IFERP Explore Your Research Journey..

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 11, Issue 7, July 2024

Computational Analysis of a Rotating Detonation Engine (RDE) for Enhanced Performance and Efficiency in an Integrated Hybrid Turbojet Propulsion System

[1] Vrajesh Dinesh Rathod*, [2] Dr. Shashikant B. Thombre

[1][2] Visvesvaraya National Institute of Technology. (VNIT), Nagpur, India
Email: [1] bt20mec092@students.vnit.ac.in*, [2] sbthombre@mec.vnit.ac.in

Abstract*— Rotating Detonation Engines (RDEs) have recently acquired popularity in propulsion systems as a realistic way to boost thermal efficiency using Pressure Gain Combustion (PGC). They are easier to design and build since they include few or no rotating components. Theoretically, they can give higher thrust-to-weight ratios than traditional jet engines that use deflagration, on a smaller scale of working. Unlike Pulse Detonation Engines (PDEs), RDEs provide near-steady exit conditions and thrust, making them excellent and versatile for a wide range of applications. In this research, we intend to explore the feasibility of employing an RDE unit as an add-on or booster to an existing vehicle. This project aims to analyze the possibility of using a Rotating Detonation engine as an auxiliary support thruster in place of a Scramjet in the SR-71 Black Eagle Fighter jet model. The results found through simulation indicate that RDE can overcome the main shortcomings of the Scramjet engine which is the operational condition of Mach 1 or higher flow velocity of aircraft for using liquid fuel for combustion. Since RDE is dependent on Liquid fuel we need not worry about using Solid fuels as in the Scramjet engine. Further into the study we conducted, we tried to understand the noise generated by the combustion system and its effects which cause the de-stabilization.

Index Terms*— Rotating Detonation Engine (RDE), Detonation, Pressure Gain Combustion (PGC)

I. INTRODUCTION

Rotating Detonation Engine (RDE) is the by-product of controlled explosion research for advanced propulsion, carried out since the Second World War. To delve a bit deeper into the history of detonation engines we could see that RDE was found as an observation of thermoacoustic instabilities initially during combustion. During the early testing of Saturn V and Apollo 13 missions, the instability that particularly stood out was the bursting of walls of the combustion chamber in a helical shape [23]. Compared to detonation waves, we observe that the pressure and density of exhaust products are lower for deflagrative combustion [4]. In the case of detonation, it produces a strong shock wave followed by a reaction front which propagates with sonic velocity as related to the leading front. The thermal efficiency from a detonation cycle could be 20% higher than that of conventional isobaric combustion [3]. Zeldo'vich was the first person to propose enhancing the thermodynamic cycle efficiency using detonative combustion [23]. Further, in the literature review section, we shall explain the basics of detonation physics along with its thermodynamic cycle. Detonation in engines can be stationary to the engine frame, quasi-stationary to a shifting coordinate system, transient with changeable parameters during operation, or pulsing [11]. Originally during the 1980s Pulse detonation was at the forefront of research as it was developed over the design of Pulsejet engines but due to the fatal flaw of discrete Thrust output and poor Specific fuel consumption rates, it was hard to use for powering any aircraft. Rotating Detonation Engine uses the concept of path deviation of shock wave through an annulus chamber using a pre-detonator for continuously burning air-fuel mixture. Despite those flaws being found out later it had still proven the point of how detonative combustion can improve propulsion efficiency. The Pressure Gain Combustion (PGC) principle explains why RDE performs better. This is an unsteady and periodic process commonly utilized in gas turbines where exhaust expansion is restricted, resulting in an increase in stagnation pressure. This differs from typical gas turbines, which add heat to expanding gas through the combustor, resulting in pressure loss across the chamber. Some other devices based on this concept include resonant pulse combustors (RPC) or pulse jets, and pulsed detonation combustors/engines (PDC or PDE) [4]. The reason for stagnation pressure to be higher is, that stagnation pressure at the inlet dictates the net total mass flow rate through the chamber in case of compressible fluids. The Area-Mach number relationship as given in Eq. (1) leads us to the choked mass flow rate (maximum mass flow possible) through the combustion chamber which is expressed as a function of inlet total/stagnation pressure and temperature as shown in Eq. (2).

$$\frac{A}{A'} = \frac{1}{M}\left[\left(\frac{2}{\gamma+1}\right)\cdot\left(1+\left(\frac{\gamma-1}{2}\right)\cdot M^2\right)\right]^{\frac{\gamma-1}{\gamma+1}} \quad \textbf{(1)}$$

$$\dot{m} = \frac{p_o}{\sqrt{T_o}}\cdot\frac{A_{throat}}{A_{inlet}}\cdot\sqrt{\frac{\gamma}{R}\cdot\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad \textbf{(2)}$$

RDEs have potential advantages over PDEs, RPCs, and deflagrative combustors in terms of high-power density [], no moving parts, no need to regulate periodic ignition and reactants' injection, high operating frequency, and steadier exit flow profile. Interest in detonation combustion has only increased recently in the 21st century. This is due to the development of detonation engines, which are superior to all other types of heat engines in terms of thermodynamic efficiency [24]. Major countries like Russia, China, France and Japan started almost simultaneously working on it at the beginning of this century and countries like USA and Germany then followed them thereafter.

