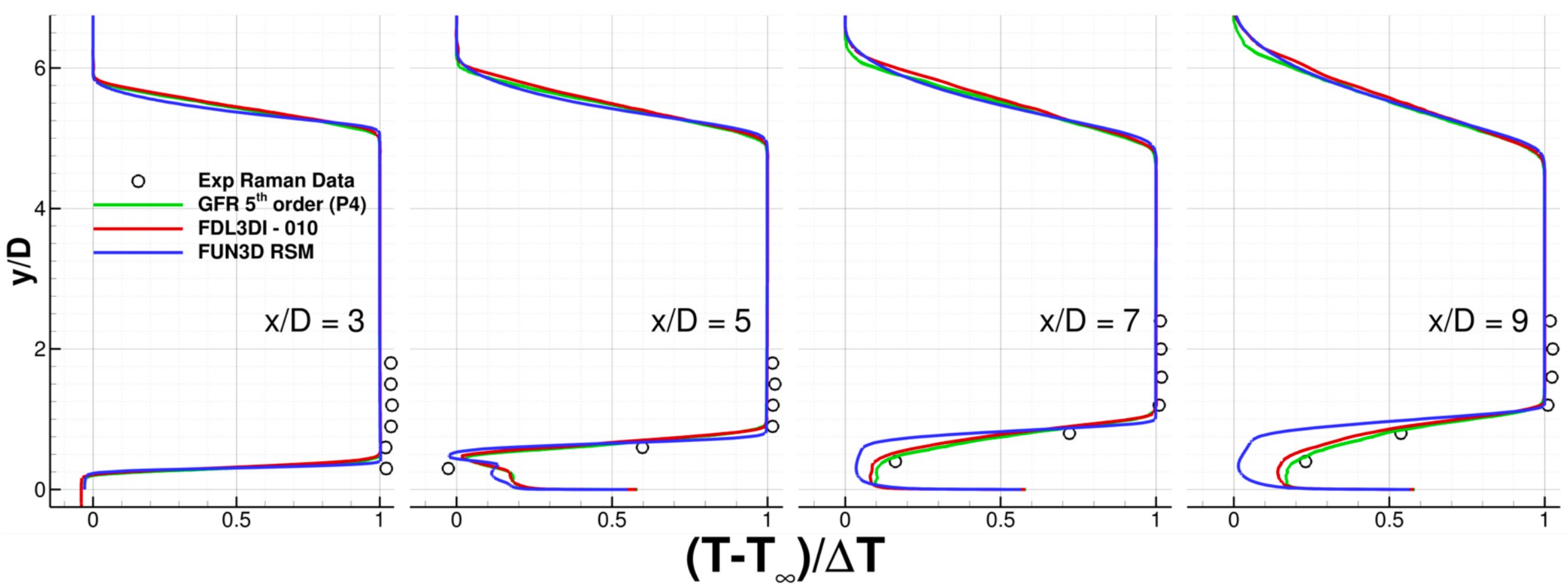

## FDL3DI, BR = 2




## FDL3DI, BR = 1, y/D = 0.1



# THX 3 – Temperature Comparisons for BR = 1



# THX 3 – Turbulent Heat Flux for BR = 1

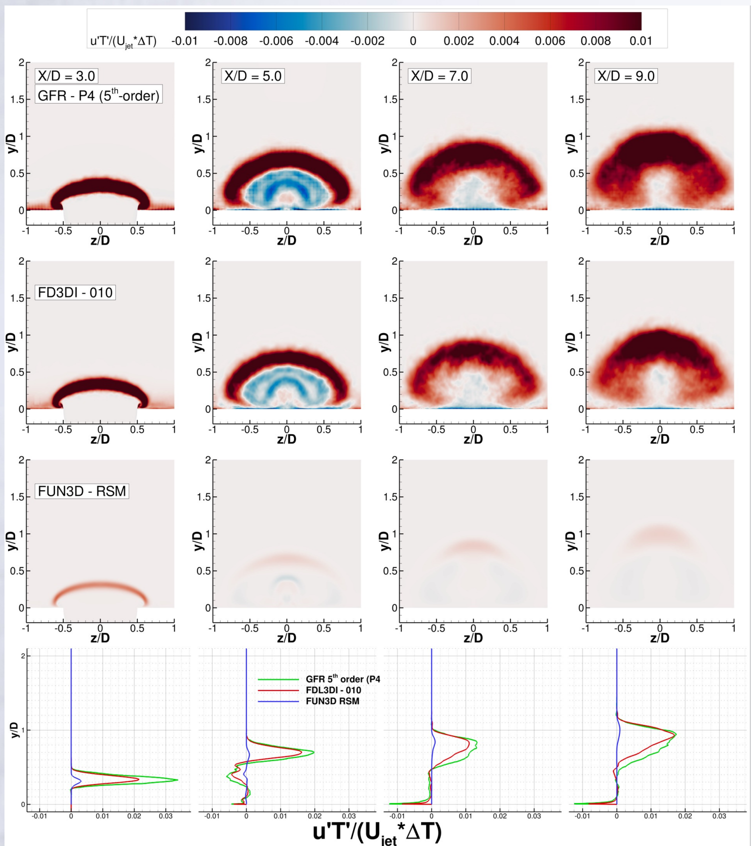
u'T'

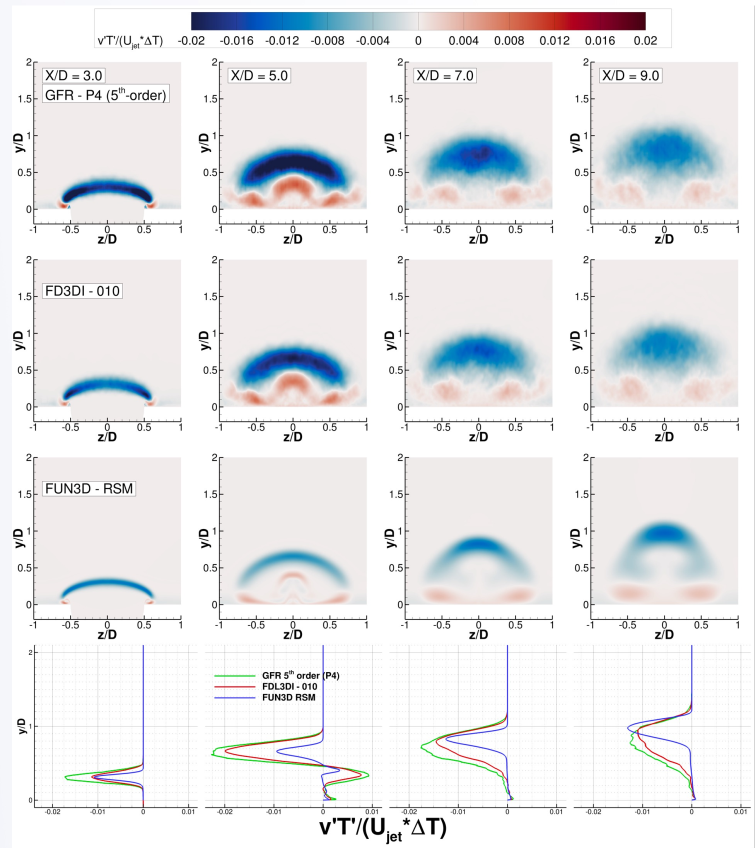
v'T'

GFR - WRLES

FDL3DI - WRLES

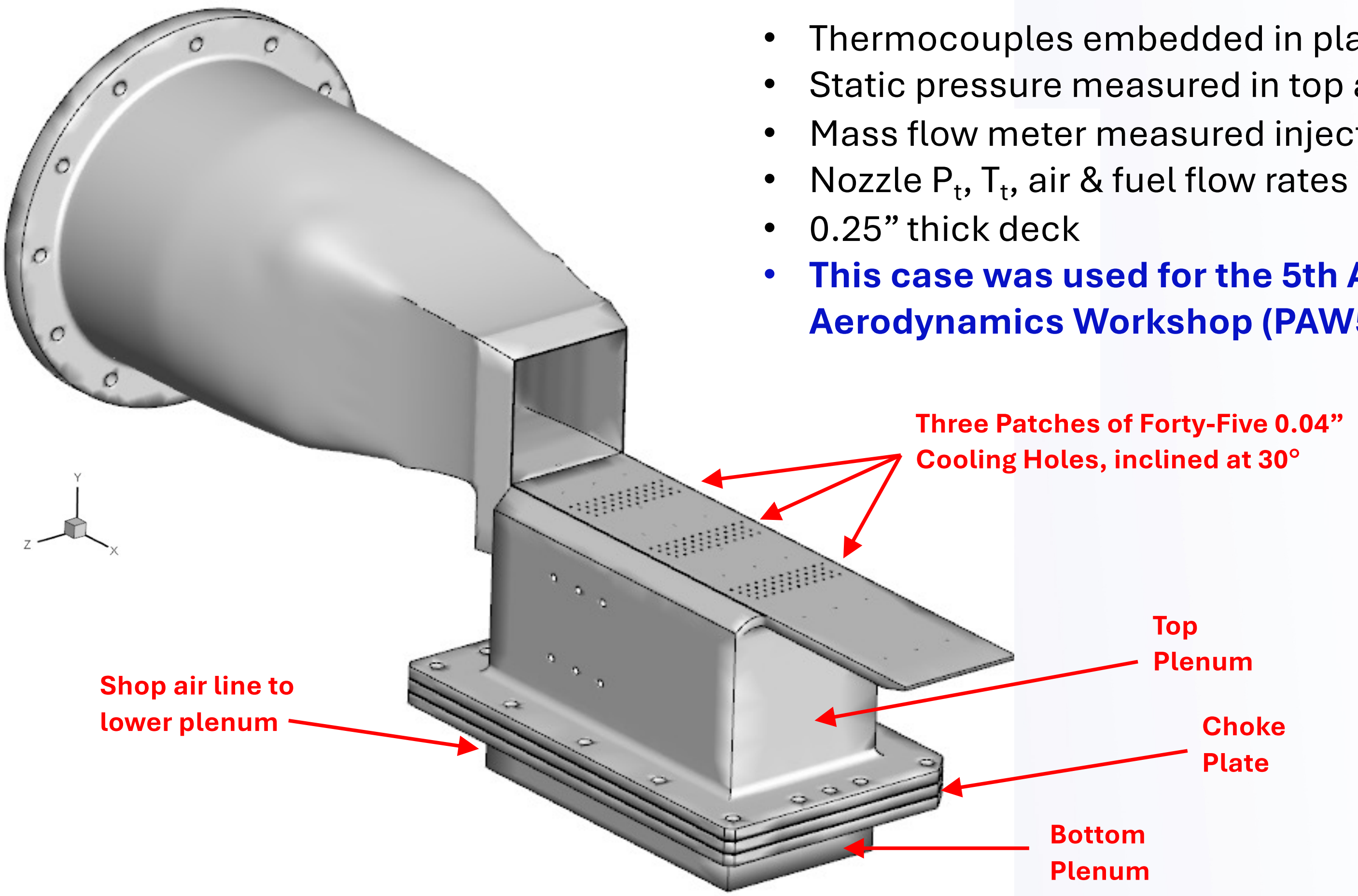
FUN3D – RANS, RSM



# THX Phase 4 – Porous Plate Geometry

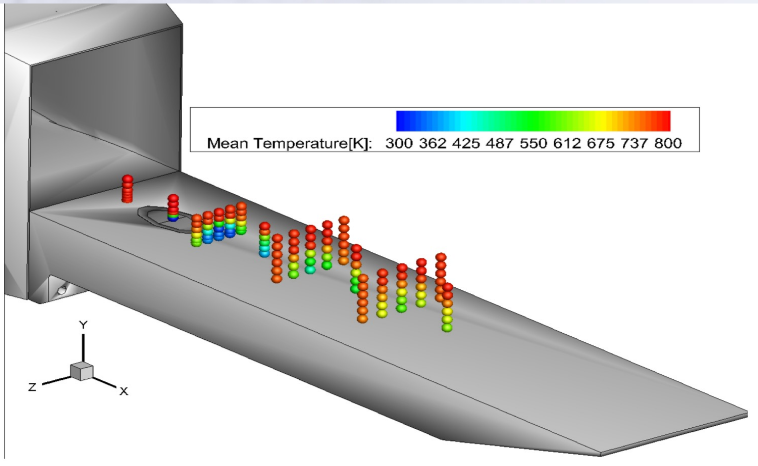
- Thermocouples embedded in plate surface
- Static pressure measured in top and bottom plenums
- Mass flow meter measured injector flow
- Nozzle $P_t$, $T_t$, air & fuel flow rates measured upstream
- 0.25” thick deck
- **This case was used for the 5th AIAA Propulsion Aerodynamics Workshop (PAW5).**



