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Rotating Detonation Engines: Future of Rocket Propulsion

Hareendran M.R., Jesna Jenson Pukkoden, Nikhil Christy Joy, Sangeeth Krishnan N.G.*, Santo K. Johny
Student, Department of Mechanical Engineering, Government Engineering College, Thrissur, Kerala Technological University, India

ABSTRACT
Almost all of the rocket engines in use today are chemical rockets. These engines have high thrust to weight ratio, but they have very low specific impulse and use of heavier chemicals leads to a reduced exhaust velocity and higher emissions. Even though alternative fuels have been used, the mass of propellant required remains an issue. Therefore, methods that can replace chemical propulsion have been researched and developed, like electric propulsion, solar sails, laser propulsion and nuclear propulsion. However, there is still significant potential in chemical rocket engine fuels and more efficient engine designs. Considering dependency on chemical rockets in coming years, development of Rotating Detonation Engines (RDE), which uses detonation instead of deflagration combustion is quite significant and can be considered to be the future of chemical rocket propulsion. This paper reviews the design aspects of RDE and highlights its advantage over the conventional rocket engines, due to increased thermal efficiency and pressure gain.

Keywords: *Engine fuels, conventional rocket engines, pressure gain, rotating detonation engines, rocket propulsion*

****Corresponding Author***
E-mail: sangkrishna1@gmail.com

INTRODUCTION

Combustion, or burning, is a high temperature exothermic redox chemical reaction between a fuel and an oxidant. Depending on the confinement, mixture ratio and ignition source the type of combustion may be detonation or deflagration.

Deflagration combustion is brought about by a subsonic wave sustained by a chemical reaction and detonation combustion by a supersonic shock wave closely followed by a combustion wave which releases energy to sustain the shock wave. In present day, rocket engines combustion by deflagration is used.

The transition from deflagration to detonation (DDT) may be triggered by an appropriate change of parameters, e.g., ambient pressure or temperature, or the reaction rate prefactor [1]. Detonations engines are widely studied due to their compact configurations and high thermal efficiency. The studies were mainly focused on three kinds of detonation engines.

Firstly, the Standing Detonation Engine, in which detonation waves was positioned in the combustion chamber, normal or oblique to wedge. These had many technical difficulties in practical applications and therefore seemed feasible only in principle.

Secondly, the Pulsed Detonation Engine (PDE), the simplest PDE or PDRE configuration consists of a straight, constant area thrust chamber that is fully filled with a detonable gaseous mixture. This simple configuration has received significant analytical numerical and experimental treatment in the literature [2]. It can operate in a wide range of conditions (e.g. for a flight Mach number in the range 0–5), but its thrust changes during the operation cycles, periodically increasing and decreasing [3].

The third group of detonation engines is called the Rotating Detonation Engine (also known as the Continuous Detonation Wave Engine). The RDE can operate for any flight velocity, generating a stable thrust value, because the engine has a very high frequency of repetition (thousands of cycles per second depending only on the mixture and geometry of the engine). Compared to pulse detonation engines (PDEs), an RDE can operate continuously once initiated, and the operating frequency is much higher than PDE. Therefore, RDEs have received much attention in the propulsion research field [4].

LITERATURE REVIEW

The basic concept of continuous detonation waves was proposed by Voitsekhovskii in 1960 [5]. He experimentally achieved a short-lived continuous detonation wave in a disk-shaped chamber, using premixed acetylene and oxygen.

Progress of continuously rotating detonation Engines by Zhou Rui, Wu Dan, Wang Jianping, summarizes the basic concepts of Rotating detonation engines and experimental studies conducted over the years [3].

In Detonation Control for Propulsion by Jiun-Ming Li et al, [6] the application of RDE in Rocket engines is explained, along the experiments, types numerical simulations performed, to study the sensitivity, resolution etc. of RDE.

In another paper done on detonation engines by R. Vutthivithayarak, Braun and Lu [7], the thermodynamic cycles used to represent the detonation engines, i.e., Humphrey, Fickett–Jacobs, and ZND were studied and compared with Brayton cycle. This was used to show the higher thermodynamic efficiency of RDE, when compared to conventional rocket engines.

Numerical simulations on different combustion chamber design and dimensions were analysed by Anand, V. & Gutmark, in the work-Rotating detonation combustors and their similarities to rocket instabilities [8], and the results were used to compare and understand the design parameters affecting the efficiency of engine. The results conclude that the annular design is best suited.

