# COE CST Eleventh Annual Technical Meeting

# Task 325: Optical Measurements of Rocket Nozzle Thrust and Noise

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Center of Excellence for
Commercial Space Transportation

# Agenda

- Team Members
- Challenges and Motivation
- Task Description
- Test Facilities
- Nozzle Design & Instrumentation
- Measurements
- Schedule and Milestones
- Conclusions

# Team Members

## Team

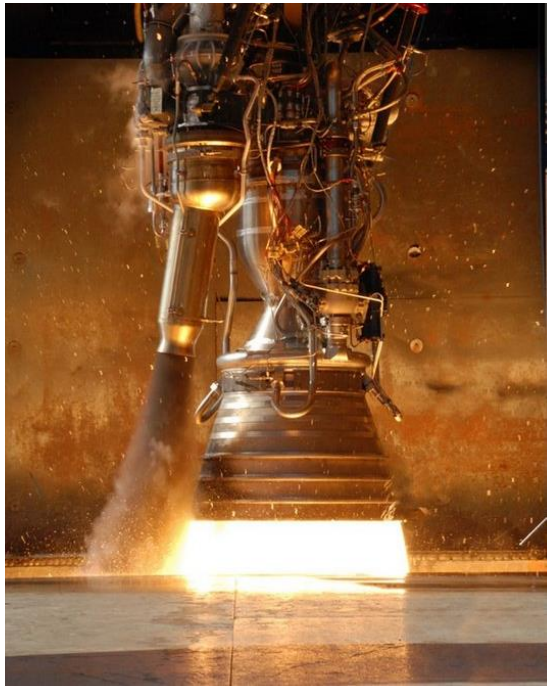
- Rajan Kumar & Farrukh Alvi
- Jonas Gustavsson, Michael Sheehan
- Rohit Vemula, Nikhil Khobragade

Samuel Lee, Timothy Willms, Vikas Bhargav, Yogesh Mehta (Post-doc)

## Organizations Involved

- FSU / FCAAP
- Space Florida
- SpaceX

# Challenges & Motivation



**70% accidents in aerospace missions are due to engine malfunction or propulsion system failures!!**

**Rocket propulsion studies are limited (only National Labs. & big corporations)**

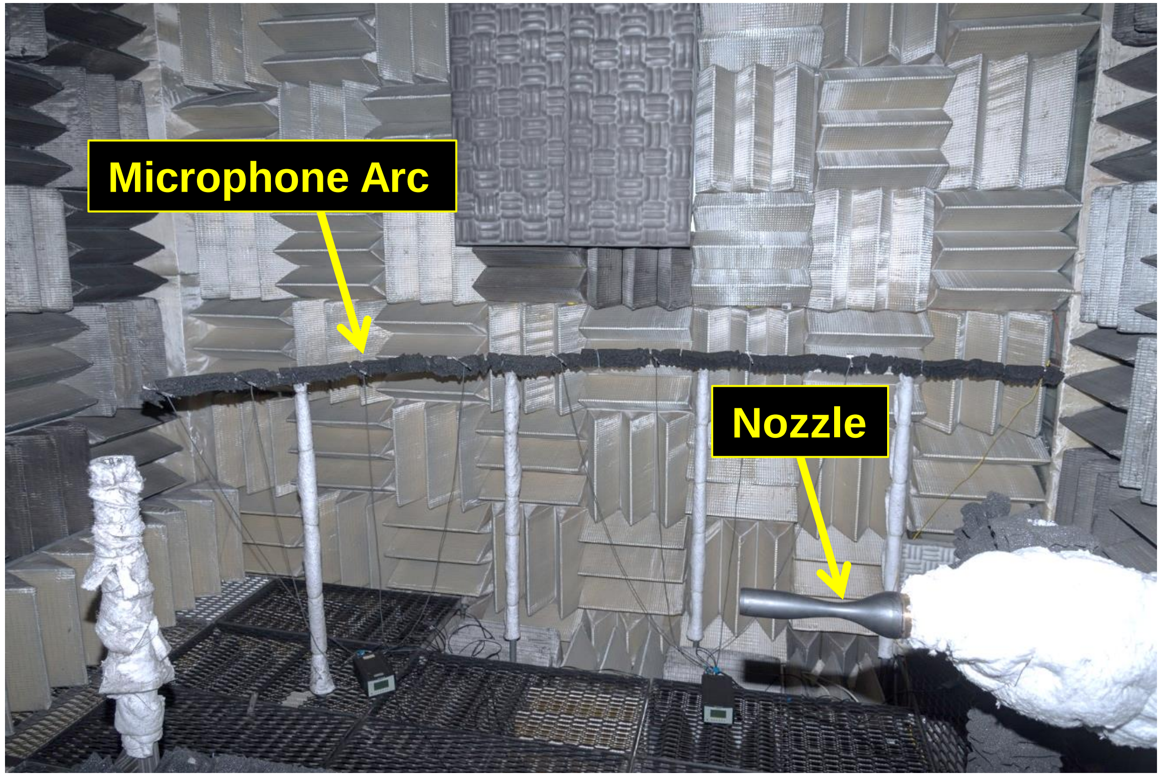
- **High temperature and pressure environment**
- **Complex chemistry – unstable fuels**
- **Large scale tests are expensive & require specialized rigs**

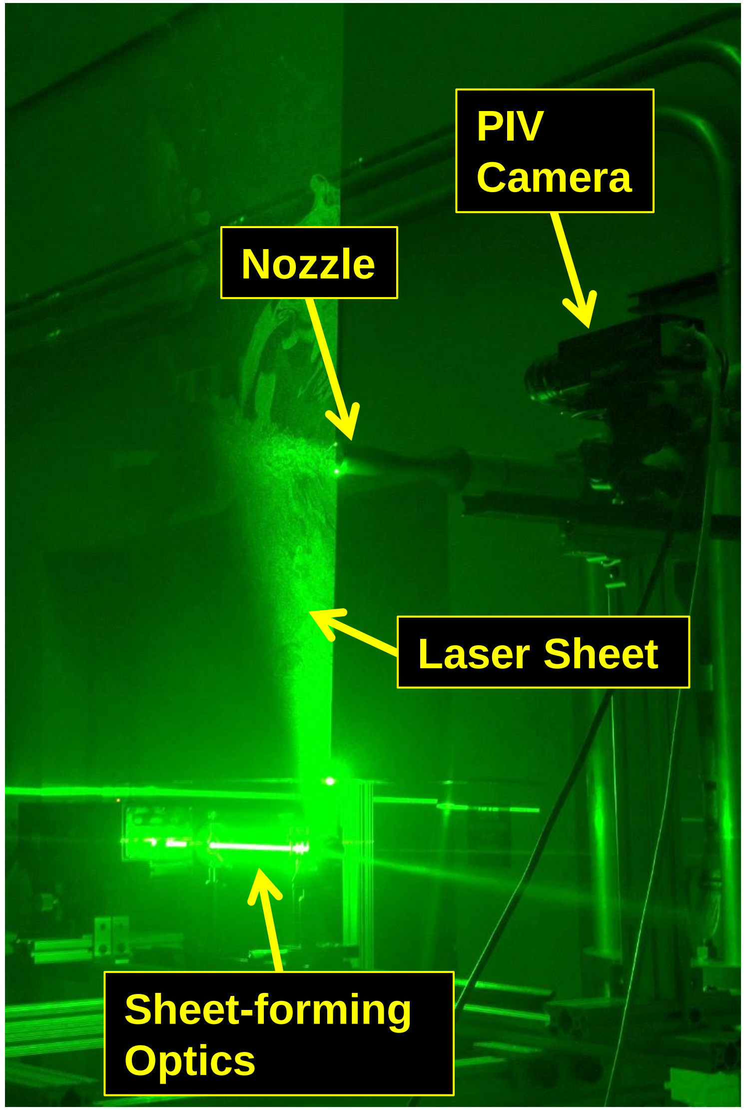
- **Need to develop high temperature pressure sensors – activity initiated under COE-CST**
- **Measure steady and transient loading on the nozzle and ground surface – material characterization**
- **Jet plume development and flow field analysis**
- **Nearfield & farfield noise measurement and prediction tools**
- **Study of next generation hybrid fuels**

# Tasks Description

- **Development of a research plan based on state-of-art thrust and noise measurement techniques.**
- **Discussion with NASA /commercial launch engineers to ensure the transition of technology from laboratory to full-scale implementation.**
- **Design of a scaled nozzle and simulate realistic temperature and pressure conditions of the jet exhaust in the FSU jet facility**
- **Design and develop advanced optical techniques for thrust measurements and characterize its performance at controlled conditions.**
- **Optical measurement of thrust using PIV and pressure distribution at the nozzle exhaust. The measured thrust using optical method compared to thrust measurement using load cell thrust stand.**
- **Noise measurements in the FSU hot jet anechoic facility over a range of nozzle pressure conditions.**
- **Flow control system implemented and tested over a wide range of test conditions.**
- **Simulate take-off and landing conditions of a rocket engine as impinging jet on a launch/landing surface.**
- **Surface pressure measurements(steady and unsteady) for range of heights.**

