



Computational Fluid Dynamic Optimization of an Experimental Rotating Detonation Rocket Engine Nozzle

Daniel E. Paxson, Kenji Miki, H. Douglas Perkins
*NASA Glenn Research Center
Cleveland, Ohio*

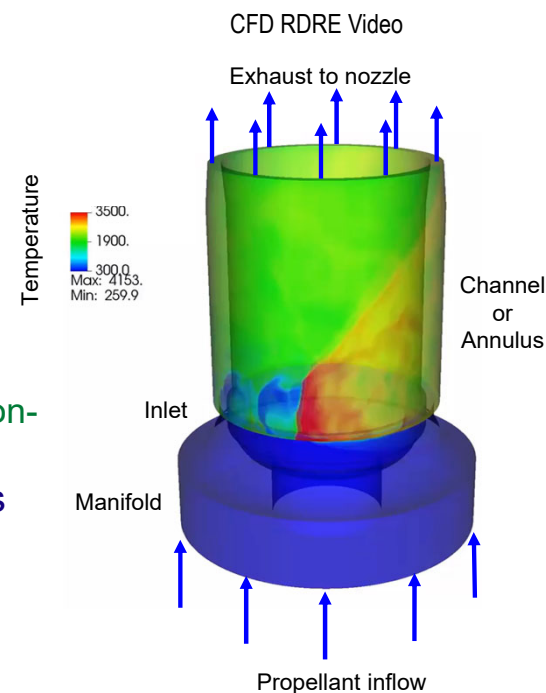
Shaye Yungster
*HX5, LLC
Cleveland, Ohio*

Aviation 2022
Hybrid Edition
Chicago, IL
June 27- July 1, 2022

Motivation

- Rotating Detonation Rocket Engines (RDRE's) are a promising approach for achieving Pressure Gain Combustion (PGC) in chemical propulsion systems
 - High pressure gain potential
 - Compact
 - No moving parts
- RDRE flow fields are remarkably complex
 - Multiple length and time scales
 - Multiple fluid states
 - Fundamentally unsteady; steady-state design rules do not apply
- How can a nozzle be designed for this environment?
 - Need to maximize thrust from an expanding flow that is spatially and temporally non-uniform
- One Method: Computational Fluid Dynamic (CFD) modeling with two domains
 - Detailed in AIAA-2020-3872
 - RDRE annulus modeled with simplified in-house quasi-two-dimensional (Q2D) reacting flow solver
 - RDRE nozzle modeled with Open NCC three dimensional (3D) non-reacting flow solver using non-steady inlet boundary conditions (b.c.) supplied from Q2D
 - Combination provides high-fidelity with rapid turnaround of solutions

This Paper Describes the Application of This Methodology to Optimize the Nozzle of an Experimental RDRE