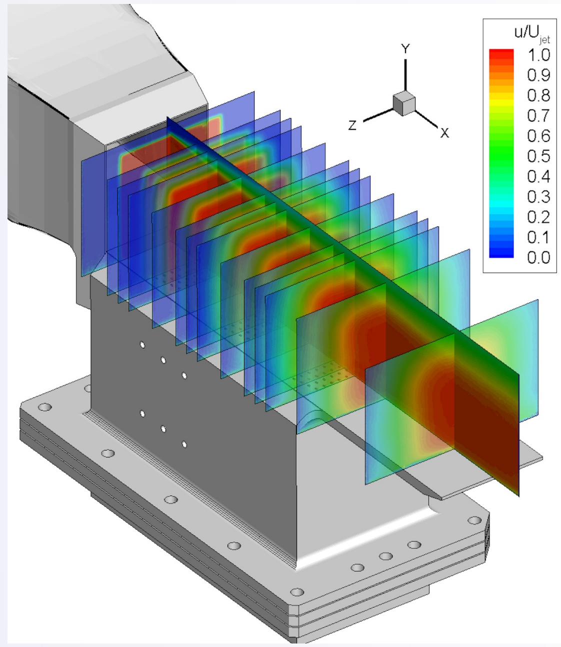
# THX – Phases 3 & 4

- **Sample experimental measurements:**

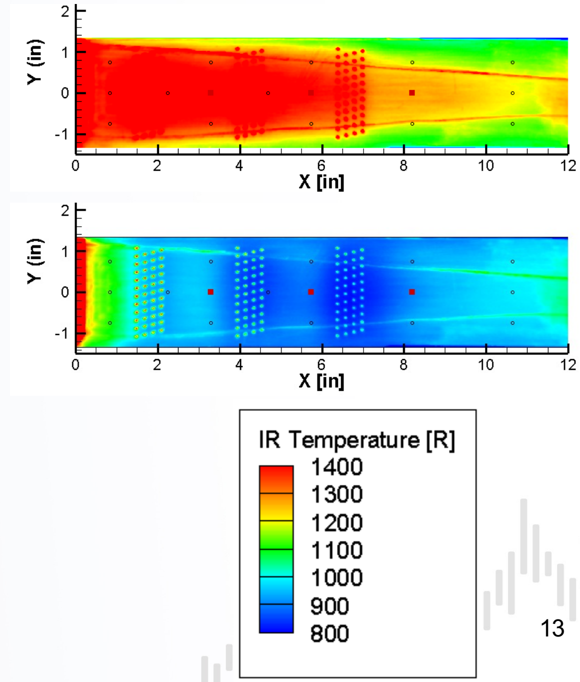
THX 3: Raman temperature measurements (mean and rms)



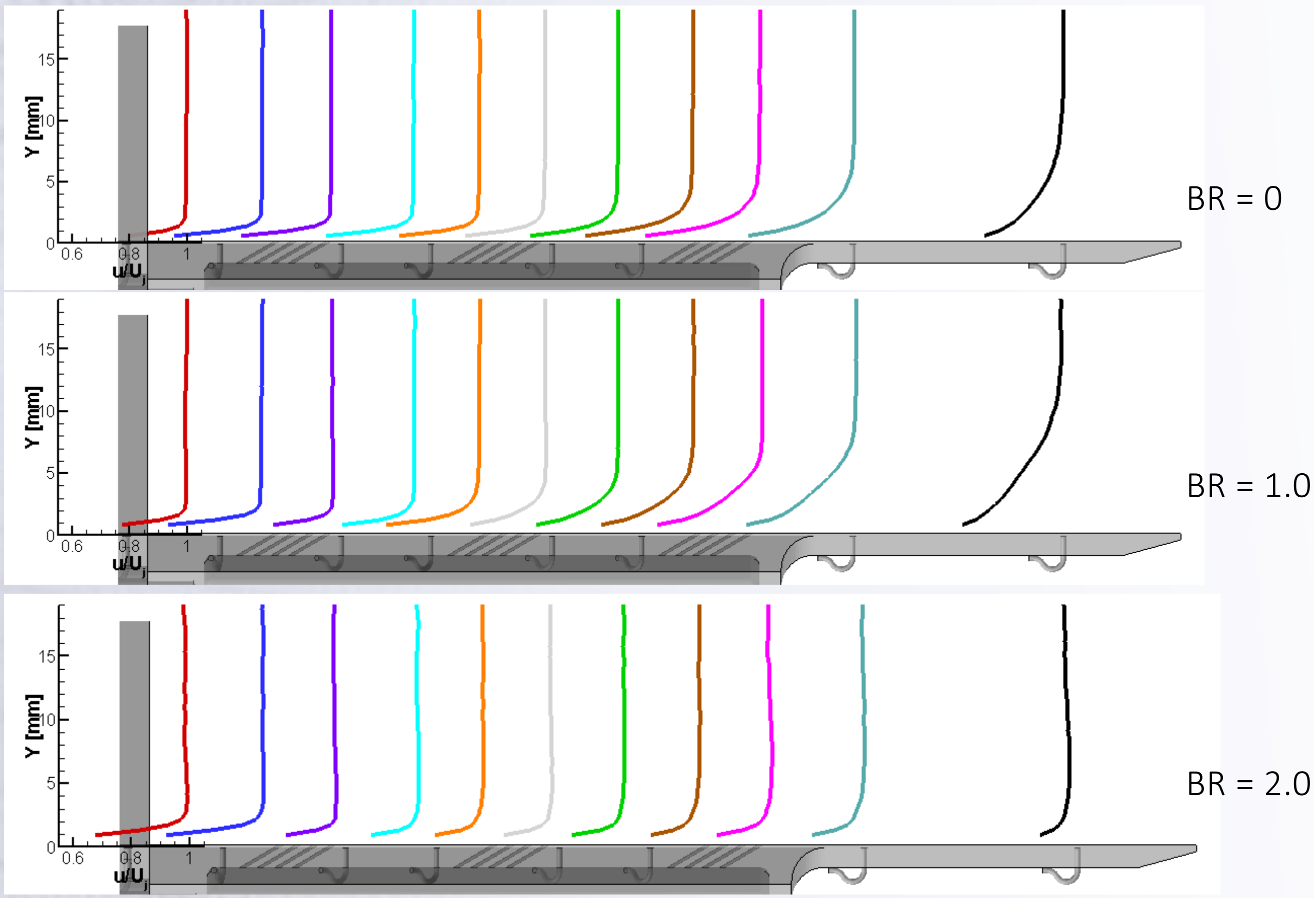

THX 4: PIV velocity measurements (mean and rms)

