# Design and In-house Manufacturing Dynamics of a Modular RDE at NCSU

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**Rotating Detonation Combustors (RDC) are seen as a high potential technology to increase the performance of chemical rockets by up to 20%. This paper explores the design and fabrication of a RDC with an expected thrust of ~200N using a pressure fed gaseous hydrogen and oxygen/air fuel mixture and a doublet injector scheme, all built in-house at North Carolina State. Design and analysis of the RDC started with a 0D MATLAB model using isentropic and choked flow equations to establish the baseline for a CFD analysis using a K-ε viscosity model. Work by [1]Nakata et. was referenced to provide a starting point for the injector scheme. The modeling was done through detailed Computer Aided Design (CAD) in SolidWorks that was then incorporated into a CFD software for computational testing. From this data a student manufacturer will be provided with any required Computational Fluid Dynamics (CFD) analysis before manufacturing the parts. Each individual part of the RDE will be 3D printed using an in house 3D printer and hard PLA. The 3D printed parts will be analyzed for stability and analyze the process on the best method of creating the parts to be assembled through the in house machine shop. The 3D printing process will help provide initial fit check testing to ensure the parts will be able to be assembled and disassembled to become a movable model for multiple testing configurations.**

## I. Nomenclature

*N* - *newton*
*CFD* – *computational fluid dynamics*
*RA* – *average roughness*
*K* - *kelvin*
*MPa* - *megapascal*
*m/s* - *meters per second*
*kg/s* - *kilograms per second*
*0D* - *zero dimensional*
*Cd* - *discharge coefficient*
$\dot{m}$ - *mass flow rate*
$\gamma$ - *specific heat ratio*
*Pt* - *total pressure*
*Tt* - *total temperature*
$R_{spec}$ - *specific gas constant*
$A_{inj}$ - *area of injector hole*
$Mol_{fuel}$ - *molar mass of the fuel*
$Mol_{ox}$ - *molar mass of the oxidizer*
*FAR* - *fuel to air ratio*

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## II. Introduction

Rotating Detonation Combustors (RDC) are seen as a high potential technology to increase the performance of chemical rockets by 5%[2] up to 25%[3]. Recent advances in copper alloys and 3D printing from NASA[4] have allowed for RDC's to advance from earlier lab scale engines to near practical use. Japanese researchers have successfully demonstrated an RDE powered system in space as of 2021[5]. CFD work continues to be advanced on the topic of detonation waves within an RDC with numerous papers exploring the topic such as the work from Braun Et.[6] Numerous other developments have created an environment where RDC's are poised to be adopted by defense and the space industry.

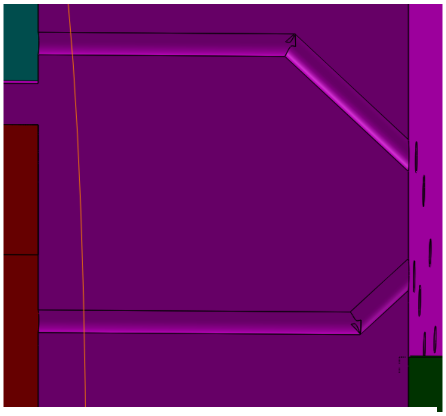

***Figure 1*** *– Injector Design*

This paper explores the design and fabrication of a RDC with an expected thrust of ~200N using a pressure fed gaseous hydrogen and oxygen/air fuel mixture and a doublet injector scheme, all built in-house at North Carolina State University. Design and analysis of the RDC started with a 0D MATLAB model using isentropic and choked flow equations to establish the baseline for a CFD analysis using a K-ε viscosity model. Work by Nakata et. was referenced to provide a starting point for the injector scheme.

The RDC will serve as a test platform for the Braun's Engineering For Supersonic Technologies (BEFAST) lab at NCSU. This modular design will enable a rapid start to the lab's goal of pursuing gas turbine, rocket, and air breathing technologies. Keeping the design at a small scale removes some of the safety concerns for a higher pressure and larger combustor which is slated for development pending the success of the lab scale RDC described in this paper.