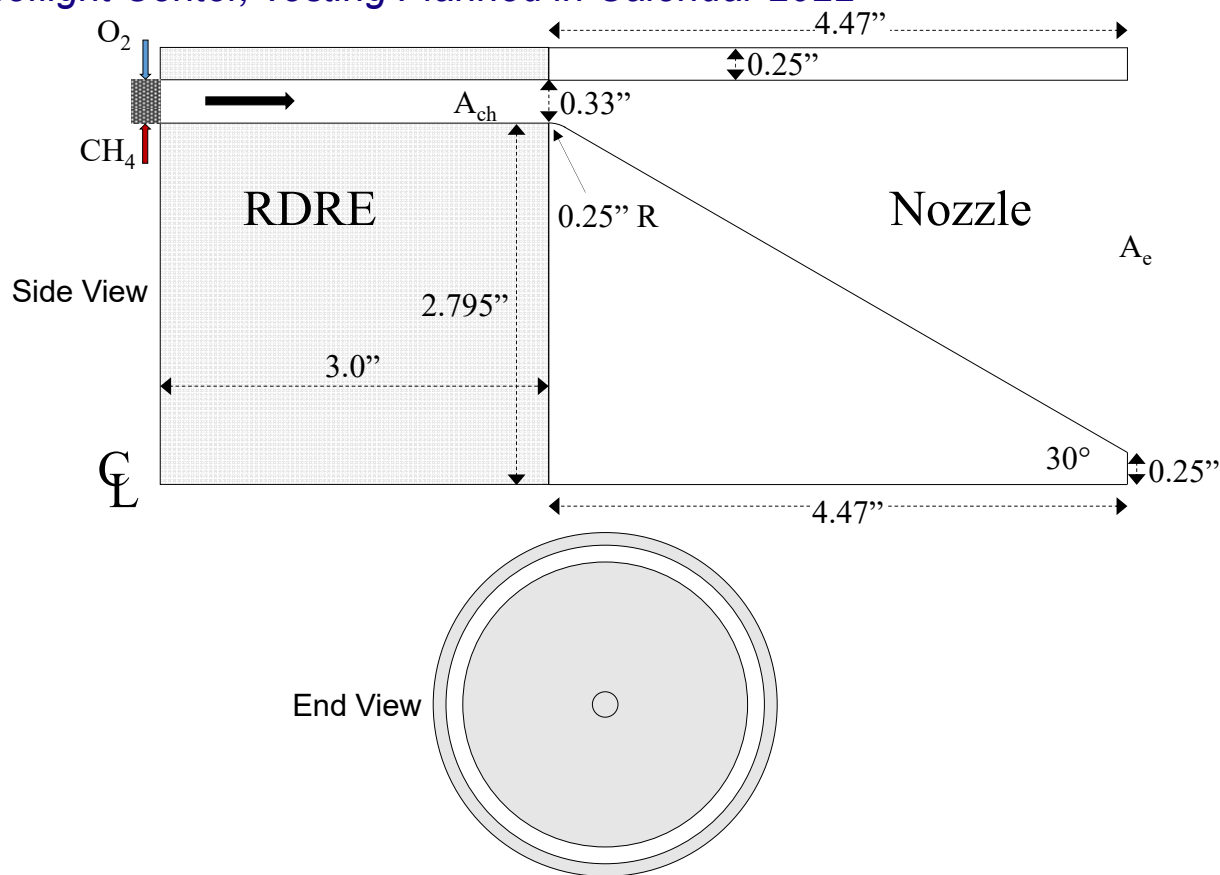


Experimental RDRE

NASA Marshall Spaceflight Center, Testing Planned in Calendar 2022

Specifications and Features

- Baseline (Version 1) nozzle shown
- Propellant flow rate $\approx 18 \text{ lb}_m/\text{s}$
- Thrust $\approx 5,000 \text{ lb}_f$
- Gaseous CH_4 and LOX operation
- Equivalence Ratio = 1.3
- Cooled walls $\approx 1460 \text{ R}$
- Ambient exit pressure (14.7 psia)
- Additively manufactured
- RDRE Designed with INSpace, LLC under NASA's Announcement of Cooperative Opportunities (ACO) program