This document delves into understanding the basics of detonation to understand the combustion physics of RDE. The expected result of this research is to generate a successful 2-dimensional RDE simulation and determine its performance parameters to compare with the scramjet engine. We shall also briefly observe the acoustic characteristics of normal combustors to develop a model for Acoustics for RDE in future

II. LITERATURE REVIEW

A. Detonation Engine

We will now focus on understanding the detonation physics that we have studied for this research. A thermonuclear reaction can occur when a gas or plasma is compressed quickly to very high temperatures and pressures, as explained by the physics concept of detonation theory. Numerous disciplines, such as engineering, nuclear physics, and astrophysics, can benefit from the use of this idea. Explosions, engine combustion, nuclear reactors, and other situations.

When a fuel-air mixture is ignited and constantly burned, a kind of explosive combustion known as sustained detonation takes place, producing a wave of pressure and heat that lasts for a long time. This can happen in several settings, such as gas turbines, explosive devices, and rocket propulsion. When there is a prolonged detonation, energy is released continuously as opposed to quickly because the burning rate is slower than the rate of pressure rise. The 1-dimensional theory of detonation was originally proposed by Zeldo'vich, von Neumann, and Doring during the Second World War this model admits finite-rate chemical reactions, and thus the process of detonation consists of the following. It describes a self-sustained detonation wave in an explosive material. It consists of a shock wave, a reaction zone, and a rarefaction wave. The shock wave compresses the explosive material, leading to the initiation of chemical reactions, which occur in the reaction zone. The energy released by these reactions sustains the shock wave and creates a high-pressure zone behind it. This high-pressure zone continues to propagate through the material as a detonation wave [18].

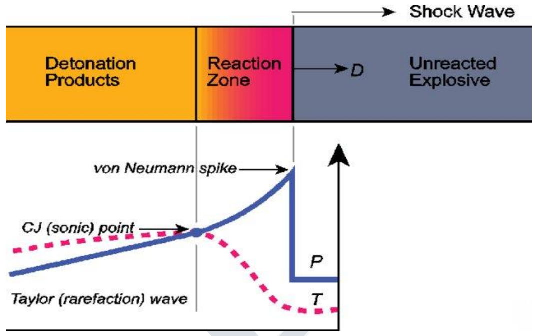

Figure 1. ZND 1-dimension detonation propagation [23]

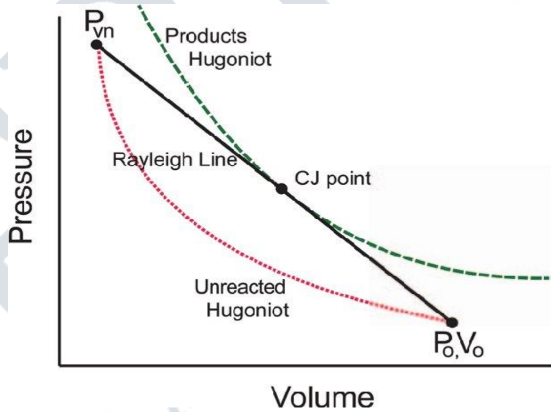

Figure 2. PV diagram for detonation [23]

The detonation in itself is an unstable state the diagram above shows the state of combustion which is found using the governing equations of Rayleigh, Rankine, and Hugoniot for understanding Detonation. The said equations are given below.

$$\rho_o \cdot \dot{R}_S = \rho \cdot \left(\dot{R}_S - u_1\right) \quad \textbf{(3)}$$

$$p - p_o = \rho_o \cdot \dot{R}_S \cdot \left(\dot{R}_S - u_1\right) \quad \textbf{(4)}$$

$$\frac{\gamma}{\gamma-1}\cdot\left(\frac{p}{\rho}-\frac{p_o}{\rho_o}\right) = \frac{1}{2}\cdot\left(p-p_o\right)\cdot\left(\frac{1}{\rho_o}+\frac{1}{\rho}\right) \quad \textbf{(5)}$$

Going forward we see the work done recently on the topic of Rotating Detonation itself. The paper of Pal (2021) discusses how RDE gives a better combustion efficiency at lean mixture conditions [3]. They also observe that heat release is higher under rich conditions from rich fuel regions whereas during the lean case, the heat release is higher from zones with less fuel. Other than this RDEs are generally avoided for large-scale modelling due to shear layer instabilities and high vibrations, but through methane

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 11, Issue 7, July 2024

detonative type combustion simulation it is observed that the shear layer instability can be avoided [5]. The paper of Zhang (), discusses the use of a Spike diffuser similar to that of a Scramjet for creating a Hybrid between the 2 models. The model for the spike diffuser shows the net total pressure rise till the inlet of the combustion chamber (isolator) by sacrificing the total inlet velocity, as shown below.

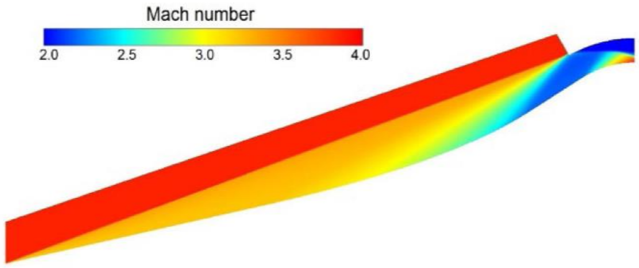

Figure 3. Mach number contour of spike diffuser [18]

The pressure rise in stagnation pressure would increase the net mass flow through the system for increasing the oxidizer amount through the chamber.