The manufacturing process will include preparing mechanical drawings with dimensions, tolerances, gas seal requirements, and the material of each part. The RDC in-house manufactured parts will include the plenum, thrust plate, injector face, and the combustor walls. Most of these components will be machined using a milling machine for drilling the holes and facing the material for a clean finish. One section of the model, the injector face, will have 24 0.8 mm injector holes for both gaseous air and fuel. The injector holes will be drilled at a 45-degree impinged so that the flows meet 3mm above the surface of the plate in the combustion chamber. The parts with outer threads or grooves in the design will be analyzed to verify if using a lathe is the best option or 3D printing for manufacturing. Before manufacturing begins each part will be 3D printed using an in-house 3D printer with hard PLA as the material. The 3D printed parts will be analyzed for stability. The process of manufacturing the components will be analyzed for ease of assembly. These parts will need to consider that a 16 RA surface roughness is applied to all surfaces where gas seal is required.

## III. Methodology

### A. Design of the RDC

The first iteration of the RDC was designed using SolidWorks in October 2023 and the finalized design was finished in February 2024. A total of five major design iterations were required to meet research objectives. The first iteration incorporated a diverging nozzle, the second iteration expanded the plenum diameter, the third iteration introduced the wavy combustor walls and again increased the diameter of the plenum, the fourth iteration merged the two-piece plenum into a one-piece design, the fifth iteration extended the oxygen plenum to allow for fittings to be placed. SolidWorks was utilized for the CAD design and generation of the fluid body that was used in the CFD analysis. The injector design (Figure 1) leaned heavily on research by Nakata et. for their successful RDC. Doublet injector scheme impinged at a 45-degree angle[1] to achieve mixing was incorporated according to the designs in the paper by Nakata et.

Plenum design is a pressure fed design with a center oxidizer plenum and an outer fuel plenum. Four ¼ inch inlets for the fuel and one ½ inch inlet for the oxidizer were selected using straight thread fittings. Quick disconnect pressure fittings for the pressure transducers were fitted to ⅛ inch holes seen in Figure 2.

### B. Computational Analysis

Ansys workbench, including space claim and Fluent were utilized during the CFD process. MATLAB was used to create the 0D model using ideal conditions and choked flow equations. The Hazel HPC cluster at NCSU was utilized to compute the solution.

### C. Machining timeline

The machining timeline consists of finalizing drawings and 3D printed models once the CFD and FEA calculations are determined. Ordering parts and material will take place in late spring. Once the materials arrive the student manufacturer will begin with the mechanical drawings and proceed to plan which parts can be easily manufactured in house while the others might require sending off to the faculty machinist at NC State. The parts will need to consider the gaseous seal needed for proper testing of the RDE so this challenge will need to be discussed with the machine shop faculty. After the design challenges are overcome for proper machining of parts the student machinist will continue to manufacture each part that will be feasible with provided resources in the on-site shop.

## IV. Results and Discussion

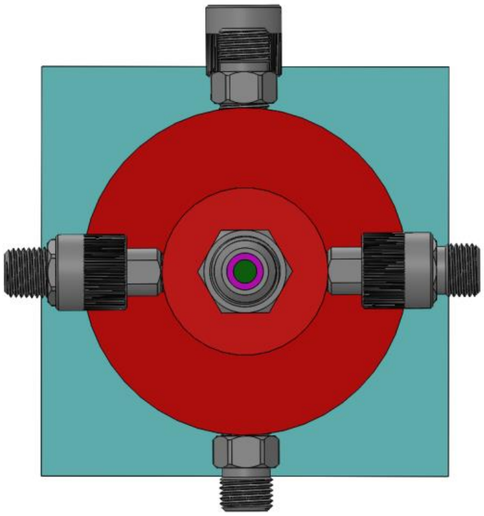

***Figure 2*** *– Final Fitting Configuration*

### A. Design Goals

The primary performance goal of the design was to develop a modular RDC to allow for components to be optimized individually while lowering the cost and time by saving the unmodified pieces. The design needed to have the optimal characteristics for the gas flow in the plenum, particularly low Mach number, even pressure, while being safe to operate.