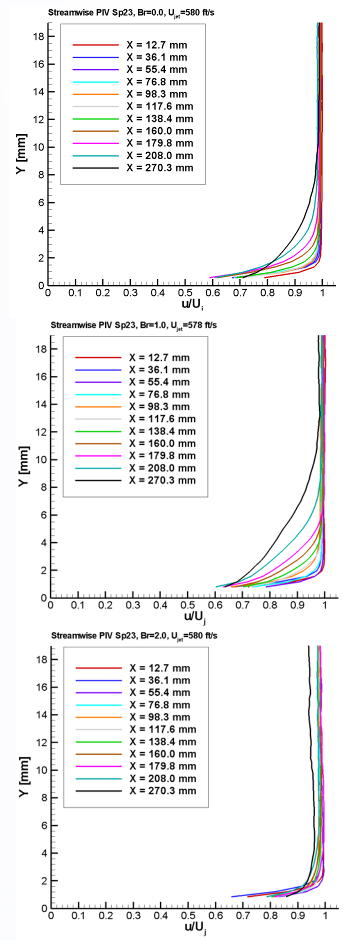



THX 4: Surface IR temperature measurements

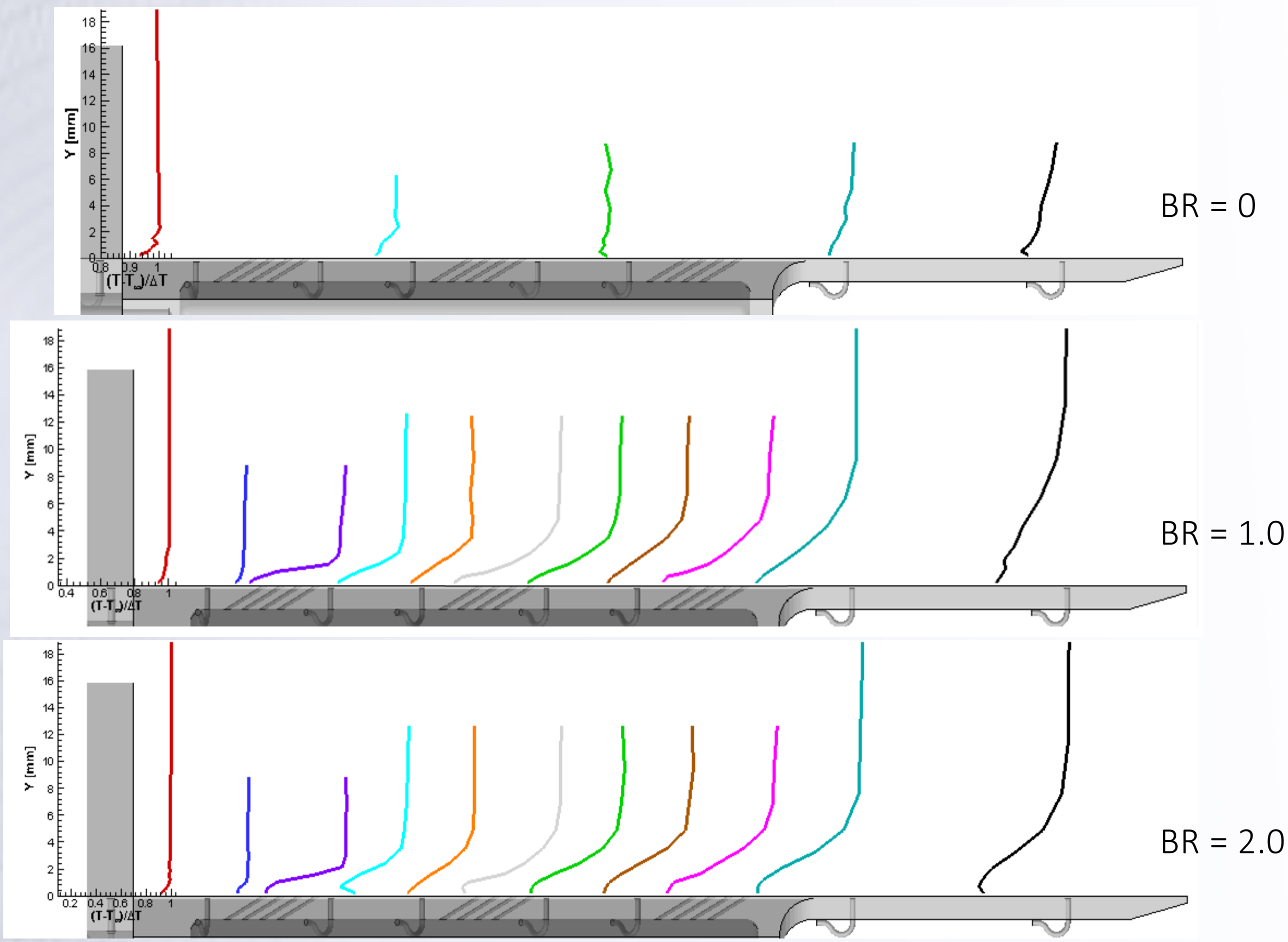


# Mean Axial Velocity – THX 4: Set Point 23, Mach 0.38, ΔT = 233K

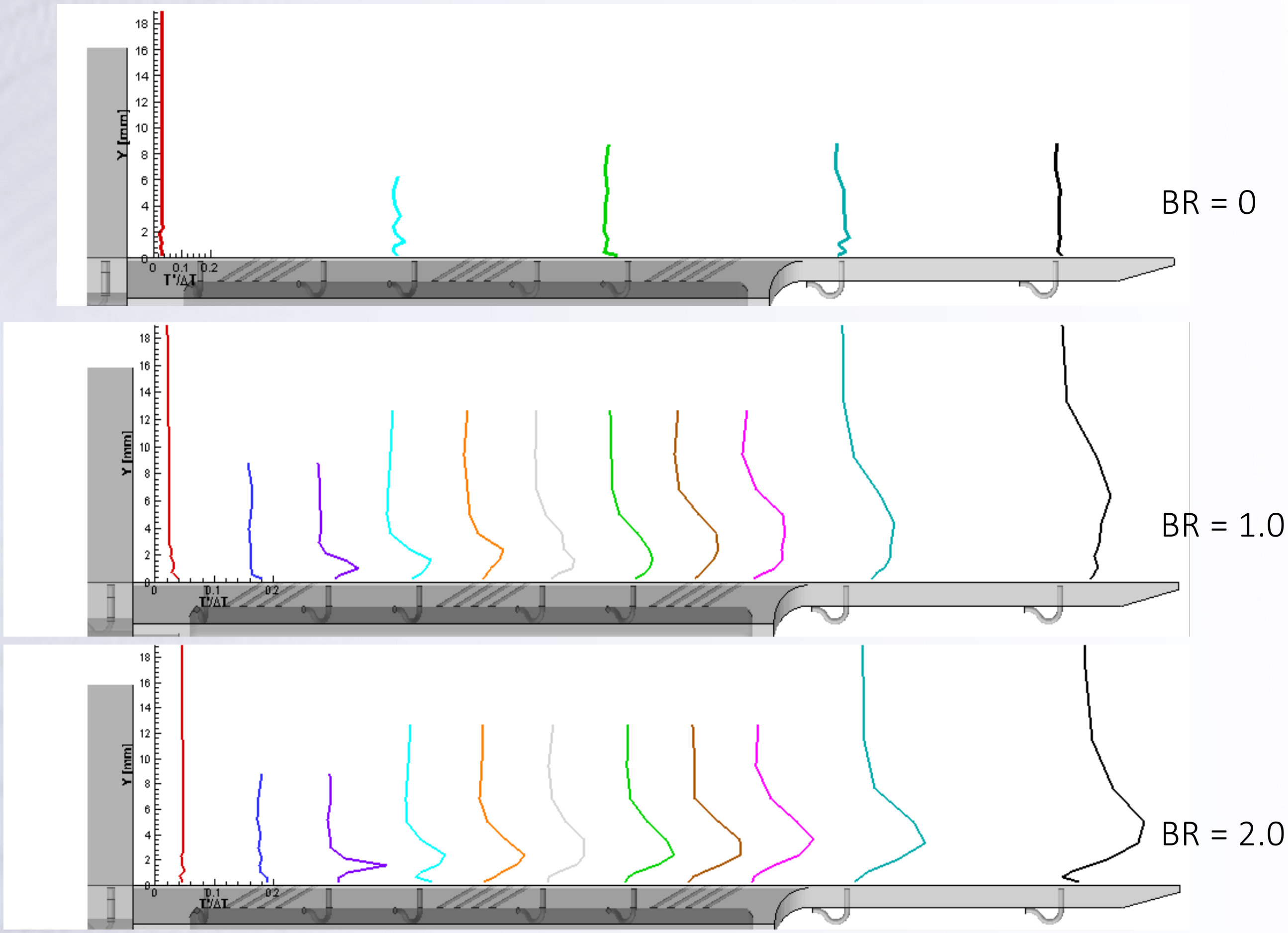


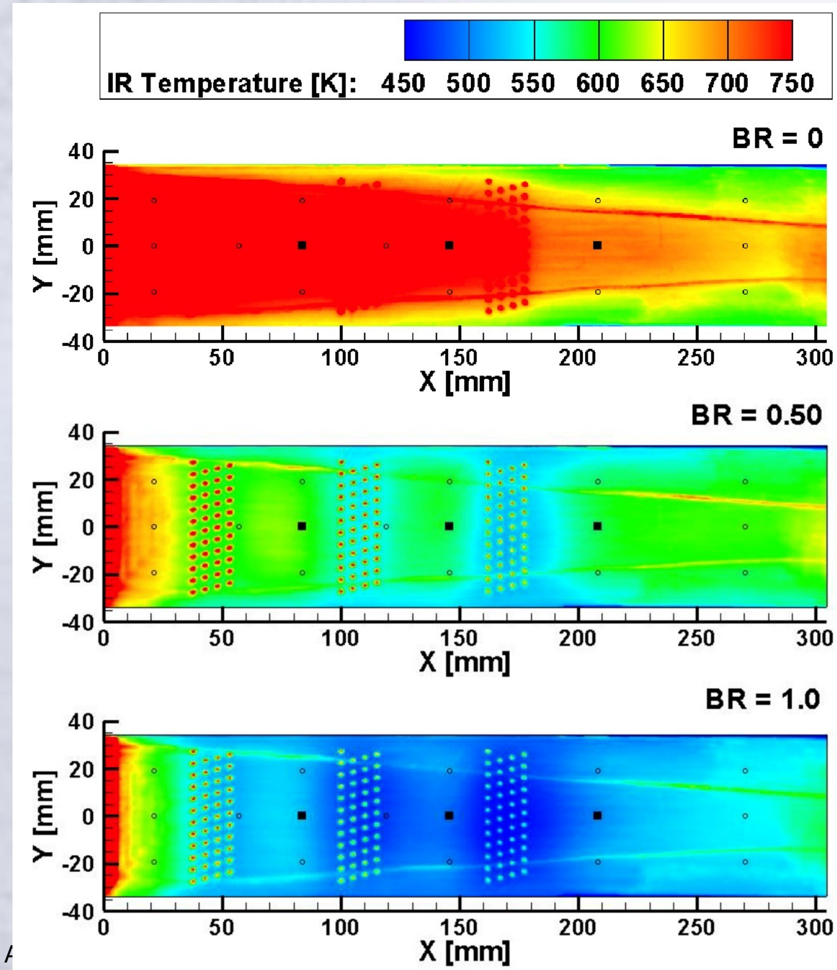
# Mean Temperature – THX 4: Set Point 23, Mach 0.38, ΔT = 233K



# RMS of Temperature – THX 4: Set Point 23, Mach 0.38, ΔT = 233K



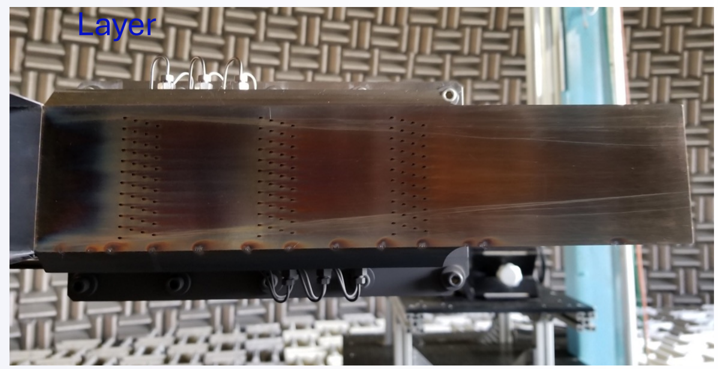
# Raw IR Surface Temperature Measurements




FLIR SC655 infrared camera

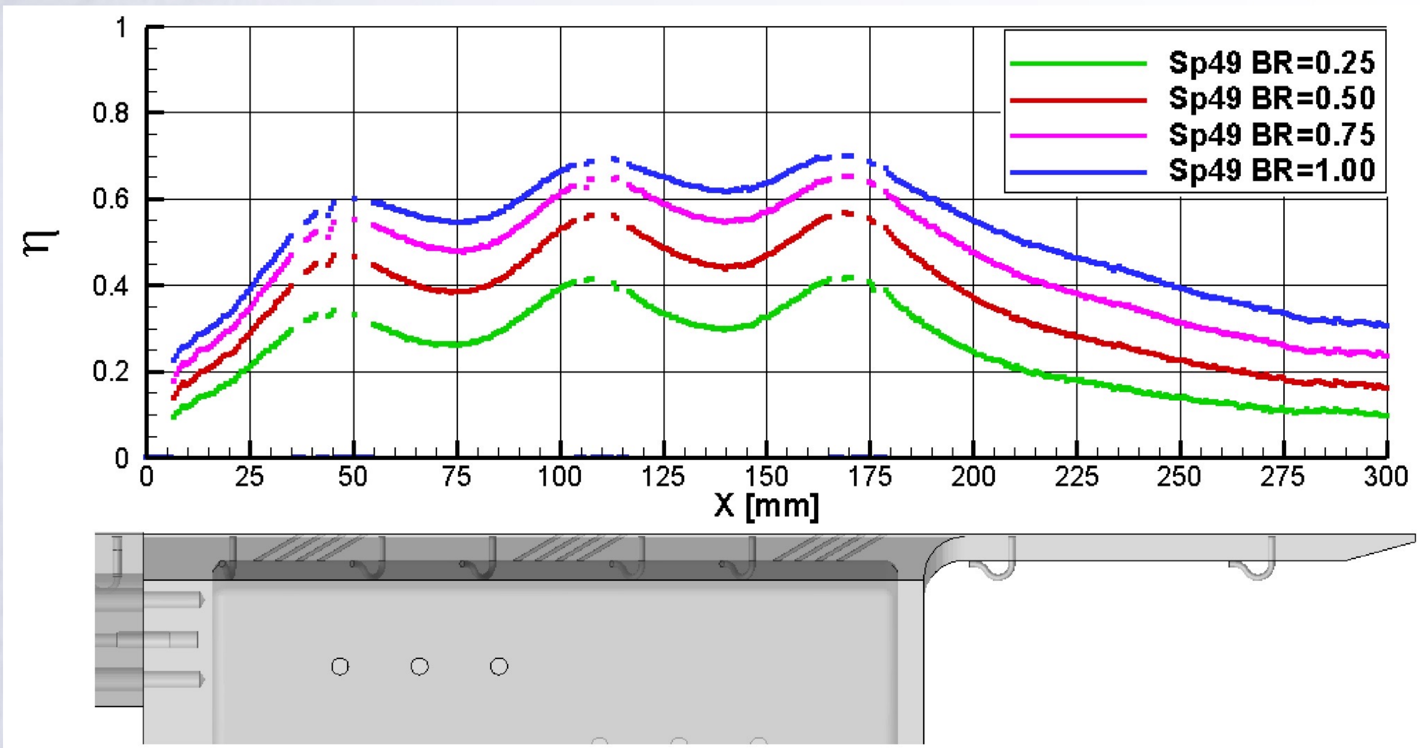
- 640 x 480 pixels (roughly 0.024”/pixel)
- Stainless steel plate not painted black
- Emissivity of surface was nominally 0.2

Plate Discoloration due to Jet Shear Layer

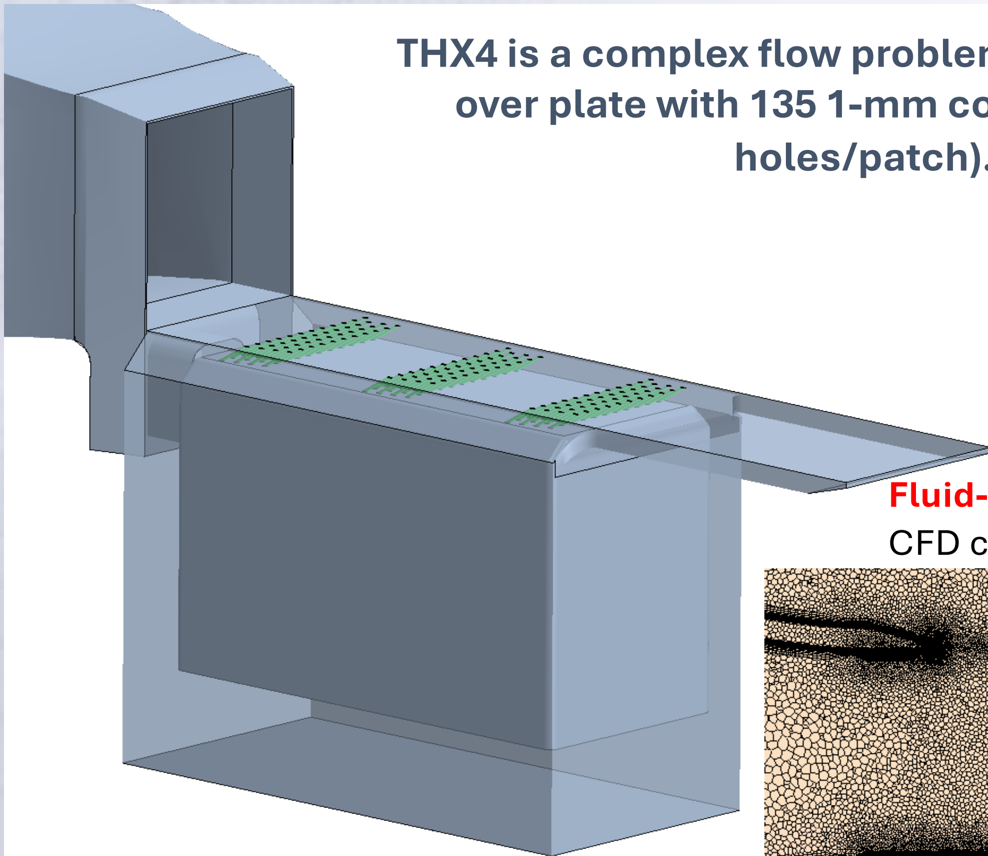


# Centerline Film Cooling Effectiveness: THX 4

$$\eta = \frac{T_{Br=0} - T_{Br}}{T_{Br=0} - T_{Plenum}}$$

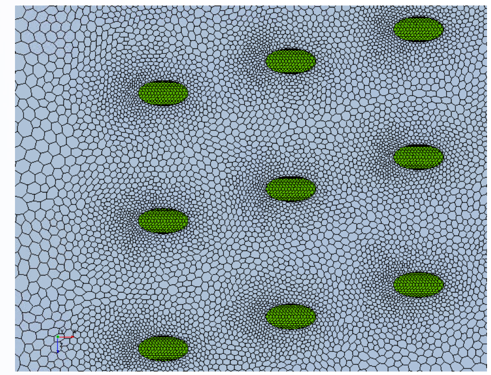


# THX4 Model Geometry & Flow Problem Setup

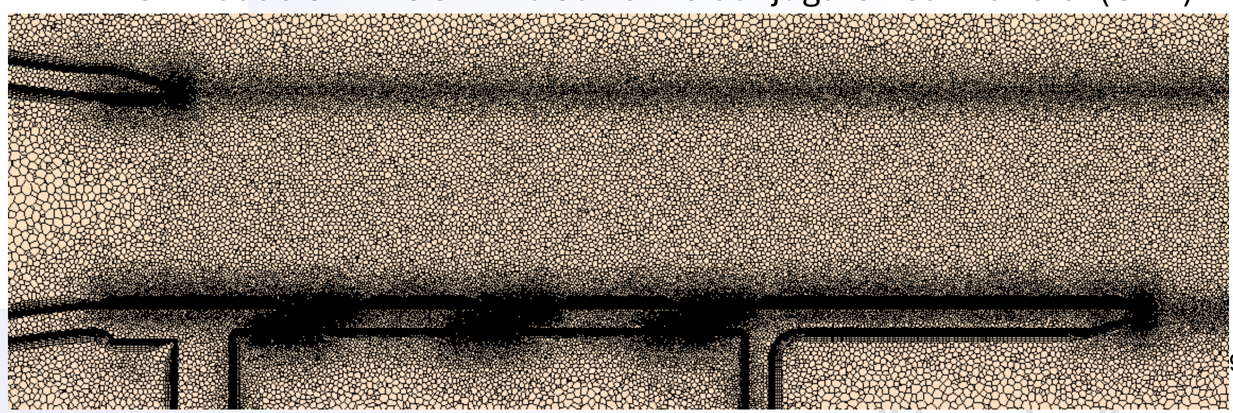


**THX4 is a complex flow problem: hot jet exhaust over plate with 135 1-mm cooling holes (45 holes/patch).**

***Looking down on plate:***



**Fluid-Solid conformal polyhedral grid created** in commercial CFD code STAR-CCM+ to solve the conjugate heat transfer (CHT)



