The NASA Turbulent Heat Flux (THX) Experiments: Summary and Lessons Learned

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Note: several individuals contributed to the experimental and computational efforts documented herein. See the references in the paper for these authors/contributors.

Motivation

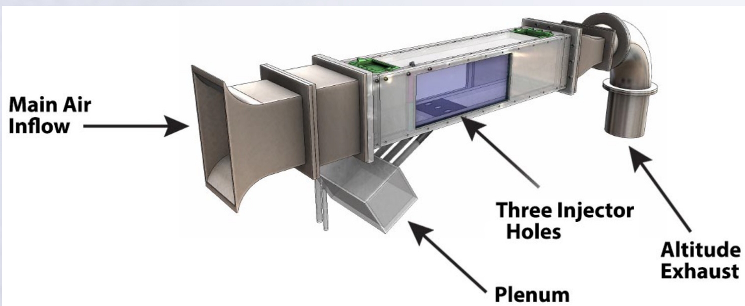
- In CFD, turbulent temperature variations & heat flux haven't received as much attention as traditional aerodynamic turbulence, yet are important to many flows.
- Examples include: (1) high Mach number applications, (2) propulsion systems, (3) systems requiring active cooling – just to name a few
- NASA's 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.

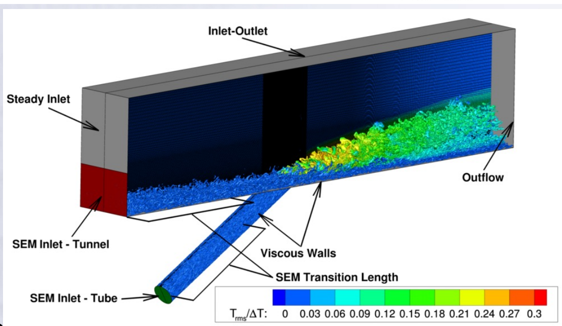
Turbulent Heat Flux (THX) Experiments Phases

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

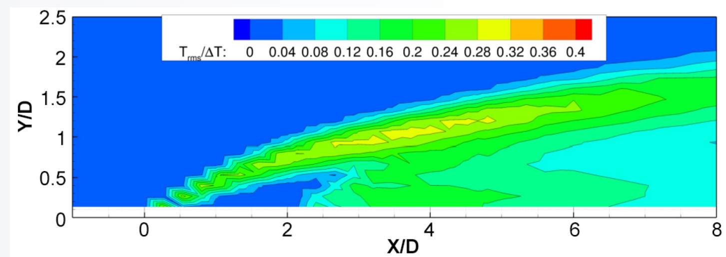
- Low speed / temperature cooling hole experiments in GRC Fundamental Film Cooling and Heat Transfer Facility (SW6).
- Hotwire measurements of velocity, temperature, and turbulent heat flux (u’T’), also PIV for velocities. WRLES performed by Borghi, et al. RANS & HRLES shown to be inferior.



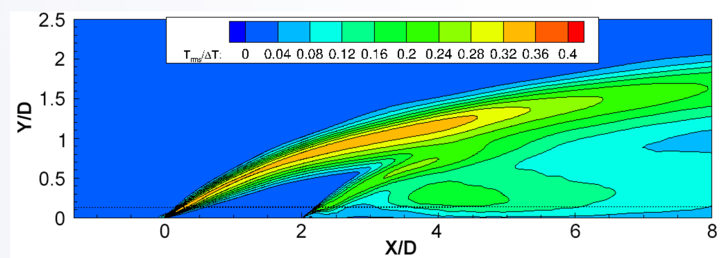


T’ / ΔT

Expt.



LES



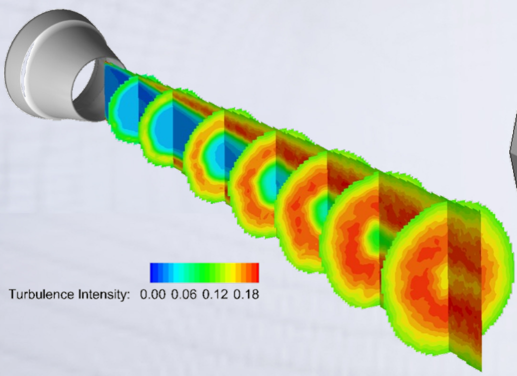
Off-Body Measurements for THX Experiments

- 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

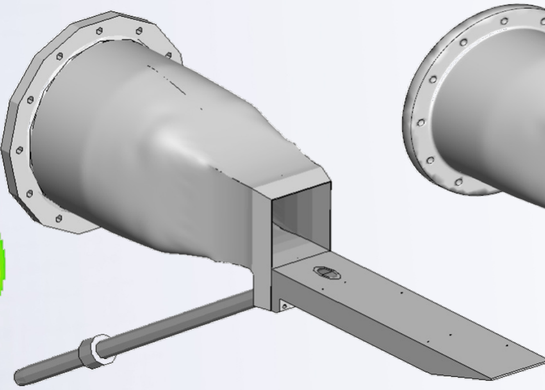
THX Phases 2 - 5

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.