The analysis design goal was to ensure that the model was symmetric about at least one axis if not two, to allow for a half or quarter model to be used in the computational phase.

The manufacturing goal of the design was to enable the RDC components to be manufactured on-site at NCSU by the machine shop. The shop's limitations include a 3 axis CNC machine opposed to a 6-axis machine which requires more hand tooling to be used especially for the O-Ring grooves and the injector holes.

### B. Design Challenges

The small design size was a challenge to design a modular system that can be manufactured and support the fittings required for instrumentation and propellants. To counter this challenge the design was built with a tiered plenum to allow for more instrument fittings to be attached to the inner oxygen plenum. Additionally, the design was gradually scaled up as the iterations of the model progressed.

Originally a 25mm diameter injector face with a short plenum, this design proved too limiting for the propellant fitting dimensions visualized in Image 3. The final design settled on a 51mm diameter with a long plenum which allowed for a fitting scheme that is feasible to be installed with hand tools.

Commercial off the shelf (COTS) product dimensions were not taken into account until the assembly was completed, which resulted in double work done for the design since no real-world products were compatible with the first iteration's dimensions. The fittings for the propellants lacked enough clearance to be placed next to each other, nor did the O-ring groove dimensions have any COTS O-ring that would fit in the original design.

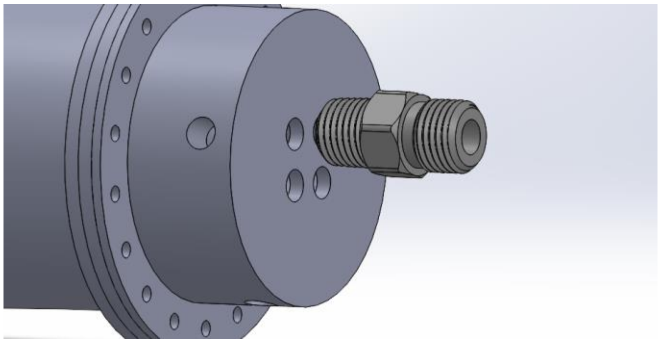

***Figure 3****- Fitting issue with iteration 1*

Symmetrical design also provided a challenge that dictated the length of the plenum as well as the choice to use a ½ inch inlet for the oxidizer. Originally designed to have 4 ¼ inch inlets, the symmetry of the design caused the plenum to be unnecessarily long which would complicate the manufacturability. A cutaway of the final design can be seen in Figure 4.

Some manufacturing challenges could potentially be the combustor wall chamber where the grooves are seen in Image 4 highlighted in yellow. Another challenge that will require more calculations will be for the injector face holes. These holes are evenly spaced but on the inner part of the injector face (seen in Figure 1) the holes diverge in different directions at different angles. These holes will be difficult to produce with such a sharp angle, the mills in the machine shop have a specific way the parts will need to be set up but creating the angles will produce a challenge. The holes themselves will require the in-house milling machine. This machine can have a program put into it to map out each individual hole to follow along and drill exactly where is needed, this program will require all dimensions and will take time to set up.

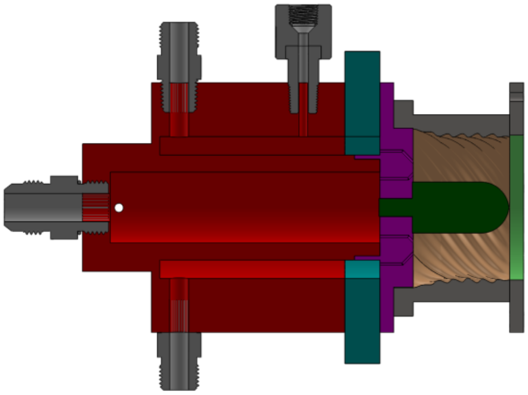

***Figure 4*** *– Finalized Design*

### C. 0D Model Results

Using the boundary conditions in Table 1 the 0D model calculated the conditions at the injector inlet and then progressed backwards through the plenum and finally to the propellant inlets using choked isentropic flow equation below:

$$Pt = \frac{\dot{m} * \sqrt{Tt}}{\sqrt{\frac{\gamma}{R_{spec}}}\frac{(\gamma-1)^{-(\frac{\gamma+1}{2(\gamma-1)})}}{2} * A_{inj} * (\#of\ Injectors)}$$