# THX4: RANS Cases

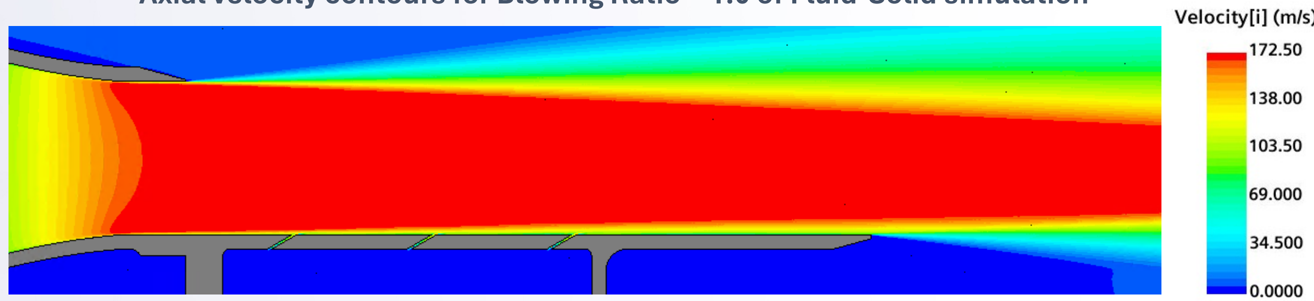
- RANS SST simulation of **complete** Phase 4 configuration

- Modeling Approaches:
  1. Fluid-only (adiabatic wall)
  2. Fluid-Solid (CFD-CHT)

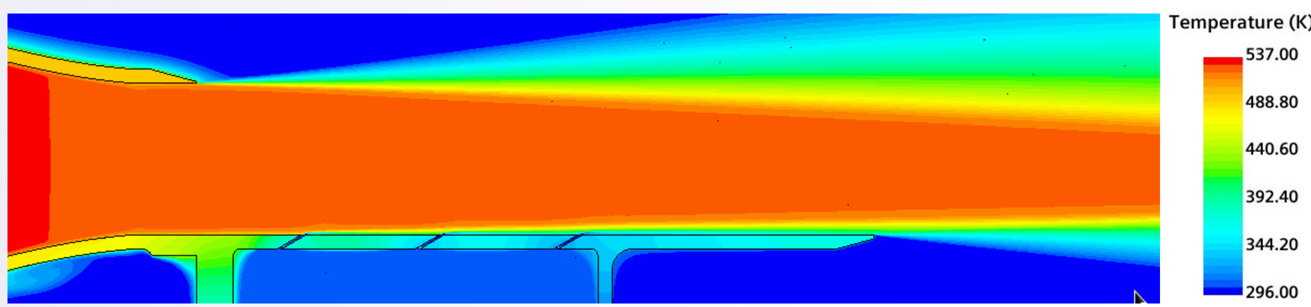
- CFD-CHT not a "typical" standard practice – complexity and cost.

- CFD-CHT examined here – due to potential to improve prediction of both (1) fluid flow and (2) temperatures of structure.

Axial velocity contours for Blowing Ratio = 1.0 of Fluid-Solid simulation

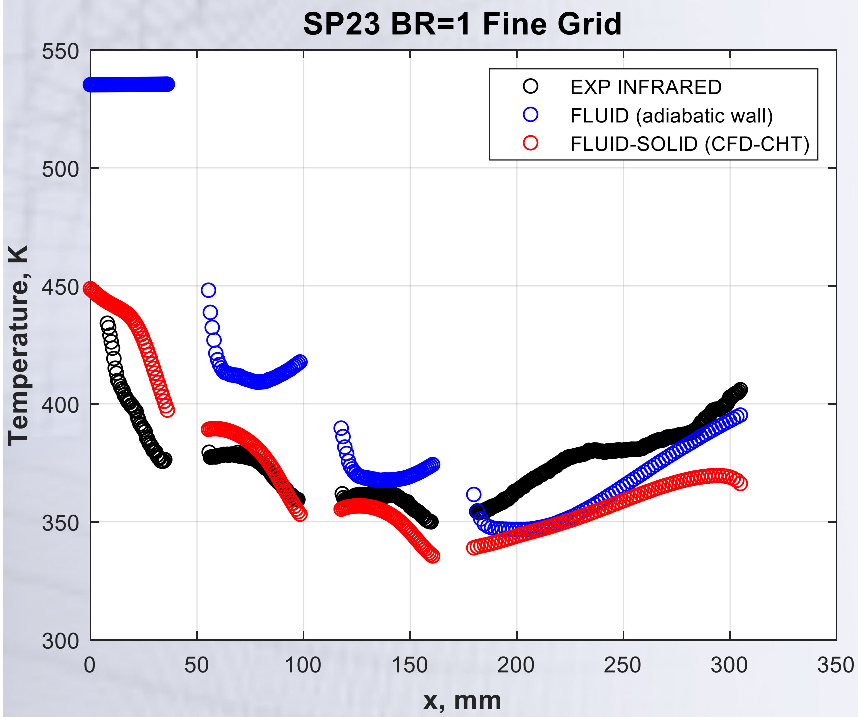


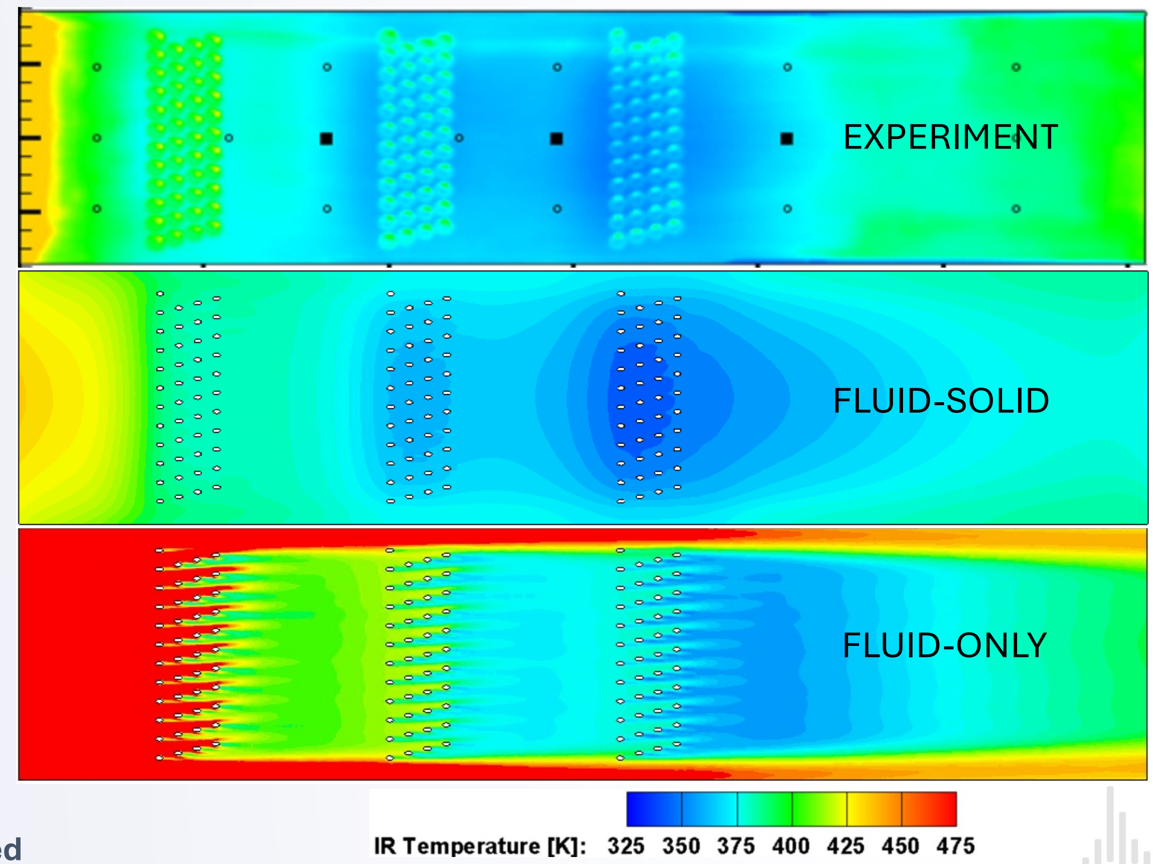

Temperature contours for Blowing Ratio = 1.0 of Fluid-Solid simulation




| Grid | Fluid-only # cells | Fluid-Solid # cells | Blowing Ratio | # Cores | Numerical Scheme |
|---|---|---|---|---|---|
| Coarse | 26.3 million | 29.9 million | 0.0, 1.0, 2.0 | 4,200 | 2$^{nd}$ order upwind |
| Medium | 70.3 million | 78.9 million | 1.0 | 4,200 | 2$^{nd}$ order upwind |
| Fine | 143.3 million | 143.3 million | 1.0 | 5,600 | 2$^{nd}$ order upwind |
| XFine | N/A | 321.4 million | 1.0 | 5,600 | 2$^{nd}$ order upwind |

# THX4 RANS Centerline Surface Temperature



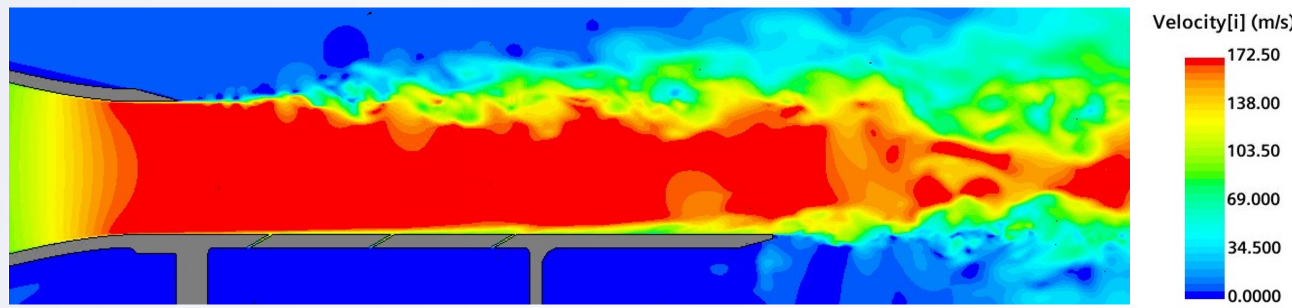




<u>**LESSON LEARNED / BEST PRACTICE**</u>**: Thermally coupled CFD-CHT significantly improves surface temperature prediction.**

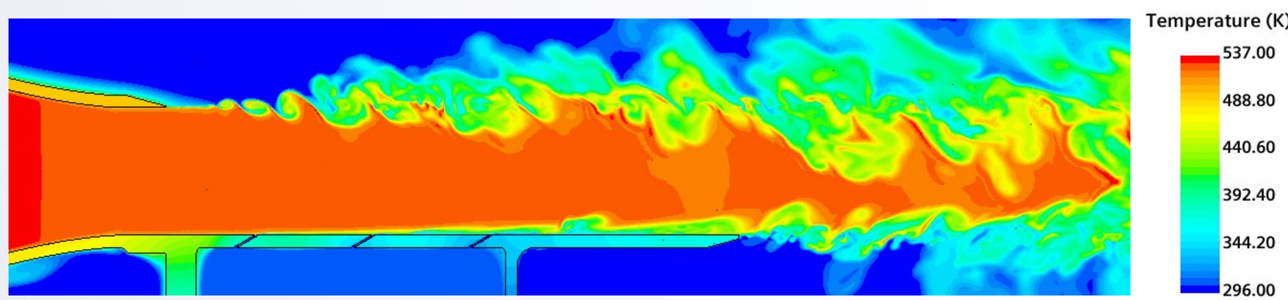
# THX4: SRS (hybrid RANS-LES) Cases

- Per THX3 simulations, WRLES was prohibitively expensive.
- Scale-Resolved Simulation (SRS) of complete Phase 4 configuration completed using hybrid RANS-LES: 320 M points.
- Delayed Detached Eddy Simulation (DDES) technique successfully used within CFD-CHT model framework

Instantaneous axial velocity contours for Blowing Ratio = 1.0 of Fluid-Solid simulation




Instantaneous temperature contours for Blowing Ratio = 1.0 of Fluid-Solid simulation




| Grid | Fluid-Solid # cells | Blowing Ratio | # Cores | dt | Total Tau Averaged* | Numerical Scheme |
|---|---|---|---|---|---|---|
| Fine | 143.3 million | 1.0 | 5,600 | 1E-6 s | 41 | Hybrid BCD |
| XFine | 321.4 million | 1.0 | 5,600 | 1E-6 s | 42 | Hybrid BCD |

