RDE Nozzle Computational Design Methodology Development and Application

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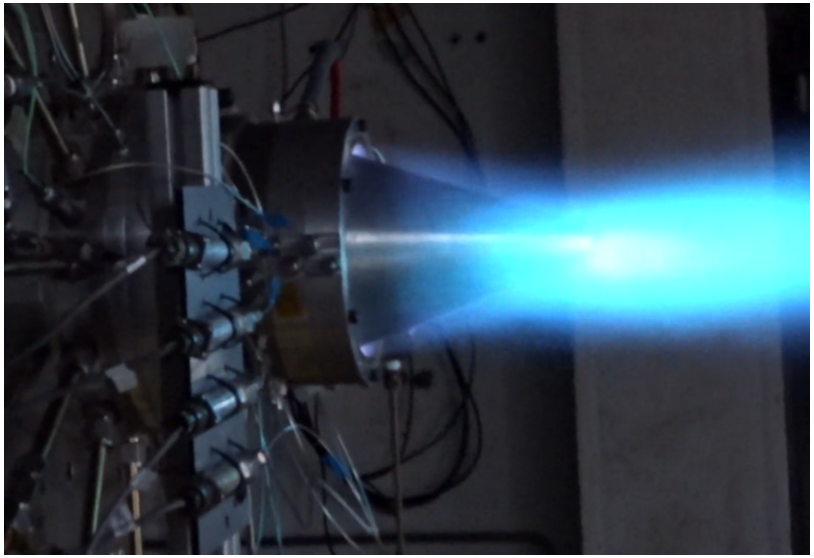
Outline

- Introduction and Motivation
- Proposed Methodology
  - Step 1: Quasi-2D CFD code for the unsteady inflow generation
  - Step 2: Data Conversion
  - Step 3: OpenNCC (3D) for the design optimization
- Results
  - Validation with the NPS exp. data
  - Design Optimization
- Conclusions

Introduction and Motivation



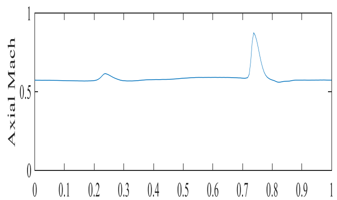
Operational Rotating Detonation Engine
(courtesy, Naval Postgraduate School)

- The design of a nozzle for an RDE combustor is somewhat problematic due to the spatially and temporally varying nozzle inlet flow
- While an "aerospike" nozzle geometry has generally been assumed for the RDE because of the annular combustor geometry, it is not yet clear that this geometry will provide optimal performance.

A relatively <u>fast</u> nozzle design methodology is needed in order to explore a wide variety of nozzle geometries in a relatively short amount of time!

Overview of Proposed Methodology

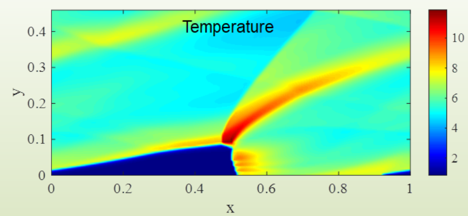
2D Unsteady Inflow BC Generation



Output at axial location just upstream of physical throat

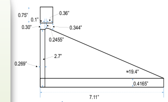
Quasi-2D CFD code [1-4]

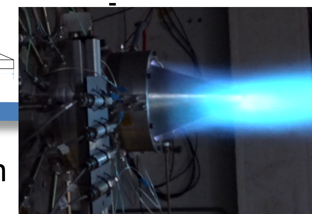
Single species, premixed, calorically perfect, inviscid flow solver



- Simulate RDE with very fine 2D mesh
- Throat effect is included as source terms
- P_{in} = 131.7 psia, T_{in}=510 R, Phi=0.972

Naval Postgraduate School (NPS) Rig Data



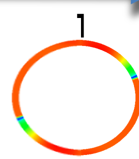


Validation data & geometry

Design optimization

Data Conversion

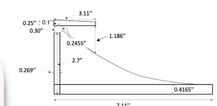
1. Exact detonation frame data (P_t, T_t, u, v)
2. Convert data from CPG to multi-species mixture, (P_t, T_t, u, v, y_i)
3. Convert data from detonation to lab. frame, (P_t, T_t, u, v, w, y_i)



Provide unsteady inflow BCs

OpenNCC 3D CFD code [5-7]

Multi- species, thermally perfect, viscous flow solver

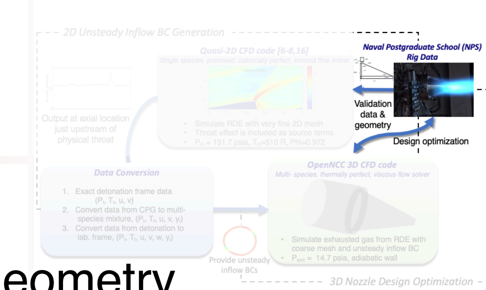


- Simulate exhausted gas from RDE with coarse mesh and unsteady inflow BC
- P_{exit} = 14.7 psia, adiabatic wall

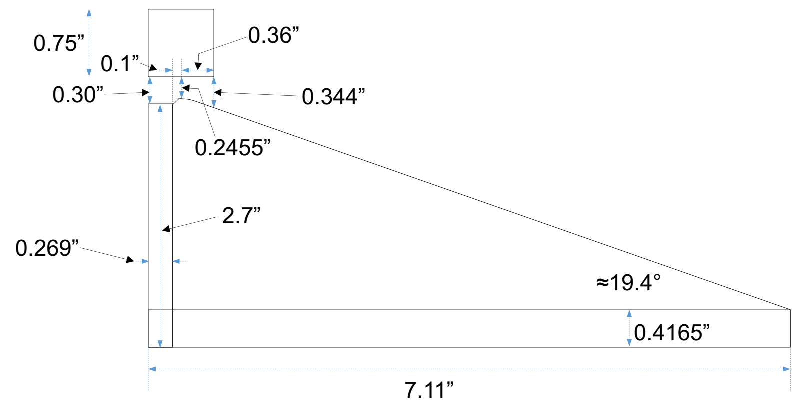
3D Nozzle Design Optimization

[1] Paxson, D.,, AIAA Paper 2016-1647, [2] Paxson, D., Fotia, M. L., Hoke, J., and Schauer, F., AIAA Paper 2015-1101. [3]Paxson, D., and Schwer, D. A., AIAA Paper 2019-0748. [4] Yungster, S., Paxson, D. E., and Perkins, H. D., Proceedings of the 66th JANNAF Propulsion Meeting, Dayton, Ohio, June 2019., [5} Ajmani, K., and Chen, K.-H., AIAA Paper 2001-0972. [6] Wey, T., and Liu, N.-S., AIAA 2015-0099. [7] Miki, K., Moder, J., and Liou, M.-S., Journal of Propulsion and Power, Vol. 34, 2018, pp. 415-427.