Additionally, the model calculated the proper fuel to oxidizer ratio based upon their equivalence ratio and the stoichiometric ratio of the reacting propellants using the formulas:

$$FAR = (Mol_{Fuel} * Stoichometric\ Fuel\ Part)/(Mol_{Ox} * Stoichometric\ Oxidizer\ Part)$$

$$Oxidizer\ Mass = \frac{\dot{m}}{FAR + 1}$$

$$Fuel\ Mass = \dot{m} - Oxidizer\ Mass$$

The results from the model are in Tables 2 through 4. The results from the 0D model were utilized to benchmark against the CFD results as a sanity check for the computational analysis. The model indicates that the design is theoretically achieving the goal of a low-speed plenum flow.

| Mass Flow Rate | Temperature of Incoming Gas | Equivalence Ratio |
|---|---|---|
| .025 kg/s | 290k | 1.02 |

***Table 1*** *– Boundary Conditions*

| Propellant | Stoichiometric Mass Flow (Kg/s) | Inlet Velocity (m/s) | Inlet Mach | Inlet Static Temperature (K) | Inlet Static Pressure (MPa) |
|---|---|---|---|---|---|
| Oxygen | 0.022 | 17.88 | 0.055 | 289.8 | 2.95 |
| Hydrogen | 0.003 | 112.4 | 0.087 | 289.6 | 0.94 |

***Table 2*** *– 0D results for Inlet*

| Propellant | Plenum Velocity (m/s) | Plenum Mach | Plenum Static Temperature (K) | Plenum Static Pressure (MPa) |
|---|---|---|---|---|
| Oxygen | 4.614 | 0.014 | 290 | 2.95 |
| Hydrogen | 29 | 0.022 | 290 | 0.94 |

***Table 3*** *– 0D results for Plenum*

| Propellant | Injector Velocity (m/s) | Injector Mach | Injector Static Temperature (K) | Injector Static Pressure (MPa) |
|---|---|---|---|---|
| Oxygen | 324.3 | 1 | 242.1 | 1.56 |
| Hydrogen | 1291 | 1 | 242.4 | 0.498 |

***Table 4*** *– 0D results for Injector*

### D. 3D Printing

The 3D printing for this project consists of 1:1 scaled parts for the RDE model so it can be fit tested to ensure all parts are properly fitted. The models are made of Polylactic Acid (PLA) material. The 3D model provides insight to any anticipated manufacturing challenges that could cause a fit issue or machining issue. Another benefit of this method during the design portion of the project, it helps visualize bolt placement along with O-ring fit checks for the outer and inner diameters in the injector face. Overall 3D printing the parts provides the validation of the design working well together before undergoing testing. The 3D printed RDC is seen in Figure 5.