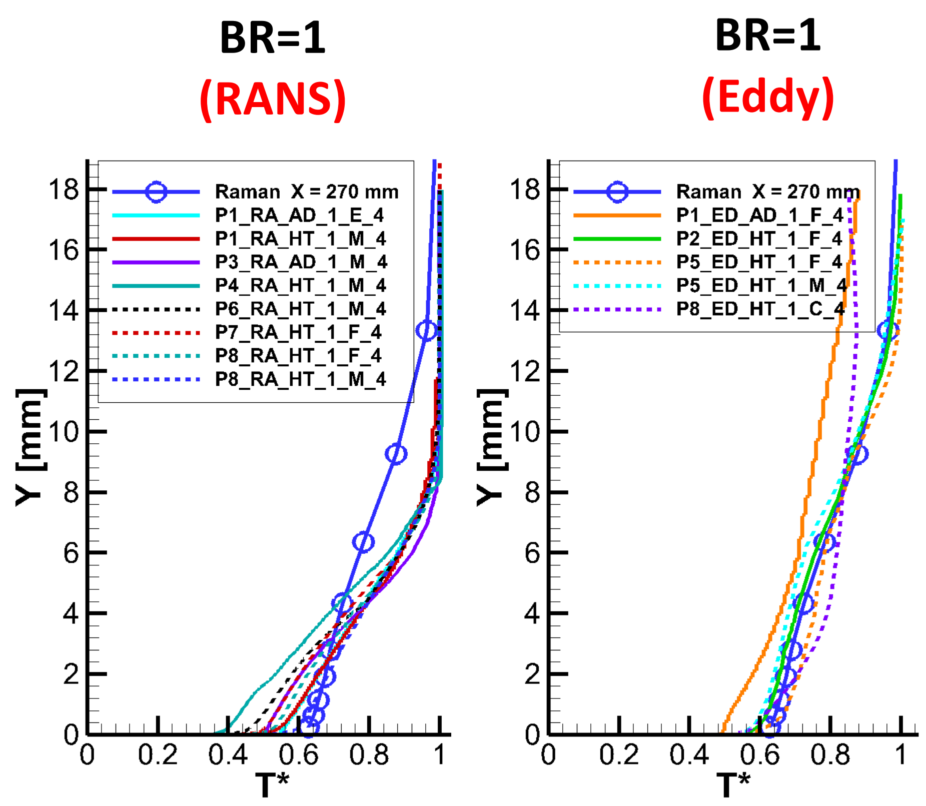
$$*\tau = \frac{U_{jet}}{L_{plate}} t$$

# Temperature Profiles – THX5, x = 270 mm

- **Near end of plate, on overhang.**
- **AD = adiabatic**
- **HT = Conjugate Heat Transfer**
- **RA = RANS**
- **ED = eddy-resolving**

- **KEY OBSERVATION:** - in comparing SRS to RANS – is the difference in temperature profiles. Perhaps indicative of inability of RANS gradient-diffusion capability for modeling thermal transport?

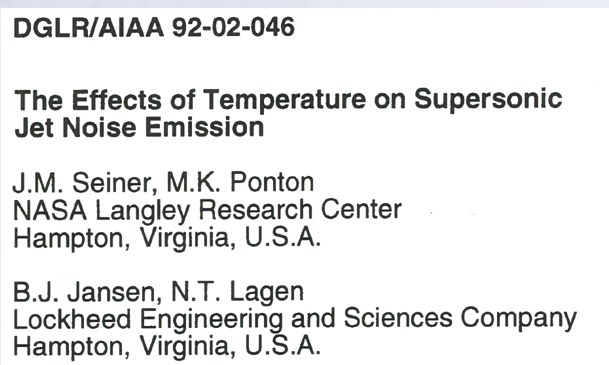
- **These results are from AIAA PAW6 (multiple submissions) summary paper:** Georgiadis, N. J., Wernet, M. P., Crowe, D. S., Woeber, C. D., Karman-Shoemake, K.C., Winkler, C.M., "Assessment of Multiphysics Computations of Flow Over A Film Cooled Plate," *Journal of Thermophysics and Heat Transfer*, Articles in Advance, Mar. 2025, pp. 1-19.



# Background:  THX5 -NASA GRC Supersonic Jet Tests

- The THX5 NASA experiments examined heated supersonic round jets.
- Experiments of Seiner et al. for a Mach 2.0 nozzle were used as the starting point.
- ***The goal of this test program was to provide modern validation quality data for high temperature supersonic jets where compressibility and jet heating impact the jet mixing rate.***

*AIAA 92-02-046*


DGLR/AIAA 92-02-046

**The Effects of Temperature on Supersonic Jet Noise Emission**

J.M. Seiner, M.K. Ponton
NASA Langley Research Center
Hampton, Virginia, U.S.A.

B.J. Jansen, N.T. Lagen
Lockheed Engineering and Sciences Company
Hampton, Virginia, U.S.A.

**Centerline Velocity Decay from Seiner Experiments**

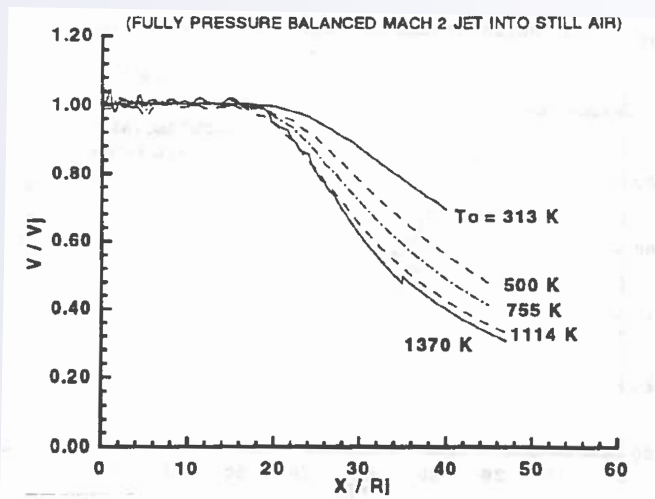
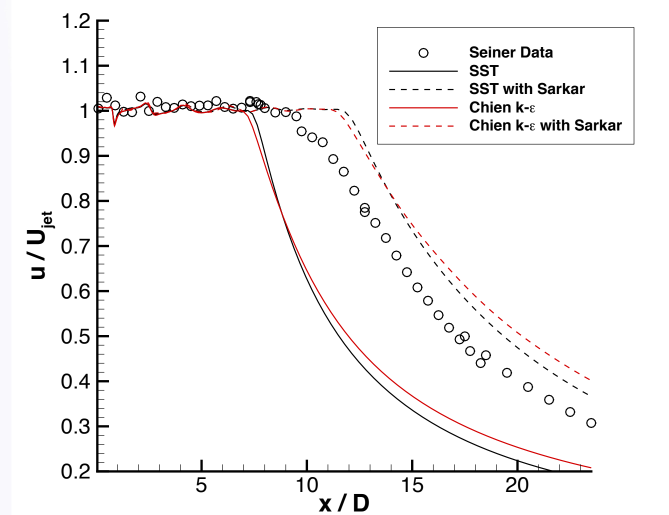



Figure 6. Centerline velocity decay with jet temperature.

**Typical RANS CFD Result & Comparison with Seiner Data**



# THX 5 – Supersonic Jet Experiments

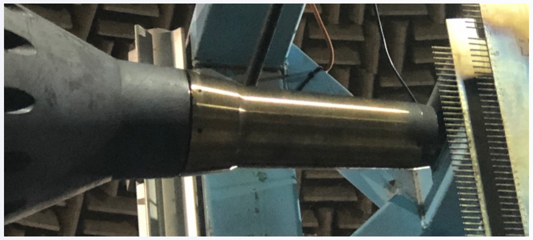
**TEST MATRIX:**

- Test program conducted in GRC Aeroacoustic Propulsion Laboratory (AAPL).
- Test Matrix: Mach 1.36, 1.63, and 2.0 nozzles were investigated at temperatures from unheated up to $T_t$ = 1700° R. Most on-design, 2 off-design test points.

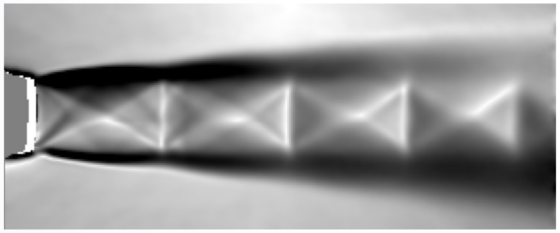
**TEST PROGRAM RESULTS:**

- Background-oriented Schlieren (BOS) and legacy probe measurements were obtained first.
- Streamwise and Cross-stream Particle Image Velocimetry (PIV) used to obtained velocities and turbulent stresses.
- Rotationally Resolved Raman Spectroscopy used to measure mean and rms velocities.
- **This case was used for the 6th AIAA Propulsion Aerodynamics Workshop (PAW6).**

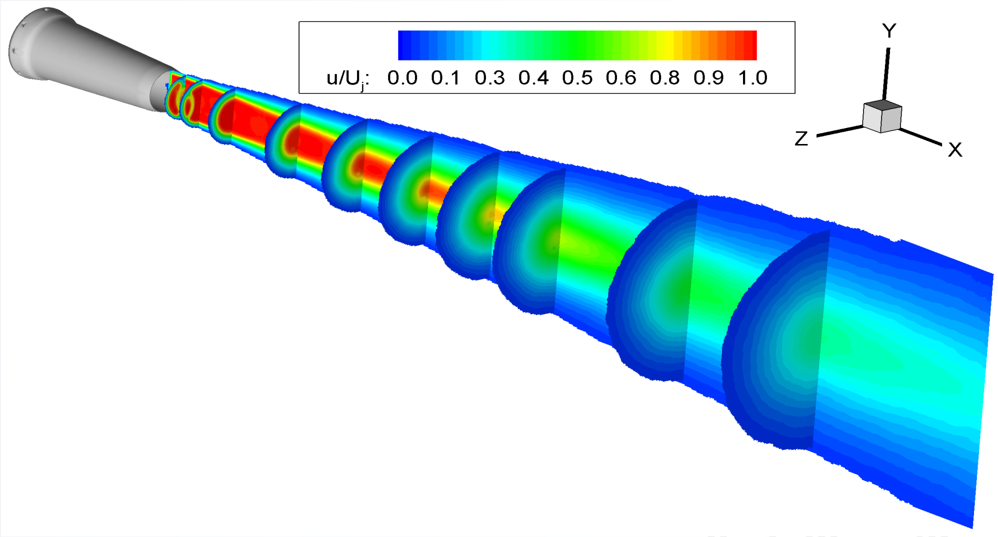
Mach 2.0 nozzle installed in GRC AAPL



BOS image showing shock-cells at off-design test point



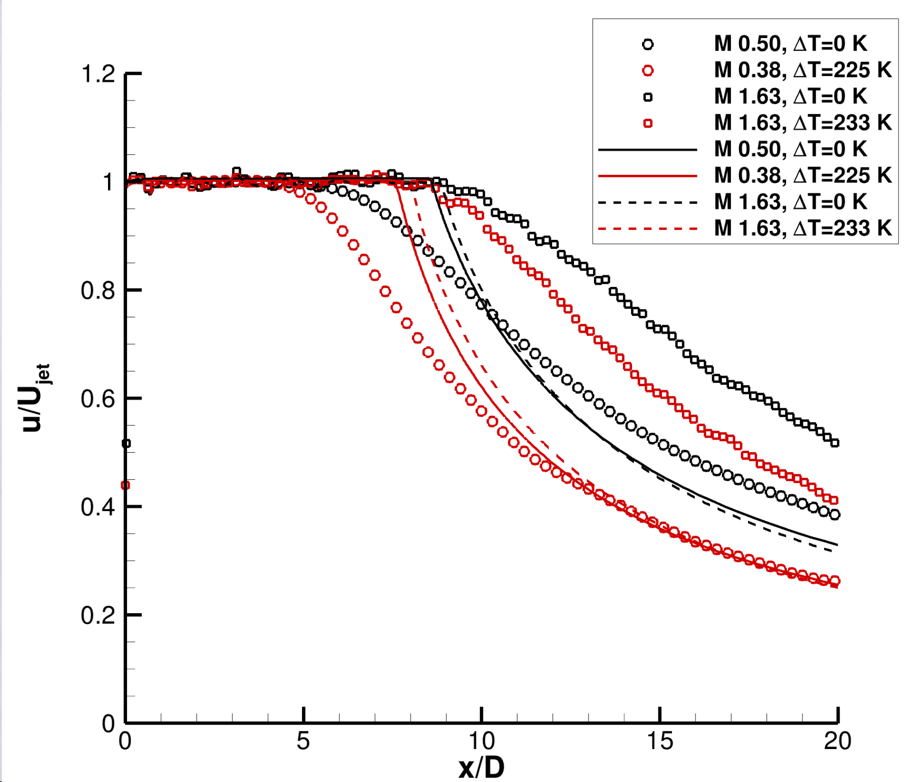
PIV of mean axial velocity



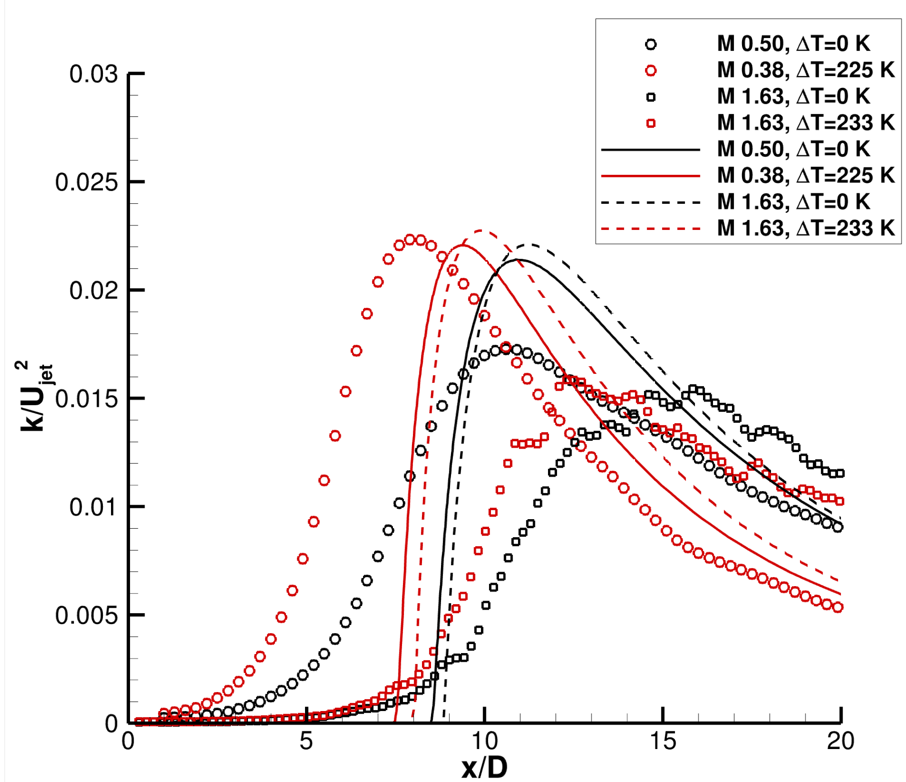
# Typical Subsonic-Supersonic Jets Comparison of Experiment to RANS