# Test Facilities



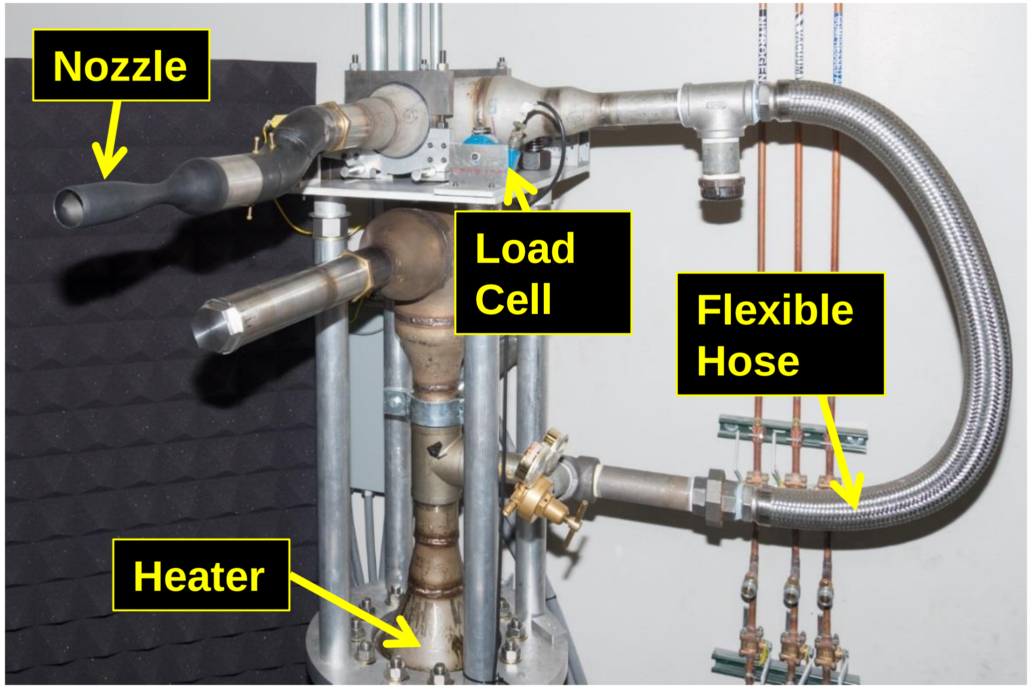


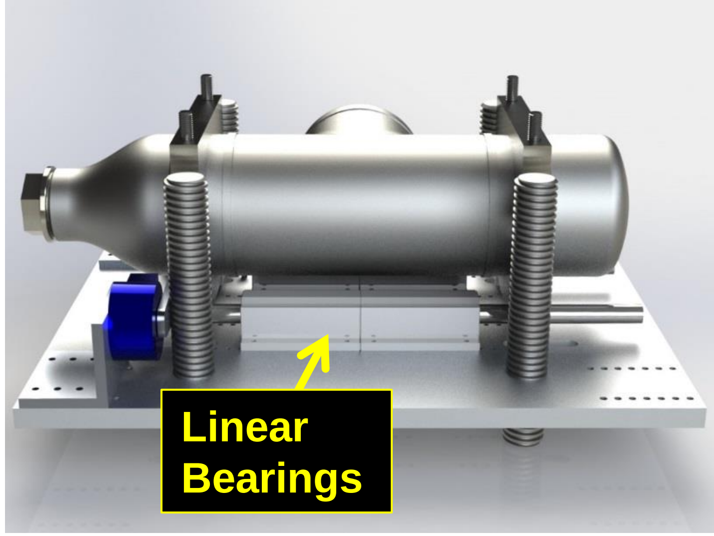
**Operational/Test Capabilities**

- *Mach Number = 0.5 - 2.5*
- *$T_o$= 70 - 2000 F*
- *$D_{Jet}$ = 25.4 – 76.2 mm*
- *NPR = Under-ideal-over expanded*
- *Anechoic chamber: 5.8 m x 5.2 m x 4.0 m, Calibrated to 100 Hz*

# Thrust Measurements

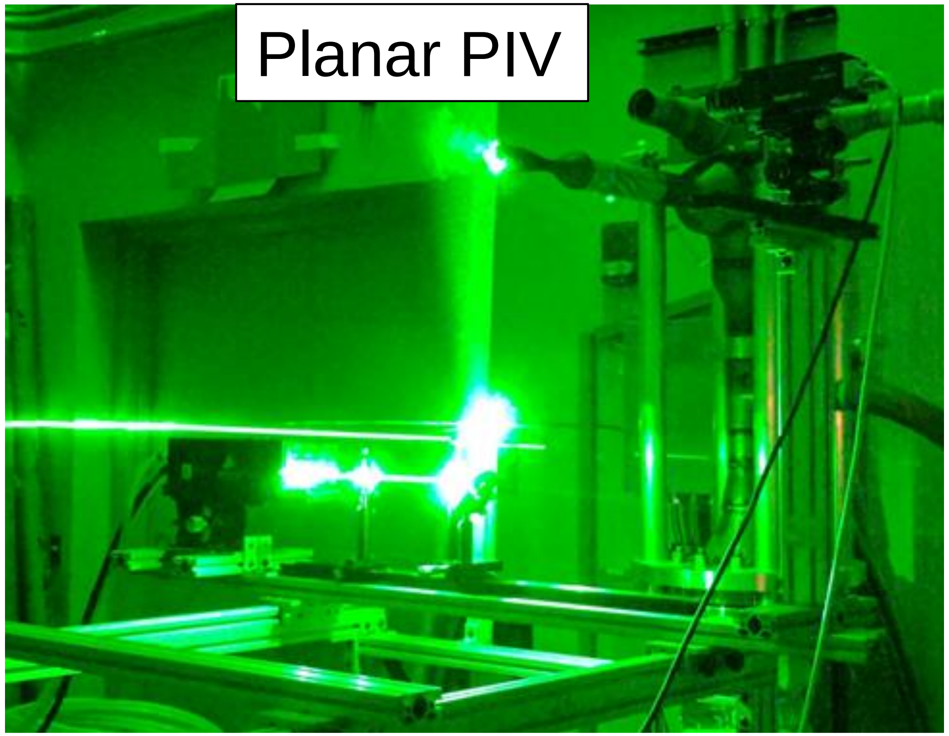
**A thrust measurement system was designed that allowed the nozzle stagnation chamber to traverse axially on linear bearings. Heated air was supplied from the side through a flexible hose, allowing all axial loads to be captured by the load cell.**

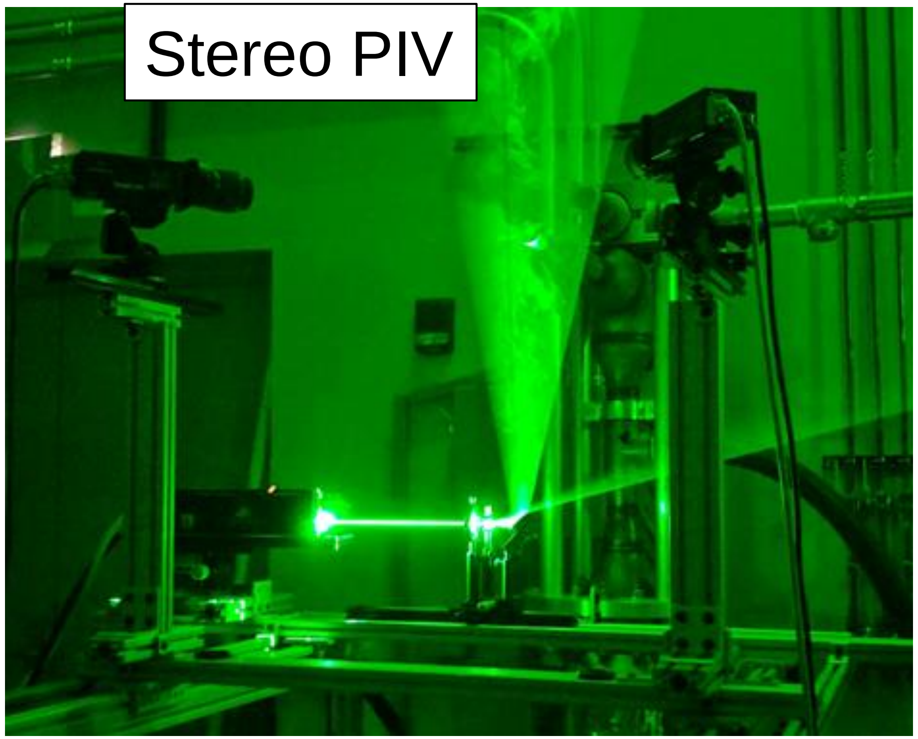




Design by William McCormack

# Particle Image Velocimetry


Planar PIV


Stereo PIV

Planar: Downstream development of plume
Stereo: Velocity distribution over exit plane

# Thrust Calculation

The PIV and pressure rake measurements are combined with stagnation pressure and temperature from the stagnation chamber to calculate the thrust.

Thrust equation: $F = \dot{m}u + (P - P_a)A$

Pressure rake

Rewriting using $P_0$ & $M$: $$F = \iint_A \frac{P_0}{\left(1 + \left(\frac{\gamma - 1}{2}\right) M^2\right)^{\frac{\gamma}{\gamma - 1}}} (\gamma M^2 + 1)\ dA - P_a A$$

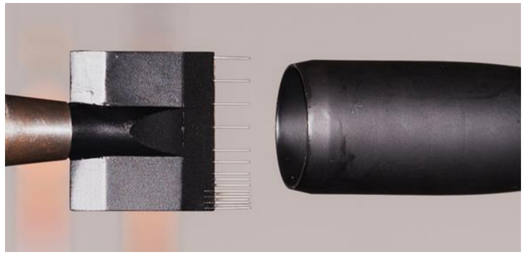
Ambient

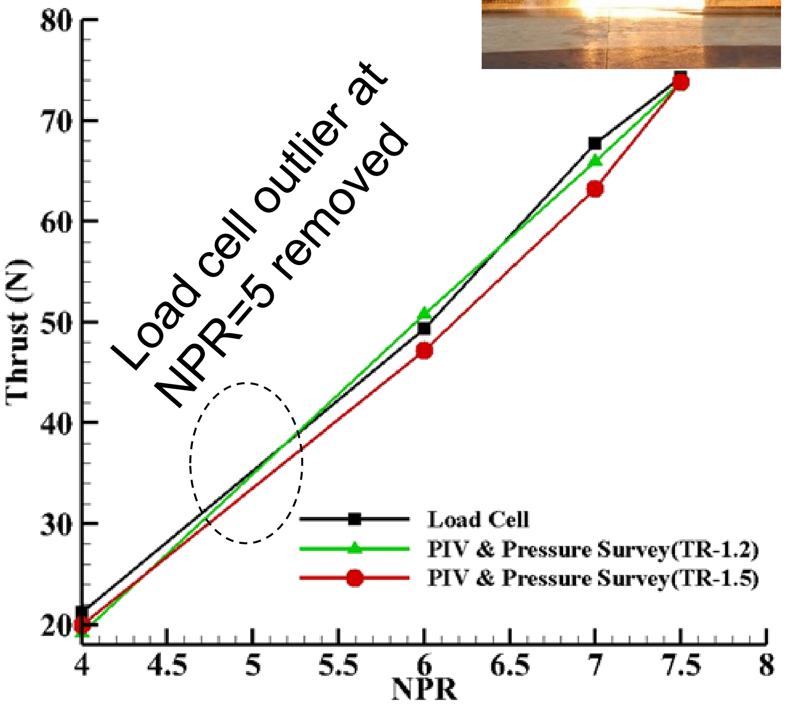
Mach number is obtained from:

PIV

$$M^2 \left(1 - \left(\frac{\gamma - 1}{2}\right) \frac{u^2}{\gamma R T_o}\right) = \frac{u^2}{\gamma R T_o}$$

Stag. Ch.