B. Combustion Chemistry

In the field of transport, hydrogen energy has become a new type of energy that people pay attention to due to its easy production and nonpolluting generation. The use of hydrogen as a fuel in internal combustion engines can be a good way to make a low-cost and clean conversion of the current internal combustion engine, thus understanding the application of hydrogen energy in vehicles [3]. Hydrogen's low molecular weight and high diffusivity facilitate fast reaction rates, allowing for very rapid energy release and high-speed detonation waves [8]. This trait is advantageous for maximizing the output power of the rotating detonation engine.

$$H_2 + O_2 \xrightarrow{\Delta} H_2O$$

$$\dot{H} + O_2 \rightarrow \dot{O} + \dot{O}H$$

$$\dot{O}H + H_2 \rightarrow \dot{H} + H_2O$$

$$\dot{O} + H_2O \rightarrow \dot{O}H + \dot{O}H$$

$$\lambda = A \cdot e^{\left(\frac{E_a}{R \cdot T}\right)} \cdot \rho \cdot Y \qquad (6)$$

The paper of Marcus O Conaire (2004) does research on premixed laminar flame combustion for hydrogen using the 9 species & 21 reaction mechanism data [22]. Using that same data, we will be generating our results for the 2-D RDE model. The initial step mechanism of H2 combustion can be seen above along with the rxn. rate formula, which will be used in analyzing the premixed flamelet speed and energy output. Based on this chemistry model we plan to utilize the Fickkets-Jacob (FJ) detonation cycle. Compared to normal air-breathing cycle like the Brayton cycle, Humphrey and FJ cycles give better results for producing work as they have almost constant volume heat addition which raises the metallurgical limit for the cycle which directly affects the efficiency of the cycle.

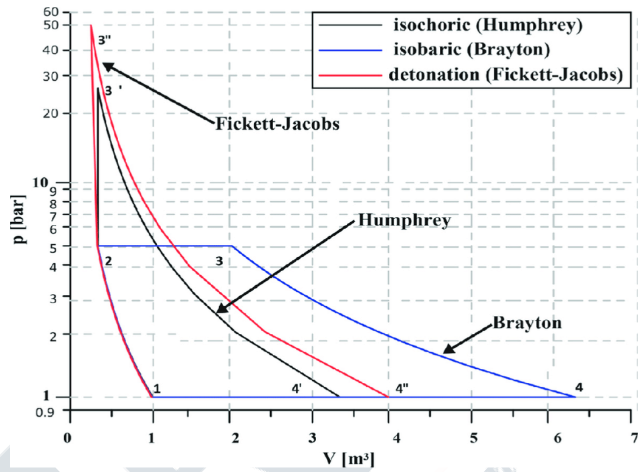

Figure 5. Thermodynamic cycles for combustion [23]

In the diagram above it is clear that the pressure gain through the FJ cycle reaches as high as 50 bars implying that we can generate greater thrust due to pressure difference. Also, high-pressure gain also implies that more air mass can be sucked inside the system since the inlet stagnation pressure shall also rise which is a constraining parameter of choked flow rate as we had seen before.

C. Why not Scramjet?

Due to the unique operating principles of Supersonic combustion, Scramjets require greater than Mach 1 speeds. To achieve efficient combustion of fuel, the airflow entering the combustor must be at a suitable pressure, temperature, and mass flow rate [20]. The supersonic airflow in scramjet engines ensures that combustion occurs at relatively high speeds, optimizing the combustion process and overall engine efficiency. This feature is essential for achieving the high-speed propulsion capabilities characteristic of scramjet technology, with speeds exceeding Mach 6 or higher [20]. This high-speed airflow is crucial for maintaining efficient combustion and achieving the required performance levels of the engine at such extreme speeds. The combustion process in a supersonic airflow is highly dynamic, involving rapid reaction rates and intense turbulence due to the high velocities involved. Combustion cannot occur until mixing has been achieved at a molecular level, highlighting the intricate coupling of turbulent mixing and chemical reaction rates in the supersonic combustion chamber [20].

III. PERFORMANCE PARAMETERS

Several key parameters that define overall engine performance are utilized to assess the suitability of a given engine design. '*Thrust*' is the engine's very first and primary

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 11, Issue 7, July 2024

parameter for sustaining flight. Thrust is the force produced due to momentum and pressure increases across the engine. It is used to sustain (thrust = drag), accelerate (thrust > drag), or decelerate (thrust < drag) a flight. To increase thrust, one can introduce an additional nozzle to raise jet velocities or add an afterburner [24].

$$F = \left[\left(\dot{m}_a + \dot{m}_f\right)\cdot v_e - \dot{m}_a \cdot v_0\right] + A_e \cdot \left(P_e - P_0\right) = \int (P.dA)_x \quad (7)$$

$$SFC = \frac{\dot{m}_f}{F} \quad (8)$$

$$SFN = \frac{F}{\dot{m}_a} \quad (9)$$

$$\eta_{th} = \frac{\left(\dot{m}_e \cdot v_e^2 - \dot{m}_a \cdot v_a^2\right)}{2 \cdot \dot{m}_f \cdot H_L} \quad (10)$$

The next important parameter when it comes to flight is the conservation of fuel, which is measured by '*Specific Fuel Consumption*' (SFC). Lower the value of SFC better the engine is considered since it indirectly represents better conversion of fuel's energy into useful work. Similar to this another parameter called the '*Specific Net Thrust'* shows the amount of thrust generated in terms of consumption of air mass. Lastly, the *'Thermal Efficiency'* is the most crucial parameter for judging an engine's performance. This parameter is the layman's term for determining the better engine amongst a group.