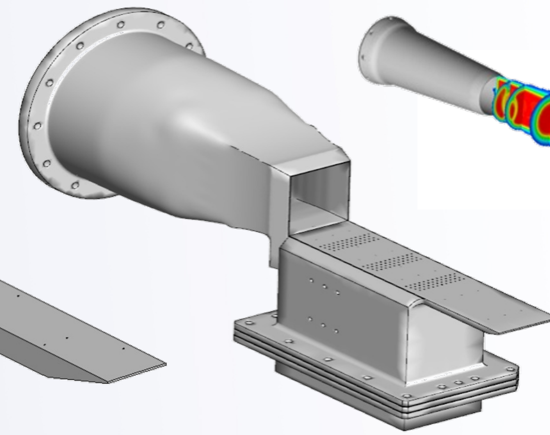
THX 2
SMC000



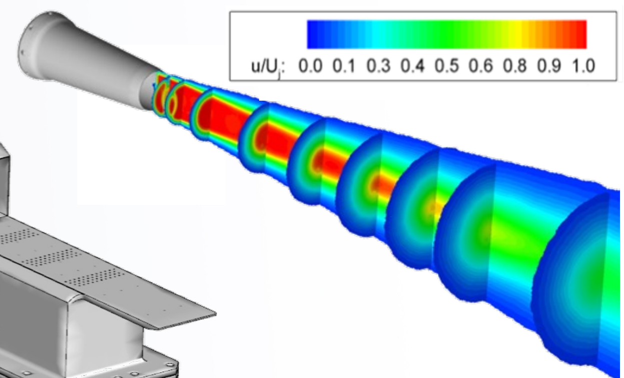
THX 3
Single Hole Plate



THX 4
Multi-Hole Plate



THX 5
Supersonic Jets

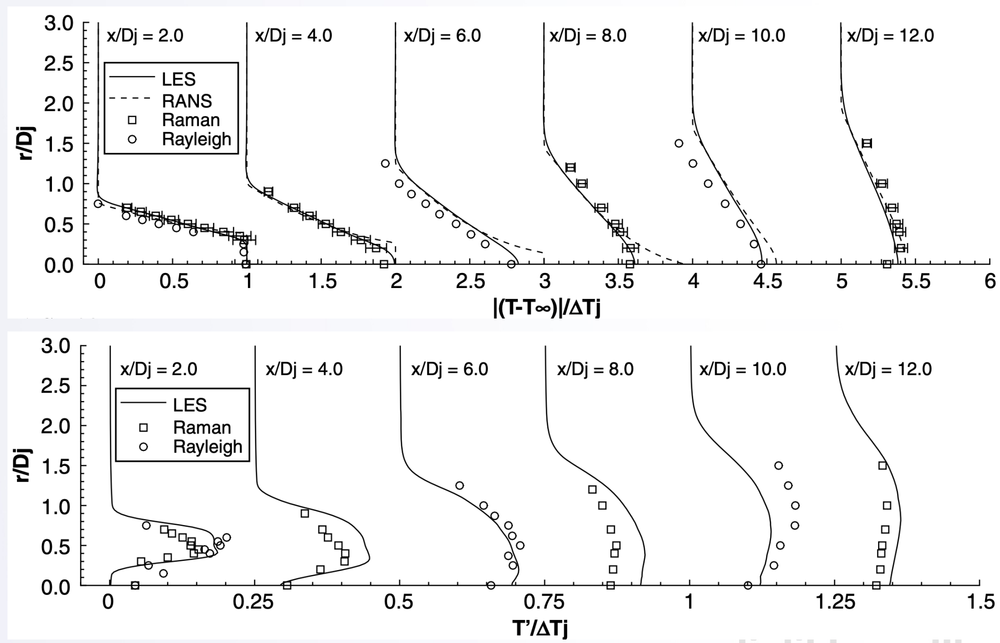


THX 2 – Subsonic Jets Tested at GRC AAPL

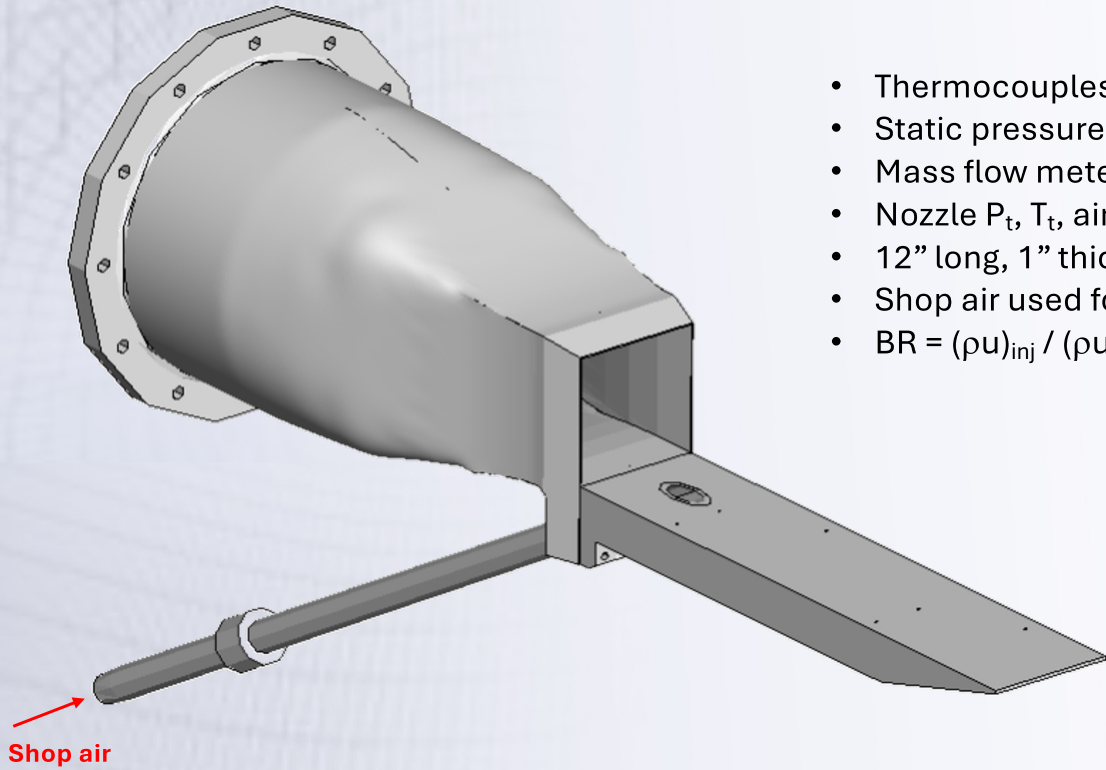
- **Raman Scattering technique implemented and demonstrated using this phase.**
- **Examined the "SMC000" convergent nozzle, for many of the same points as the Bridges and Wernet PIV Consensus Data (AIAA Paper 2010-3751) – also taken in GRC AAPL, data used on NASA TMR**

- Comparisons of temperature measurements and LES (DeBonis) for consensus data SP23, Mach 0.38, ΔT = 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.



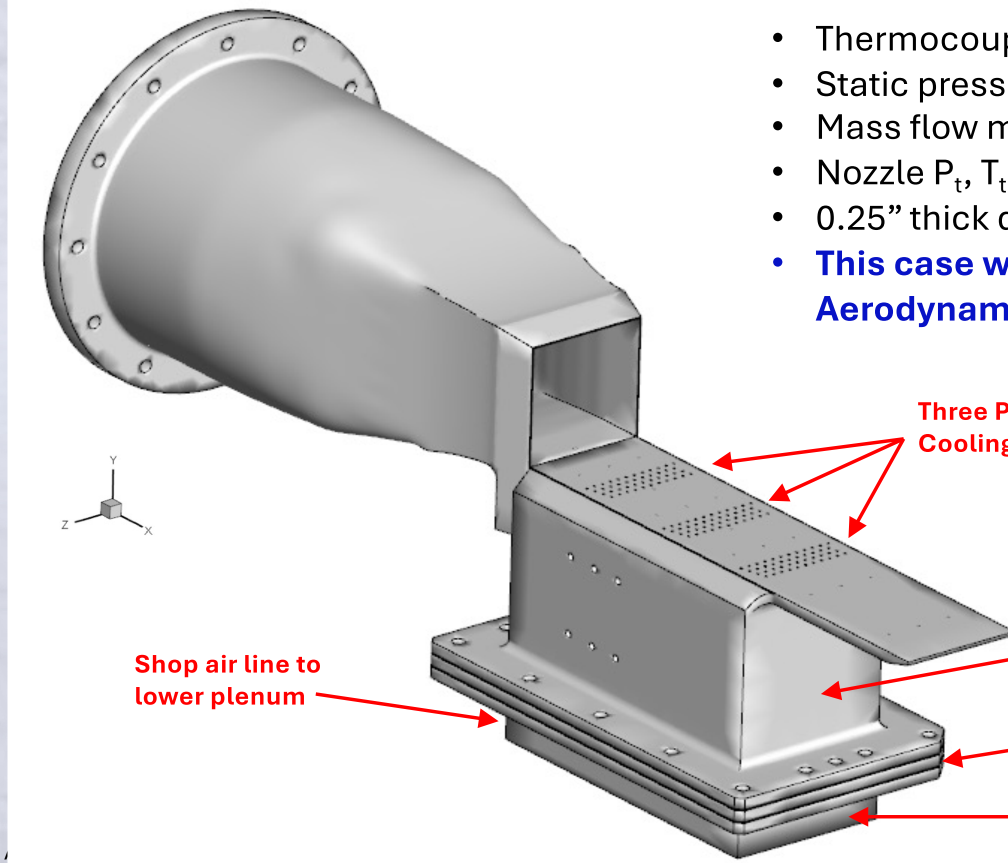
THX Phase 3 – Single Cooling Hole



- 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 = $(\rho u)_{inj}$ / $(\rho u)_{jet}$

THX Phase 4 – Porous Plate Geometry

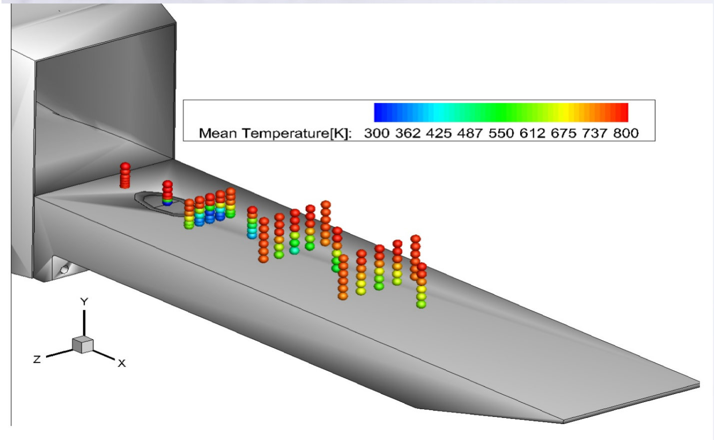
- Thermocouples embedded in plate surface
- Static pressure measured in top and bottom plenums
- Mass flow meter measured injector flow
- Nozzle P_t, T_t, air & fuel flow rates measured upstream
- 0.25” thick deck
- **This case was used for the 5th AIAA Propulsion Aerodynamics Workshop (PAW5).**



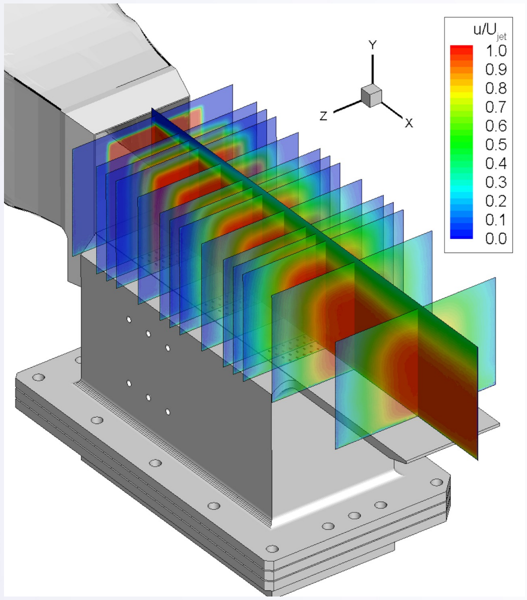
THX – Phases 3 & 4

- **Sample experimental measurements:**

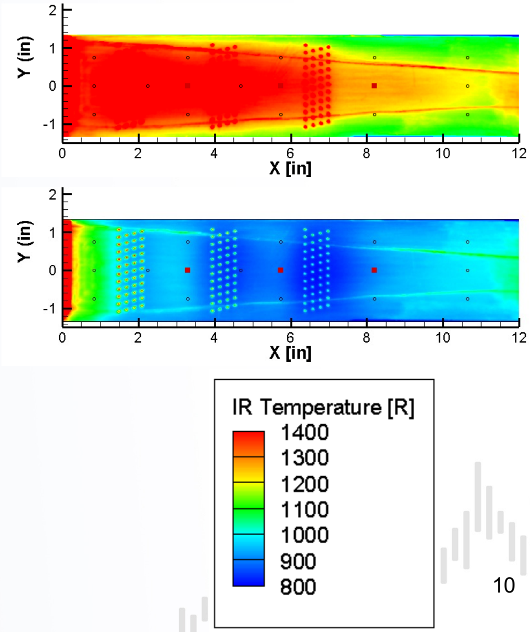
THX 3: Raman temperature measurements (mean and rms)



THX 4: PIV velocity measurements (mean and rms)



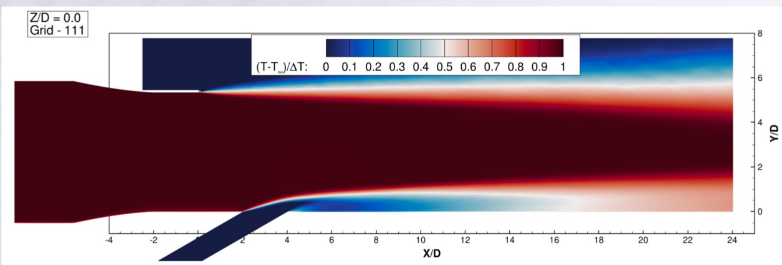
THX 4: Surface IR temperature measurements



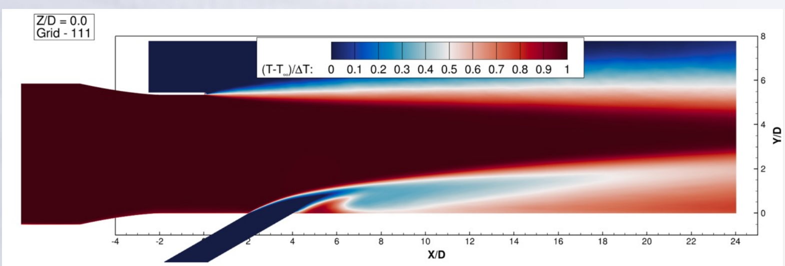
THX Phase 3 – Single Cooling Hole

- 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.