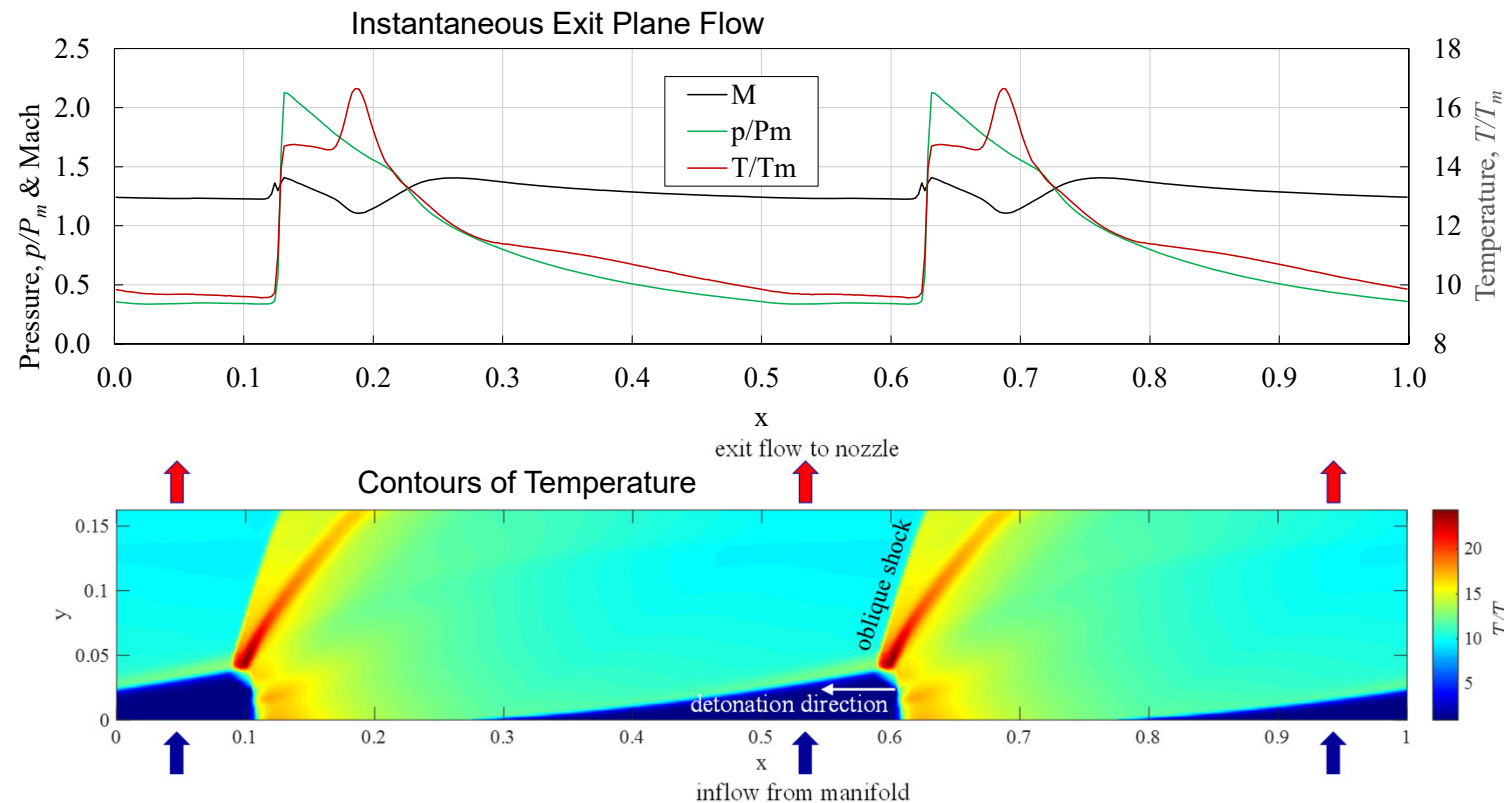


Baseline Nozzle is Not an Arbitrary Design

Q2D RDRE Annulus Solution (Unwrapped, 400×65 Uniform Cells)

Computed Results

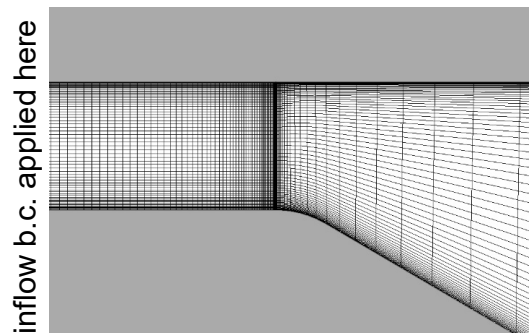
- $P_m=320$ psia; $T_m=540$ R
- Two waves assumed
- No nozzle present, ambient back pressure
- Ideal inlet w/ no backflow
- Mass flow rate= 16.1 lb_m/s
- Ideal thrust, $F_i=5003$ lb_f
 - Requires a notional nozzle that can change shape spatially and temporally
 - Impossibly ideal, but consistent
- Thrust w/o nozzle, $F_{no_nozzle}=3993$ lb_f
- Exit plane is supersonic