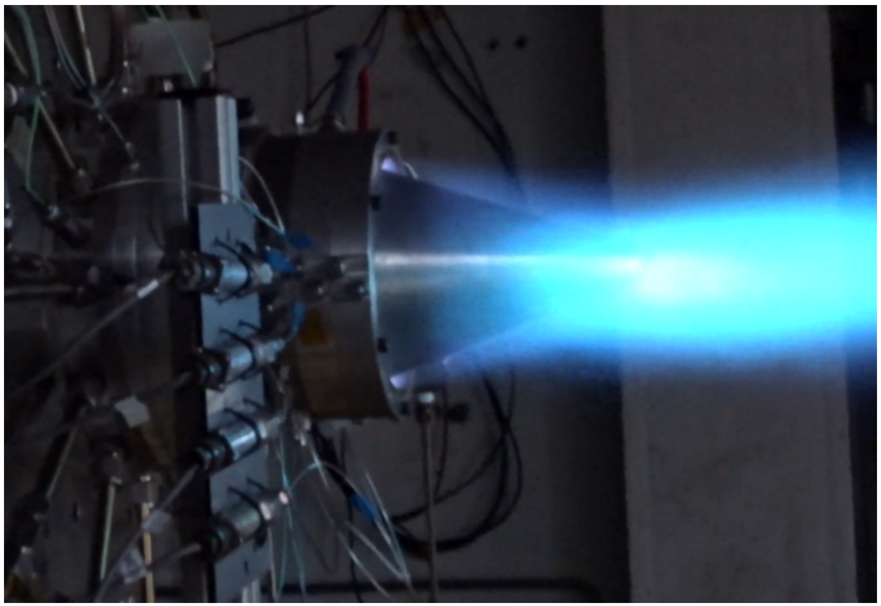
Validation Test Data from NPS



- RDE and nozzle geometry



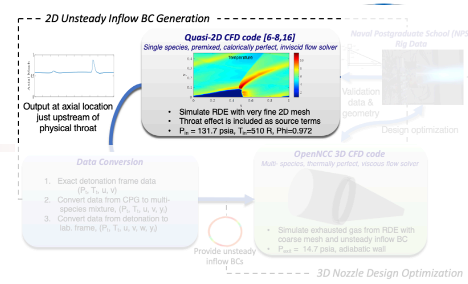
- Air and H_2 flow rates
- Manifold pressures and temperatures
- Gross thrust
- Time averaged surface pressures at:
  - 2 interior locations
  - 5 nozzle cone locations
- Operational video footage
- Wave count



Detailed Data From One Test Point

2D Unsteady Inflow BC Generation -1-

Quasi-2D CFD



Physical Setup

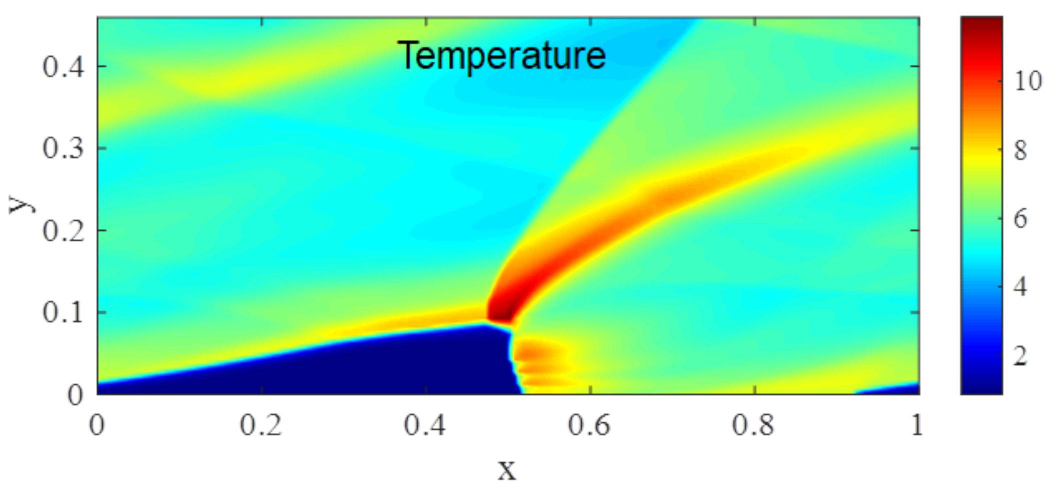
- P_m=131.7 psia; T_m=510 R; P_{amb}=14.7 psia
- ϕ=0.972; Air mass flow rate=200.2 lb_m/min
- A_{th}/A_{ch}=0.8245

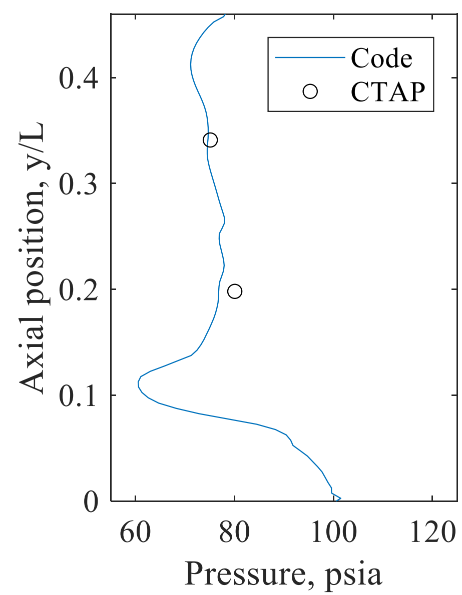
Code Setup

- γ=1.272; R_g=73.38 ft-lb_f/lb_m/R
- Simulation ends @ throat; 1 of 2 waves simulated
- A_i/A_{ch}= 0.41- adjusted to match mass flow rate

Results

- F_g=474.0 lb_f (15% above measured)
- CTAPS-see below
- 17% of chem. energy lost to walls
- 52% of manifold total pressure lost to inlet
- EAP_i/P_m-1=-22%
- Backflow=12% of throughflow
- The value of Ai/Ach used by the code was within 5% of the actual Ai/Ach





2D Unsteady Inflow BC Generation -2-

Data Conversion

- Extract detonation frame data from Q2D code output at axial location just upstream of physical throat
- Convert data from single calorically perfect gas to multi-species mixture.
  - *Should increases mass flow rate by 15%*
  - *Should increases thrust by an unknown amount*
- Convert data from detonation to laboratory frame
  - *Spatially non-uniform data becomes spatially and temporally non-uniform (though still periodic)*
  - *OpenNCC requires total conditions*
- *Converted data becomes unsteady bc input for OpenNCC*
  - *Spatially non-uniform data becomes spatially and temporally non-uniform (though still periodic)*

Data Conversion

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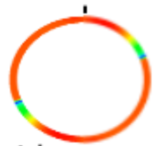

Provide unsteady inflow BCs

OpenNCC 3D CFD code

Multi- species, thermally perfect, viscous flow solver

- Simulate exhausted gas from RDE with coarse mesh and unsteady inflow BC
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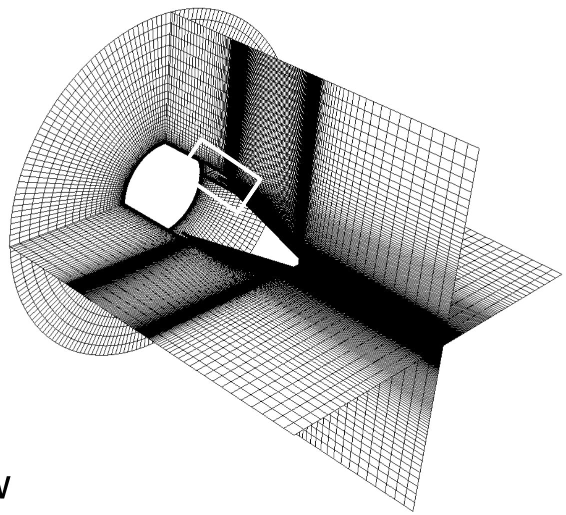
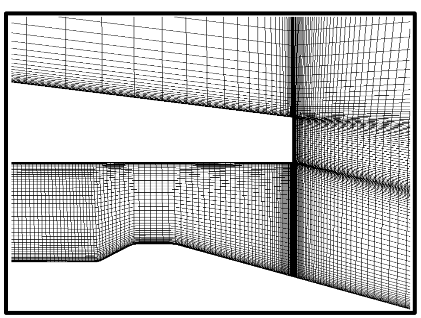
3D Nozzle Design Optimization

Features of Open National Combustion Code (OpenNCC)

- OpenNCC [1] is the releasable version of the National Combustion Code (NCC), which has been continuously updated for more than two decades at NASA Glenn Research Center (GRC)