IV. METHODOLOGY

To begin with, we will first study normal deflagration which will be the basics for understanding combustion. We will conduct normal non-premixed mixture combustion and observe the performance parameters which were discussed before to evaluate such systems. Then we do a steady-state acoustic analysis to find the acoustic power generated in sound levels by the combustion chamber.

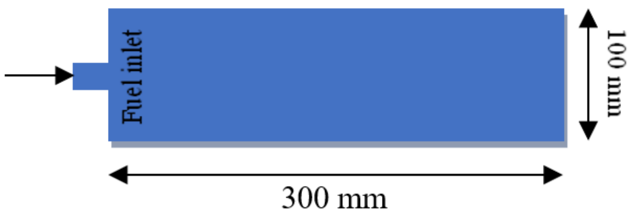

Figure 6. Normal Combustor Geometry

This combustor is modelled after one of the multiple circular combustors of the Turbojet engine. Even though the model is in the most simplified form it can still give us insights into deflagrative combustion. The boundary condition is a subsonic airflow speed of 80 m/s with Jet-A fuel incoming from the small opening in the middle with 20 m/s. The size of the fuel inlet is 6 mm in diameter to ensure proper mixing of air and fuel. Next, we shall look at the domain for Rotating Detonation computation. The domain is designed for a 2-dimensional open system with periodic boundaries at either side to replicate the annular combustor's internal behaviour. It has been divided into four sections first being the area of fresh charge containing Air and hydrogen at an equivalence ratio of 0.7, next is the area of detonation initiation where the initial conditions of detonations are maintained momentarily, after this adjoining to it is the area of detonation traverse and lastly the product region where the combustion products are driven towards the outlet. Fig. (7) shows the described domain. The target mass flow is considered to be 1 kg for ease of calculation.

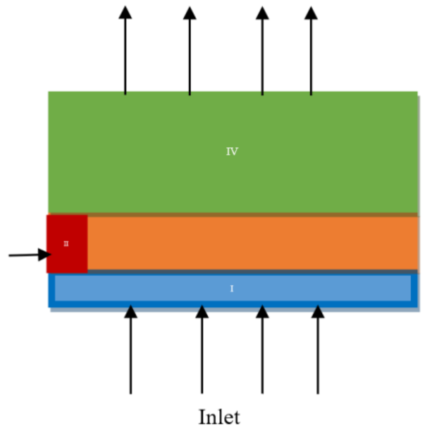

Figure 7. 2-dimensional RDE geometry

V. NUMERICAL APPROACH

We have used Ansys' © Fluent Software for generating the simulation results. The first model i.e. of the normal combustor was simulated with the k-ω turbulence modelling and for the acoustic model we used the broadband noise model considering the source for noise to be combustor walls. Let us understand a bit about these models starting with the k- ω model, which is a substitution for the Reynolds Average Navier stroke model (RANS). This model aims to solve turbulence by solving the turbulence kinetic energy (k) and specific energy dissipation rate (ω).

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial\left(\rho \cdot u_j \cdot k\right)}{\partial x_j} = \rho P - \beta' \rho \omega k + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_k \cdot \frac{\rho k}{\omega}\right) \cdot \frac{\partial k}{\partial x_j}\right]$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial\left(\rho \cdot u_j \cdot \omega\right)}{\partial x_j} = \frac{\alpha \omega}{k} \cdot \rho \cdot P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_\omega \cdot \frac{\rho k}{\omega}\right) \cdot \frac{\partial \omega}{\partial x_j}\right] + \frac{\rho \cdot \sigma_d}{\omega} \cdot \frac{\partial k}{\partial x_j} \cdot \frac{\partial \omega}{\partial x_j}$$

$$P = \tau_{ij} \cdot \frac{\partial u_i}{\partial x_j}$$

(11), (12), & (13)

Rotating Detonation Engine (RDE) for a 2-dimensional domain will use the Detached Eddy simulation model which uses the k-ω turbulence modelling method and the combustion model is the Partial Premix model which

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 11, Issue 7, July 2024

considers the Zimont flame speed structure. Unlike the other research papers, I have decided to use a Pressure-based Solver in this simulation because I found it easy to model the Detonation wave when compared to modelling it through the Detonation Shock tube method which uses a Transient-Density based Solver. We will be considering a time step of 5e-7 and 0.5 CFL based on Lim's paper [21]

VI. RESULTS & DISCUSSION

The results are represented in the form of contours majorly for a better understanding. Unlike how we expected we have found a lot of discrepancy in the results for RDE while for the normal combustor, most of the results were similar to the experimental results.