In another work by, Thornton, B.E.A. [9], the working of detonation engines is explained, and this was used to understand the propagation of the wave and the different zones in a detonation wave propagation.

Numerical simulations on the thrust performance and Isp for different modes of propagation (single wave, multi wave, longitudinal pulse detonation) were conducted by N. Tsuboi et al. [10] and Numerical estimation of the thrust performance on a rotating detonation engine for a hydrogen-oxygen mixture by Tsuboi, N., Watanabe, Y., Kojima, T. & Hayashi [11], these results were used to compare the thrust and specific impulse of RDE with conventional engines.

The effect of adding nozzle, different types of nozzles were studies from the works done by Fotia, M, Schauer F, Force U et al. [12] and the works done by Eto, S., Watanabe, Y., Tsuboi et al. [13]. After years of development, it has become more difficult to make many improvements in conventional rocket engines in terms of efficiency and specific impulse. Hence more focus has been given to development of detonation engines, over conventional engines which use deflagrative combustion. This paper is a comparison of conventional rocket engines and detonation engines, by comparing the thermodynamic cycles, efficiency and thrust values. Furthermore, comparison is done on the detonation chamber design and effect of nozzles.

BASIC CONCEPTS

Detonation is characterized by the existence of a shock wave in the front of which the reactions start.

When the state of premixed combustible mixtures is changed, two Rayleigh lines of different slopes and one Hugoniot curve will be obtained (Figure 1) [3].

The upper branch of the curve and upper Chapman Jouget point is obtained for detonation and lower branch of Hugoniot curve and lower Chapman Jouget point for deflagration.

As evident from the Figure 1, in deflagration process, there is only slight decrease in pressure, and it is therefore considered an isobaric process. Whereas detonation combustion is treated as an isochoric process as there is only slight variation in volume, but there is abrupt increase in pressure and temperature, as the combustion wave is tightly coupled with a shock wave.

Another way to increase pressure in combustion chamber is the increase of mixture's combustion speed.

Because of its thermodynamic efficiency, the detonation is the most attractive mode of fast combustion [14]. In detonation wave which propagates at 1500–2500 m/s, the maximum concentration of chemical energy that was stored in fuel is reached

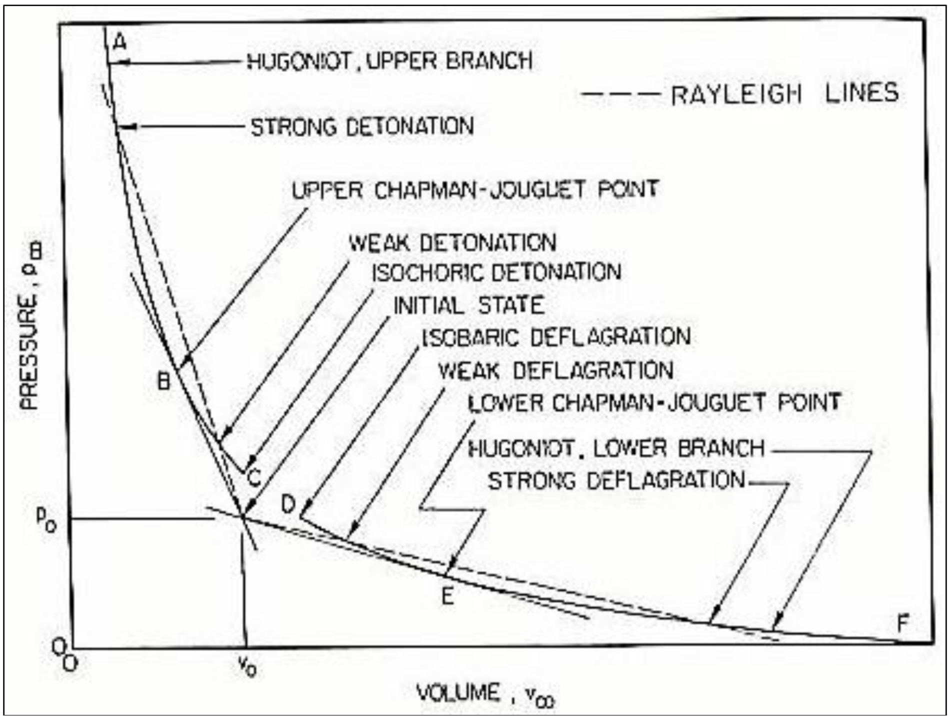


Fig. 1. Rayleigh lines and Hugoniot curve in P-V diagram.