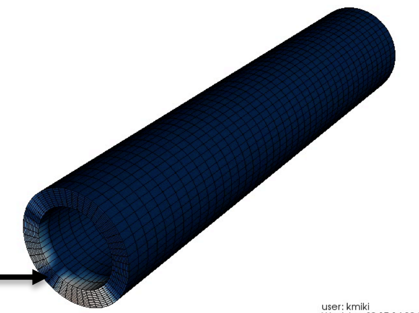


Overview



Closeup near the exit

Unsteady inflow test

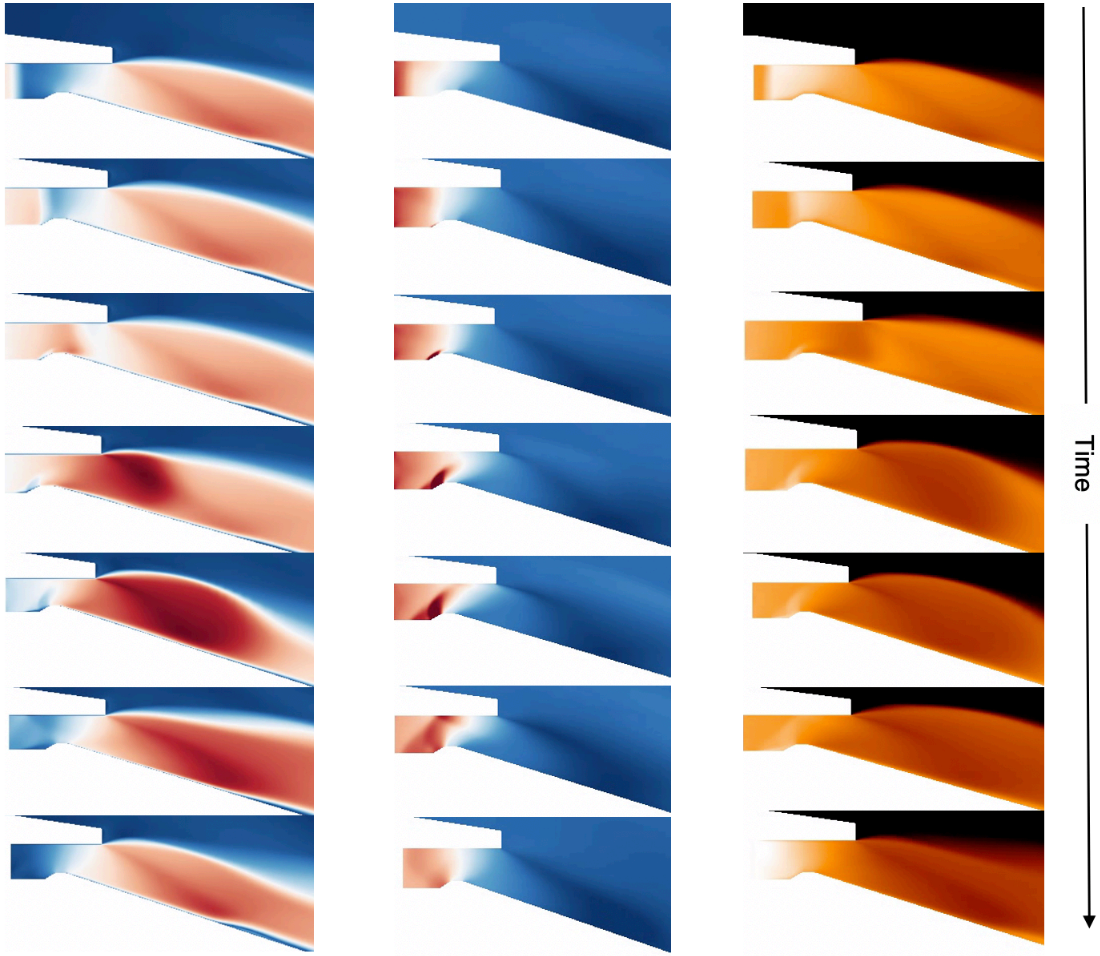


Relevant Main Features

- ✓ Numerics: Jameson-Schmidt-Turkel (JST) scheme and Roe's upwind scheme, and Advection Upstream Splitting Method (AUSM)(2-3)
- ✓ Turbulence: Cubic non-linear k-ε(4) model with the wall function, Low-Re model, LES
- ✓ Other features: Low-Mach preconditioning, transition model(5), unstructured mesh, adaptive mesh refinement (AMR)(6), massively parallel computing (with almost perfectly linear scalability achieved for non-spray cases up to 4000 central processing units)

(1) Stubbs, R., and Liu, N.-S., "Preview of the National Combustion Code," AIAA Paper 1997-3114, July 1997. (2) Liou, M.-S. and Steen, C. J., Journal of Computational Physics, Vol. 107, (1993), (3) Liou, M.-S., Journal of Computational Physics, Vol. 129, 1996) and (2006), (4) Shih, T.-H., Chen, K.-H., and Liu, N.-S., AIAA 1998-35684 (1998). (5) Liou, W. and Shih, T.-H., No. NASA/CR-2000-209923 (2000).(6) Wey, T. and Liu, N.-S., AIAA 2014-1385 (2014).

Instantaneous Flow Fields from OpenNCC



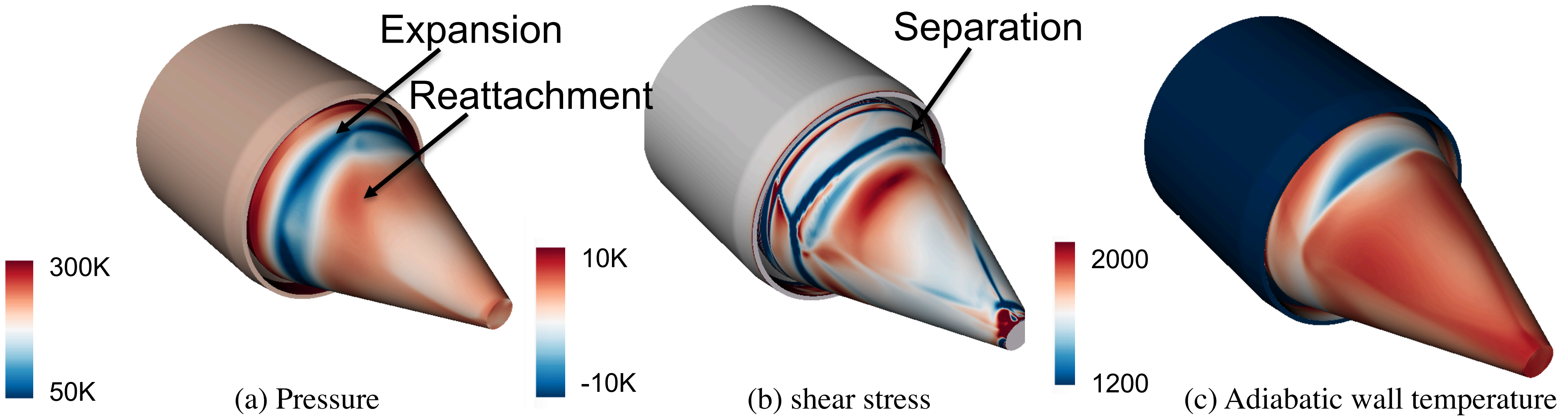
(a) Mach number
(Red:2.5 and blue:0)

(b) Pressure [Pa]
(Red:$5x10^5$ and blue:$-5x10^4$)