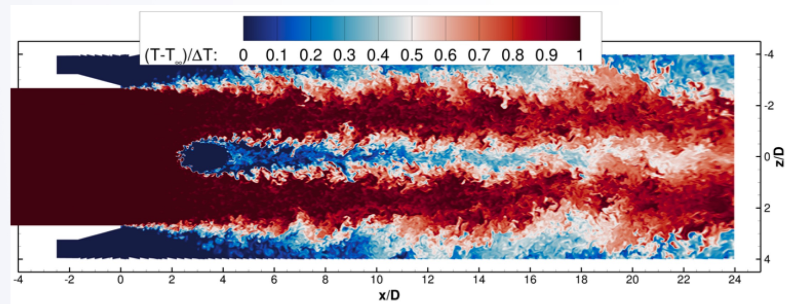
FDL3DI, BR = 1



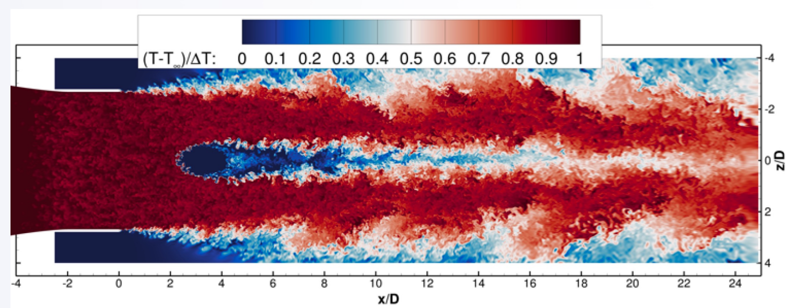
FDL3DI, BR = 2



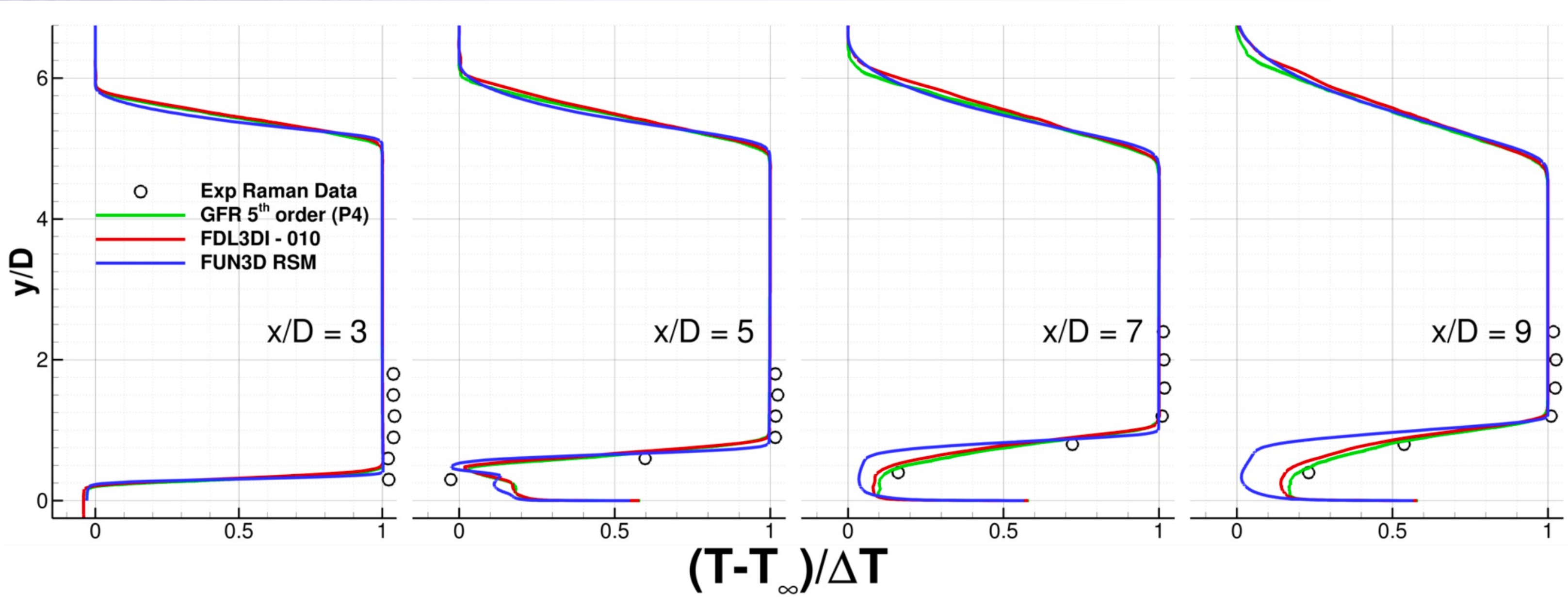
GFR, BR = 1, y/D = 0.1



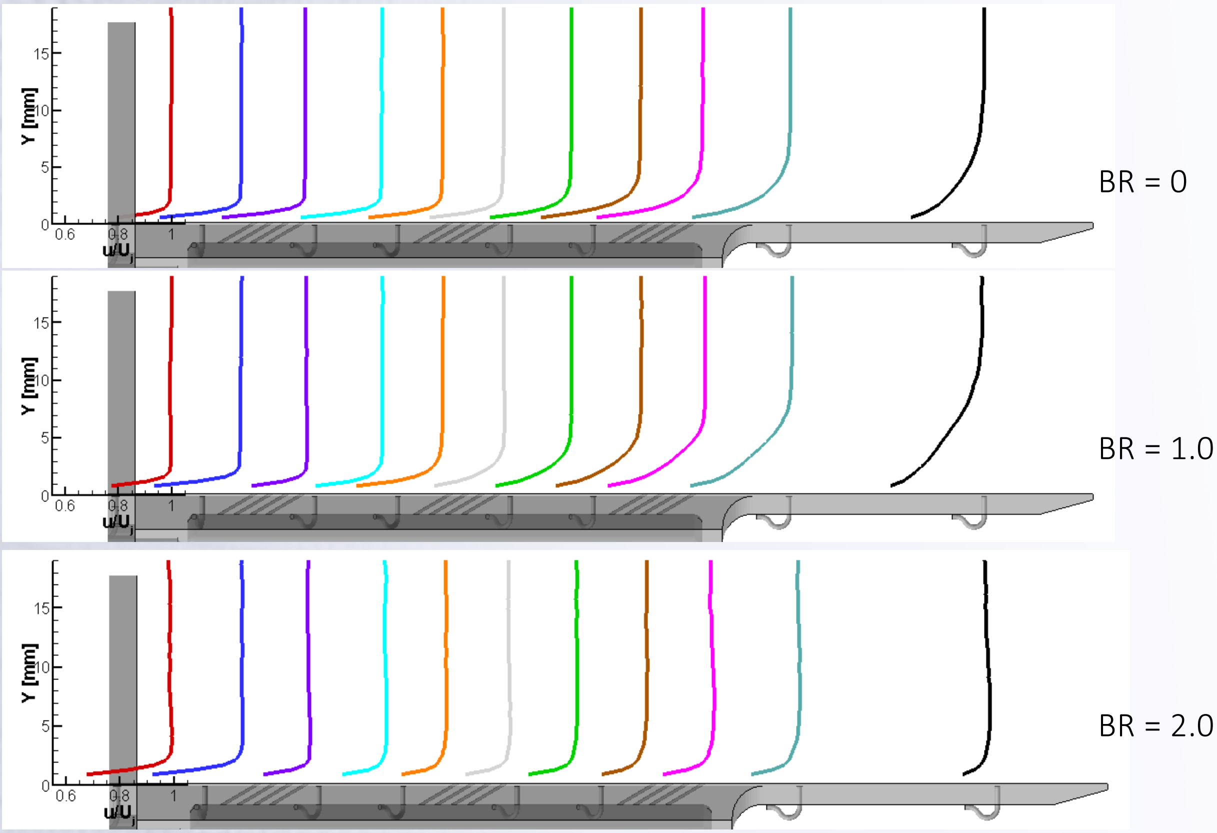
FDL3DI, BR = 1, y/D = 0.1

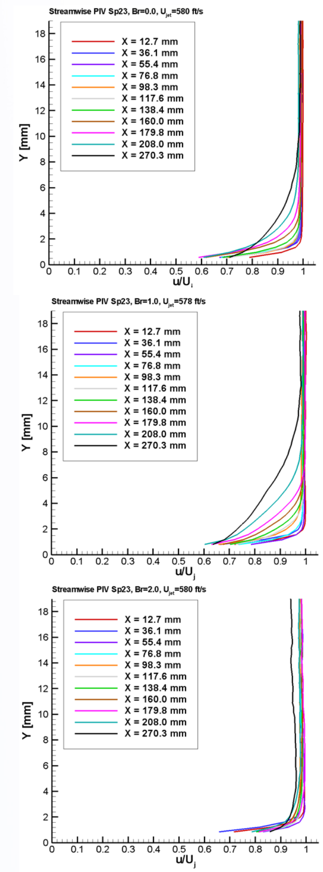