A. Normal Combustor

Upon doing simulations, we found that the maximum temperatures of the combustor went as high as 1880 K for the combustor and the products formed during this process contained severe amounts of CO_2, CO, and NO_x. The major temperature was under the concentration of CO_2 & CO. Whereas the amounts of Ionic residue were negligible. The figures below show the temperature and velocity contour for the normal combustor.

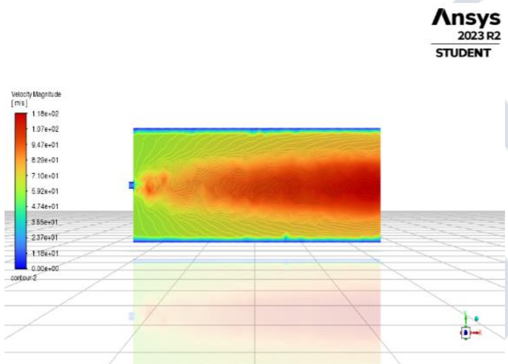

Figure 8. Velocity variation through combustor

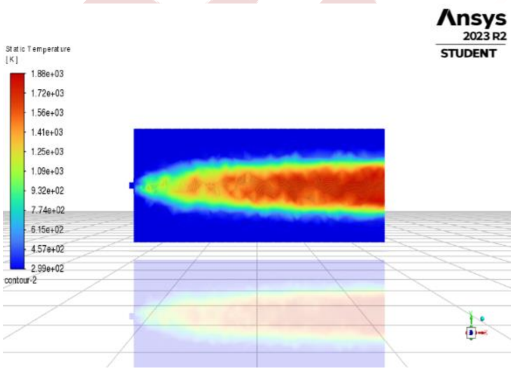

Figure 9. Temperature variation through combustor

Figure 10. Surface Acoustic power of combustor

Let us now see the acoustic results which were considered well within the expected ranges of 80-120 dB and were also found to be true to that. Fig (10) shows the surface acoustic power in terms of dBs and the entire surface is at an average of 95 dBs. Upon doing a transient analysis of this combustor we also found the following results for pressure rise by using the Fast Fourier transformation (FFT) on Acoustic Sound Signal.

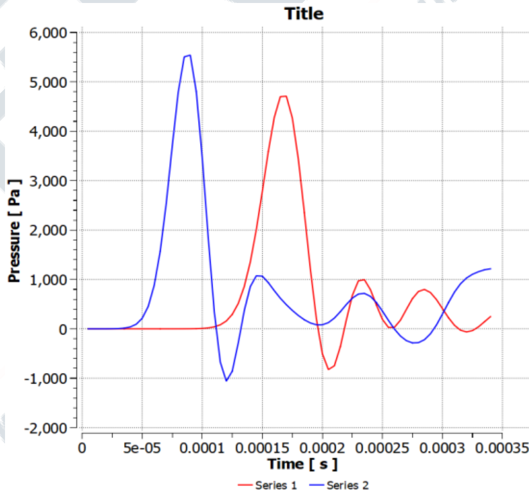

Figure 11. FFT modulation transient sound waves

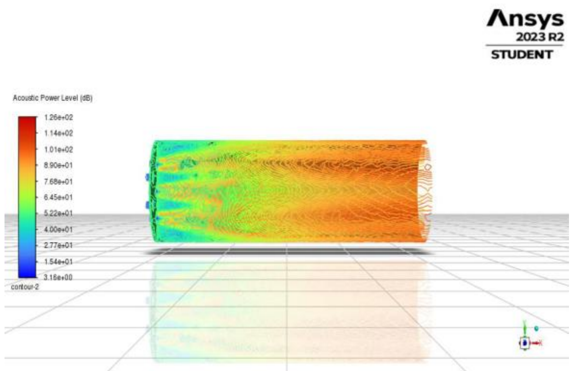

Figure 12. Acoustic Analysis of Multi-fuel supply model

Based on a single supply fuel model his model was made with multiple fuel suppliers around the entrance periphery and this model gave higher acoustic noise on analysis.

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Volume 11, Issue 7, July 2024

B. Hydrogen Premixed Laminar Combustion

To understand the kinetics of the reaction better we decided to do a small test on hydrogen combustion to find out the premixed laminar flamelet velocity as well as the energy released per kg of fuel during the combustion. The charts below are the results that were obtained with the help of Ansys © ChemKin software which used the Laminar flame model.