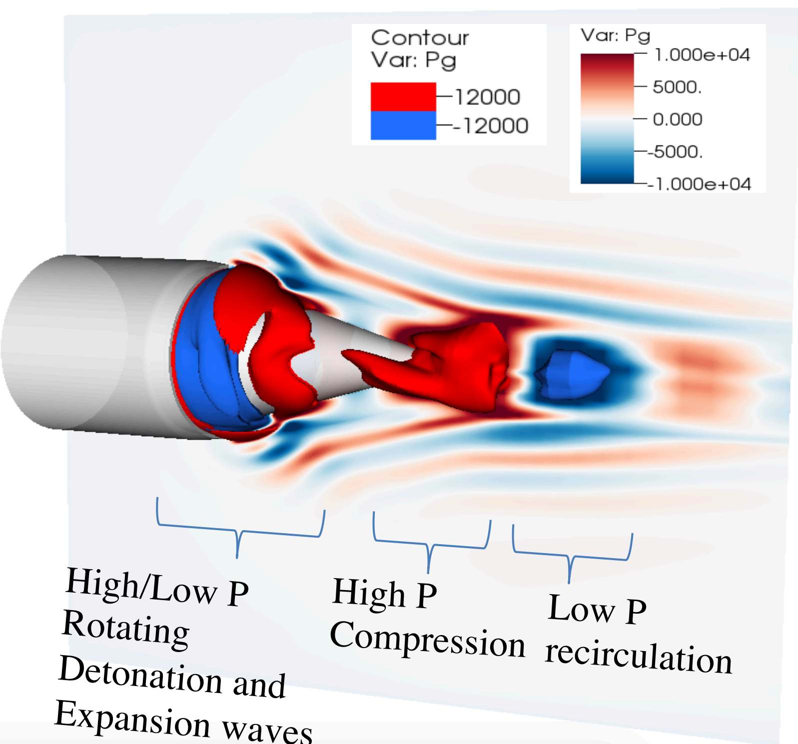
(c) Temperature [K]
(Red:2000 and blue:300)

- The pressure increases in the upstream region of the throat, and then the strong shock wave starts forming at the left edge of the throat.
- The flow is chocked at the throat and then expand outside the throat.

3D Nozzle Surface Profiles and Pressure Waves

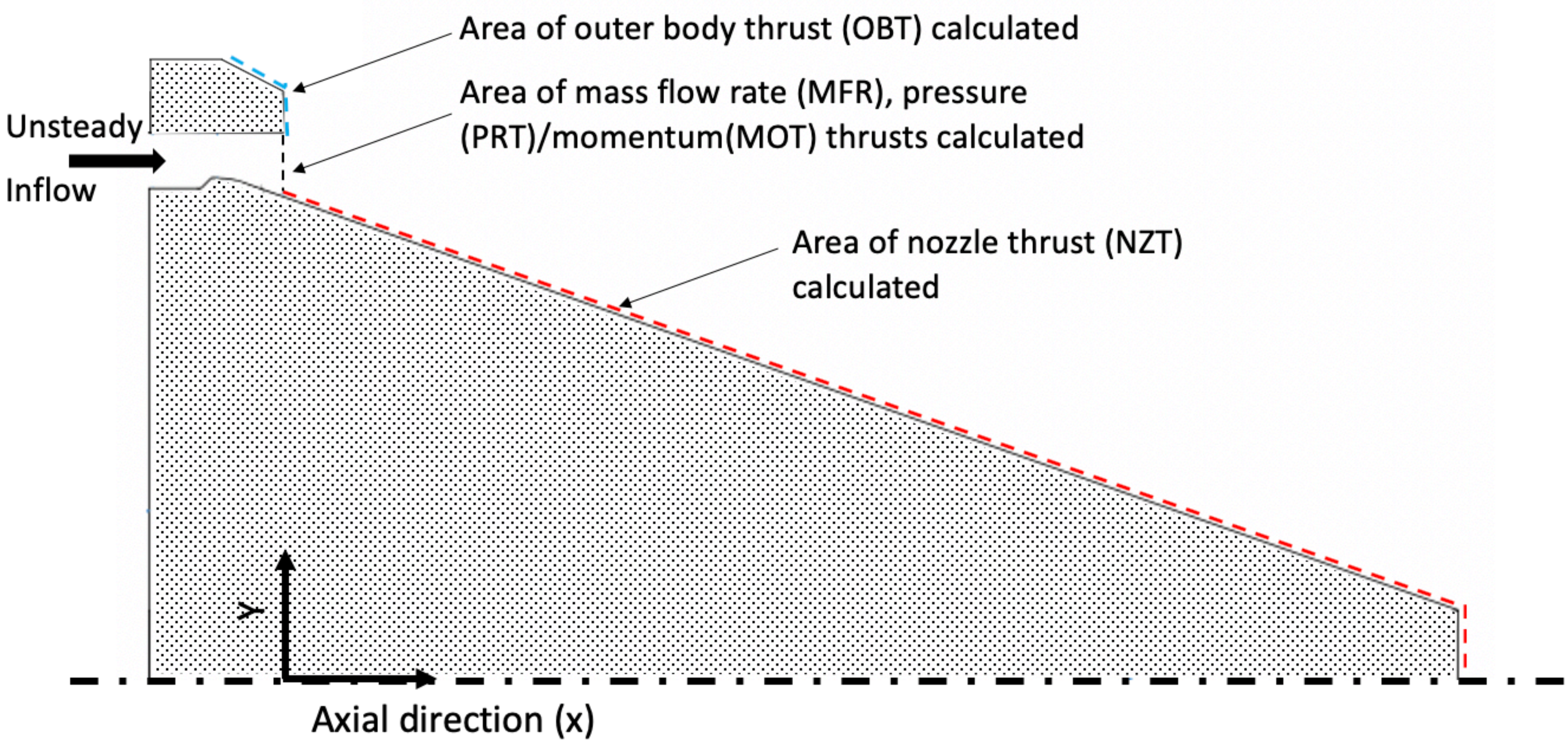


(a) Pressure (b) shear stress (c) Adiabatic wall temperature

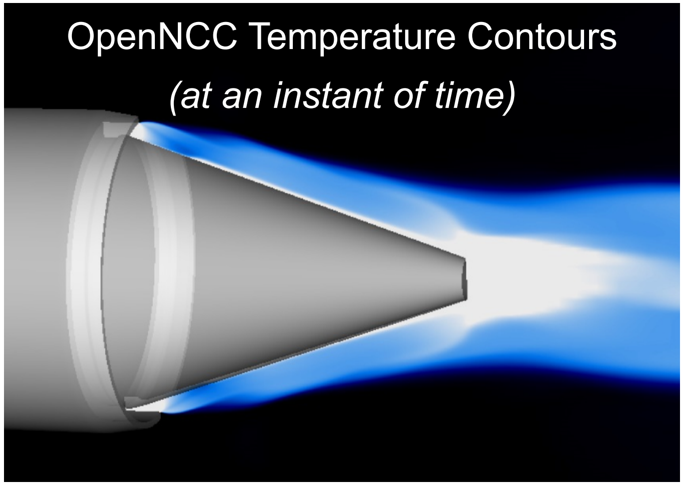


- A low-pressure (and relatively cold temperature) region associated with the expansion wave at the throat exit
- Steep gradient of the shear stress related to the complex inflow profiles remains downstream of the nozzle.
- There are a spiral propagation generated by the two rotating detonation waves, and a strong dynamic motion (i.e., pressure waves) propagating toward the far-field region.