*Subsonic data is from Bridges and Wernet (AIAA Paper 2010-3751) – also taken in GRC AAPL, data used on NASA TMR*

**Centerline Velocity**



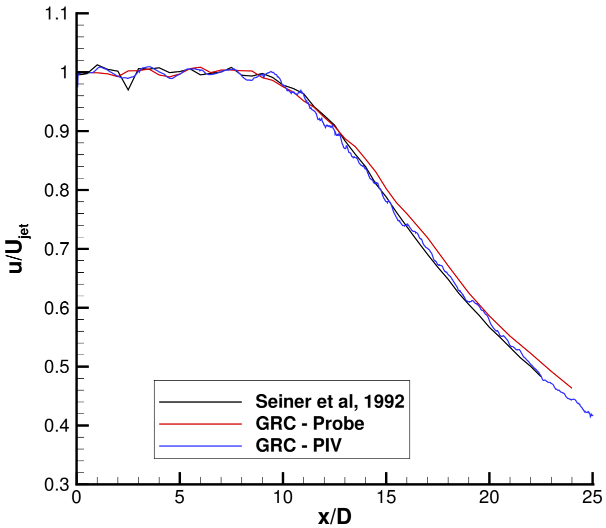

**Centerline TKE**



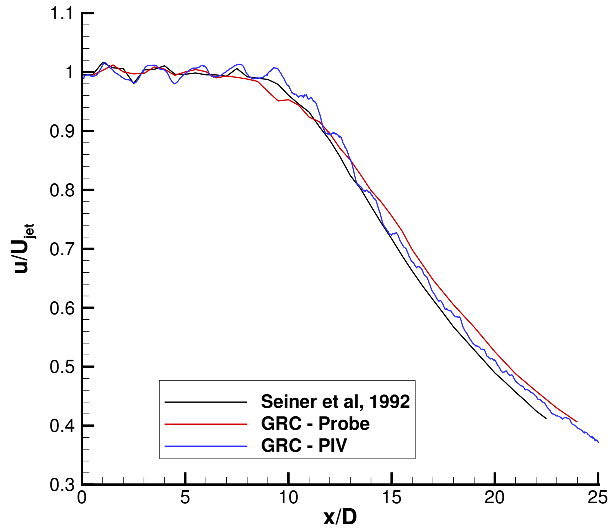
# Mach 2.0 Velocity Comparisons – Seiner to THX5 & Probe to PIV

- $\Delta T = T_{jet} - T_{\infty}$ , 3 matched points between Seiner experiments and current experiments, 2 shown here.
- $\Delta T = 233^{o}$ K represents highest temperature of SHJAR.
- Centerline velocities shown – purpose is to verify that current experiments are consistent with previous well-respected test data set.

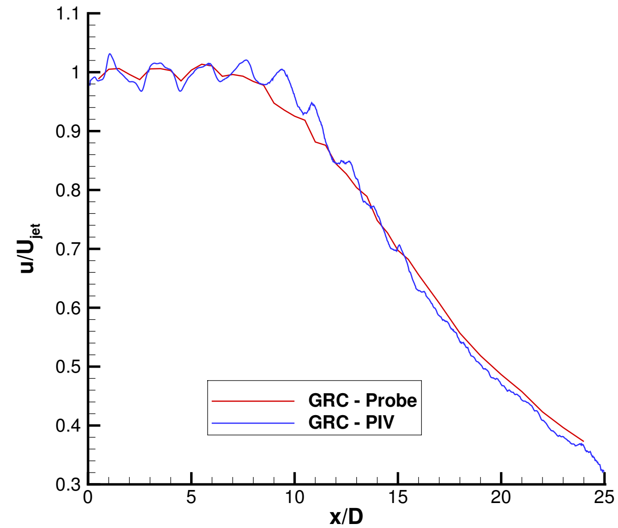
**ΔT = 0º K**




**ΔT = 133º K**



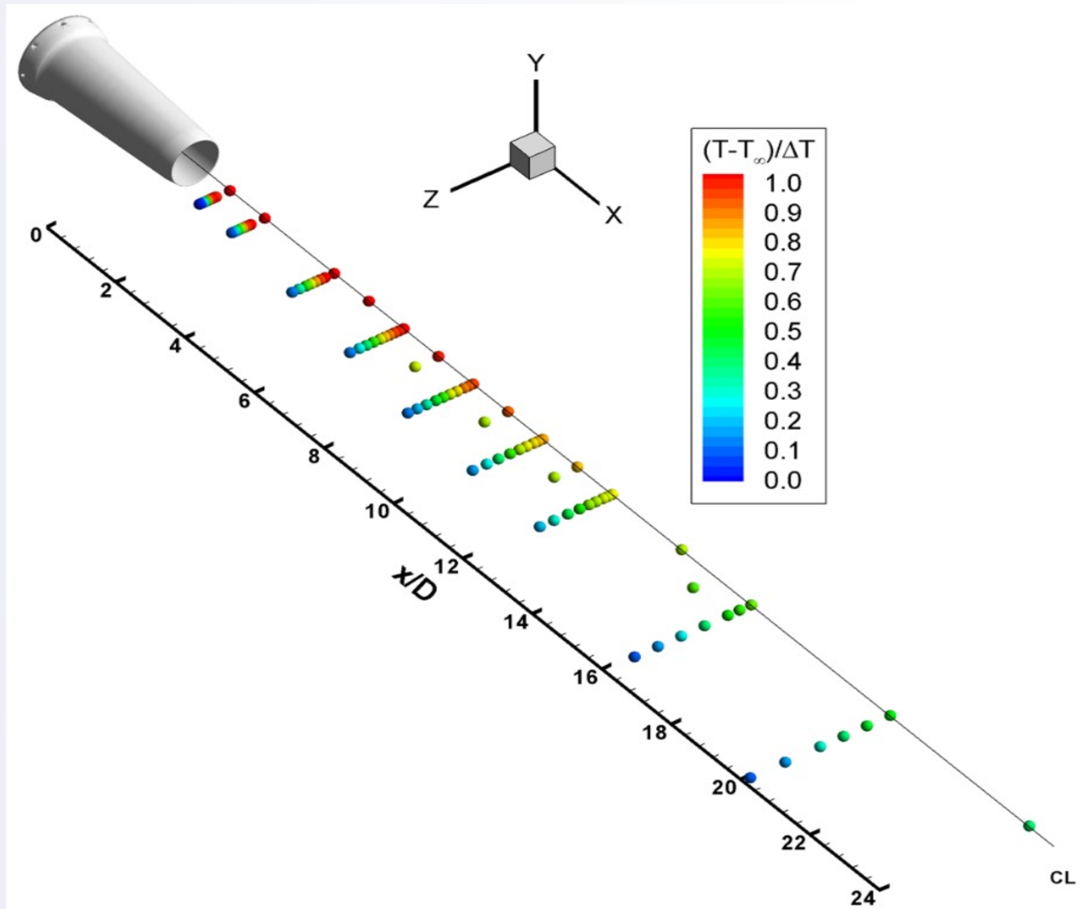

**ΔT = 233º K**



# Typical Raman Spectroscopy Results

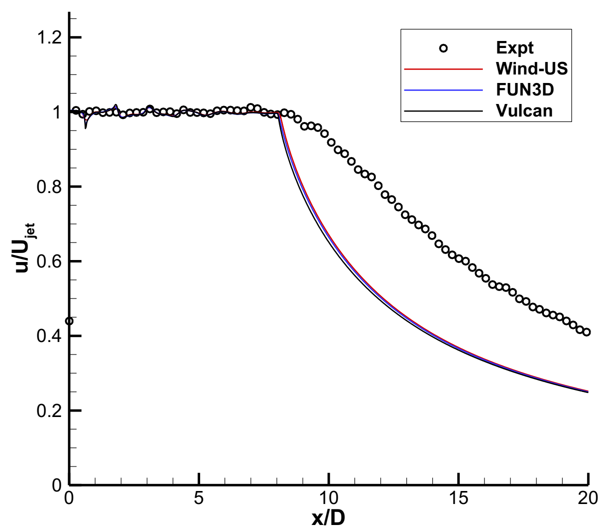
**Raman temperature measurements for Mach 1.36 jet, ΔT = 133° K:**

- **Approximately 125 individual point measurements per set point.**
- **Measurements along centerline (approximately 15 axial stations), lipline, and radial profiles at 9 axial stations.**

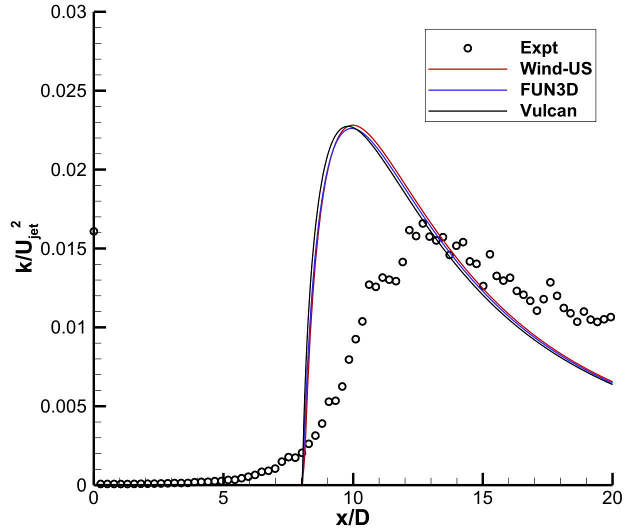


# NASA TMR: Heated Mach 1.63 Jet

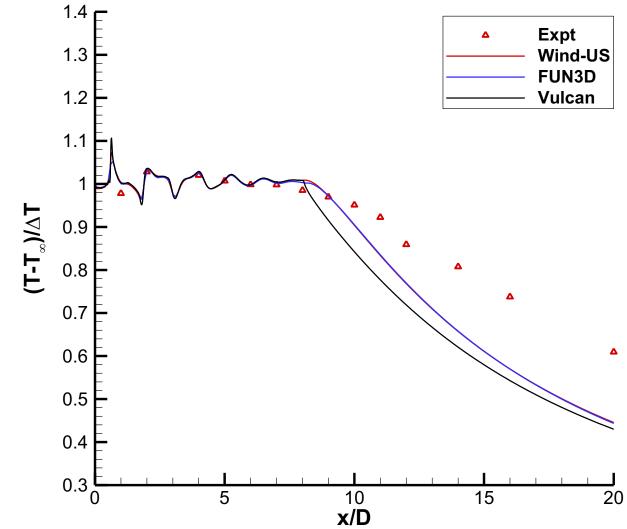
## Centerline Axial Velocity




## Centerline TKE




## Centerline Temperature



# Effect of Turbulent Kinetic Energy on Temperature

The default in many codes is to ignore contribution of turbulent kinetic energy (k) in total energy expression.