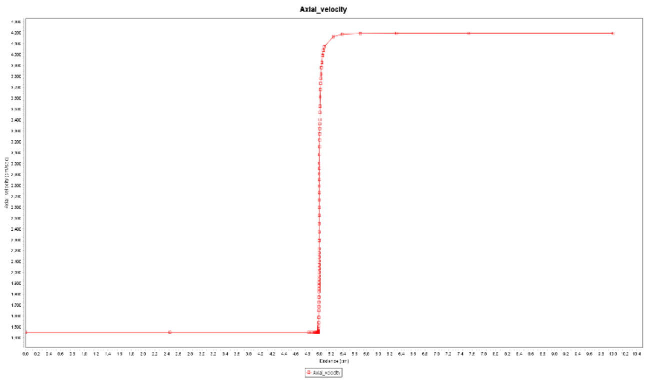

Figure 11. Measuring of Axial velocity of laminar flamelet

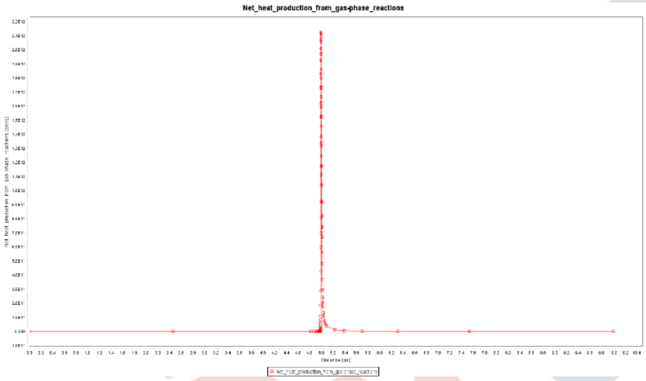

Figure 12. Measuring Energy release of H2 combustion

Here we find that the Laminar flamelet speed for Hydrogen combustion is 47 m/s whereas the Heat released in this process is 2.1 * 10^5 gm/ Joule. Based on this parameter we can calculate the expected turbulence flamelet speed for hydrogen combustion. Also, the Calorific Value of hydrogen from the database of ChemKin is found to be 150 MJ.

C. RDE Results

For the first iteration of the simulation, we had considered the CJ temperature to be 750 K based on the wrong calculation but surprisingly we still found detonation propagation through the mixture due to the high initial pressurization of the detonation mixture. The figures below show the contours of Temperature, Pressure, and Velocity for the first iteration.

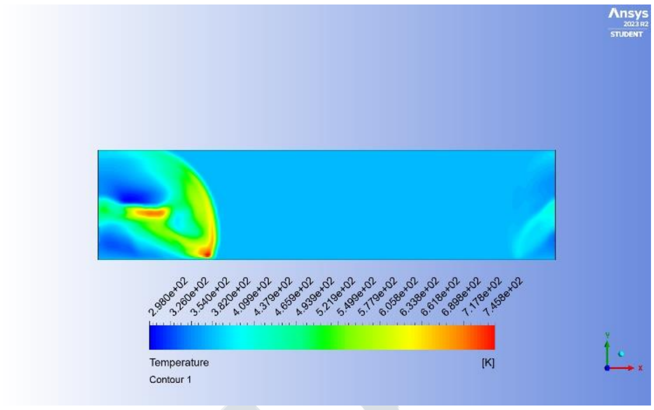

Figure 15. Temperature contour of RDE itr. 1

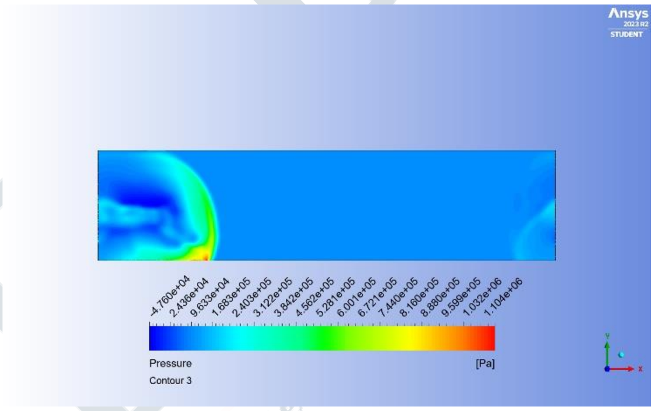

Figure 16. Pressure contour of RDE itr.1

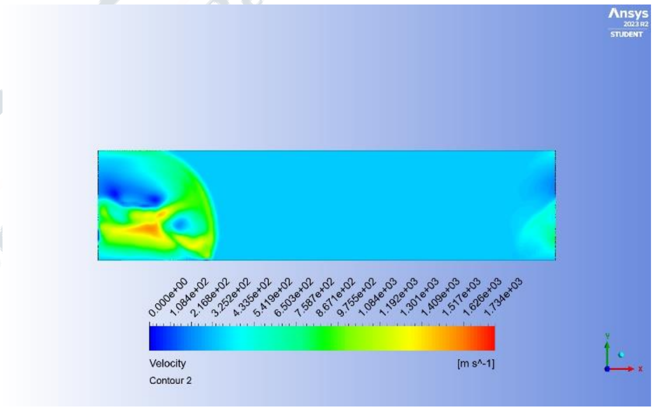

Figure 17. Velocity contour of RDE itr.1

We observed that the detonation forefront pressure was close to 10.5 bar but the pressure of the product leaving the outlet was a bit lower than the expected, nearly 1.87 bar. The outlet Mach number of exhaust was 1.47 while the detonation front itself travelled at Sonic speed. The low temperature led to combustion problems for the mixture reducing the combustion efficiency of the system. Upon calculation, the net thrust developed by the results of this solution assuming a detonation height of 4 mm was 681.6 N.

Moving onto the next iteration we used NASA's CEA software for calculation of detonation parameters using input condition for 1 bar operating pressure we got 45.38 bar

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 11, Issue 7, July 2024

initiation pressure, 3045 K Chapman Jouguet Temperature and 2041.3 m/s Detonation velocity. Based on these calculations we did a simulation for a small-time frame of about 500 µs just to see if the detonation layer formed or not. Those results are as follows.