THX 3 – Temperature Comparisons for BR = 1

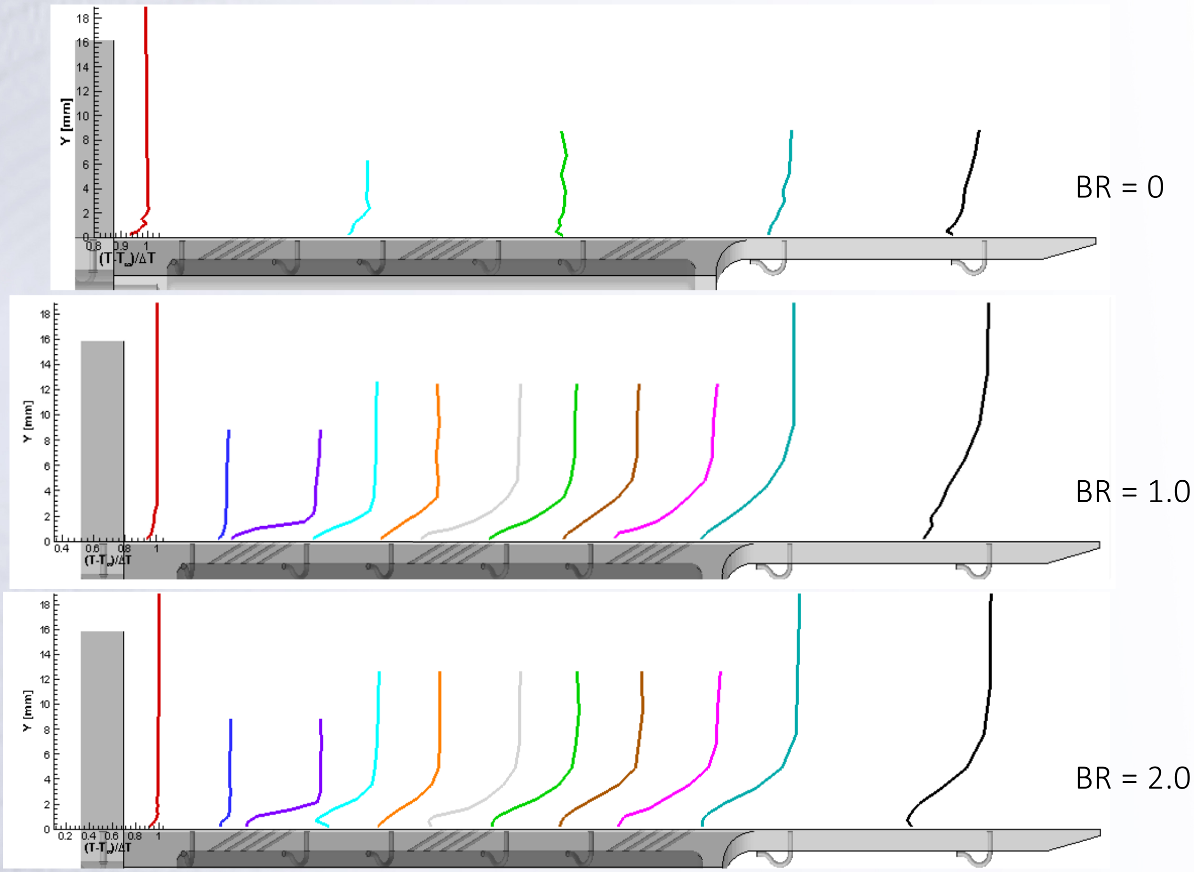


Mean Axial Velocity – THX 4: Set Point 23, Mach 0.38, ΔT = 233K

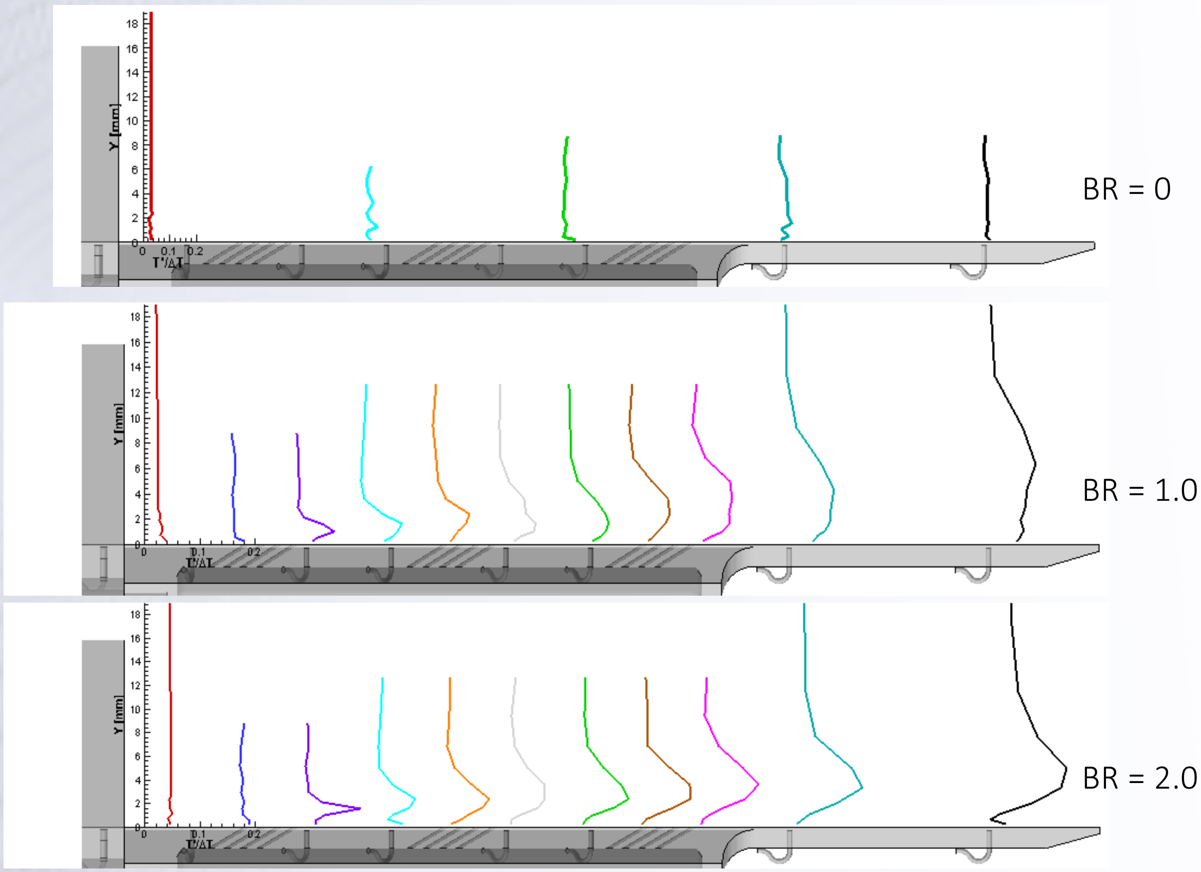




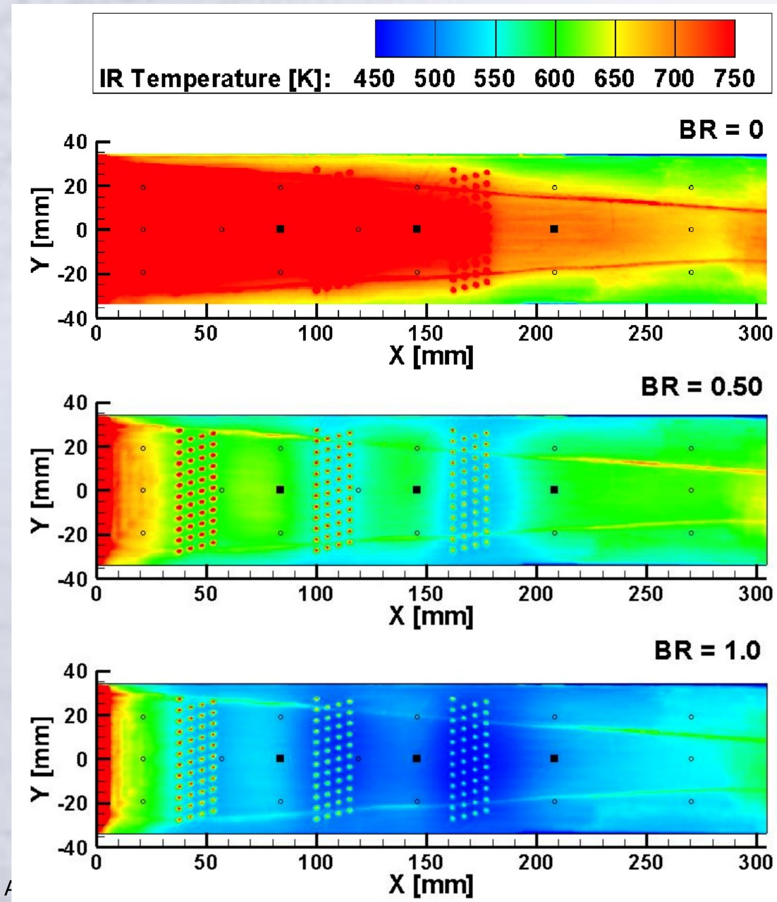
Mean Temperature – THX 4: Set Point 23, Mach 0.38, ΔT = 233K