**Total energy:**

$$E = C_v T + \frac{1}{2}(\bar{u}^2 + \bar{v}^2 + \bar{w}^2) + k$$

**Temp. Difference due to k:**

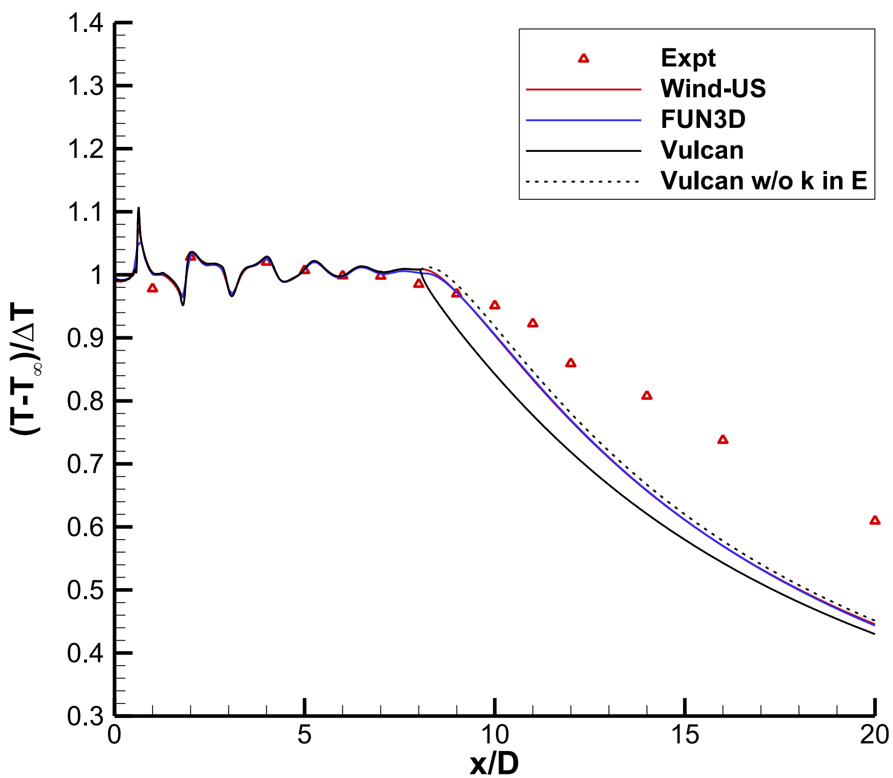
$$\Delta T_k = k(\gamma - 1)/R \cong (k / U_{jet}^2)\gamma(\gamma - 1)M_{jet}^2 T_{jet}$$
$$\cong 0.03\gamma(\gamma - 1)M_{jet}^2 T_{jet}$$

**Maximum effect of k on T (for Mach 1.63):**

$$\frac{\Delta T_k}{T} = k/C_v T \ \text{(maximum)} \cong .045\, T_{jet}/T$$

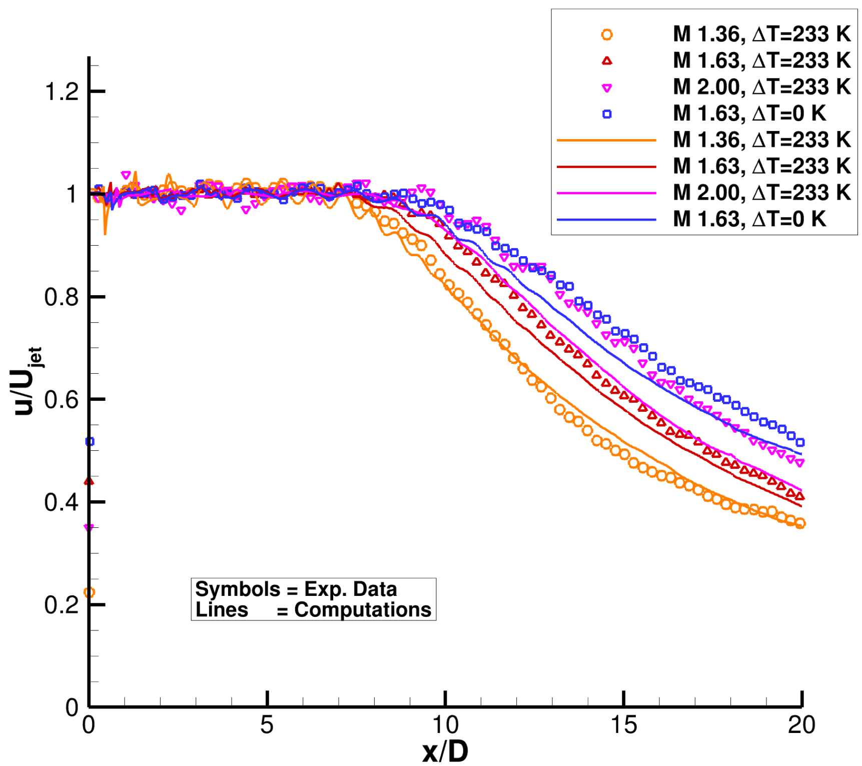
# NASA TMR: Heated Mach 1.63 Jet

**Centerline Temperature – with and w/o TKE consideration in energy equation**

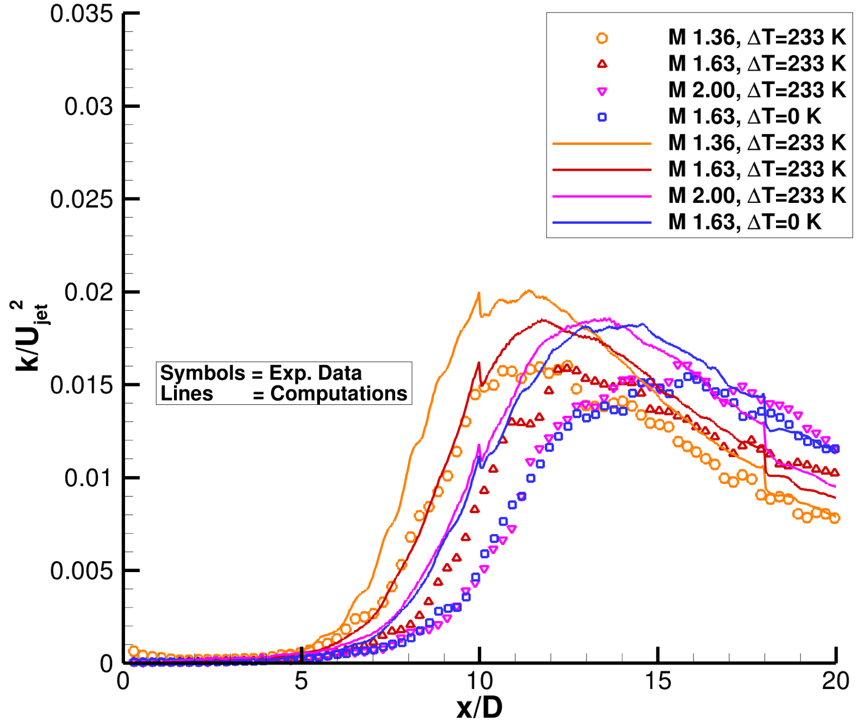


# Centerline Velocity Statistics - WMLES

## Centerline Velocity



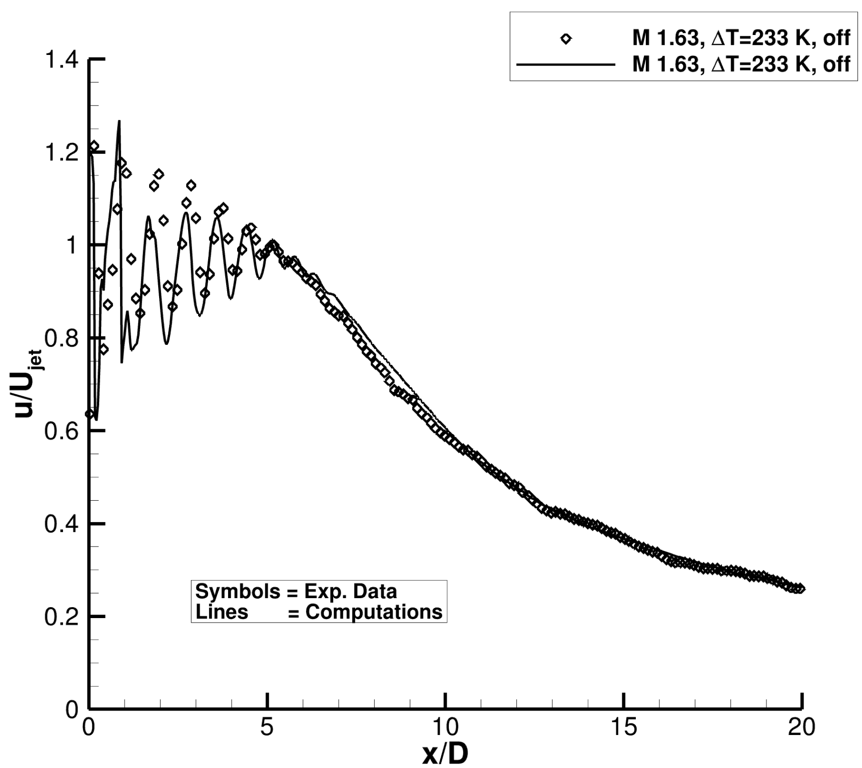

## Centerline TKE



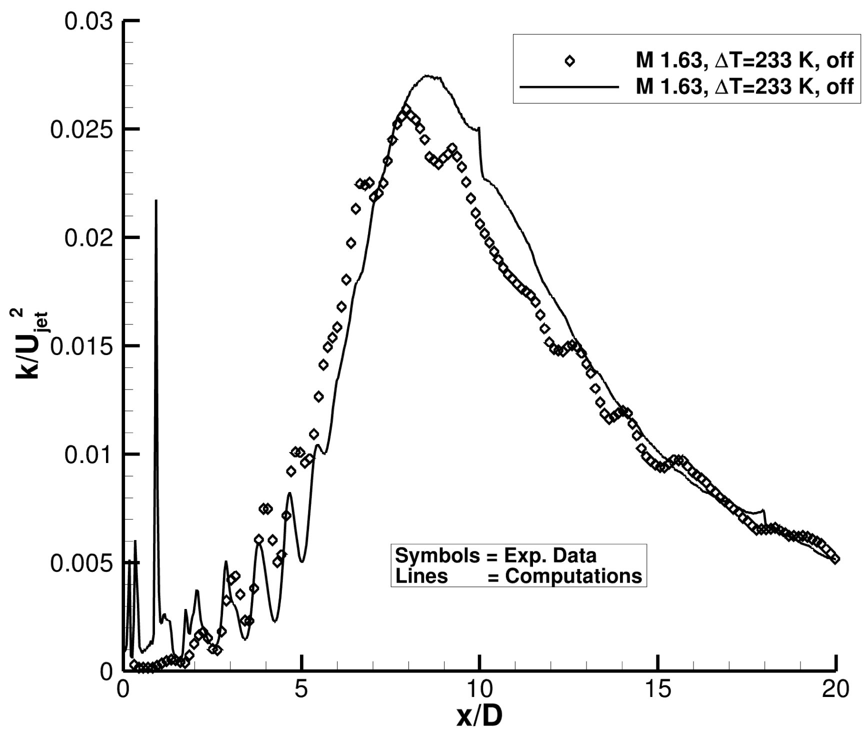

*Results are from M. Emory (prev. Cascade) using CharLES – unpublished – AIAA PAW6.*

# Off-Design Case Velocity Statistics - WMLES

## Centerline Velocity




## Centerline TKE

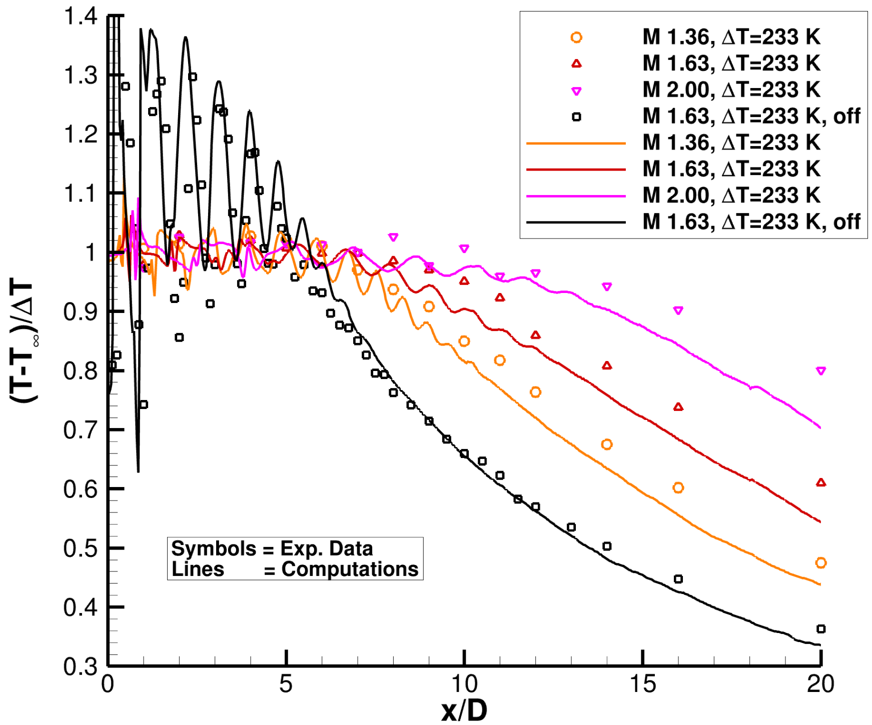




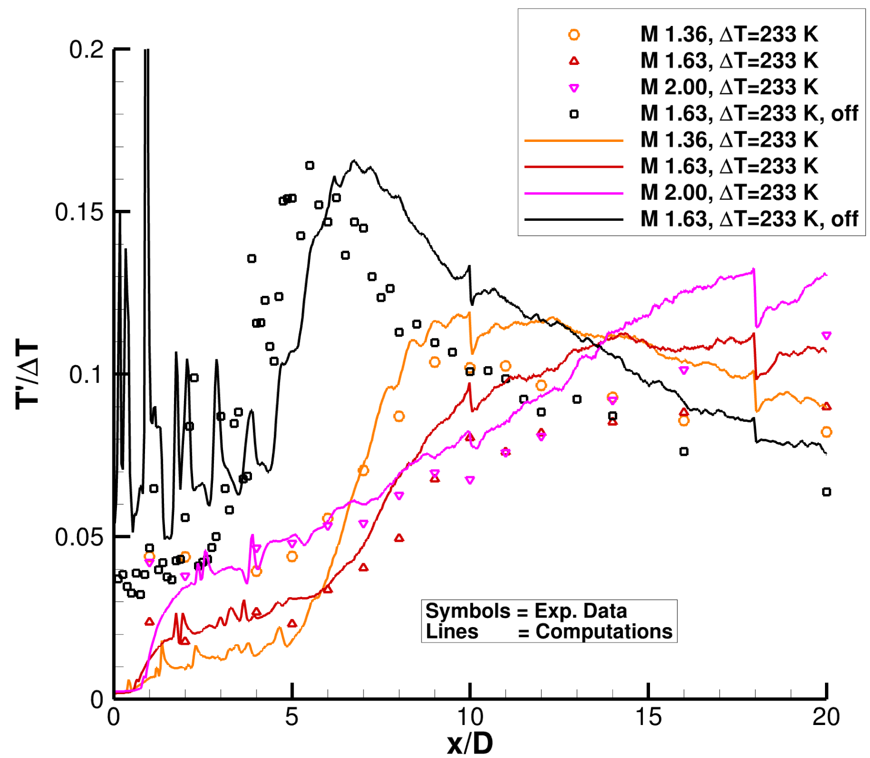

*Results are from M. Emory (prev. Cascade) using CharLES – unpublished – AIAA PAW6.*