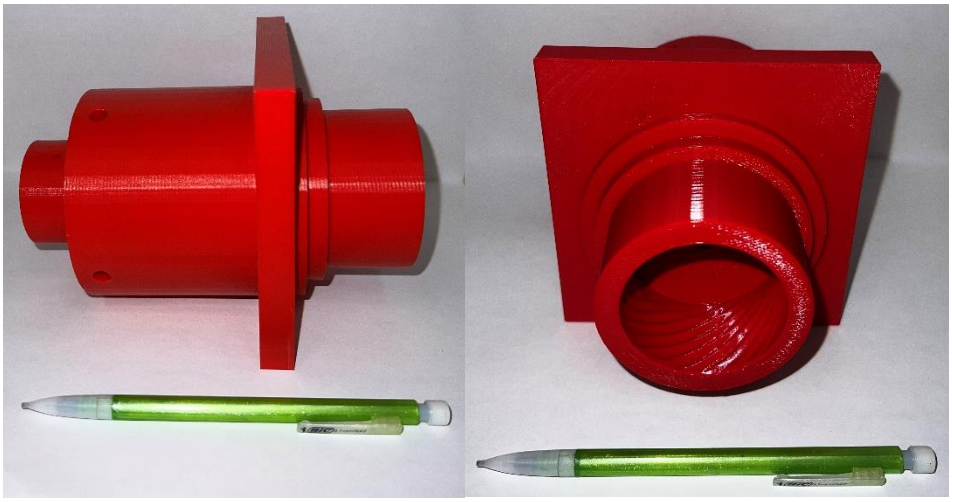

***Figure 5** – 3D Printed RDC Model*

### E. CFD Meshing

Ansys Fluent meshing was used to generate a mesh over a quarter section of the model's fluid body shown in Figure 6. Inflation was used with the first layer thickness method and 10 layers. The model was checked for any hard edges where there shouldn't be. Pinching was applied to where the 45-degree impinged injector meets the inlet length of the injector to smooth out the rough edges found. Mesh metrics were outside of the recommended metric values and can be found in Table 5.

| | Skewness | Aspect Ratio | Element Quality | Orthogonal Quality |
|---|---|---|---|---|
| Min | 3.56e-004 | 1.16 | 2.8e-003 | 2.7e-002 |
| Max | .93 | 509.27 | .99 | .99 |
| Average | .32 | 12.64 | .39 | .67 |

***Table 5** – Mesh Metrics*

## F. CFD Analysis

The case setup was another challenge for this research. A complex 3d model that required species transport and supersonic flows required a series of viscosity model sensitivity tests and a trial-and-error process on the initialization of the solution.

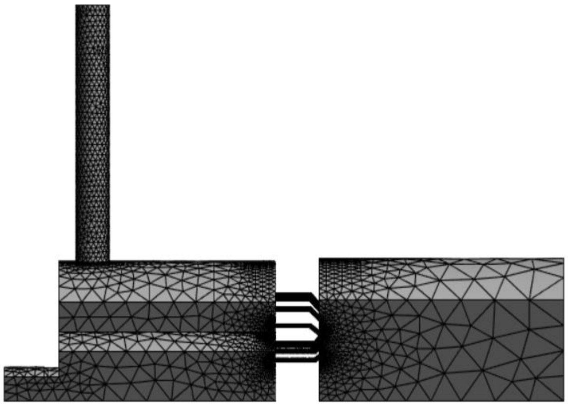

***Figure 6*** *– Mesh used for CFD*

Meshing was done iteratively with the most refinement required where the injectors transitioned from a straight tube to a 45-degree bend. The CAD model left hard edges where the two portions of the injectors intersected so local sizing and pinching was required to smooth out those regions for the solver to converge.

Well over 20 attempts were made in the effort to refine the case and solver setup. The solution setup was tested using a density solver initially, but the final converging case utilized a pressure solver. A K-ε realizable viscosity model was chosen from a sensitivity analysis that showed K-ω, S-A, and SST models were prone to divergence with this case. The rear mounted oxygen inlet allowed for standard initialization velocities in the x and y directions to be set up for oxygen and hydrogen respectively. Using values like the 0D model results as the velocities in the x and y direction, the case was solvable after 17000 iterations.