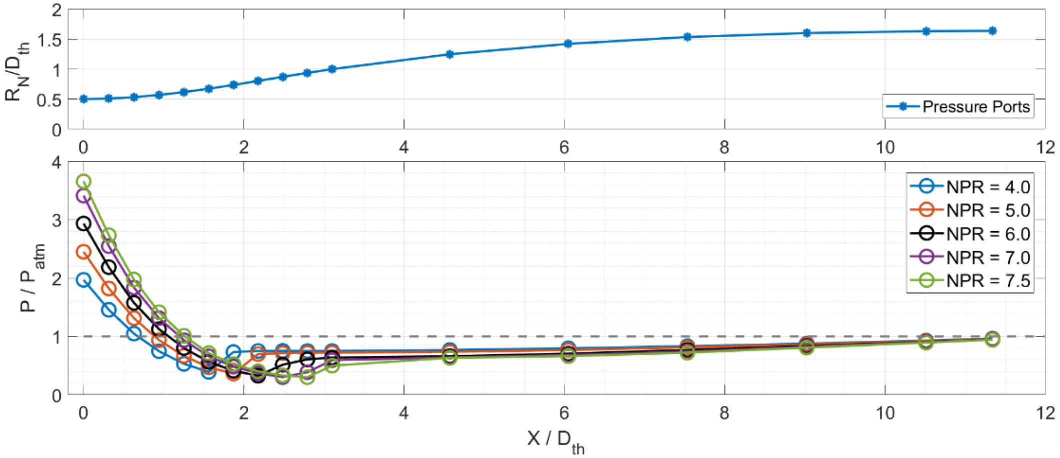


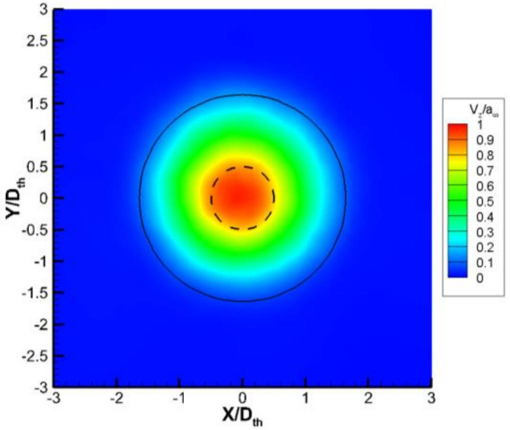
Load cell outlier at NPR=5 removed

- Thrust increases linearly with NPR
- Excellent agreement indirect-direct thrust measurement

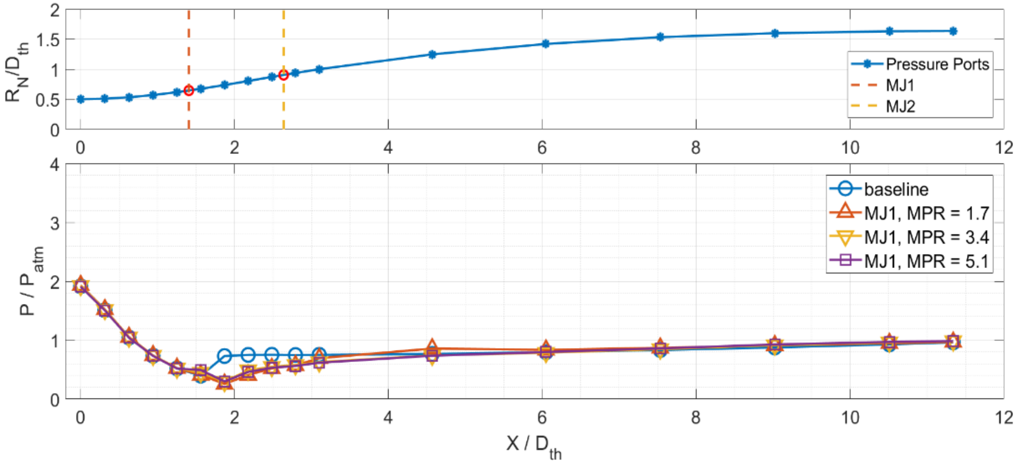
# Pressure Measurements Inside Nozzle

**Rocket nozzle with pressure taps and a sketch of a cross-section indicating locations of pressure ports and microjet arrays**



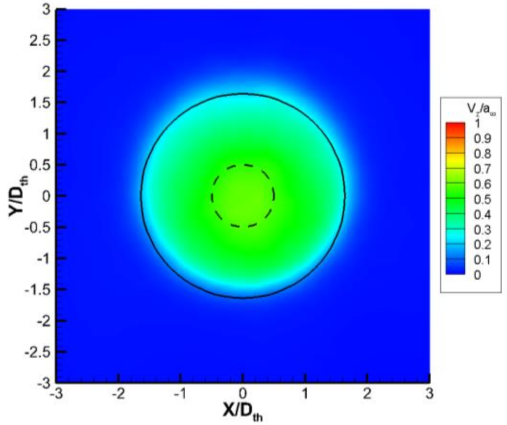


Baseline jet



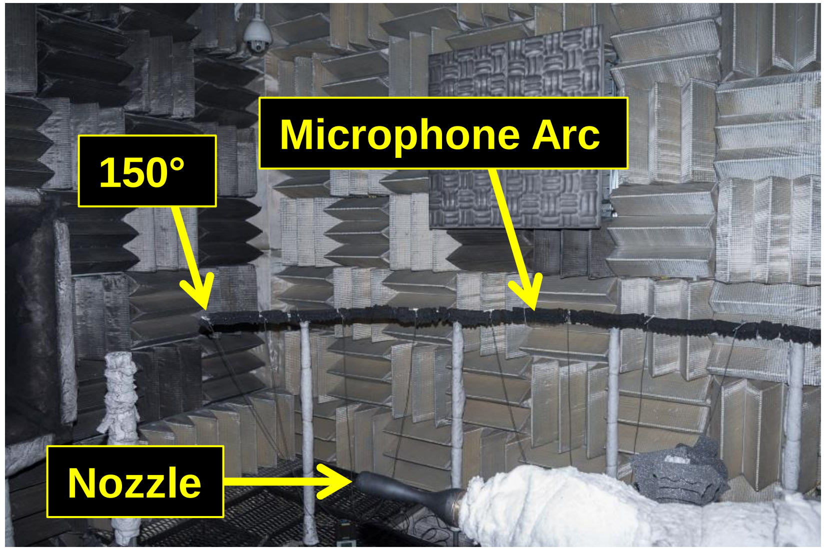
- **Delay in flow separation with microjet control.**
- **Reduction in core velocity, increase in jet diameter and better stability of the jet plume with microjet control**

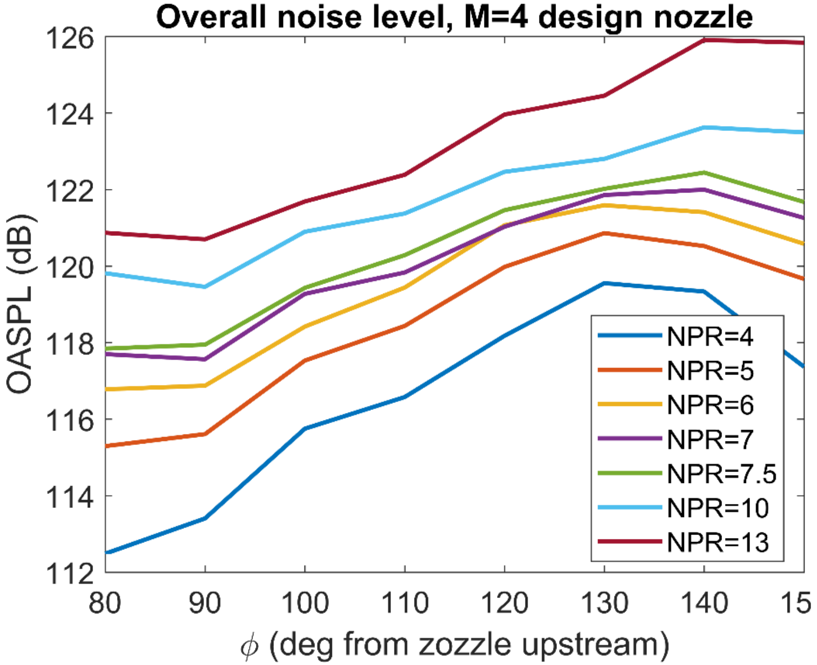
**With microjet control**

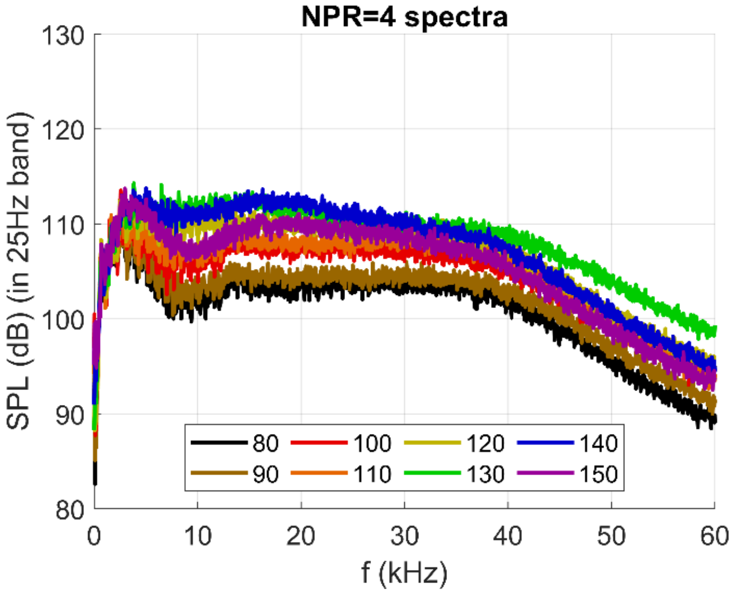


# Free jets: Noise Measurements

Noise measured for an isothermal jet (TR=1.0) at a wide range of NPR (4-13) in the FSU/FCAAP HotJet facility's anechoic chamber. Microphones were placed on an arc 200D* from the nozzle exit at 80-150 degrees from the nozzle upstream axial direction.