Nozzle Can Contribute Significantly (20%) to Total Thrust

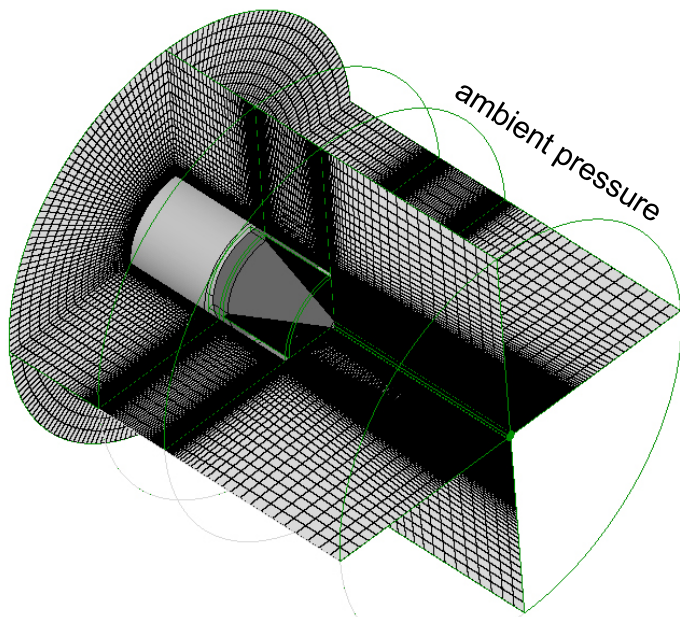
3D Setup (Baseline V1 Nozzle)

detail near nozzle entrance



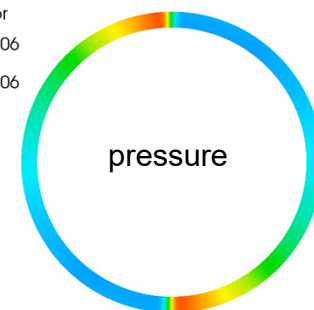
computational domain

ambient pressure



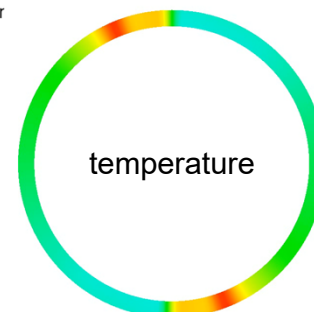
unsteady inflow boundary condition
converted from Q2D outflow

Pseudocolor
Var: p
4.750e+06
2.375e+06
0.000



animation of unsteady b.c.

Pseudocolor
Var: t
5000.
3500.
2000.



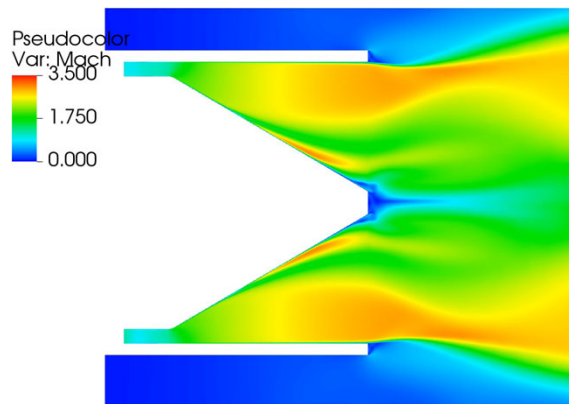
Characteristics:

- 4 million numerical cells
- 15 wave revolutions required for limit cycle
- 1.5 days per solution on NASA Advanced Supercomputing facilities (360 cores)

NCC Runs Rapidly Enough to Allow Parametric Optimization

Results (Baseline V1 Nozzle)

Sideview CFD video of Mach number



Endview CFD video of Mach number

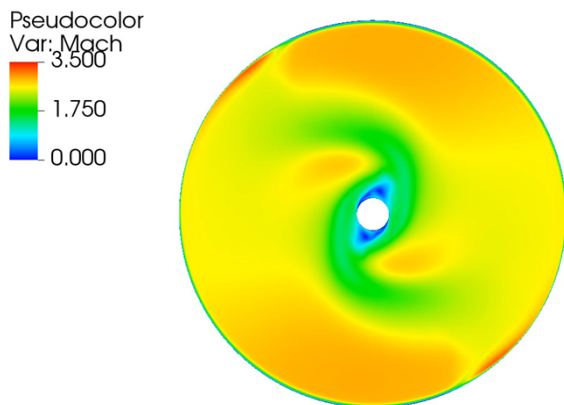


Figure of Merit (FoM):