## G. CFD Results

Checking for mass conservation as the primary metric for convergence, the final mass flow through the outlet was .0249 Kg/s compared to the input mass flow of .025 Kg/s. Values for the scaled residuals did not decrease by 3 orders of magnitude for every value, but most of the residuals showed the decrease expected for a converged solution. The results compared to the 0D model can be found in Tables 6 through 8.

| Propellant | Stoichiometric Mass Flow (Kg/s) | Inlet Velocity (m/s) | Inlet Mach | Inlet Static Temperature (K) | Inlet Static Pressure (MPa) |
|---|---|---|---|---|---|
| Oxygen - CFD | 0.022 | 14.79 | 0.045 | 289.8 | 3.85 |
| Oxygen -0d | 0.022 | 17.88 | 0.055 | 289.8 | 2.95 |
| Hydrogen - CFD | 0.003 | 45.73 | 0.035 | 289.6 | 1.86 |
| Hydrogen - 0d | 0.003 | 112.4 | 0.087 | 289.6 | 0.94 |

***Table 6*** *– OD vs. CFD Results for Inlet*

| Propellant | Plenum Velocity (m/s) | Plenum Mach | Plenum Static Temperature (K) | Plenum Static Pressure (MPa) |
|---|---|---|---|---|
| Oxygen - CFD | 7.82 | 0.024 | 290 | 3.85 |
| Oxygen -0d | 4.614 | 0.014 | 290 | 2.95 |
| Hydrogen - CFD | 8.314 | 0.0064 | 290 | 1.86 |
| Hydrogen - 0d | 29 | 0.022 | 290 | 0.94 |

***Table 7*** *– OD vs. CFD Results for Plenum*

| Propellant | Injector Velocity (m/s) | Injector Mach | Injector Static Temperature (K) | Injector Static Pressure (MPa) |
|---|---|---|---|---|
| Oxygen - CFD | 256 | 0.84 | 254.6 | 2.35 |
| Oxygen -0d | 324.3 | 1 | 242.1 | 1.56 |
| Hydrogen - CFD | 1030 | 0.85 | 253.1 | 1.1 |
| Hydrogen - 0d | 1291 | 1 | 242.4 | 0.498 |

***Table 8*** *– OD vs. CFD Results for Injector*

For both the fuel and oxidizer plenums, pressures were approximately 1 MPa higher than the idealized results gathered during the 0D analysis. A comparison of the values found during CFD vs. 0D results are shown in Figure 7. Since the oxygen plenum and hydrogen plenums showed a .9 and .92 MPa increase vs the idealized results respectively, it can be concluded that the Cd is similar as expected with two identical areas and geometries for the injector inlets.

Pressure values were analyzed across the entire length of the fluid body as well as in multiple sections spanning the width of the fluid body to check for pressure differences in the entire plenum. As shown in Figure 8 the pressures were uniform across the length of the plenum and shown in Figure 9 the pressures were also nearly homogenous across the width at every measurement location. This indicates the desired pressure characteristics of the plenum were achieved with the design.

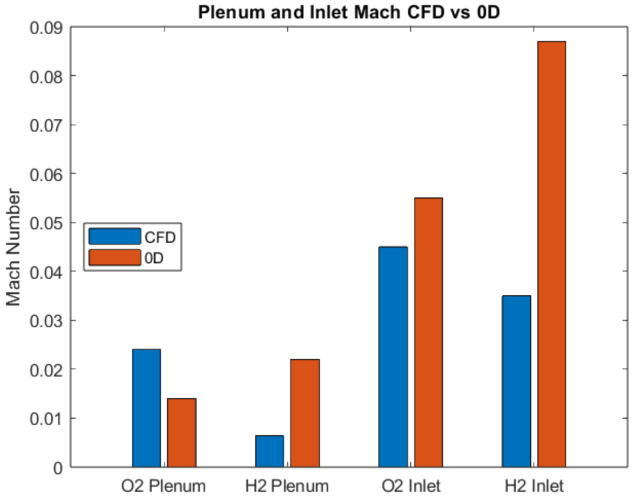

***Figure 7*** *– Plenum and Inlet Mach Comparison*

Mach values for the injector inlets showed choked flow as expected from the 0D modeling, and the Mach numbers for the plenum were well below values where compressibility effects start to appear as shown in Figure 7. A contour of the Mach number throughout the plenum is shown in Figure 10. This validated the velocity characteristics of the design. An interesting data point appears for the O2 Plenum where the Mach number is higher for the CFD vs. 0D results, a direct contradiction to the higher pressures and the rest of the compared values. While needing further study, this discrepancy in the data is likely due to the axial inlet that the O2 plenum uses vs the radial inlet that the H2 plenum utilizes. To mitigate any unwanted thrust in the +x direction, a T fitting will be tested to keep the inflow of O2 from increasing the plenum velocities.