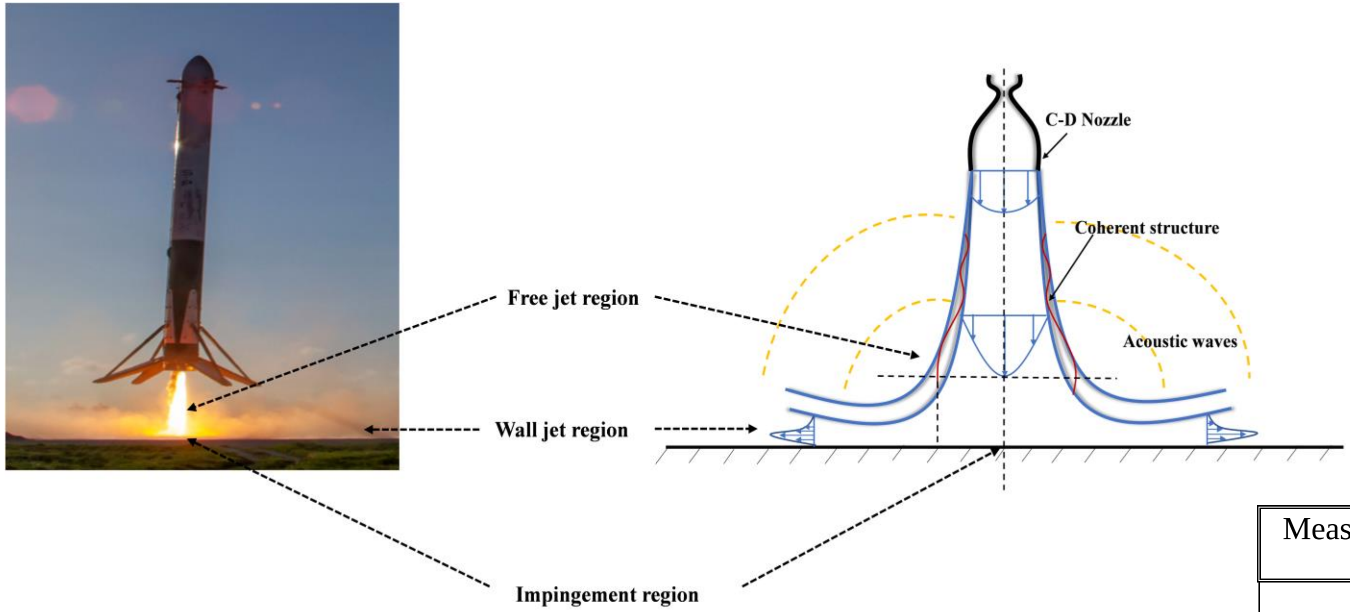


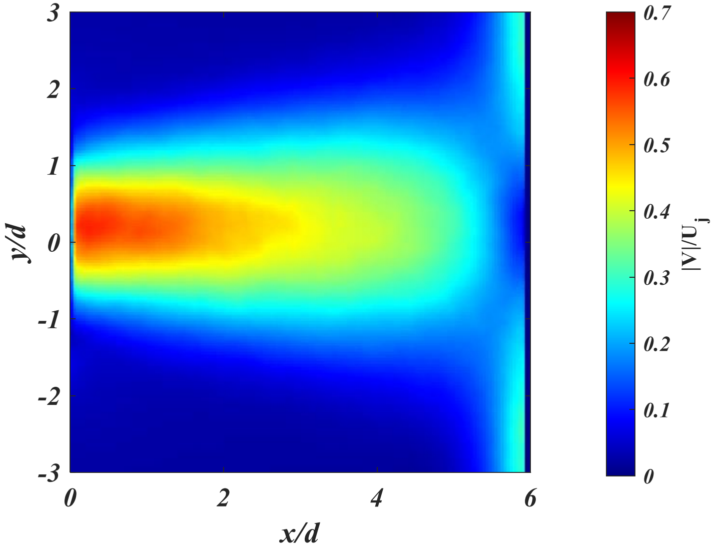


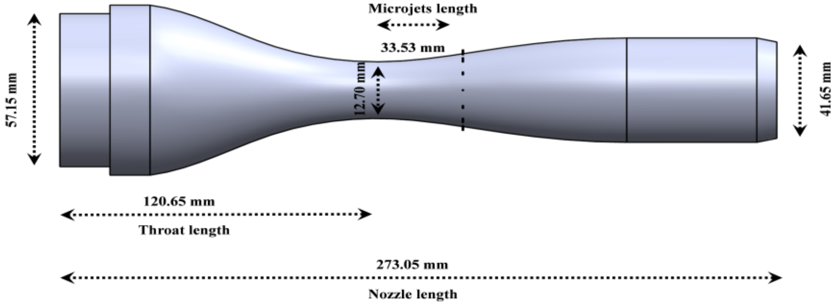
OASPL increases with NPR and has a maximum at 130-140°

- Low-frequency hump near 3 kHz strong at large angles and high NPR

# Impinging jet: Characterization and Control of a Rocket Nozzle



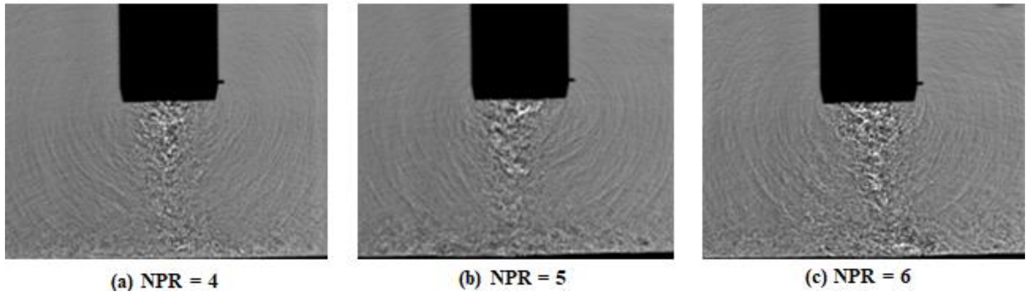




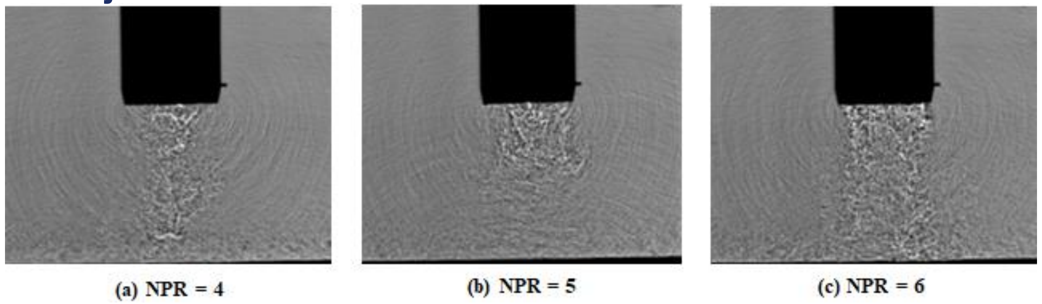
| Measurement | TR | NPR | $h/d_t$ | Measurement location |
|---|---|---|---|---|
| Static pressure | 1 | 4, 5, 6 | 2, 3, 4, 5, 6, 8, 10, 12 | Ground plane<br>$R/d_t = 0$ to 7.5 |
| Unsteady pressure | | | | Ground plane<br>$R/d_t = 0$ to 4.25 |
| Nearfield acoustics | | | | Microphone<br>$R = 30d_t$ |
| Shadowgraphy | | | | - |