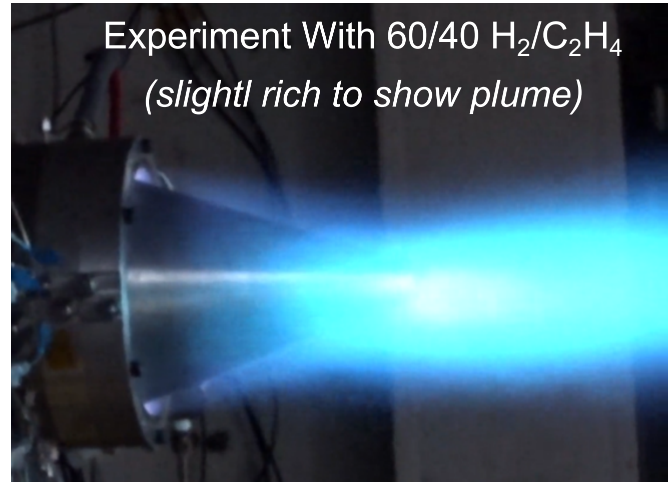
Time-Histories of MFR and Thrusts



Validation with Exp. Data

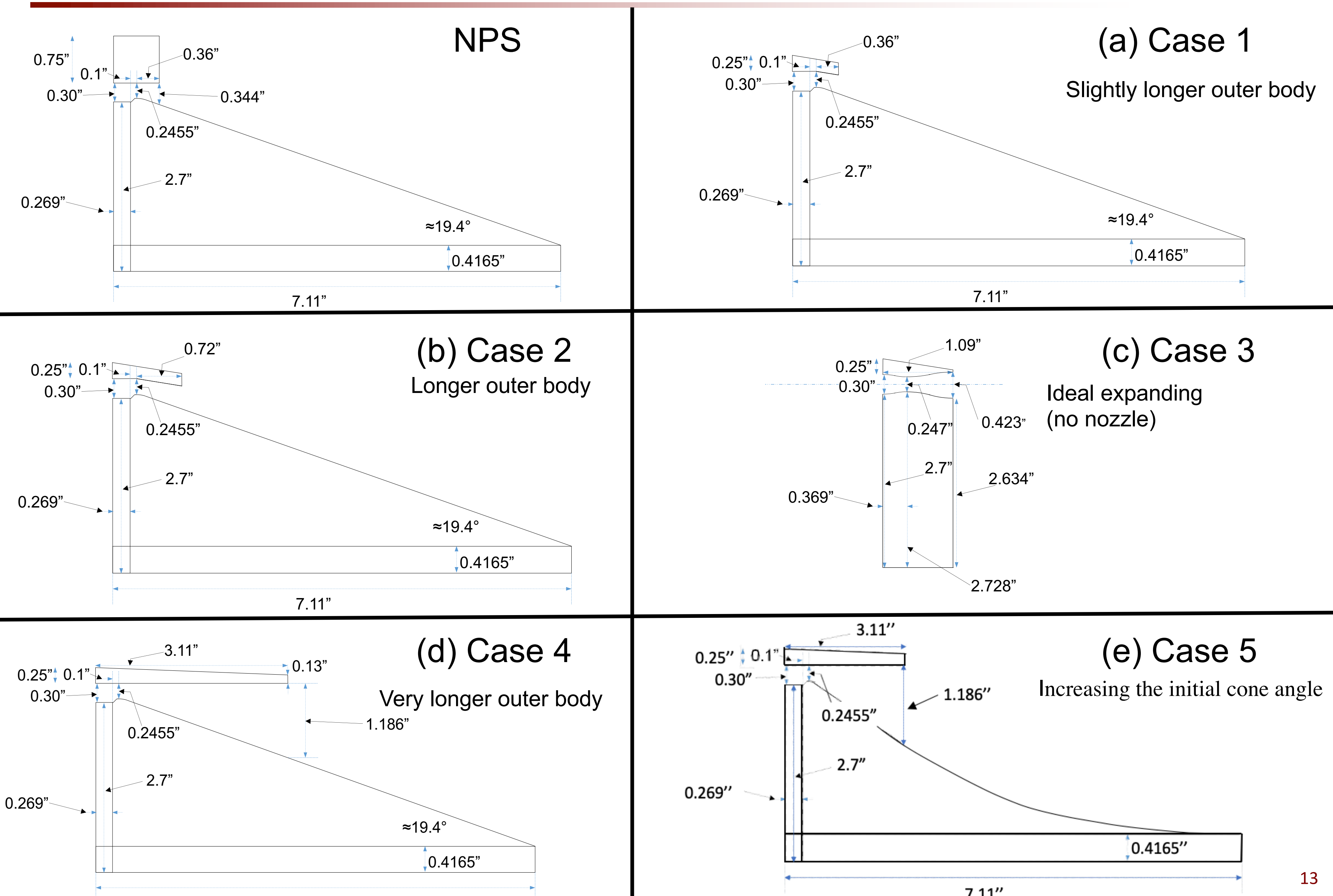


- Mass flow rate =1.65 kg/s
- Gross thrust = 487 lbf
- Isp=134 s
- Thrust from cone = -7 lbf

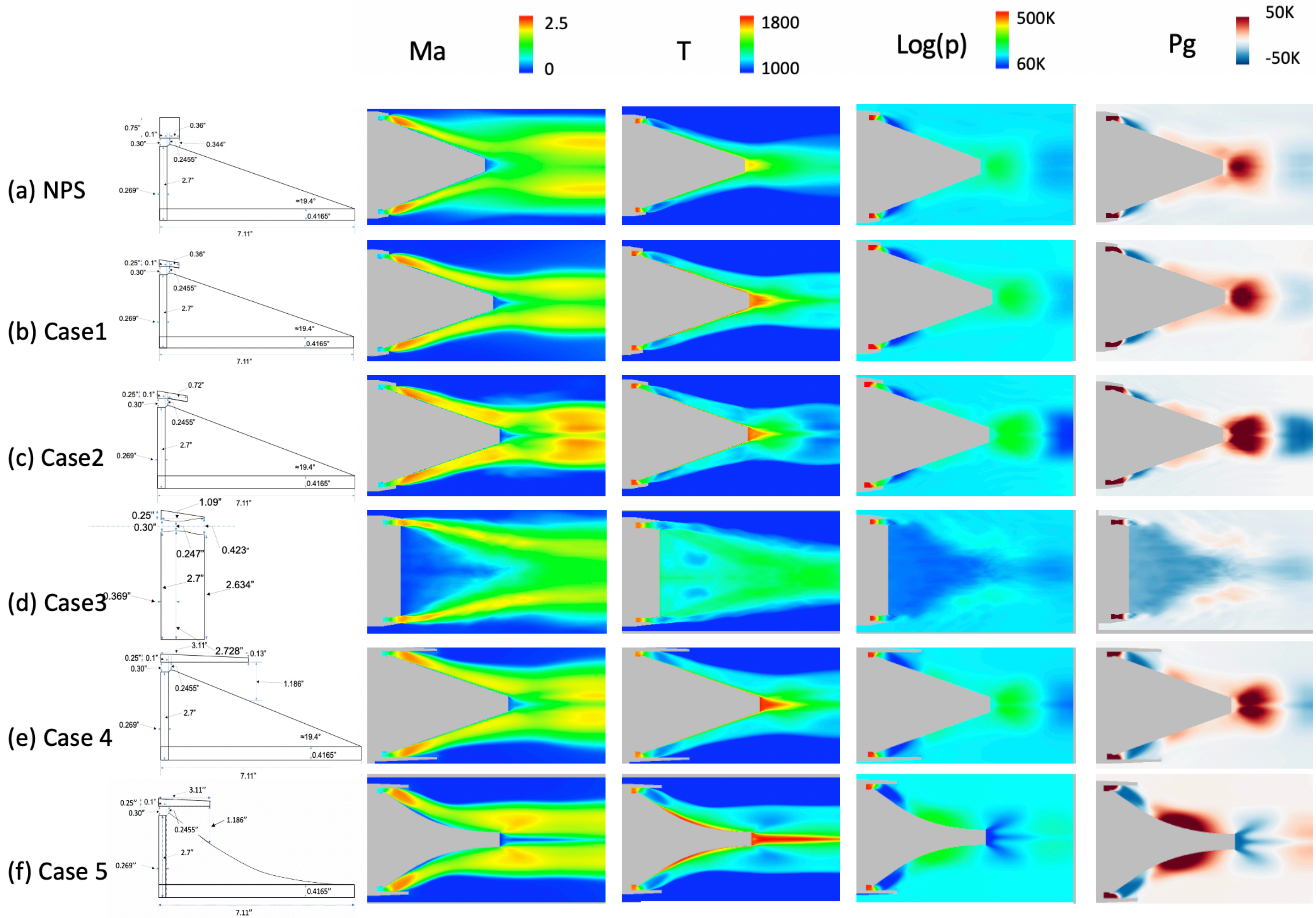


- Mass flow rate =1.56 kg/s
- Gross thrust = 413 lbf
- Isp=120
- Thrust from cone = -4 lbf