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



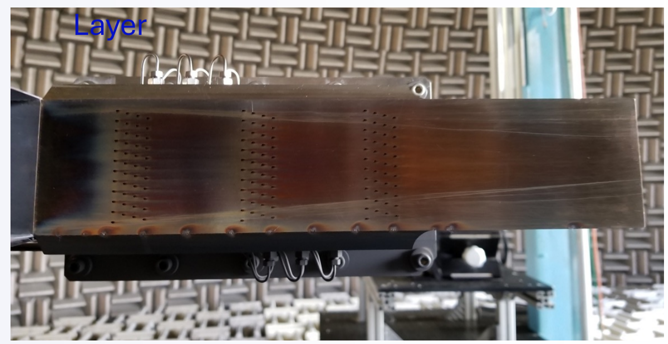
Raw IR Surface Temperature Measurements



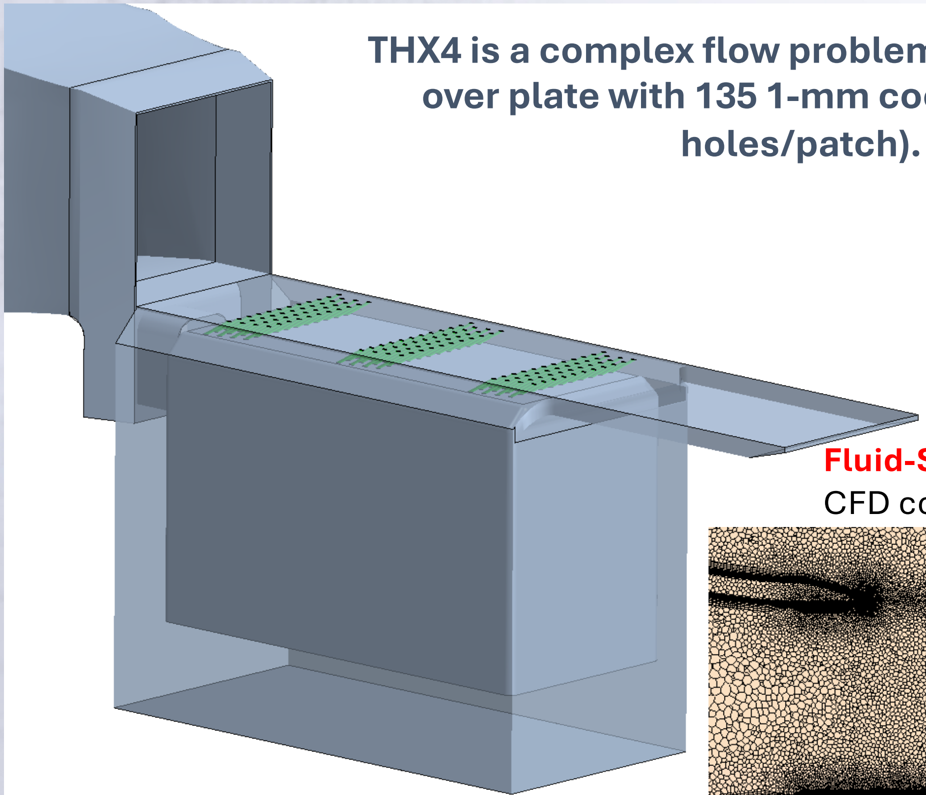
FLIR SC655 infrared camera

- 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

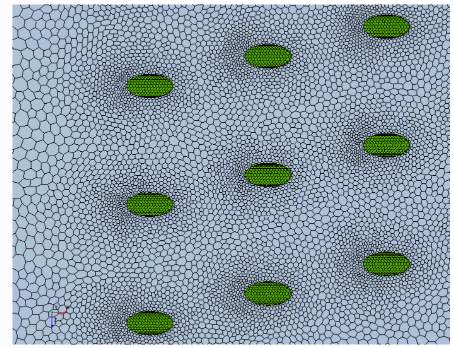


THX4 Model Geometry & CFD-CHT Problem Setup

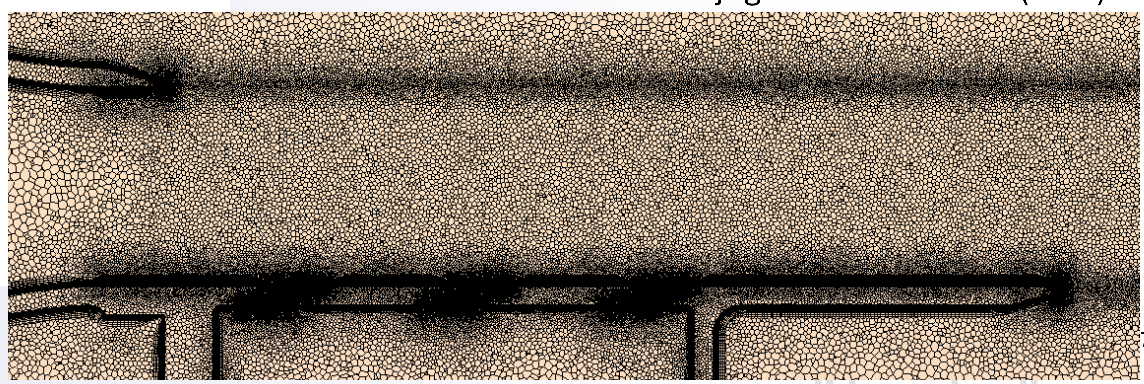


THX4 is a complex flow problem: hot jet exhaust over plate with 135 1-mm cooling holes (45 holes/patch).

Looking down on plate:



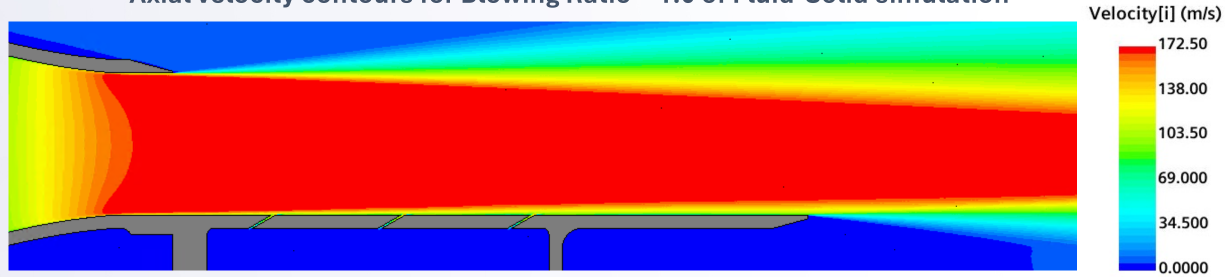
Fluid-Solid conformal polyhedral grid created in commercial CFD code STAR-CCM+ to solve the conjugate heat transfer (CHT)