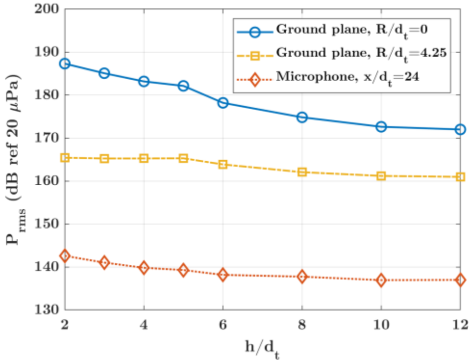
# Flowfield and Ground Pressure Results

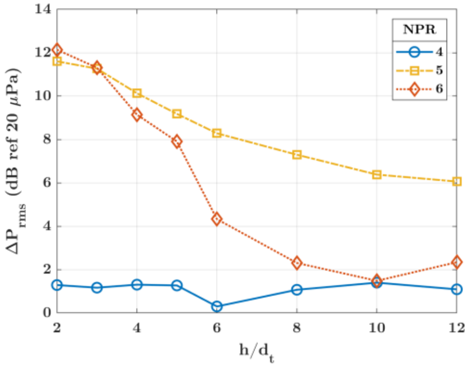
**Baseline jet**



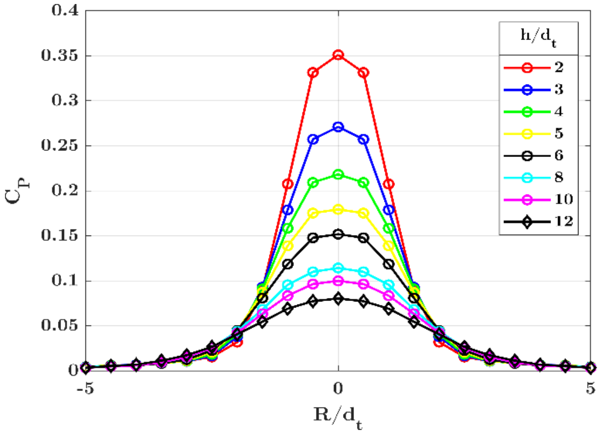
**Microjet Control**



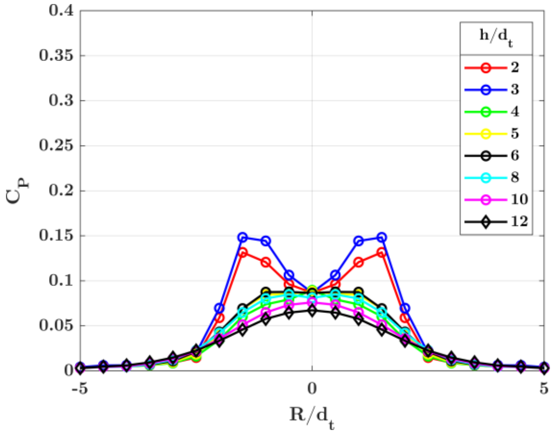


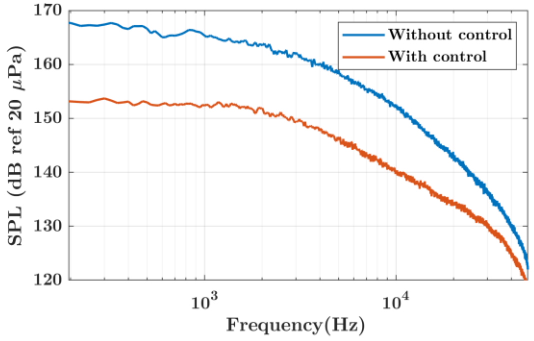


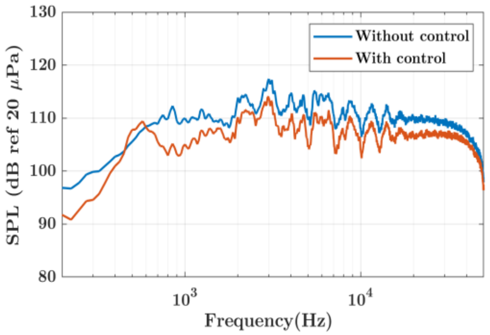
**Baseline jet**



**Microjet Control**

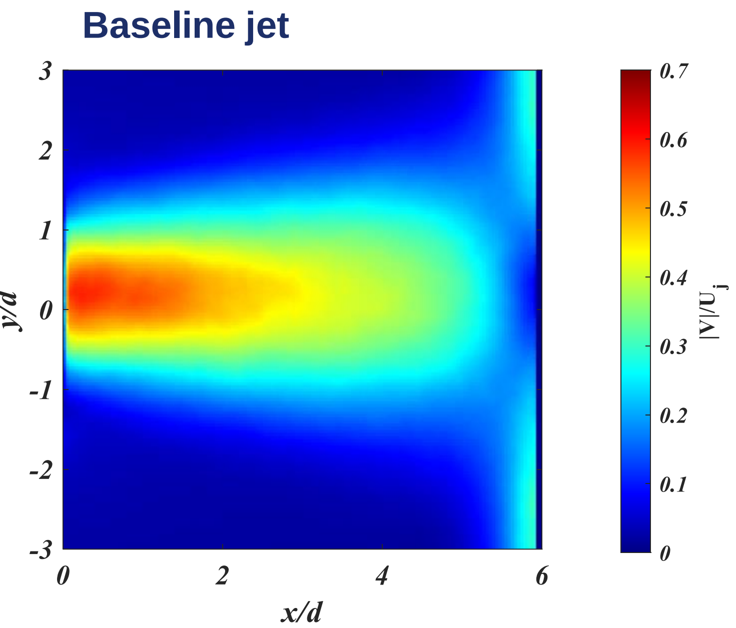


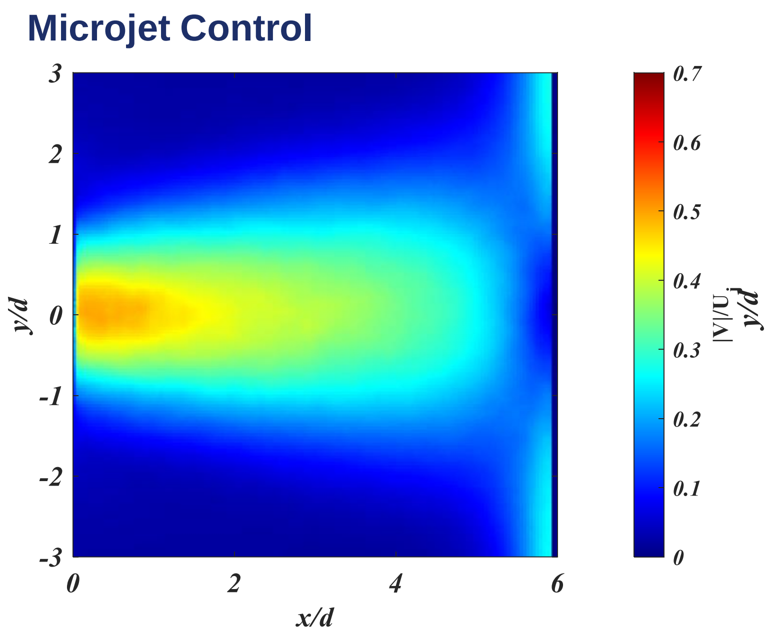


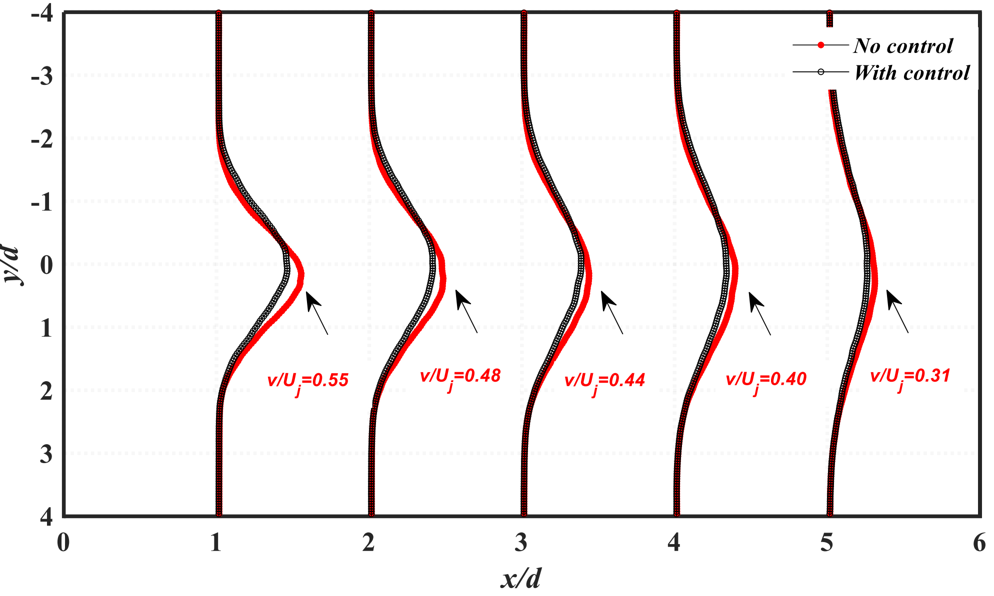


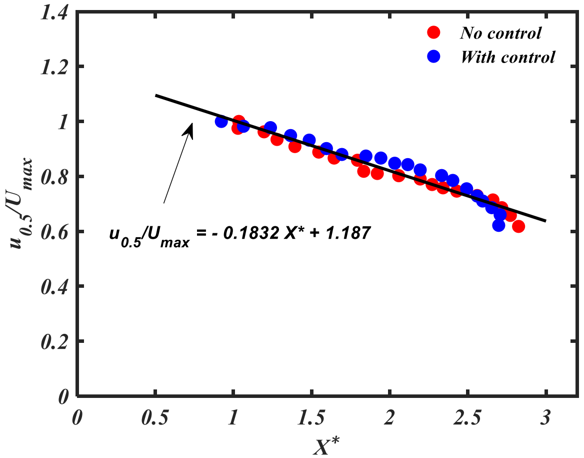
1) **Microjet flow control alters the global flow field thereby reducing both the pressure fluctuations on the ground and acoustics in the nearfield region.**
2) **Effectiveness of control is sensitive to the position of microjets to the flow separation location inside the nozzle, suggests that if the flow separation location of a rocket nozzle operating at a certain condition is known a priori, one can tailor the position of microjet flow control for maximum effectiveness.**

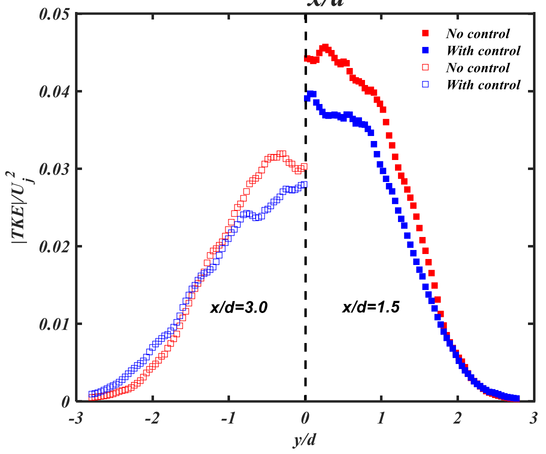
# Impinging Jet: Velocity field





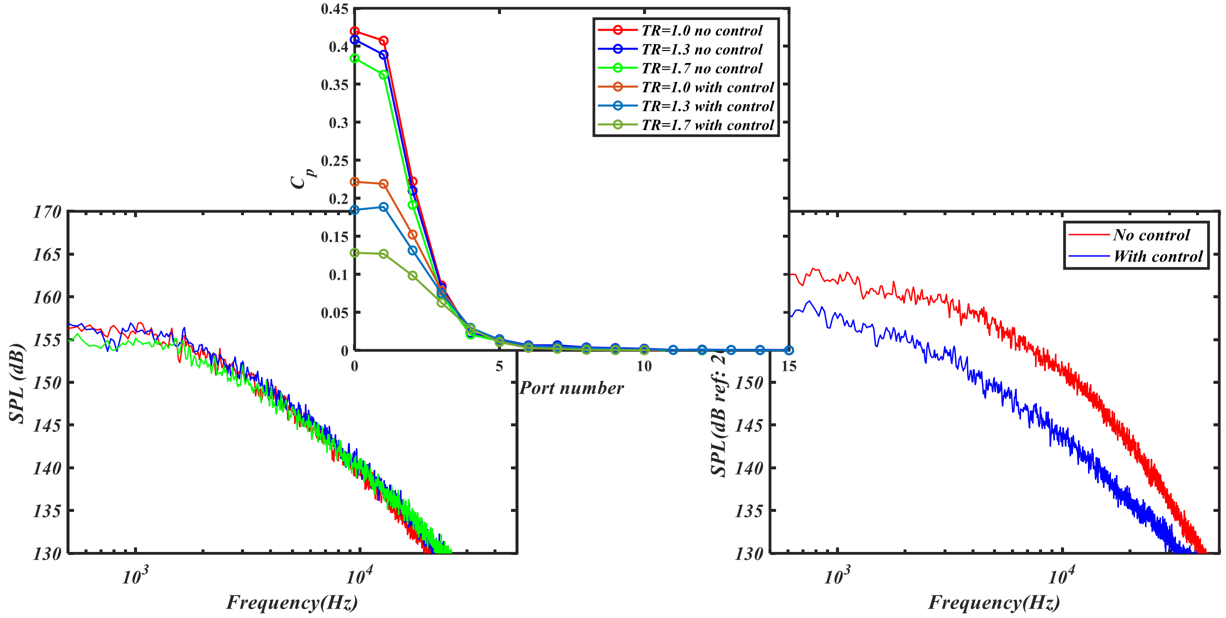


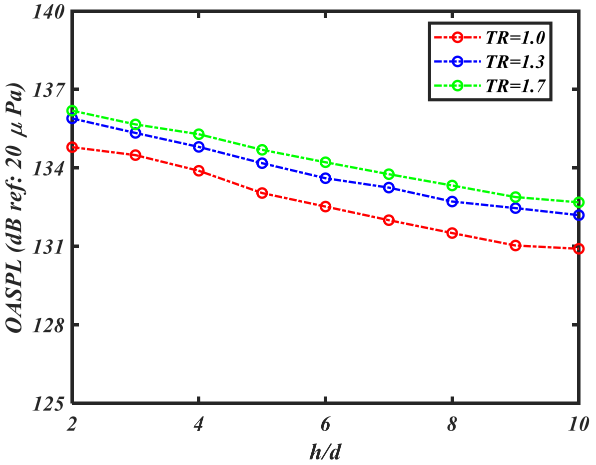


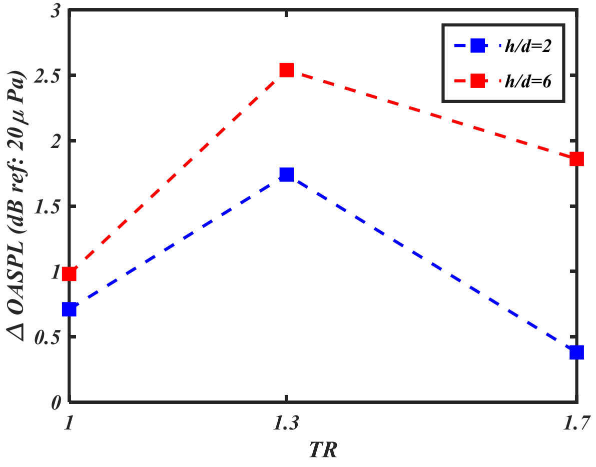


- Velocity flowfield suggested a drop in the peak centerline velocity when the microjets are injected but showed a gradual drop in axial and transverse directions.
- Significant drop in turbulent kinetic energy is noted when the control is activated.