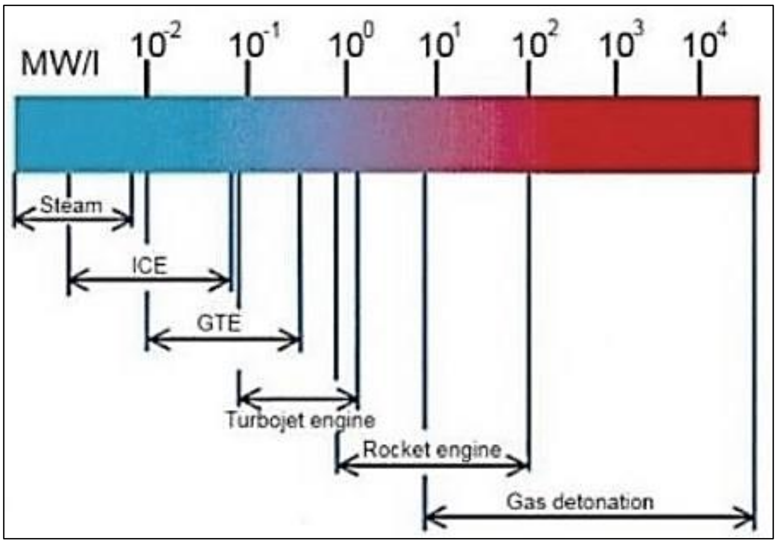


Fig. 2. *Comparison of power per liter of modern thermal engines*

(energy emits in thin layer of strike-compressed mixture). Because in detonation engine the combustion occurs in shock wave approximately 100 times faster than at slow combustion (deflagration), this type of engine differs by its record power per unit of volume, compared to other type of heat engines as shown in the Figure 2.

THERMODYNAMICS

Thermodynamic cycle used to represent the deflagration combustion in conventional rocket engines is the Brayton cycle or Joule cycle.

The ideal cycle P-V diagram and T-S is as shown in the Figure 3.

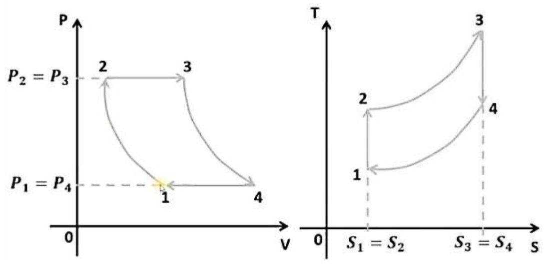


Fig. 3. *P-V and T-S diagrams of Brayton cycle.*

The cycle has an isobaric heat addition as represented by the curve 2–3, at a high pressure, after the air is compressed to a high pressure using a turbo pump, which is represented by 1–2. It is then followed by an expansion process through the nozzle which is isentropic in ideal cases, 3–4, and the cycle is closed by an isobaric, 1–4.

Based on the studies and comparisons done in (On thermodynamic cycles for detonation engines R. Vutthivithayarak, Braun and Lu) [7]. The cycle best suited to study detonation combustion is the ZND (Zel'Dovich Von Neumann Döring) cycle which is 1D model for detonation.

In the ZND Theory, the gas is shock compressed to the Von Neumann spike, followed by exothermic chemical reactions, which finishes at CJ state. While the shock process is a non-equilibrium one, the assumption of local thermodynamic equilibrium makes the cycle analysis tractable. Similarly, the heat release due to exothermic reactions between the ZND and CJ (Chapman Jouget) points was found to follow supersonic Rayleigh heating and thus could be modelled as an equilibrium process.

ZND theory captures the physics of a one-dimensional detonation wave, whereas the constant volume, or Humphrey cycle does not adequately capture the physics of the detonation phenomenon to provide a realistic estimate of the work. A more sophisticated model to account for the pressure rise in a detonation wave, known as the Fickett–Jacobs model, also fails to account for the physics of a detonation process where shock compression does not increase the pressure directly to the CJ point.