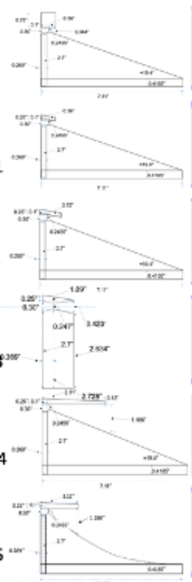
Nozzle Design Optimization



Time-Averaged Flow Fields

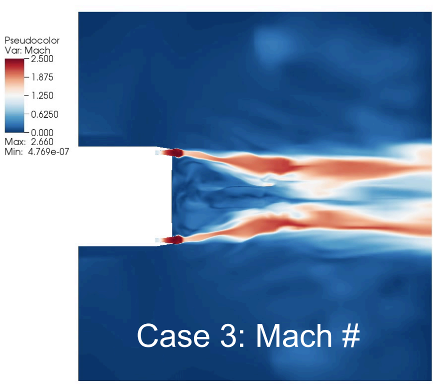


Summary of Nozzle Performance



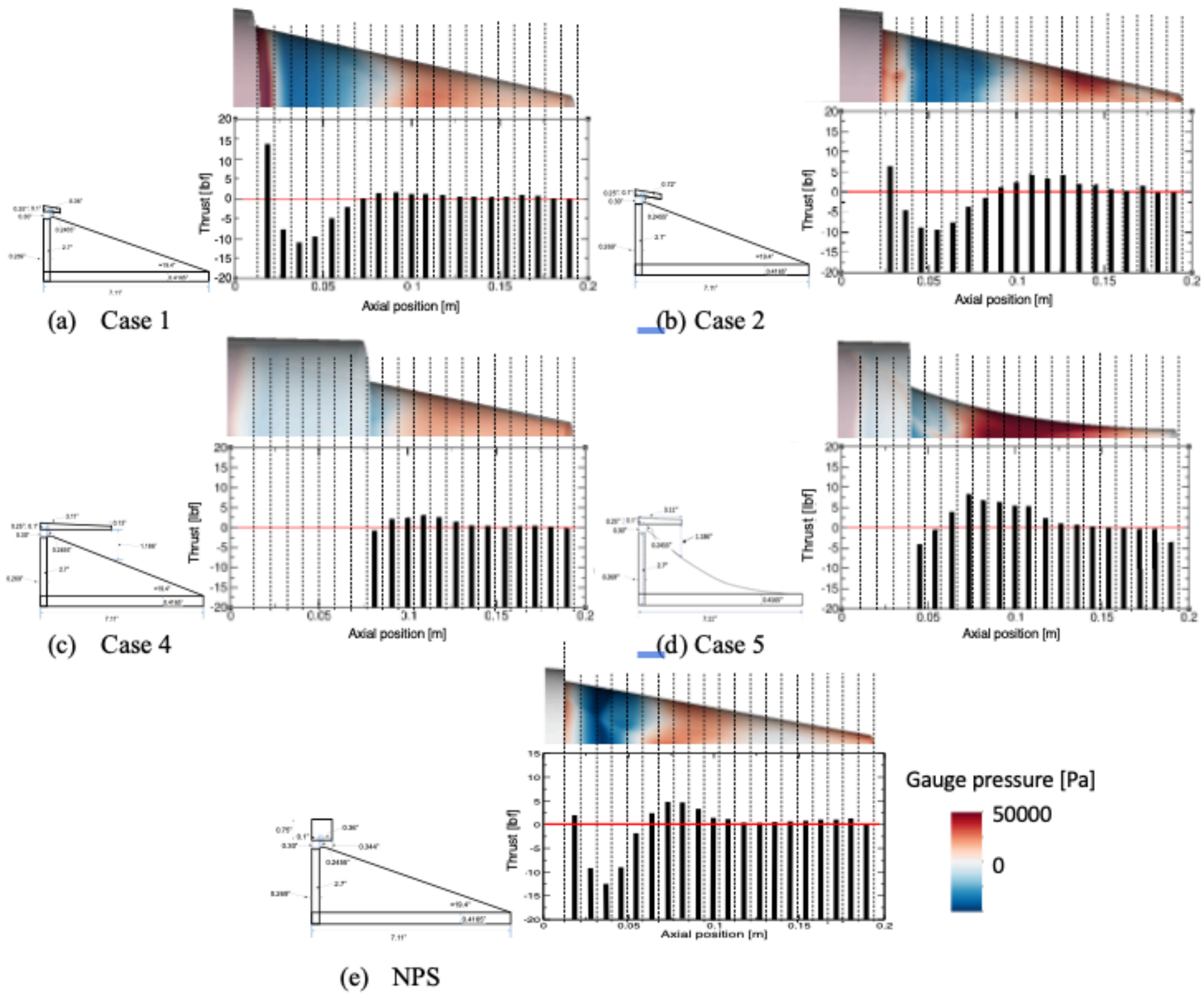
Geometry	MFR [kg/s]	PRT [lbf]	NZT [lbf]	MOT [lbf]	OBT [lbf]	Total [lbf]
NPS	1.65	51.2	-7.6	441	-0.9	483.7
Case 1	1.63	91.8	-11.1	389.2	-1.7	468.2
Case 2	1.64	36.5	-5.8	460	1.2	491.9
Case 3	1.69	-5.1	-46.5	529	0.2	478.1
Case 4	1.66	-16.5	17.5	500.3	-2	499.3
Case 5	1.64	-49	35.9	487.2	-0.4	473.7

Mass flow rate (MFR), and thrusts associated with components of pressure (PRT), momentum (MOT), nozzle (NZT) and outer body (OBT).



- Strong unsteadiness enhanced by the presence of the wake and free shear layers For Case3.
- Case 4 shows the best performance and gains ~3.2% improvement from the NPS nozzle by just extending the outer body.

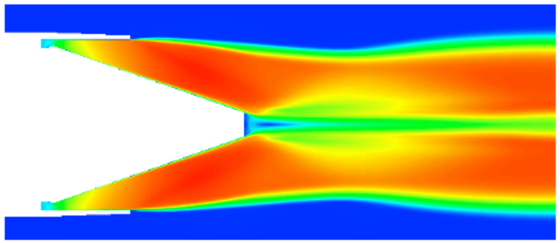
Thrust Distribution at Nozzle Surface



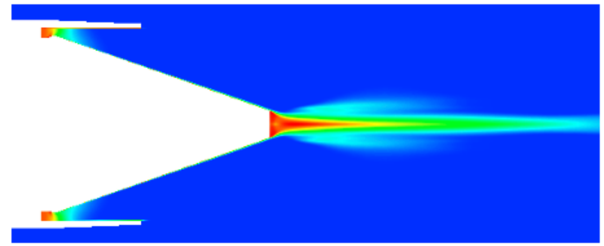
To minimize such a low-pressure region, it is beneficial to extend an outer body!