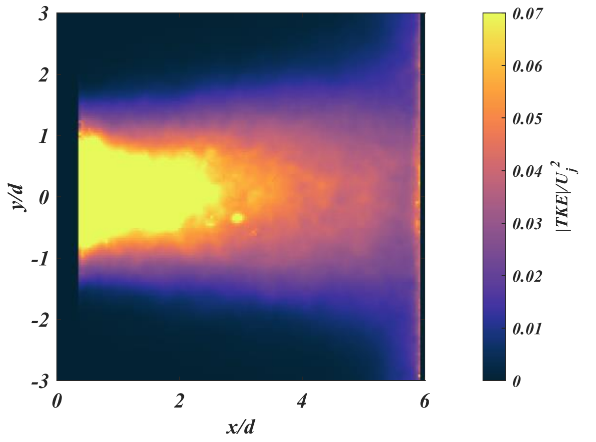
# Impinging Jet: High temperature results



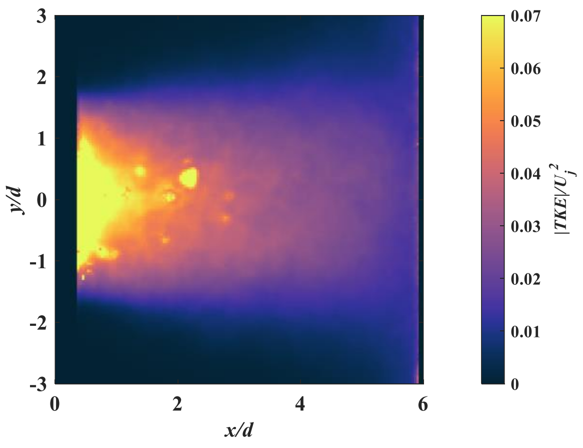




1) The results show that the static pressure on the ground plate is a strong function of the jet stagnation temperature and impingement height.
2) In general, increasing the temperature raises the overall sound pressure level at a range of conditions
3) The velocity field measurements suggest that increasing the temperature results in higher turbulent kinetic energy.
4) Further, injection of microjets also results in roughly 2-3 dB noise attenuation in some instances. The use of microjets is effective at a broad range of frequencies, temperature ratios, and impingement distances.



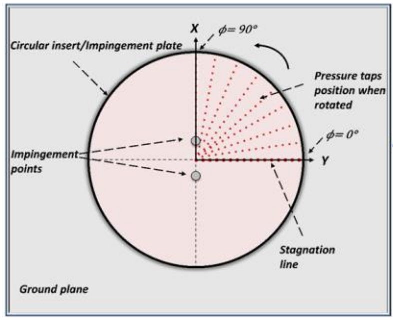
**Baseline jet**

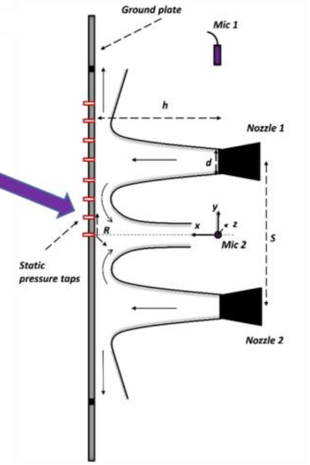


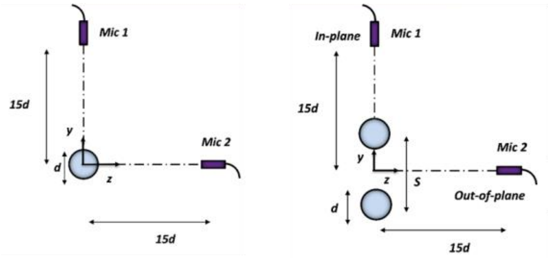
**Microjet Control**

# Twin Impinging Jets: Flow and Pressure field

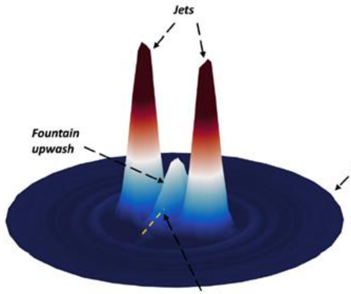
## Instrumentations

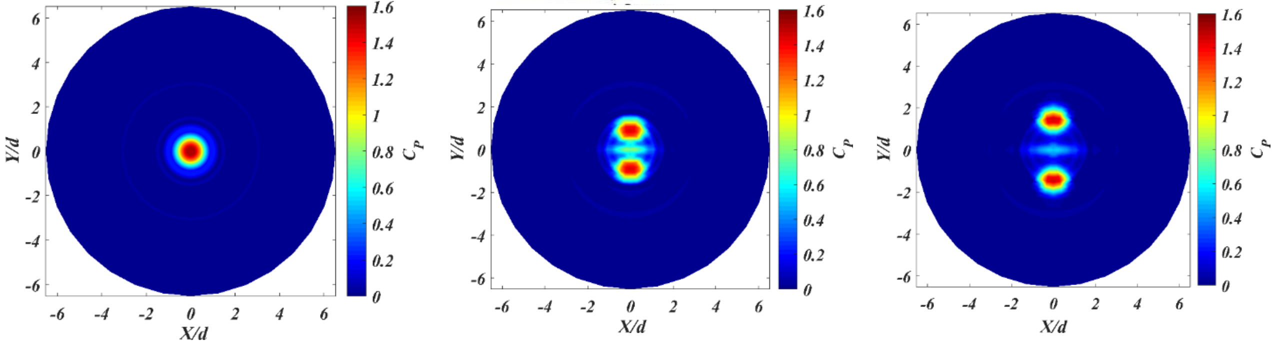


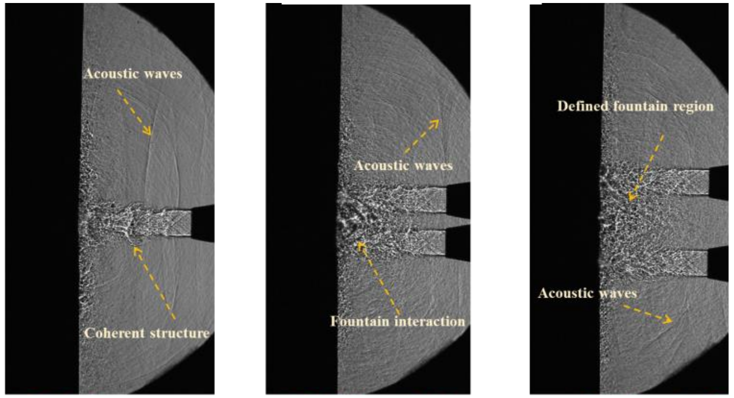




- *Shadowgraph*
- *Microphone & Static pressure*



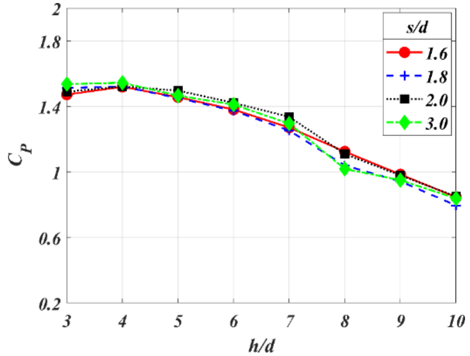




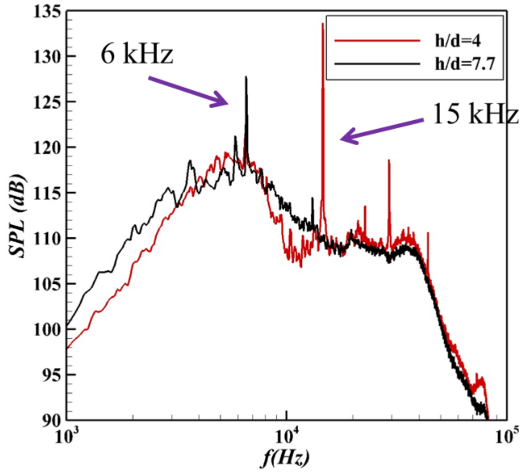
a) Single jet b) Twin jet: s/d=1.6 c) Twin jet: s/d=3.0

@h/d=4

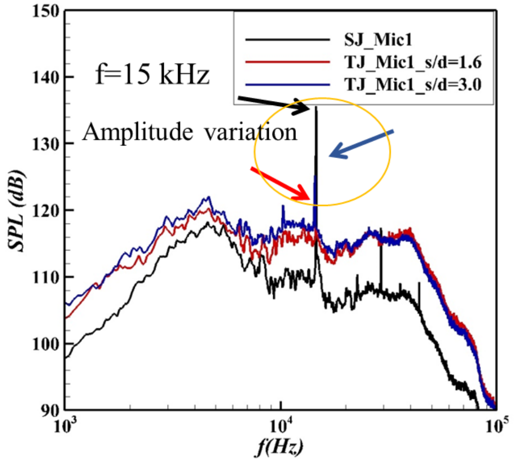
- ***Mean pressure similar for single and twin jets at impingement points.***
- ***Minimum influence of fountain flow on the mean impingement characteristics with spacing.***



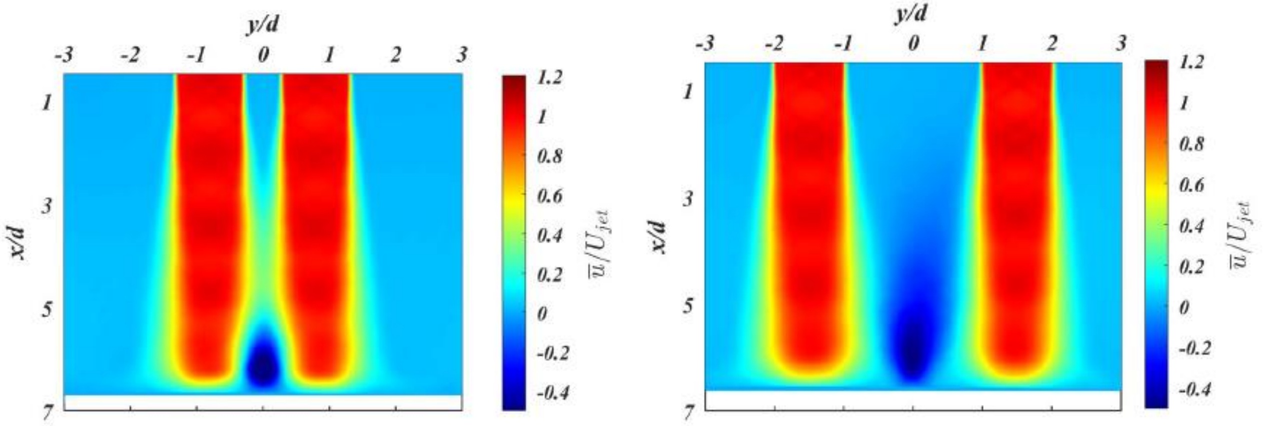
# Twin Impinging Jets: Acoustics and Velocity field