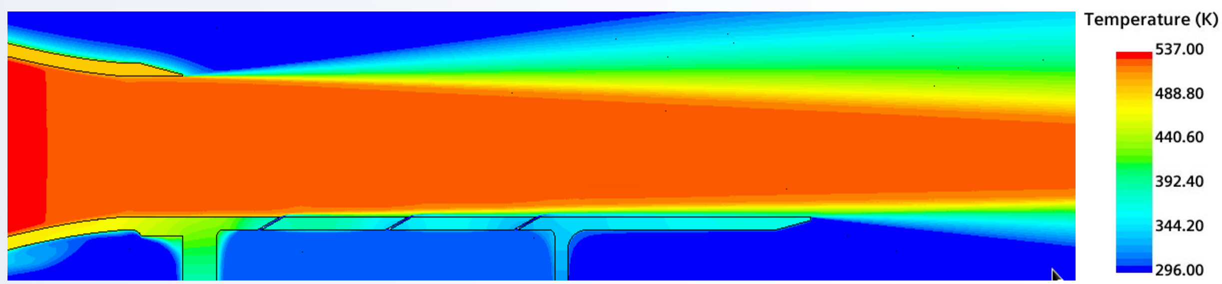
THX4: RANS Cases

- 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

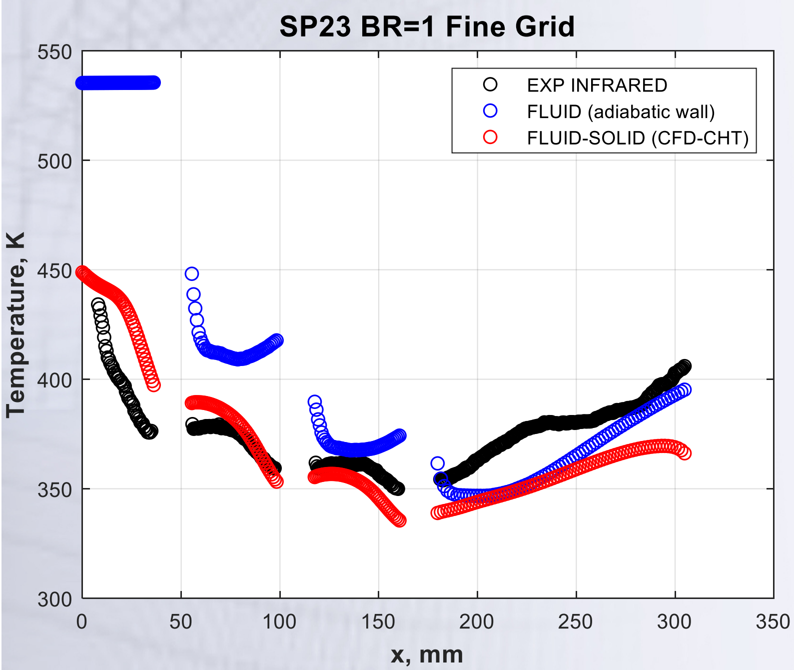


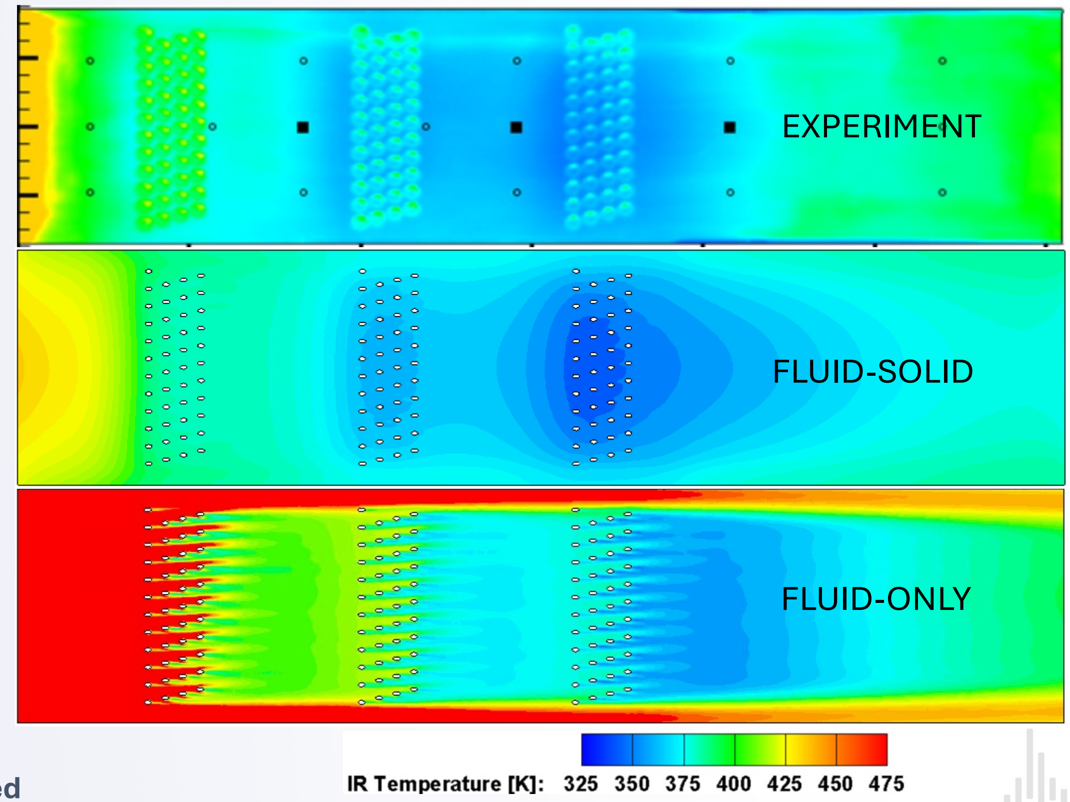
Temperature contours for Blowing Ratio = 1.0 of Fluid-Solid simulation



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	2nd order upwind
Medium	70.3 million	78.9 million	1.0	4,200	2nd order upwind
Fine	143.3 million	143.3 million	1.0	5,600	2nd order upwind
XFine	N/A	321.4 million	1.0	5,600	2nd order upwind

THX4 RANS Centerline Surface Temperature





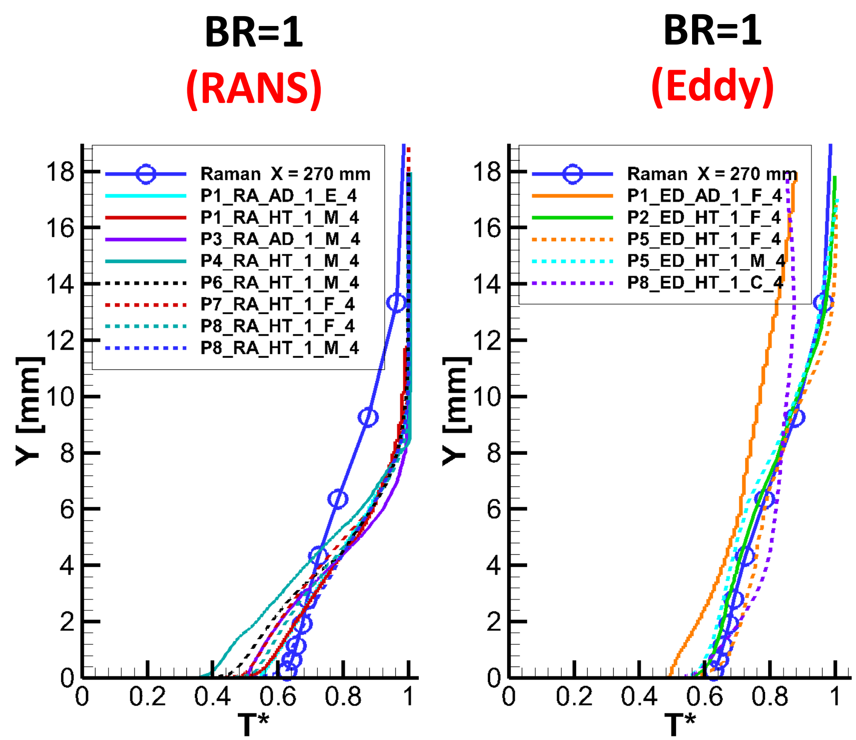
LESSON LEARNED / BEST PRACTICE: Thermally coupled CFD-CHT significantly improves surface temperature prediction.

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*, Vol. 39, No. 4., Oct. 2025, pp. 704-723.



Background: THX5 -NASA GRC Supersonic Jet Tests

- The THX5 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

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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

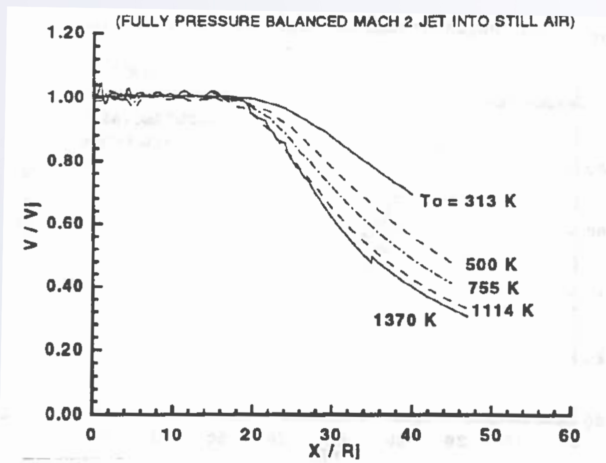
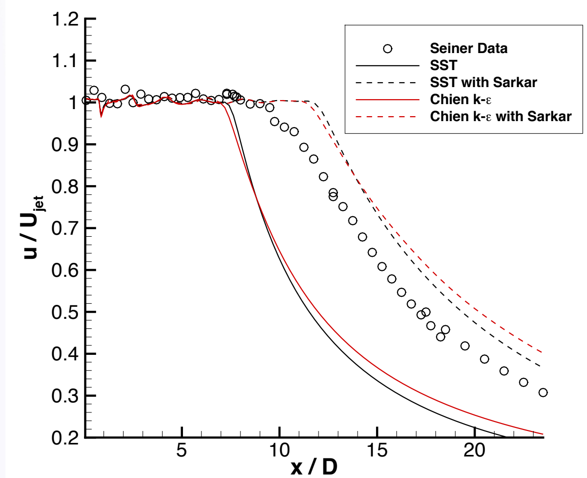


Figure 6. Centerline velocity decay with jet temperature.

Typical RANS CFD Result & Comparison with Seiner Data



THX 5 – Supersonic Jet Experiments

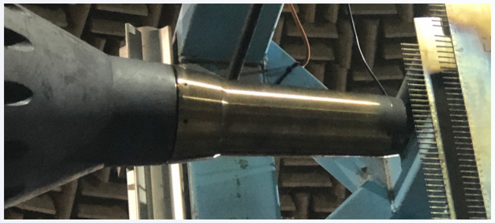
TEST MATRIX:

- 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.

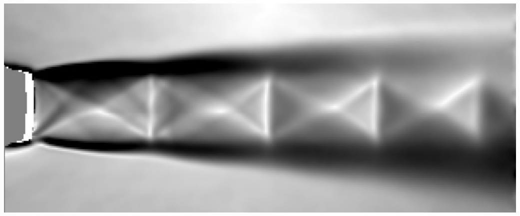
TEST PROGRAM RESULTS:

- 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).**

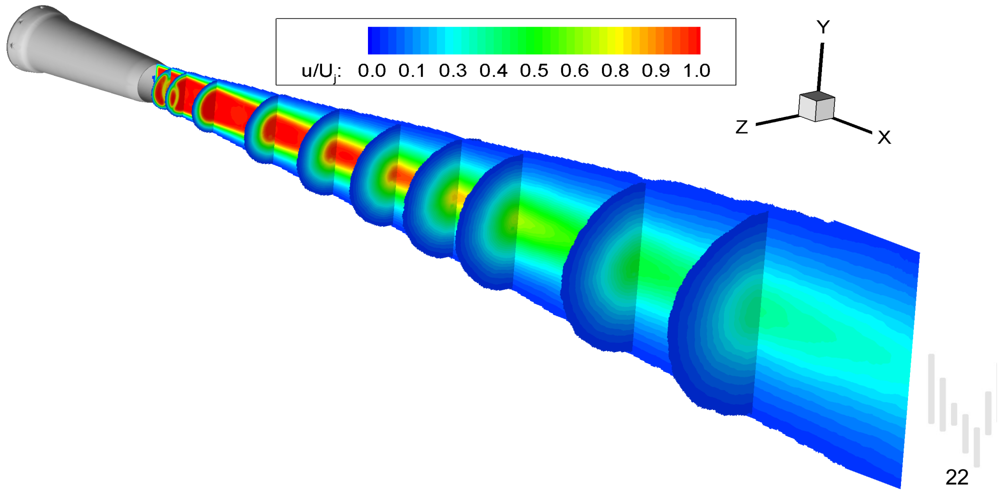
Mach 2.0 nozzle installed in GRC AAPL



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



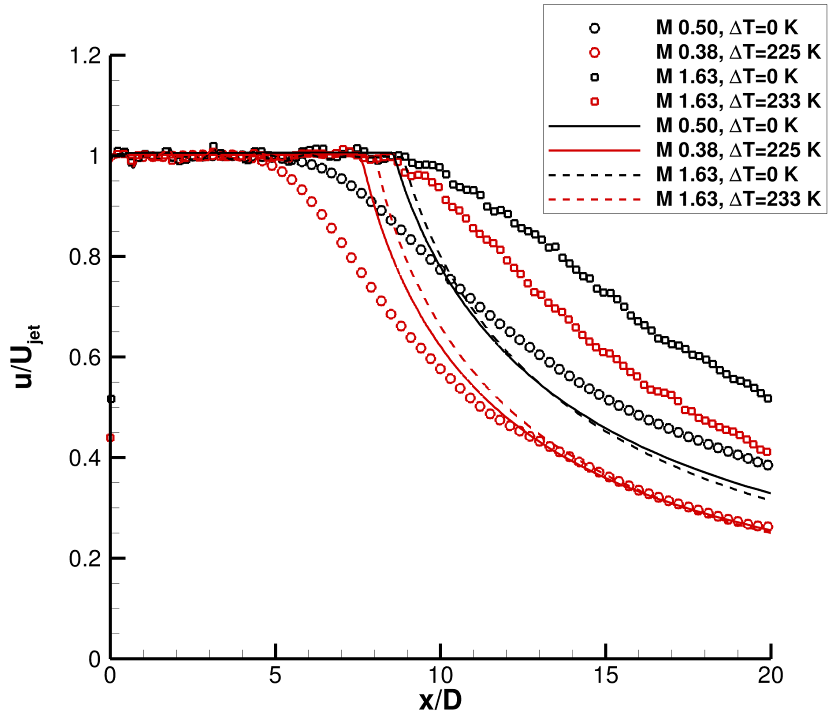
PIV of mean axial velocity



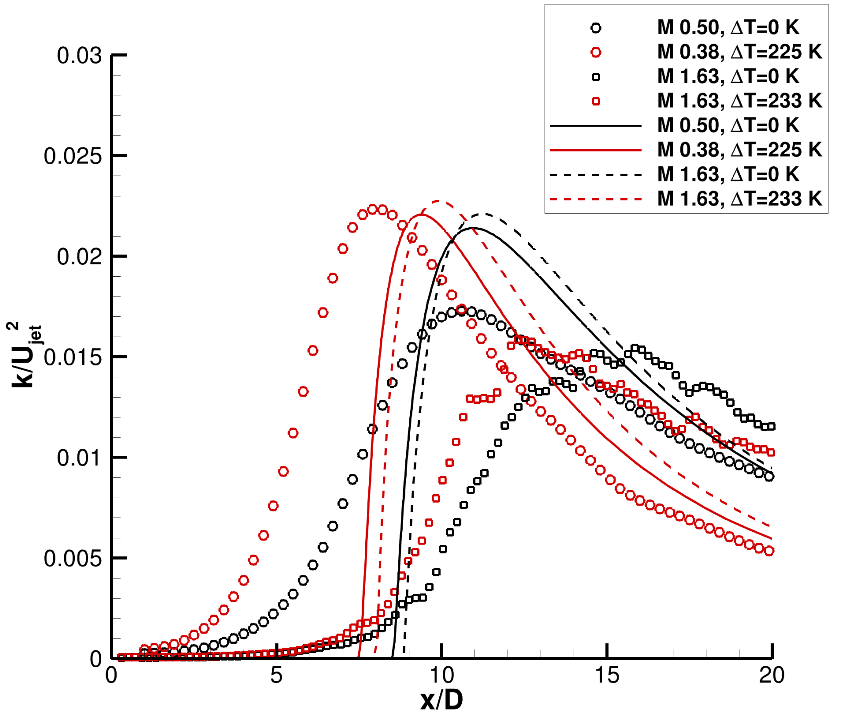
Typical Subsonic-Supersonic Jets Comparison of Experiment to RANS

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

Centerline Velocity



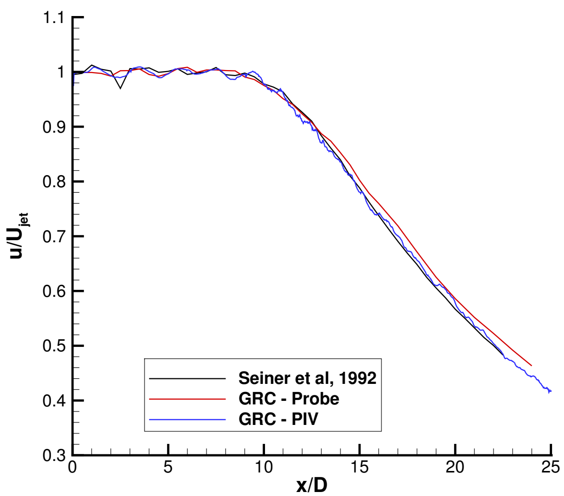
Centerline TKE



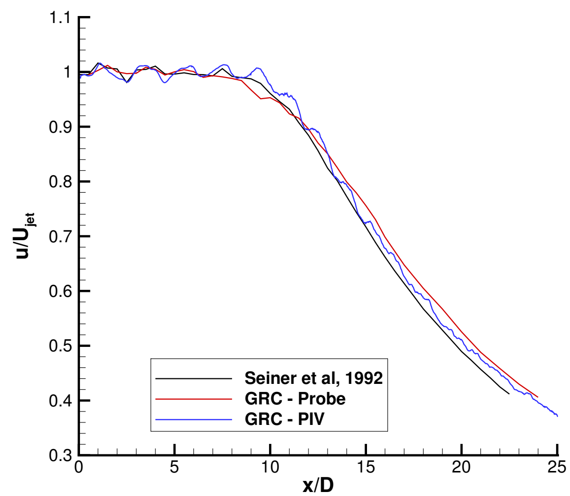
Mach 2.0 Velocity Comparisons – Seiner to THX5 & Probe to PIV

- $\Delta T = T_{jet} - T_{\infty}$, 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.