High-Pressure Condition (Case 4)

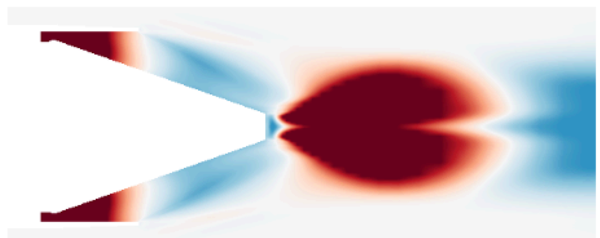
More representative higher Mach number airbreathing, or rocket nozzle operating condition (the total pressure increased by a factor of 3.9



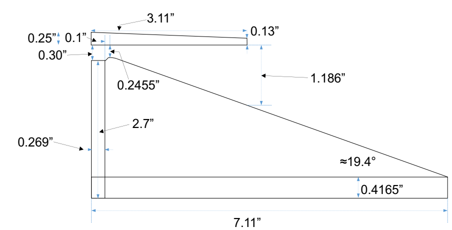
(a) Mach number



(b) Temperature



(c) Gauge pressure



Condition	MFR [kg/s]	PRT [lbf]	NZT [lbf]	MOT [lbf]	OBT [lbf]	Total [lbf]
Low-Pressure	1.66	-16.5	17.5	500.3	-2	499.3
High-Pressure	6.82	54.5	-26.9	2470	-0.7	2496.9

Mass flow rate (MFR), and thrusts associated with components of pressure (PRT), momentum (MOT), nozzle (NZT) and outer body (OBT).

- PRT and NZT are in the opposite directions in the low/high-pressure cases.
- However, these forces are a considerably smaller fraction of the total thrust.
- This suggests that this nozzle is working well, and that <u>a simple extension of the outer body on an existing aerospike nozzle can provide reasonable performance at higher pressure ratios.</u>

Conclusions

- In this paper, we developed a computationally feasible optimization tool using two in-house codes: Q2D and OpenNCC, for an RDE nozzle and validated our methodology using experimental data.
- The novel feature of the methodology is to introduce an unsteady inflow boundary condition so that we are able to decouple the combustor and the nozzle sections.
- We investigated the performance of five different nozzle designs at the low-power condition and found that gross thrusts among these nozzles vary from 468.2 [lbf] to 499.3 [lbf].
- We select the best nozzle with an extended outer body and confirmed that a simple extension of the outer body on an existing aerospike nozzle can provide reasonable performance.

This methodology is a promising tool to explore a wide variety of nozzle geometries in a relatively short amount of time.

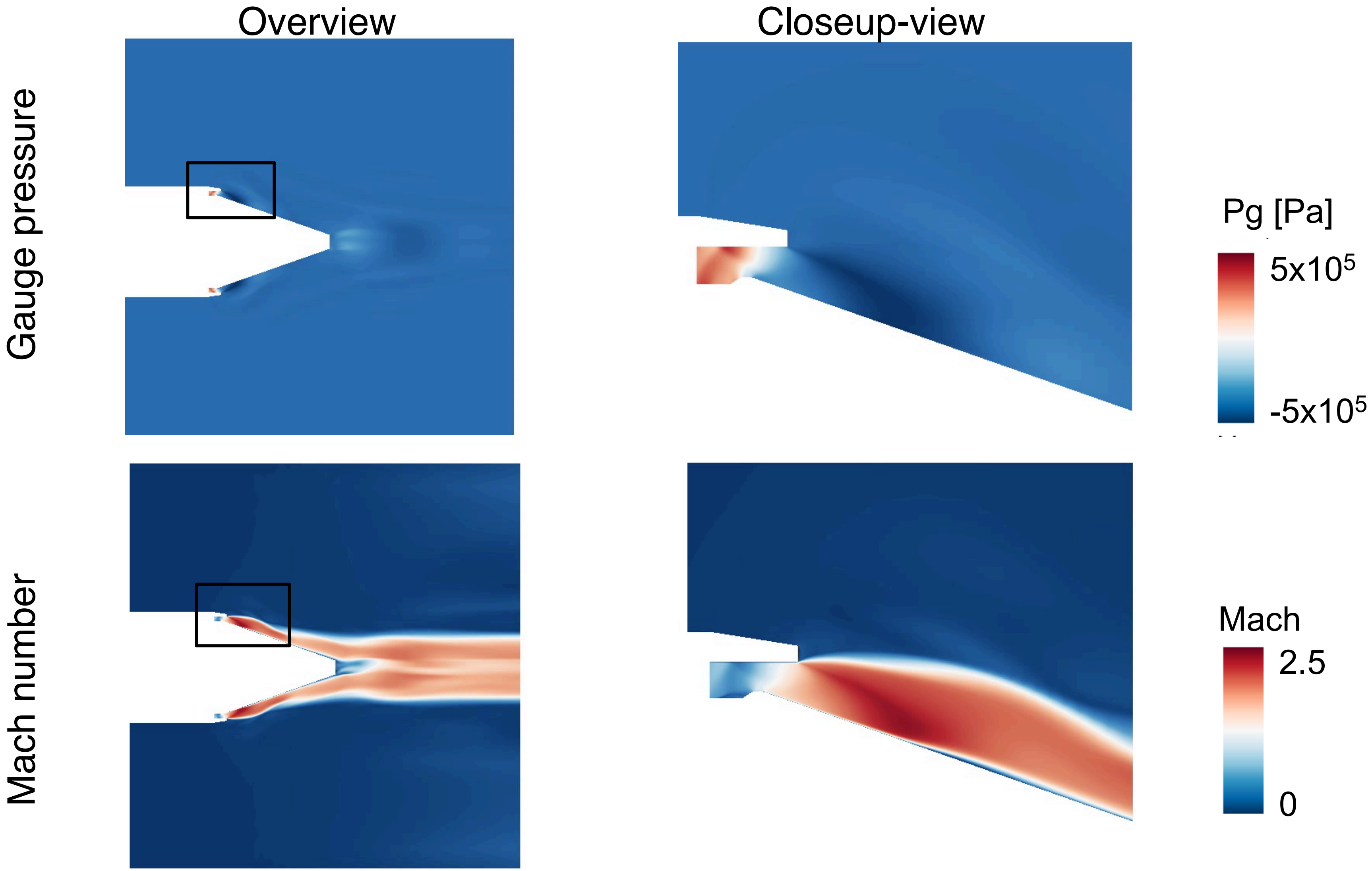
Thank you!

Questions?

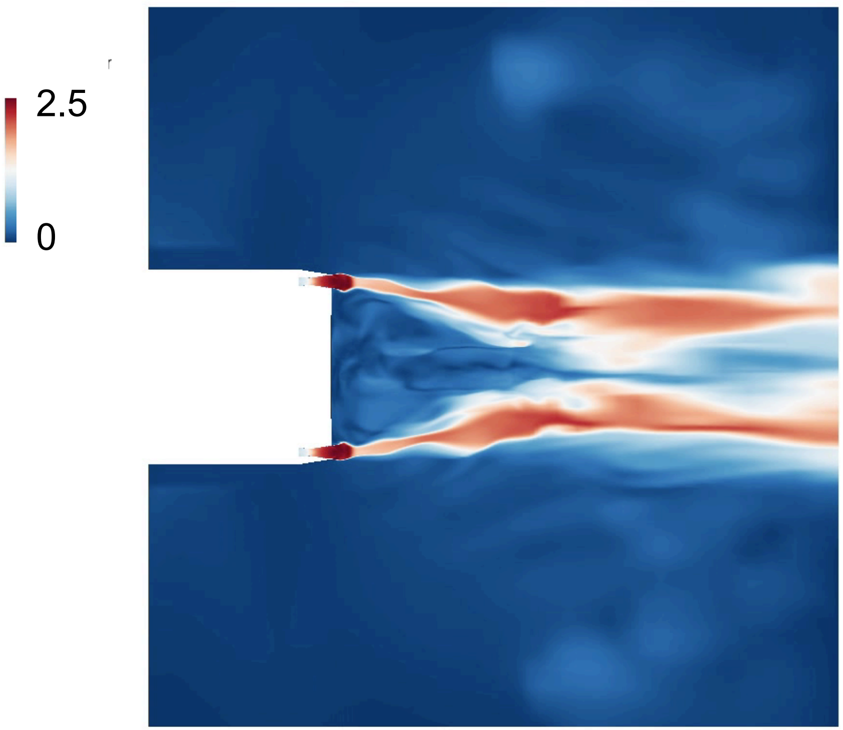
Acknowledgement

- **National Aeronautics and Space Administration Space Technology Mission Directorate's Center Innovation Fund program and Game Changing Development project**
- **Simulations conducted NASA Advanced Supercomputing (NAS) Pleiades computers**
- **Grid Generation conducted with Pointwise**
- **Flow Viz was conducted with Visit (Lawrence Livermore National Labs)**