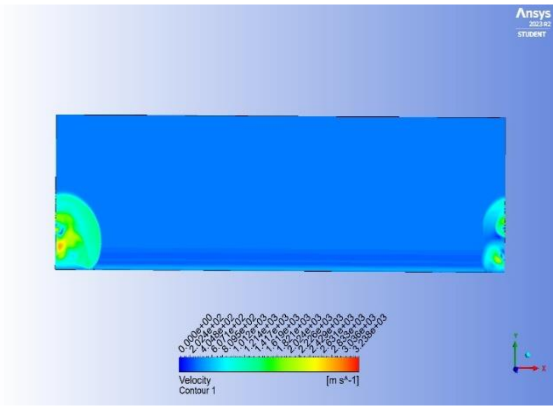

Figure 18. Velocity contour of RDE itr.2

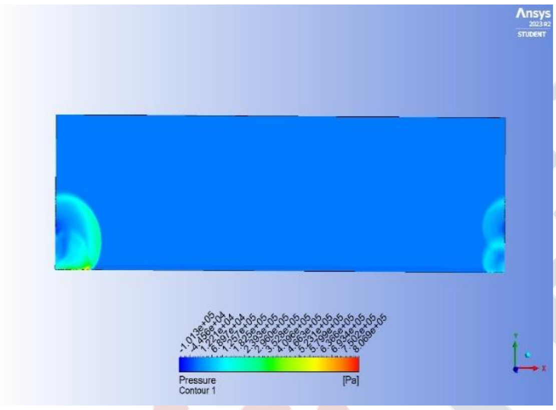

Figure 19. Pressure contour of RDE itr.2

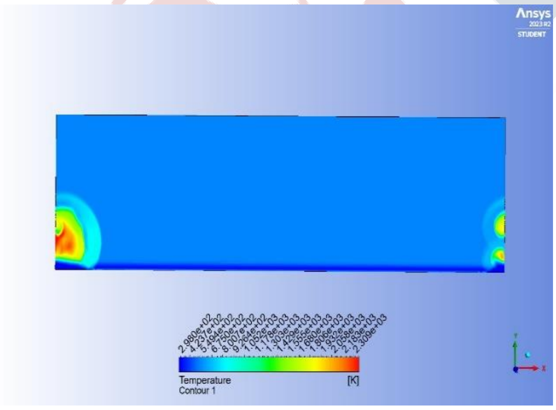

Figure 20. Temperature contour of RDE itr.2

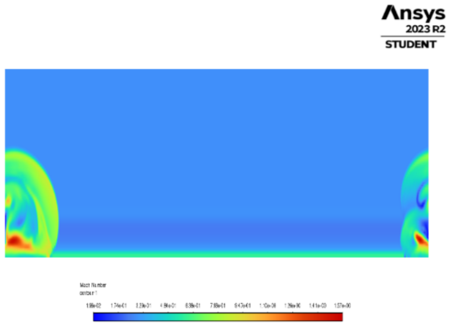

Figure 21. Mach number contour of RDE itr.2

Unlike the previous iteration combustion efficiency isn't reduced but due to uncontrolled propulsive detonation we lose the pressure gain effects. The overall thrust produced is increased due to the high velocity being achieved at the outlet despite considerable pressure loss near the detonation front. The net thrust calculated for this system is 802.365 N. Overall the results found through the simulation were quite disappointing as they are highly discrepant due to our mistakes. The thermal efficiency of the final iteration of the model is 20.317 % which is way lower the expected value of 59.3% [5].

D. Comparison with Scramjet.

We have tabulated the compared values of these simulations with the performance parameters for a Scramjet (Hypersonic engine). For this purpose, we shall borrow data from Min's paper on Thermodynamic performance analysis of scramjet at wide working conditions.

Table 1. Comparison of Performance Parameters of Scramjet [20] and RDE

Performance index	Rotating Detonation Engine	Scramjet Engine
Specific Net Thrust	802.365 (m/s)	1044.6 (m/s)
Specific Fuel Consumption	0.11778 (kg/N.hr)	0.138 (kg/N.hr)
Thermal Efficiency	20.317 %	69.2 %

It is clear enough that the model developed by this research is nowhere near close enough to even substitute for an auxiliary engine. The only advantage of this model was the lower specific fuel consumption. But we must note that the comparison done here is based on the best performance of Scramjet using a different fuel.

VII. CONCLUSION

We have studied RDE thermodynamically for a 2-dimensional model. The results obtained during the simulations always had high discrepancies with experimental results due to detonation never being stable. We believe a lot more work would be required to generate a stable detonation in a viscous model. The stable detonation could be achieved if we can simulate a shock tube combustion model in a viscous fluid. This leads to future work on solving this same problem through another Numerical Scheme, since we can clearly see the results found through the pressure-based solvers have led to uncontrolled detonative combustion. Overall, the results were quite disappointing for us since we had expected results to be not so different from those of inviscid RDE simulations [21]. Based on the results through the 2 iterations we have formulated these observations:

- During unstable detonations the maximum velocity of the mixture is found close to the inlet behind the detonation wave near the product region.
- There are formations of large eddies inside the slip zone of detonation which were not supposed to occur.
- The outlet velocities of case-1 of RDE were close 720 m/s and in case-2 was about 980 m/s. These velocities are a lot lower than the experimental values of nearly 1.8 km/s [5].
- It is observed during shock formation there would be an advanced layer and a follower layer where the maximum combustion accumulates. The advanced layer tends to separate itself from the follower layer.
- It is observed during both simulations of RDE that there exists some problem with combustion in the shear layer, also during the first simulation the combustion had stopped at a point nearly at 1.5 milliseconds.