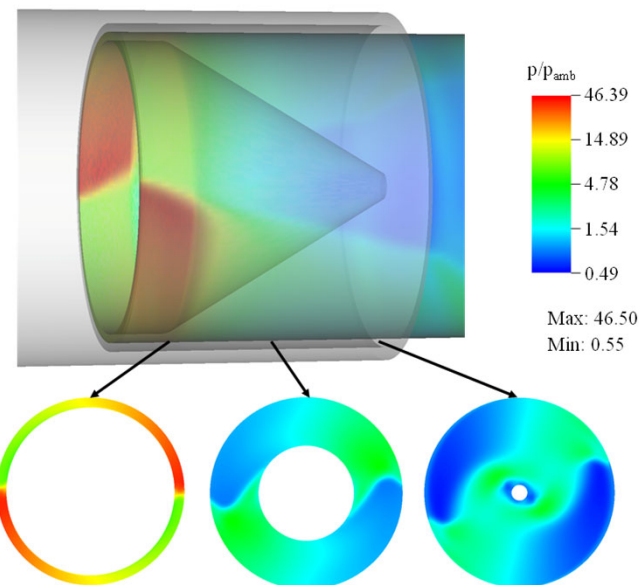
$$F_{\text{nozzle}} = F - F_{\text{no_nozzle}} \leftarrow \text{Actual nozzle thrust}$$

$$F_{\text{ni}} = F_i - F_{\text{no_nozzle}} \leftarrow \text{Ideal nozzle thrust}$$

$$\text{FoM} \equiv F_{\text{nozzle}} / F_{\text{ni}}$$

- FoM=58%
- $F/F_i=91.5\%$
- $F_{\text{pressure}}/F=4.3\%$
 - Based on time average
 - Indicates slight under expansion