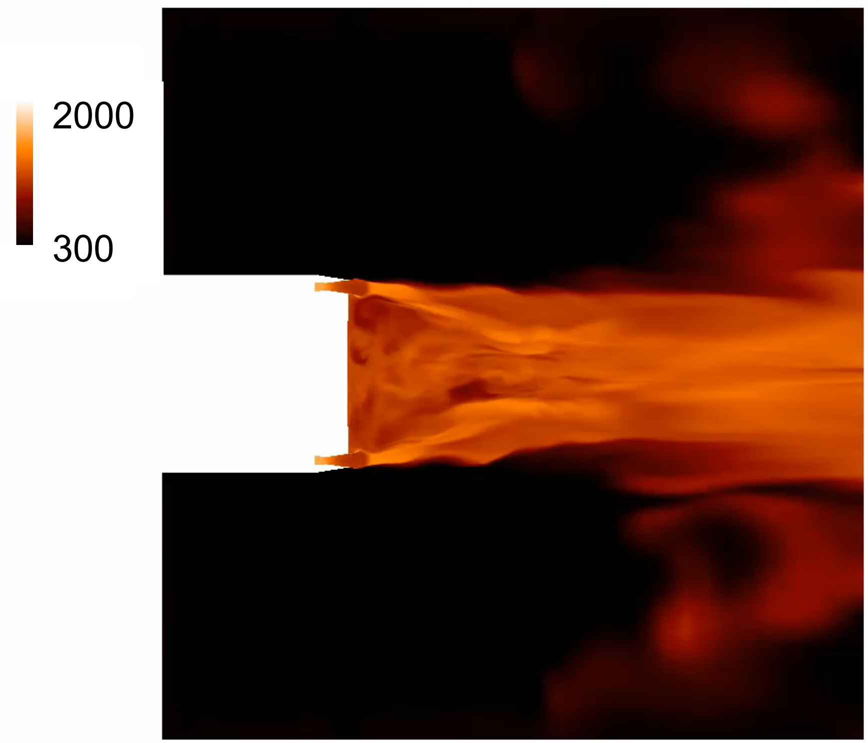
Instantaneous Flow Fields from OpenNCC



Bluff Body with Ideal Expansion Ratio (Case 3)



Mach number

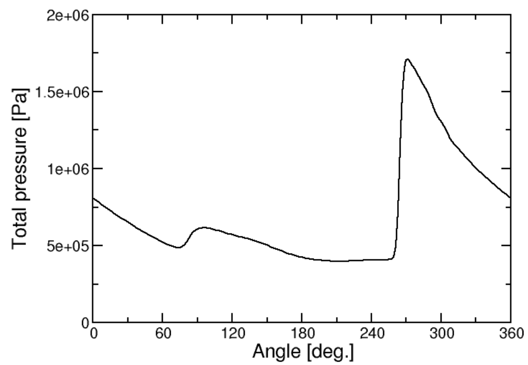


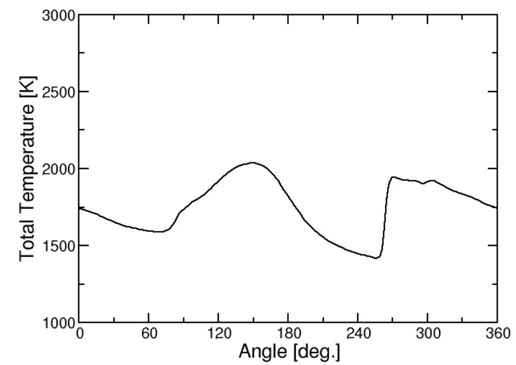
Temperature

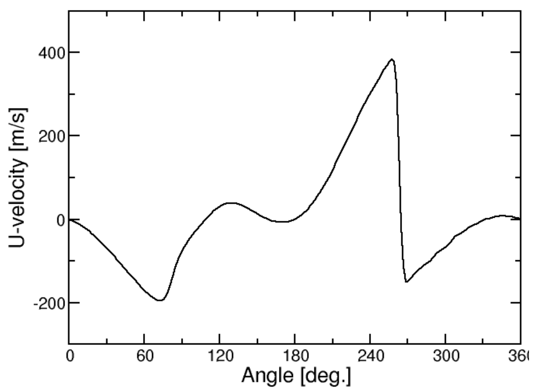
Ideal?

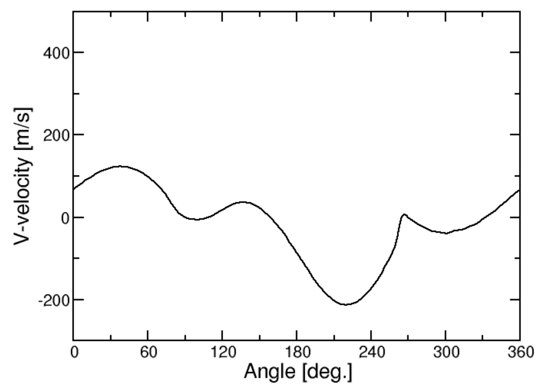
- Bluff body creates 46.5 lbf drag
- Exit flow is nearly perfectly expanded, with only -1% of thrust from pressure
- At 140 s (bluff body corrected), this is the highest Isp that we find for all configurations
- EAPi predicts 153 s (fundamental losses is ~ 8%)
- Strong unsteadiness enhanced by the presence of the wake and free shear layers

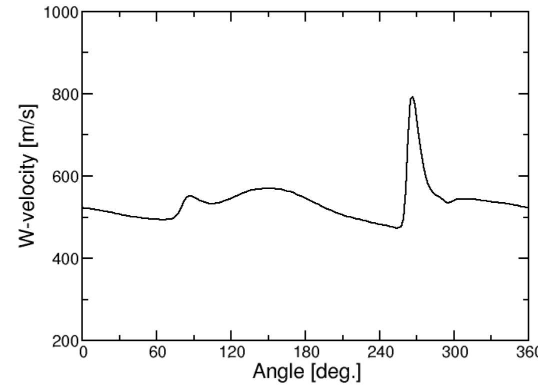
Results from Quasi-2D CFD code

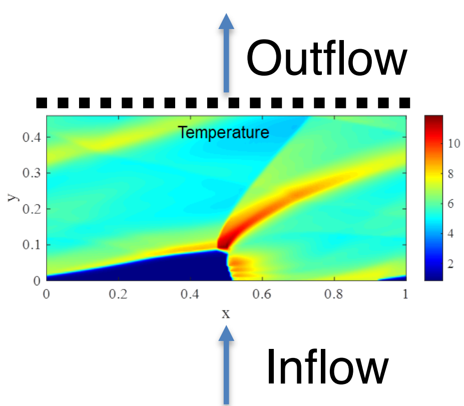












- Run the Qsuai-2D CFD code using a very fine mesh to resolve the steep detonation front.
- Output at axial location just upstream of physical throat
- Record the solution each 9.2324E-9 [s] for unsteady inflow BC for OpenNCC