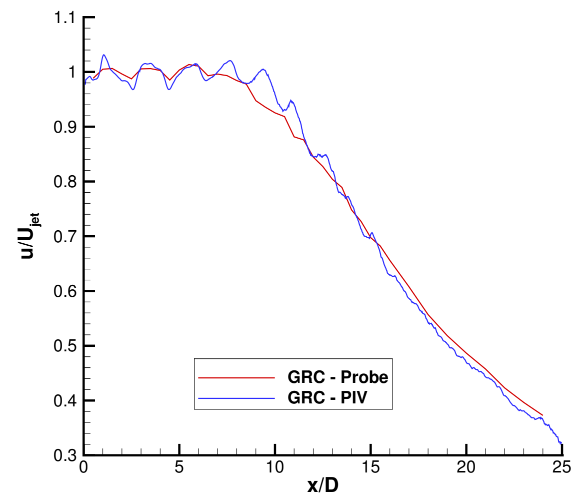
$\Delta T = 0^{o}$ K



$\Delta T = 133^{o}$ K

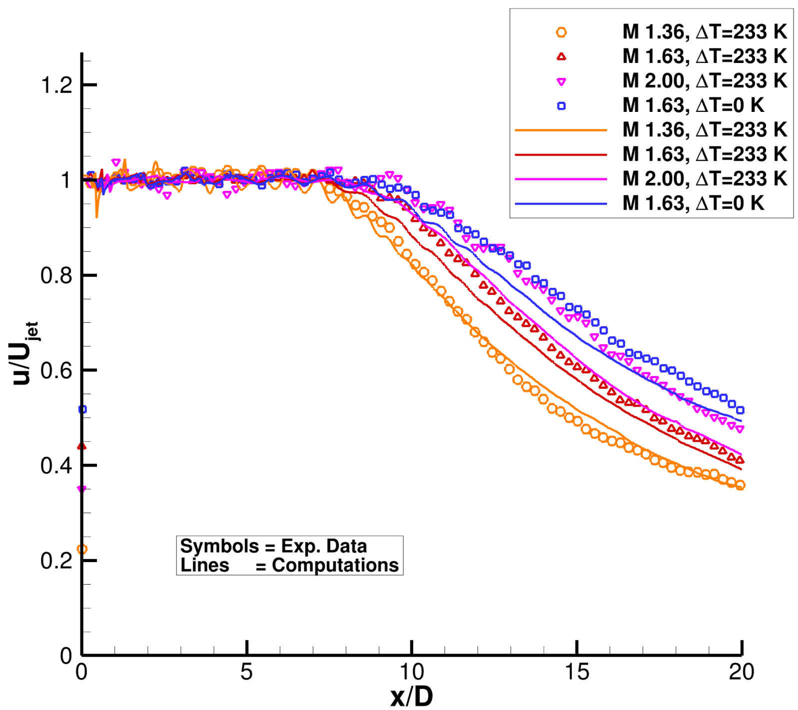


$\Delta T = 233^{o}$ K

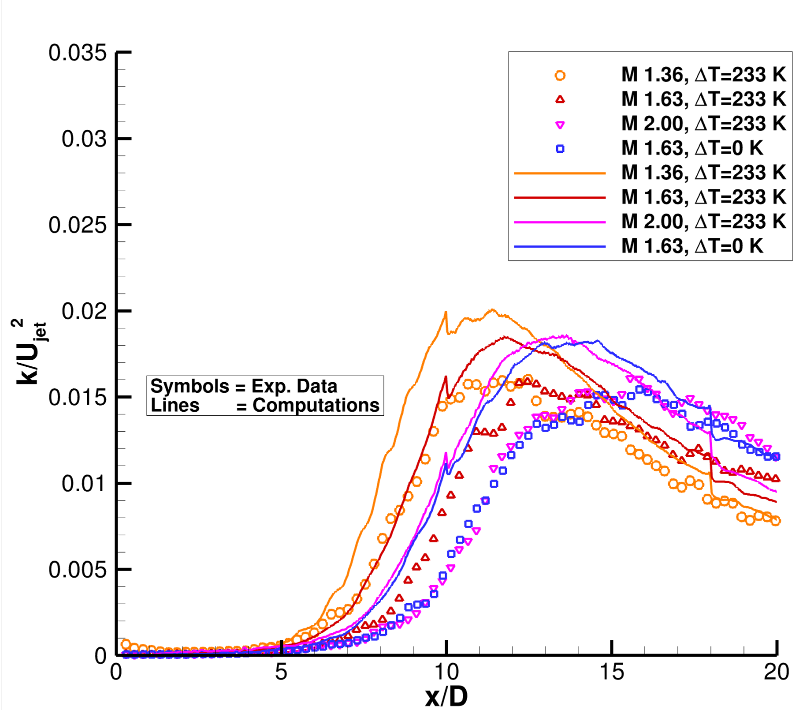


Centerline Velocity Statistics - WMLES

Centerline Velocity



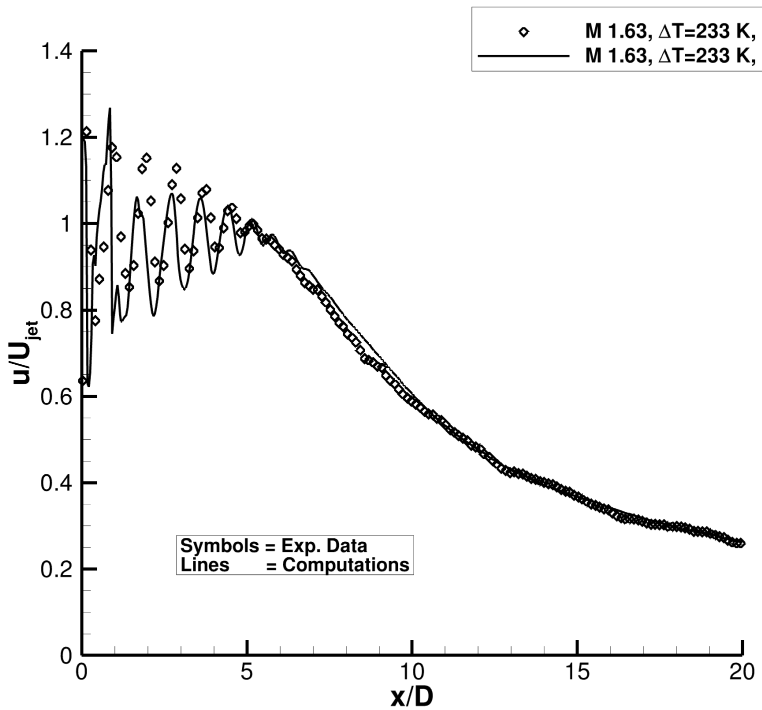
Centerline TKE



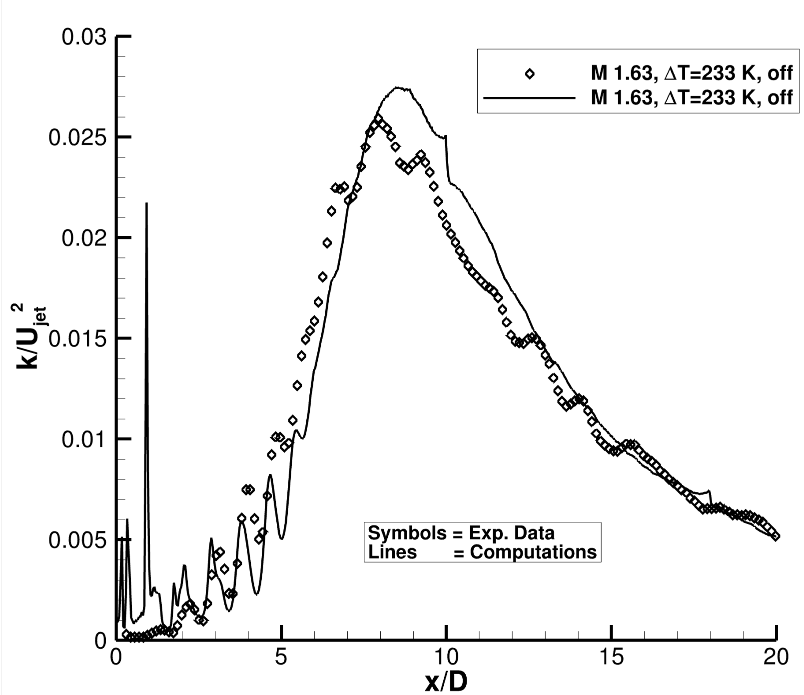
Results are from M. Emory (prev. Cascade) using CharLES – unpublished – AIAA PAW6.

Off-Design Case Velocity Statistics - WMLES

Centerline Velocity



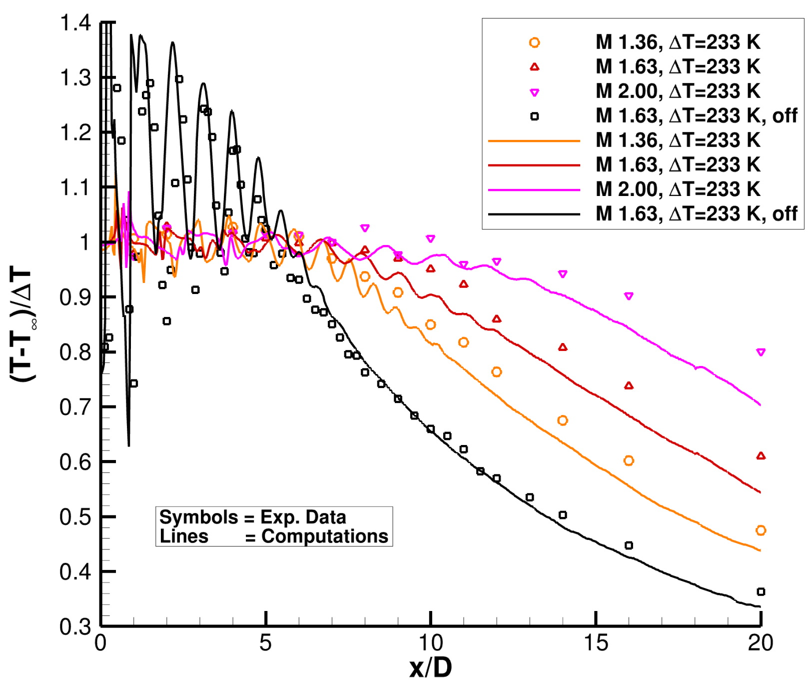
Centerline TKE



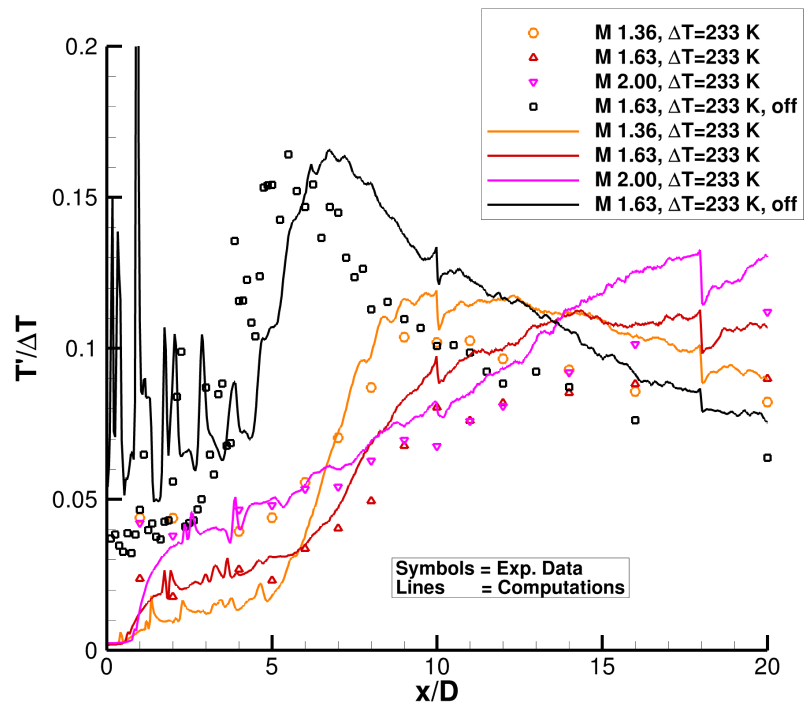
Results are from M. Emory (prev. Cascade) using CharLES – unpublished – AIAA PAW6.

Centerline Temperature Statistics - WMLES

Mean Temperature



RMS Temperature



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

Conclusions and Key Lessons Learned

- 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 developed and demonstrated 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. RANS GDH likely inadequate for many flows.
  2. RANS is inferior to LES for free shear layer mixing – jets, JICF as in film-cooling.
  3. 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 5th 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:

- 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.