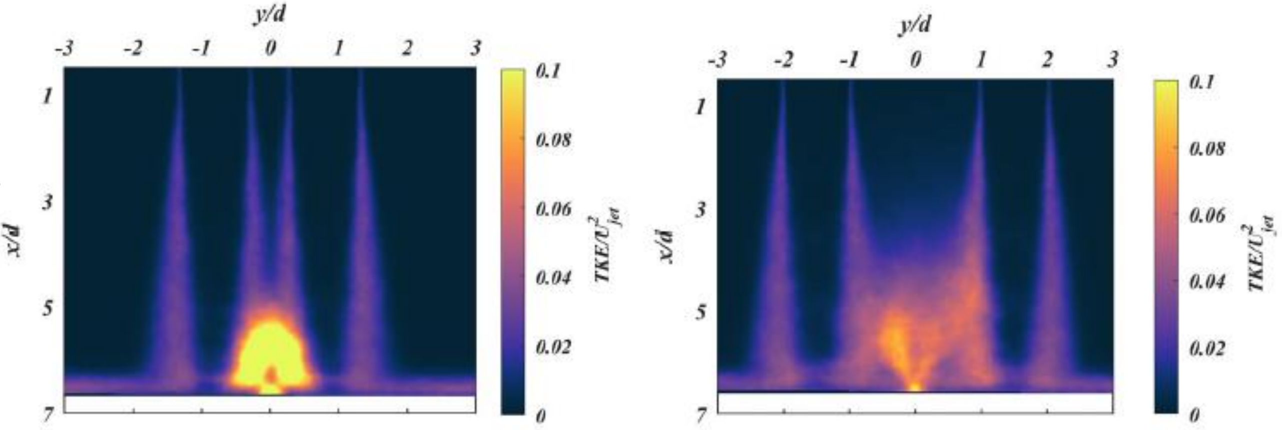


**Single jet @h/d=4**



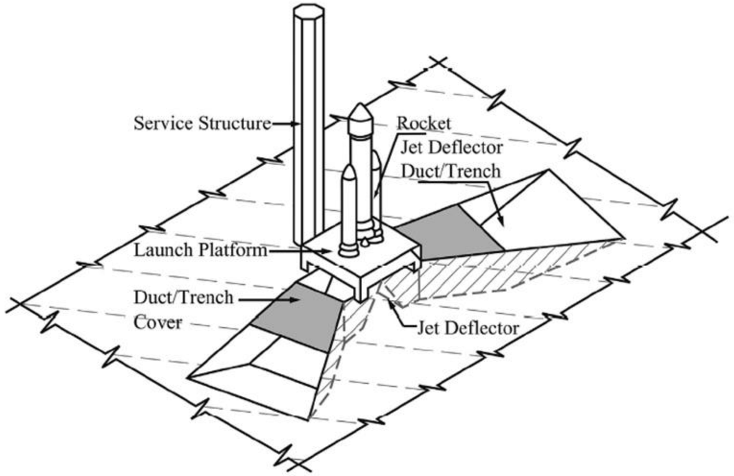
**Single and twin jets @h/d=4**

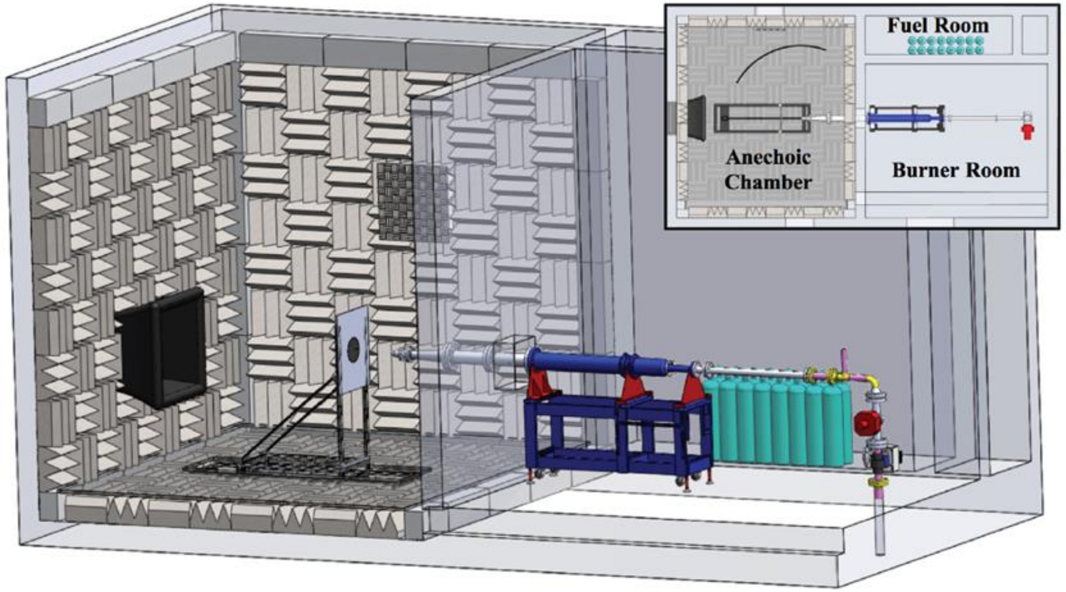


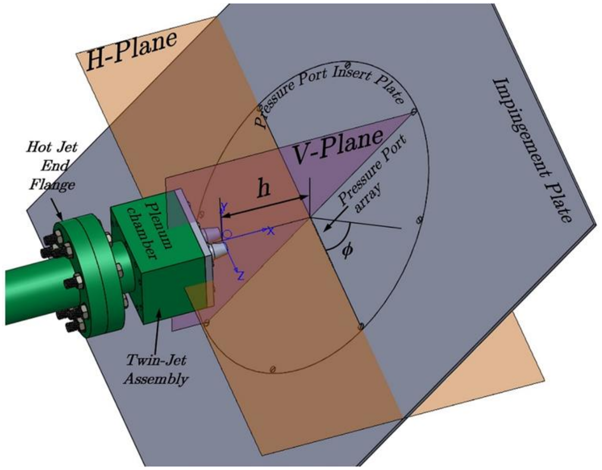


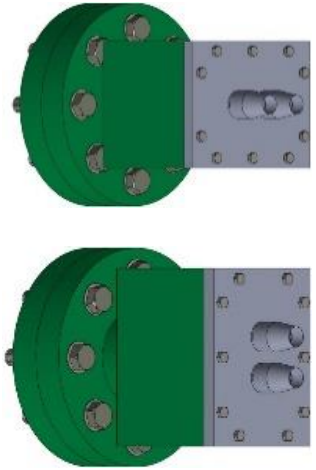
- **The results show that the pressure distributions in the jet impingement region are independent of internozzle spacing.**
- **The acoustic spectra show that the amplitudes of tones vary as a function of internozzle spacing and impingement height, which may be due to the variation in the strength of the fountain flow.**
- **The mean velocity at the core of the two jets is independent of the internozzle spacing, whereas midplane velocities between the two jets are highly sensitive to nozzle spacing and ground-plane distance.**