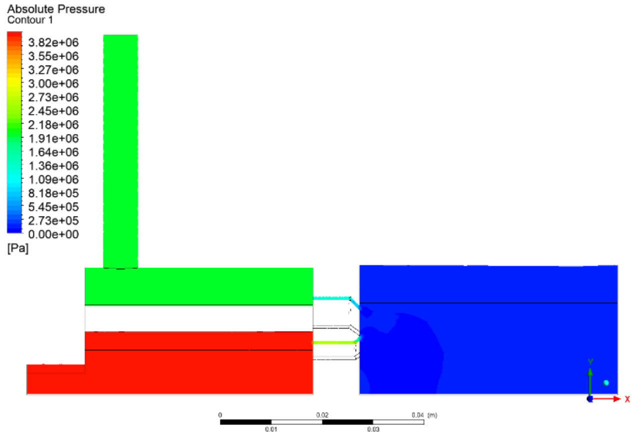

***Figure 8*** *– Pressure Contour of the RDC lengthwise*

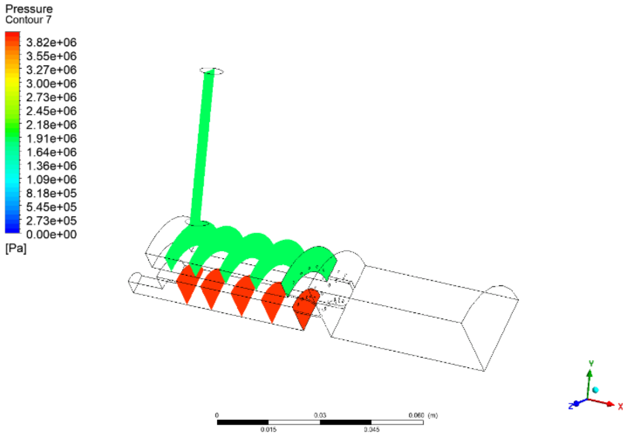

***Figure 9*** *– Pressure Contour of the RDC at various width segments*

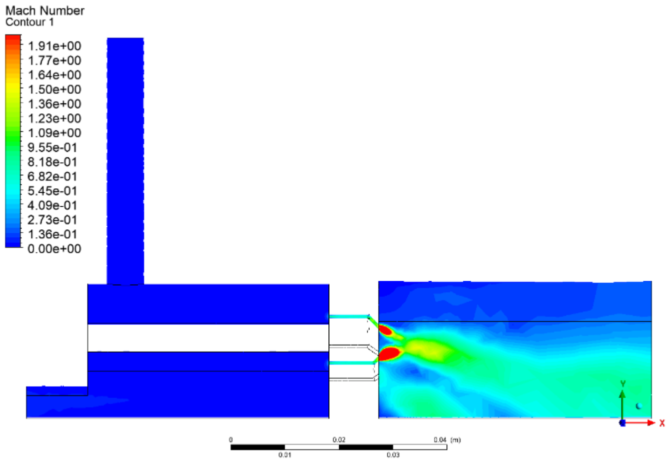

***Figure 10*** *– Mach Contour of the RDC lengthwise*

## V. Conclusion

The modular design of the RDC provides a rapidly configurable research platform for rotation detonation investigations. The design achieved the goals for performance, computational difficulty, and manufacturability and was validated through MATLAB, CFD analysis, and 3D printing. Challenges due to small dimensions, manufacturability, and COTS available equipment were overcome through design iterations that incrementally brought the design to a desired state of functionality. Further experimentation work will be needed on a machined version of the design to validate the analysis in a real-world environment, which will be published at a later date.

## Acknowledgements

B. Delgado, K. Shook, and J. Braun thank Dr. Venkat Athmanathan of Purdue University for his many helpful inputs during the design phase.

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