# Centerline Temperature Statistics - WMLES

## Mean Temperature




## RMS Temperature




*Results are from M. Emory (prev. Cascade) using CharLES – unpublished – AIAA PAW6.*

# Conclusions

- Turbulent thermal transport is an important consideration for aerospace flows; however – not as extensively studied (experimentally or computationally) as basic aerodynamic flows.
- The NASA Turbulent Heat Flux (THX) Experiments collected data for several heated problems focused on propulsion applications.
- The Raman temperature measurement capability was advanced in technology via these THX efforts - to enable model scale facility experiments.
- Concurrent CFD work was conducted to benchmark existing methods.
- Data already used extensively in AIAA PAW5 and PAW6; also NASA TMR.
- Key CFD findings:
  1. Scale-resolving methods (i.e some form of simulation including LES for a significant part of the flow) are significantly more accurate than RANS-based techniques for turbulent heat transport.
  2. A conjugate heat transfer (CHT) modeling approach, in conjunction with the CFD solver, is required to obtain accurate surface temperature measurements.

# Publications on THX Work

- **The next few pages provide a list of papers detailing experimental results from the THX efforts, phases 1-5. In addition, directly related computational work is also listed. For phases 4 & 5, this includes non-NASA publications resulting from the data being used in AIAA Propulsion Aerodynamics Workshops (PAWs) 5 and 6. The THX 5 data is also used in three NASA TMR cases, with links below:**
- **TMR Cases using THX5 supersonic jet data:**
  1. **https://turbmodels.larc.nasa.gov/jet_mach1p63_tmatched_val.html**
  2. **https://turbmodels.larc.nasa.gov/jet_mach1p63_hot_val.html**
  3. **https://turbmodels.larc.nasa.gov/jet_mach1p63_offdesign_val.html**

# THX1 References (low ΔT cooling flow)

**EXPERIMENTS:**

- Wernet, M.P., Wroblewski, A.C., and Locke, R.J., “A Dual-Plane PIV Study of Turbulent Heat Transfer Flows,” NASA TM-2016-219074, May 2017, https://ntrs.nasa.gov/api/citations/20160003685/downloads/20160003685.pdf.
- Poinsatte, P., Thurman, D., and Lucci, B., “Detailed Velocity, Temperature, and Heat Flux Measurements on a Large Scale Film Cooling Model,,” NASA TM 20220004085, May 2022, https://ntrs.nasa.gov/api/citations/20220004085/downloads/TM-20220004085.pdf.

**COMPUTATIONS:**

- Borghi, M., Thurman, D., Poinsatte, P., and Engblom,W., “Numerical and Experimental Investigation of a Heated Jet in Crossflow,” J. Thermophysics and Heat Transfer, Vol.34, No. 2, April 2020, pp. 230-242. https://doi.org/10.2514/1.T5608

# THX2 References (subsonic jet temperature measurements)

**EXPERIMENTS:**


- Locke, R. J., Wernet, M. P., Anderson, R. C., “Rotational Raman-Based Temperature Measurements in a High-Velocity Turbulent Jet,” *Measurement Science Technol*ogy, Vol. 29, No. 1, Dec. 2017, pp. 1-16, https://doi.org/10.1088/1361-6501/aa934d.


**COMPUTATIONS:**


- DeBonis, J. R., “Prediction of Turbulent Temperature Fluctuations in Hot Jets,” AIAA Journal, Vol. 56, No. 8, 2018, pp. 3097–3111, https://doi.org/10.2514/1.J056596.


***These jet temperature measurements are for the same nozzles and many similar flow conditions for which PIV data had been previously collected prior to the TTT-sponsored THX efforts and is referred to as “Consensus Turbulence Statistics for Hot Subsonic Jets.” This data is available off the NASA TMR and documented in:***


- Bridges, J. and Wernet, M. P., “The NASA Subsonic Jet Particle Image Velocimetry (PIV) Dataset,” NASA Technical Memorandum, NASA/TM-2011-216807, Nov. 2011.
- Bridges, J. and Wernet, M. P., “Establishing Consensus Turbulence Statistics for Hot Subsonic Jets,” AIAA Paper 2010-3751, June 2010, https://doi.org/10.2514/6.2010-3751.

# THX3 References (single cooling hole)


**EXPERIMENTS:**

- Wernet, M. P., Georgiadis, N. J., and Locke, R. J., "PIV and Rotational Raman-Based Temperature Measurements for CFD Validation in a Single Injector Cooling Flow," AIAA Paper 2018-3857, June 2018, https://doi.org/10.2514/6.2018-3857.

**COMPUTATIONS:**

- Spiegel, S., Borghi, M. R., and Yoder, D. A., "Large Eddy Simulations of a Single-Injector Cooling Flow Using the High-Order Flux Reconstruction Method," AIAA Paper 2022–1813, Jan. 2022, https://doi.org/10.2514/6.2022-1813 .
- Borghi, M. R., "Implicit Large-Eddy Simulation of Single-Injector Cooling Flow," AIAA Paper 2022–1814, Jan. 2022, https://doi.org/10.2514/6.2022-1814 .
- Yoder, D. A., "Assessment of Turbulence Models for a Single-Injector Cooling Flow," AIAA Paper 2022–1812, Jan. 2022, https://doi.org/10.2514/6.2022-1812 .
- Borghi, M. R., Spiegel, S., Yoder, D. A., Georgiadis, N. J., and Wernet, M. P., "Turbulent Simulations of Cooling Jets in Crossflow," AIAA Paper 2022–1815, Jan. 2022, https://doi.org/10.2514/6.2022-1815 .

# THX4 References (nozzle with film-cooled plate)


**EXPERIMENTS:**

- Wernet, M. P., Georgiadis, N. J., Locke, R. J., Thurman, D., Poinsatte, P., "PIV and Rotational Raman-Based Temperature Measurements for CFD Validation of a Perforated Plate Cooling Flow: Part I," NASA TM-2019-220227, https://ntrs.nasa.gov/api/citations/20190029113/downloads/20190029113.pdf, and AIAA Paper 2020-1230, Jan. 2020, https://doi.org/10.2514/6.2020-1230 .
- Pesich, J.M., Georgiadis, N. J., Wernet, M. P., Locke, R. J., Thurman, D. R., Poinsatte, P. E., "PIV and Rotational Raman-Based Temperature Measurements for CFD Validation of a Perforated Plate Cooling Flow: Part II," AIAA Paper 2022-0084, Jan. 2022, https://doi.org/10.2514/6.2022-0084.

**AIAA PAW5 WORKSHOP SUMMARY PAPER:**

- Georgiadis, N. J., Wernet, M. P., Crowe, D. S., Woeber, C. D., Karman-Shoemake, K.C., Winkler, C.M., "Assessment of Multiphysics Computations of Flow Over A Film Cooled Plate," ***Journal of Thermophysics and Heat Transfer***, Articles in Advance, Mar. 2025, pp. 1-19, https://doi.org/10.2514/1.t7062.

**AIAA PAW5 WORKSHOP INDIVIDUAL PAPERS:**

- Pesich, J. M., Georgiadis, N. J., and Wernet, M. P., "Multiphysics Computational Analysis of a Perforated Plate Cooling Flow," AIAA Paper 2021-1447, Jan. 2021, https://doi.org/10.2514/6.2021-1447.
- Benton, S.I., and Lamberson, S.E., "Analysis of the PAW-5 Nozzle Test Case with HPCMP CREATE-AV Kestrel," AIAA Paper 2022-0083, Jan. 2022, https://doi.org/10.2514/6.2022-0083.
- Emory, M., Shunn, L., Bose, S., and Ham, F., "Wall-modeled Large Eddy Simulation with Conjugate Heat Transfer Leveraging Clipped Voronoi-diagrams for the PAW-5 Nozzle Test Case," AIAA Paper 2022-0635, Jan. 2022, https://doi.org/10.2514/6.2022-0635.
- Zore, K., Aliaga, C., Shah, S., Stokes, J., Zori, L., and Makarov, B., "Conjugate Heat Transfer Simulations of a Nozzle Flow over a Film-Cooled Plate, ***Journal of Thermophysics and Heat Transfer***, Vol. 37, No. 2, 2023, pp. 404-423, https://doi.org/10.2514/1.t6595
- Winkler, C.M., "BCFD Analysis for the 5$^{th}$ AIAA Propulsion Aerodynamics Workshop: Film Cooled Nozzle Results, AIAA Paper 2022-0085, Jan. 2022, https://doi.org/10.2514/6.2022-0085.

# THX5 References (heated supersonic jets) (1 of 2)


**EXPERIMENTS:**

- Wernet, M. P., Georgiadis, N. J., and Locke, R. J., "Velocity, Temperature, and Density Measurements in Supersonic Jets," NASA/TM-20205007269, October 2020, https://ntrs.nasa.gov/citations/20205007269, (the entire raw data set is also available here)
- Georgiadis, N. J., Wernet, M. P., Locke, R. J., and Eck, D. G., "Mach Number and Heating Effects on Turbulent Supersonic Jets," AIAA Journal, Vol. 62, No. 1, Jan. 2024, pp. 31-51, https://doi.org/10.2514/1.j063186.
- Wernet, M. P., Georgiadis, N. J., and Locke, R. J., "Raman Temperature and Density Measurements in Supersonic Jets," Experiments In Fluids, Vol. 62, No. 3, 2021, pp. 1-21, https://doi.org/10.1007/s00348-021-03162-2

**AIAA PAW6 WORKSHOP SUMMARY PAPER:**

- Georgiadis, N. J., Wernet, M. P., Winkler, C. M., Benton, S. I., and Connolly, B. J., "Summary of the 6th Propulsion Aerodynamics Workshop Nozzle Test Case: Heated Supersonic Axisymmetric Jets," AIAA Paper 2024-0749, Jan 2024, https://doi.org/10.2514/6.2024-0749.

**AIAA PAW6 WORKSHOP INDIVIDUAL PAPERS:**

1. Zore, K., Aliaga, C., Selva, J., Zori, L., Makarov, B., “High-Fidelity SBES Simulations for Supersonic Nozzle Flows, AIAA Paper 2024-0753, Jan. 2024, https://doi.org/10.2514/6.2024-0753.

- Kramer, C. and Crowe, D. S., “Turbulence Model Assessment for Heated Supersonic Jets,” AIAA Paper 2024-0750, Jan. 2024, https://doi.org/10.2514/6.2024-0750.
- Winkler, C. M., “BCFD Analysis for the 6th AIAA Propulsion Aerodynamics Workshop: Nozzle Results, AIAA 2024-0752, Jan. 2024, https://doi.org/10.2514/6.2024-0752.
- Potturi, A.S., Batten, P., Bachchan, N., and Peroomian, O., “Modeling of Turbulent Supersonic Jet Plumes Using CFD++,” AIAA Paper 2024-0751, Jan. 2024, https://doi.org/10.2514/6.2024-0751.

# THX5 References (heated supersonic jets) (2 of 2)

**NASA TMR Cases using THX5 supersonic jet data:**

1. **https://turbmodels.larc.nasa.gov/jet_mach1p63_tmatched_val.html**
2. **https://turbmodels.larc.nasa.gov/jet_mach1p63_hot_val.html**
3. **https://turbmodels.larc.nasa.gov/jet_mach1p63_offdesign_val.html**

**AIAA Summary Paper for TMR Cases using THX5 supersonic jet data:**


- Georgiadis, N. J., Dippold, V.F., Baurle, R.A., Rumsey, C.L., "Heated Supersonic Jet Cases for the NASA Turbulence Modeling Resource," AIAA Paper 2025-2577, Jan. 2025, https://doi.org/10.2514/6.2025-2577.