Pressure at a moment in time

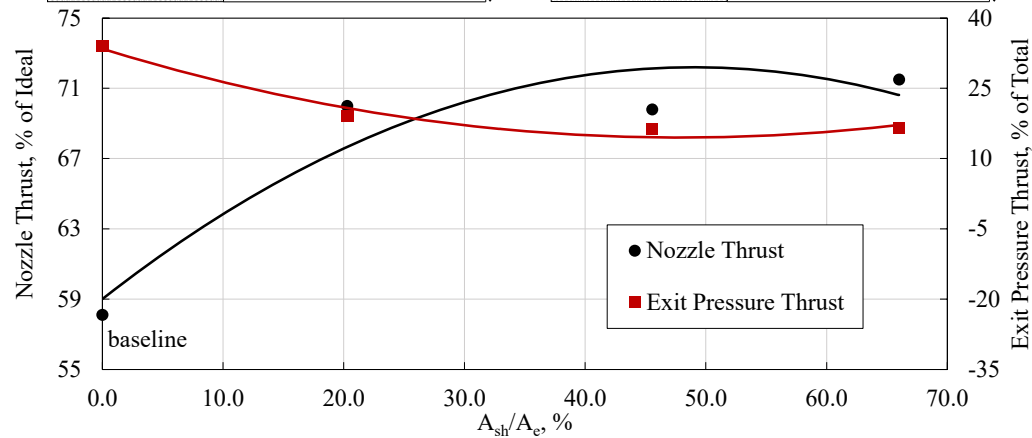
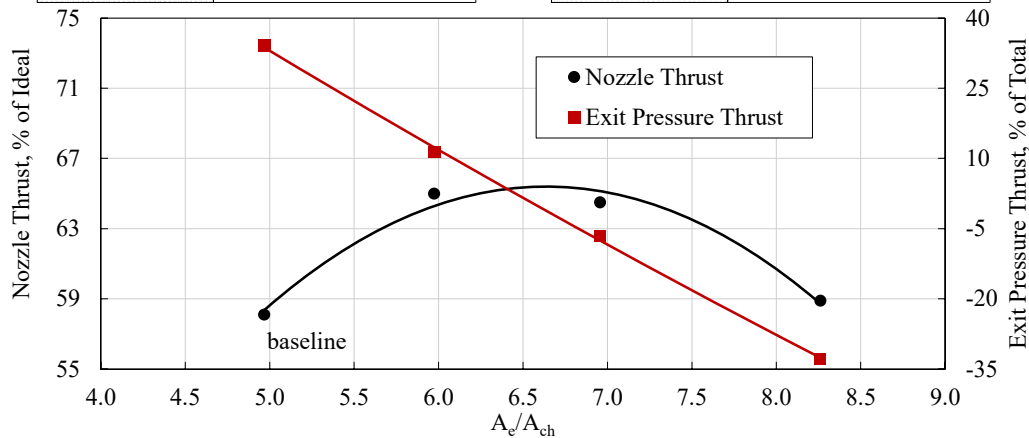
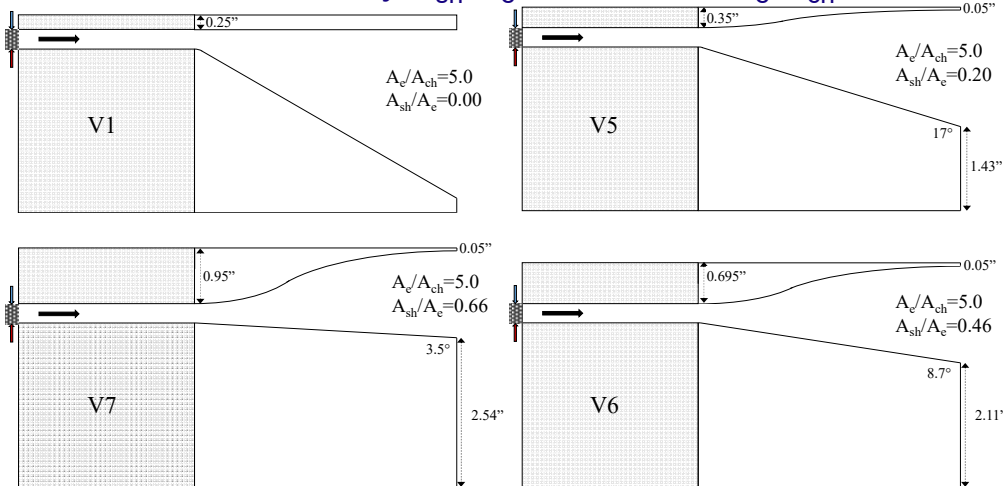
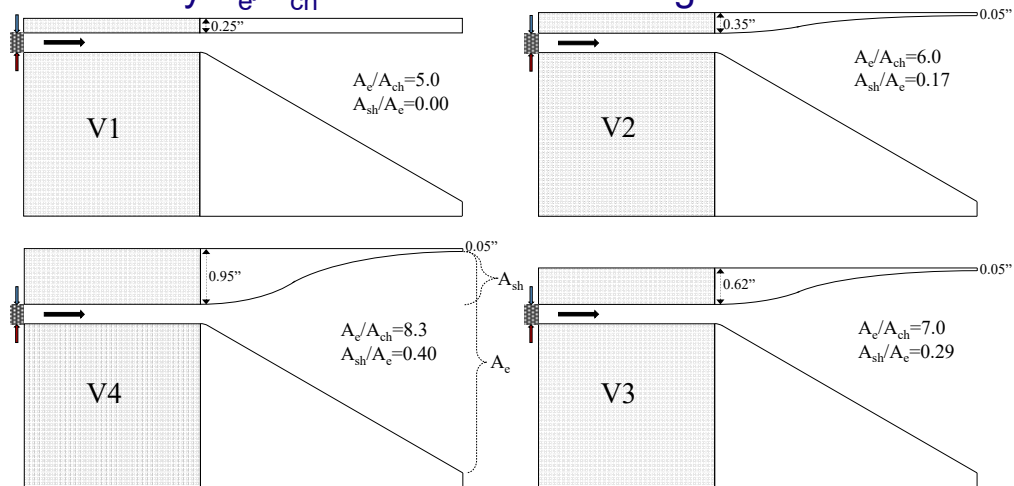


Baseline Nozzle is Already High Performer



Vary A_e/A_{ch} at constant cone angle Parametric Optimization

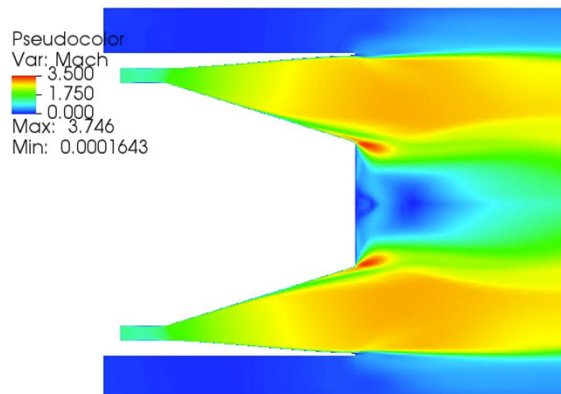
Vary A_{sh}/A_e at constant A_e/A_{ch}



Varying A_{sh}/A_e at Constant A_e/A_{ch} Shows Largest Impact

Top Performer (V5 Nozzle)