# Twin Impinging Jets: Normal vs Inclined jets



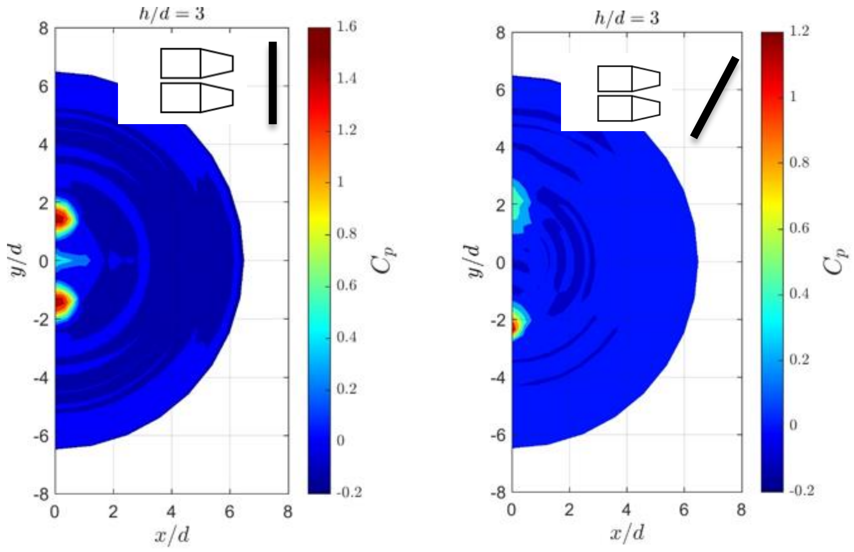


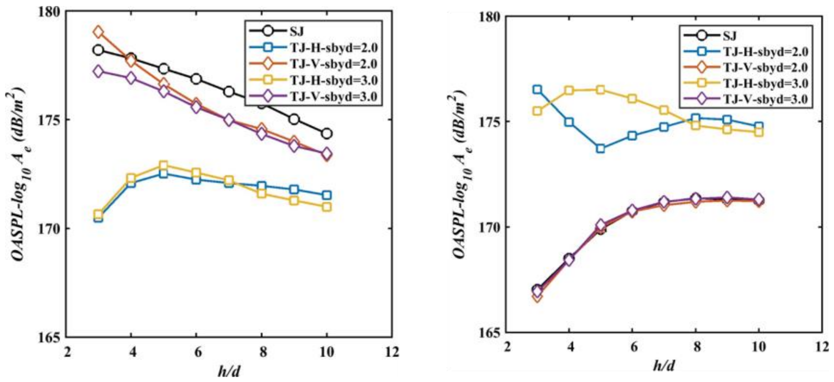


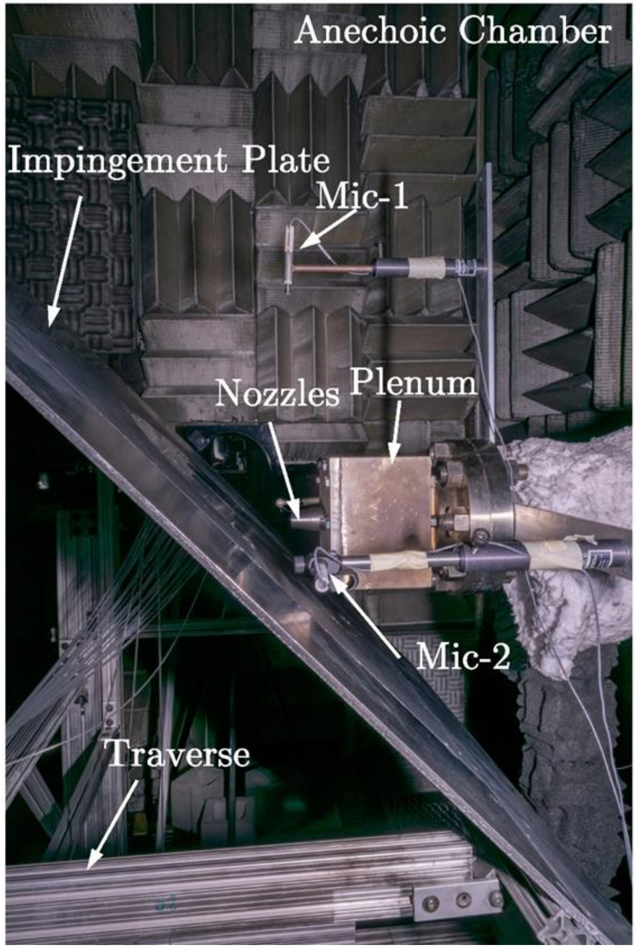


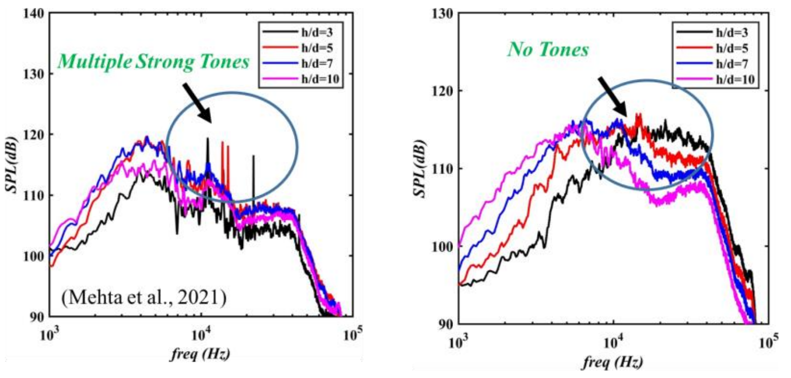
| | Geometry | Nozzle exit dia (d) | Nozzle pressure ratio (NPR) | Temperature ratio(TR) | s/d | h/d |
|---|---|---|---|---|---|---|
| **Nozzles(M=1.5)** | C-D | 19mm | 3.67 | 1 | 0, 2, 3 | 3 to 10 |

# Twin Impinging Jets: Normal vs Inclined jets









*Normal impingement*

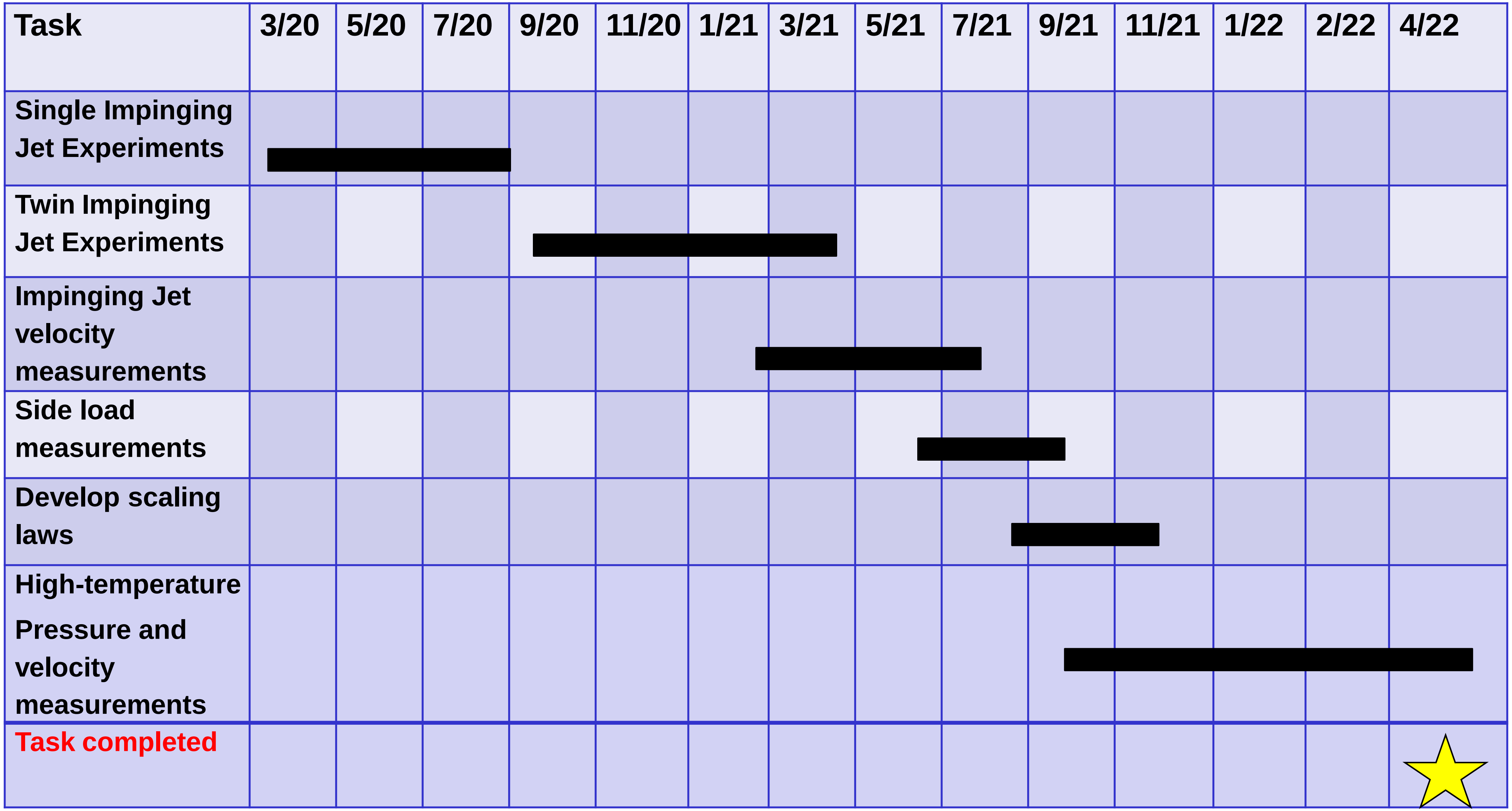
*Inclined impingement*

- *For the jets impinging in TJV configuration, the jet impinging earlier exhibits a higher-pressure peak at the point of impingement than the jet impinging further downstream.*
- *No resonance (tonal behavior)was observed for the inclined impingement cases.*
- *The maximum noise levels are observed in the plane containing nozzles than perpendicular to it.*

# Conclusions and Future Work

- Conclusions
  - Method of measuring thrust indirectly using flowfield data has been validated against load cells.
  - Microjet based flow control implemented for free jets. The surface static pressure distributions are modified and flow separation is significantly delayed with the implementation of microjet based flow control.
  - Measured farfield noise in the FSU hot jet anechoic facility over a range of nozzle pressure conditions
  - Simulated rocket take-off and landing condition as impinging jet and measured loading on the surface
  - Measured nearfield acoustics over a range of impingement distances and nozzle pressure ratio.
  - Implemented flowfield diagnostics(particle image velocimetry(PIV)) for the cold impinging jet.
  - Completed and reported mean surface pressure, unsteady pressures on the ground and nearfield acoustic measurements of high-temperature jet.
  - Implemented quantitative flowfield measurements using PIV for high-temperature jet.
  - Simulated rocket launch and landing for twin impinging jets in a tandem with different internozzle spacings.
  - Measured the surface pressure, acoustics for normal as well as inclined impinging jets in different configurations.
  - Successfully implemented active flow control for cold and high temperature impinging jets for the reduction in pressure and nearfield acoustics.

# Schedule and Milestones



| Task | 3/20 | 5/20 | 7/20 | 9/20 | 11/20 | 1/21 | 3/21 | 5/21 | 7/21 | 9/21 | 11/21 | 1/22 | 2/22 | 4/22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Single Impinging Jet Experiments** | ■ | ■ | ■ | | | | | | | | | | | |
| **Twin Impinging Jet Experiments** | | | | ■ | ■ | ■ | ■ | | | | | | | |
| **Impinging Jet velocity measurements** | | | | | | ■ | ■ | ■ | ■ | | | | | |
| **Side load measurements** | | | | | | | | ■ | ■ | ■ | | | | |
| **Develop scaling laws** | | | | | | | | | ■ | ■ | ■ | | | |
| **High-temperature Pressure and velocity measurements** | | | | | | | | | | ■ | ■ | ■ | ■ | ■ |
| **Task completed** | | | | | | | | | | | | | | ★ |

# Publications, Presentations, Awards, & Recognitions

**PUBLICATIONS**

1. Mehta, Y., Bhargav, V., and Kumar, R. "Control of High Temperature Impinging Jet Issued from Overexpanded Rocket Nozzle" Journal of Spacecraft and Rockets(To be submitted)
2. Mehta, Y., Bhargav, V., and Kumar, R. "Characterization and Control of High Temperature Impinging Jet Issued from a Mach 4 Rocket Nozzle," AIAA 2022-0124. AIAA SCITECH 2022 Forum. January 2022.
3. Mehta, Y., Natarajan, K., Sellappan, P., Gustavsson, J., and Kumar, R., "Effect of Nozzle Spacing in Supersonic Twin Impinging Jets," AIAA Journal, Vol. 60, No. 4, pp. 2423-2440 .
4. Mehta Y, Natarajan K, Gustavsson J, Kumar R (2021) An experimental investigation into the effect of nozzle spacing in supersonic twin jets. AIAA Scitech 2021 Forum DOI 10.2514/6.2021-1293
5. Mehta, Y., Bhargav, V. N., and Kumar, R., "Experimental Characterization and Control of an Impinging Jet Issued from a Rocket Nozzle," New Space, Vol. 9, No. 3, 2021, pp. 187–201.
6. Khobragade, N., Wylie, J., Gustavsson, J. & Kumar, R. (2019) Control of Flow Separation in a Rocket Nozzle Using Microjets. *New Space Journal*, Vol. 7, No. 1, pp31-42, doi: 10.1089/space.2018.0037
7. Vemula, R. C., Gustavsson, J. & Kumar, R. (2018) Rocket Nozzle Thrust and Flowfield Measurements using Particle Image Velocimetry. *New Space Journal*, Vol. 6, No. 1, 37- 47, doi: 10.1089/space.2017.0045.
8. Daniel L. Bradley, Alexander M. Sharp, and Rajan Kumar (2018) "Student-Designed Liquid Rocket Engine From Concept to Completion", 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4865)
9. Vemula, R. C., Valentich, G. & Kumar, R. (2017) Flow Field Characteristics of Non-Axisymmetric Jets at High Temperatures, AIAA SciTech, 55th AIAA Aerospace Sciences Meeting, 9-13 January 2017, Grapevine, Texas, AIAA 2017-1888
10. Vemula, R. and Kumar, R. (2016) Measurement of Rocket Nozzle Thrust and Noise. 2016 National Space & Missile Materials Symposium (NSMMS) & Commercial and Government Responsive Access to Space Technology Exchange (CRASTE), Westminster, CO, June 20-23, 2016