REFERENCES

[1]. ANSYS Inc., ANSYS FLUENT 2020 GUIDE, ANSYS, 2020.

[2]. NASA, "NASA cea," [Online].

[3]. G. &. D. S. &. R. B. &. S. S. Pinkai Pal, "Multidimensional Numerical Modeling of Combustion Dynamics in a Non-Premixed Rotating Detonation Engine With Adaptive Mesh Refinement.," *Journal of Energy Resources Technology,* vol. 143, pp. 112308-1-9, 2021.

[4]. V. Katta, "Structure of Rotating Detonation Wave in Methane-Oxygen Mixtures," in *AIAA Scitech 2019 Forum,* San Diego, 2019.

[5]. S. &. M. H. &. L. D. &. Y. Y. &. L. S. &. Z. C. Zhou, "Experimental study of a hydrogen-air rotating detonation combustor.," *International Journal of Hydrogen Energy,* vol. 42, no. 21, 2017.

[6]. I. &. F. I. &. Y. L. Borovik, "Simulation of continuous spin detonation in an annular combustion chamber in two-dimensional," *Thermophysics and Aeromechanics,* vol. 29, no. 1, pp. 125-142, 2022.

[7]. E. Gutmark, " Pressure gain combustion," *Shock Waves, Springer,* vol. 31, pp. 619-621, 2021.

[8]. X. L. C. P. P. G. S. G. a. Z. Y. Lijun Wang, "Research and Development of Hydrogen-Fueled Internal Combustion Engines in China," *ACS Omega,* vol. 8, no. 51, pp. 48590-48612, 2023.

[9]. A. Minchinton, "On the Influence of Fundamental Detonics on Blasting Practice.," in *11th International Symposium on Rock Fragmentation by Blasting*, Sydney, Australia, 2015.

[10]. H.-S. &. L. E. S. &. C. J.-Y. Han, " Experimental Investigation of Detonation Propagation Modes and Thrust Performance in a Small Rotating Detonation Engine Using C2H4/O2 Propellant.," *Energiees,* vol. 14, no. 5, p. 1381, 2021.

[11]. C. &. F. D. &. S. P. Bedick, "Characterization of Rotating Detonation Engine Injector Response Using Laser-Induced Fluorescence.," *Journal of Propulsion and Power,* vol. 35, no. 4, pp. 1-12, 2019.

[12]. P. a. K. Pandey, "Computational study of Deflagration to Detonation transition in Pulse detonation Engine using Schelkin Spiral," *Applied Mechanics and Materials,* vol. 772, pp. 136-140, 2015.

[13]. Z. V. A. K. Grishin I, "Experimental Study of Methane Combustion Efficiency in a High-Enthalpy Oxygen-Containing Flow," *Applied Sciences,* vol. 12, no. 2, p. pg 899, 2022.

[14]. N. V. M. E. S. L. Smirnov N, "Modeling a Combustion Chamber of a Pulse Detonation Engine," *Fire,* vol. 6, no. 9, p. pg 335, 2023.

[15]. D. D. F. D. Gaillard Thomas, "Numerical investigation of an unsteady injection adapted to the continuous detonation wave rocket engine operation," in *6th EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS),* Krakow, July 2015.

[16]. S. &. P. M. &. B. M. &. T. M. &. B. C. Raghav, "Numerical simulation of 2D premixed combustion within a Rotating Detonation Engine.," in *ASCenSIon, Dresden,* Germany, 2023.

[17]. S. &. P. S. &. C. I. &. F. D. &. S. P. Escobar, "Numerical Investigation of Rotating Detonation Engine," in *Proceedings of the ASME Turbo Expo.,* Texas, 2013.

[18]. Z. L. H. W. Y. H. Y. Y. Zhao Mengmeng, "Performance analysis of a rotating detonation model for future thermal power system using hydrogen as fuel," *Energy Reports,* vol. 8, pp. 66-74, 2021.

[19]. A. C. &. P. B. Benim, "Prediction of burning velocity and quenching distance of hydrogen flames.," *E3S Web of Conferences.,* vol. 128, no. 7, 2019.

[20]. L. Y. W. H. X.-q. C. Min Ou, "Thermodynamic performance analysis of scramjet at wide," in *EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES*, 2017.

[21]. H. E. Lim Wei, "Gas Dynamics inlet isolation in RDE (Thesis)," *Calhoun, Institutional Archive of Naval Postgraduate School,* Monterey, California, 2010-12.

[22]. M. O. Conaire, "A Comprehensive Modeling Study of Hydrogen Oxidation," *International journal of Chemical Kinetics*, vol. 36, pp. 603-622, 204.

[23]. P. Wolanski, "Detonative Propulsion," *Proceedings of the Combustion Institute*, pp. 125-158, 2017.

[24]. N. D. N. D. BA Haider, "Parametric Analysis of Expendable type Single-Spool Turbojet Engine with a Short Afterburner," in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition Volume: AIAA 2011-574,* New Orlando, Florida, 2011.