Sideview CFD video of Mach number



Endview CFD video of Mach number

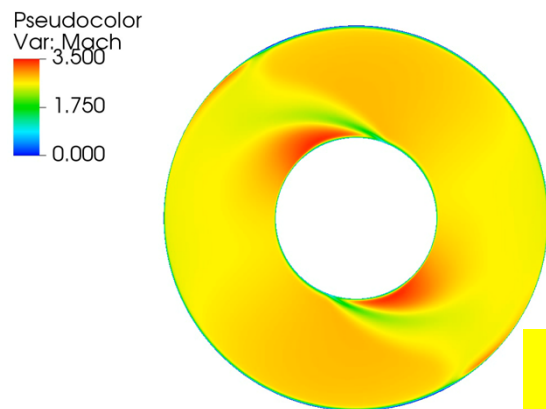


Figure of Merit (FoM):

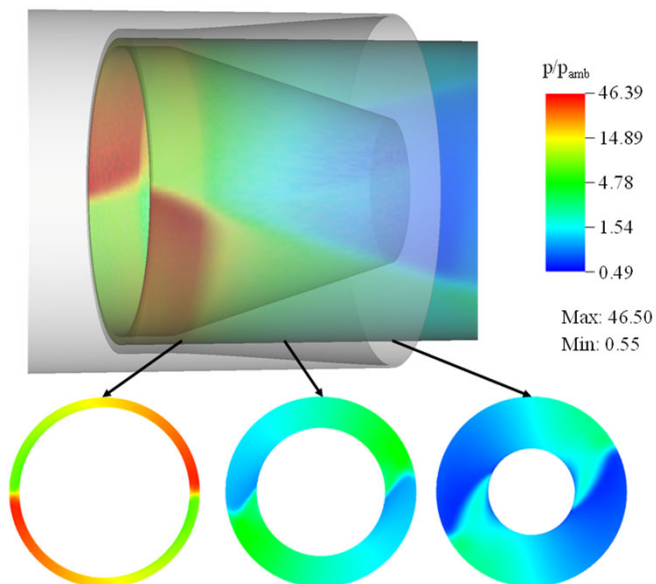
$$F_{\text{nozzle}} = F - F_{\text{no_nozzle}} \leftarrow \text{Actual nozzle thrust}$$

$$F_{\text{ni}} = F_i - F_{\text{no_nozzle}} \leftarrow \text{Ideal nozzle thrust}$$

$$\text{FoM} = F_{\text{nozzle}} / F_{\text{ni}}$$

- FoM=70%
- $F/F_i=94\%$
- $F_{\text{pressure}}/F=2.8\%$
 - Based on time average
 - Indicates slight under expansion
- $F_{\text{base}}/F=-1.4\%$
 - Minor base drag

Pressure at a moment in time



Version 5 Nozzle Provides 12% Improvement Over Baseline With Minimum Additional Material To Cool



Summary

- The nozzle for a 5,000 lb_f thrust RDRE was designed using a 3D CFD simulation with unsteady boundary conditions representing the upstream RDRE combustor.
- The design objective was to optimize nozzle thrust at a particular operating point.
- A baseline shrouded and truncated plug nozzle configuration served as a starting point.
- Two optimization parameters examined
- Fraction of the expansion area provided by the shroud was parameter with greatest impact
- The baseline nozzle performed well
 - Produced 58% of the thrust calculated for a notional ideal RDRE nozzle
 - Total thrust of the RDRE chamber-plus-baseline nozzle combination was 91.5% of the ideal total thrust
- Optimization improved the performance
 - Produced 70% of the thrust calculated for a notional ideal RDRE nozzle
 - Total thrust of the RDRE chamber-plus-nozzle combination was 94% of the ideal total thrust
- Baseline and optimized nozzles are planned for fabrication and testing.
- Results demonstrate that the numerical simulation methodology described can be used to efficiently enhance RDRE nozzle performance.



Thank You for Viewing