Figure 4 shows the three ideal processes under discussion in both the p–v and T–s diagrams. The states portrayed in the plots are the total (or stagnation) states. The initial state of the reactants is (1). The Hugoniot running through (1) is shown in Figure 4(a) as a dashed line. The post-detonation Hugoniot is also shown in the Figure 4(b) by another dashed line. This Hugoniot was obtained using data obtained from the NASA CEA code [15]. The performance comparisons of the 3 cycles are as shown are shown in the Table 1.

Table 1. *Performance comparisons of the 3 cycles [6].*

	Work (Mj/kg)	**Heat (Mj/kg)**	**Efficiency (%)**
Humphrey	0.709	1.07	66.5
Fickett–Jacobs	0.834	1.3	64.3
ZND	2.08	2.95	70

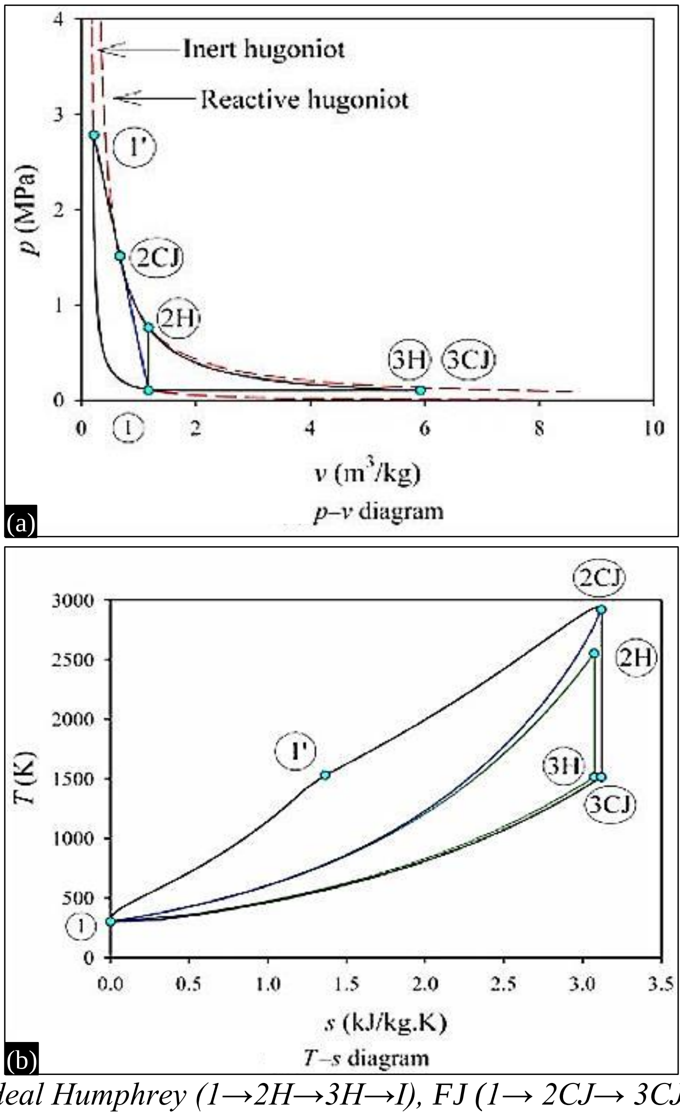


Fig. 4. *Ideal Humphrey (1→2H→3H→I), FJ (1→ 2CJ→ 3CJ→1) and ZND (1→ 1'→ 2CJ→3CJ→1) cycles for stoichiometric hydrogen/air mixture initially at STB [6].*

Unlike the Brayton cycle, ZND cycle has an isochoric heat addition with sudden increase in temperature and pressure and has minimum entropy change.

In Detonation Jet Engine. Part 1–Thermodynamic Cycle by Pavel V. et al. [14], the efficiency of the thermodynamic detonative combustion cycle over Humphrey combustion cycle at constant volume and Brayton combustion cycle at constant pressure were analysed.

The detailed analysis and comparison of various thermodynamic cycles is presented in a work by Wintenberger AND Shepherd, 2006 [16]. The following Figure 5 shows the T-S diagram comparing detonation cycles ZND, Humphrey and Brayton cycle for deflagration.

From the Figure 5, its seen that detonation cycles as mentioned earlier have less entropy change and higher rise in temperature, as compared to Brayton cycle. This increases the exhaust velocity and also the efficiency of the detonation engines relative to conventional engines. The following Figure 6 shows thermodynamic energy conversion coefficient at various compression rates in compressor.

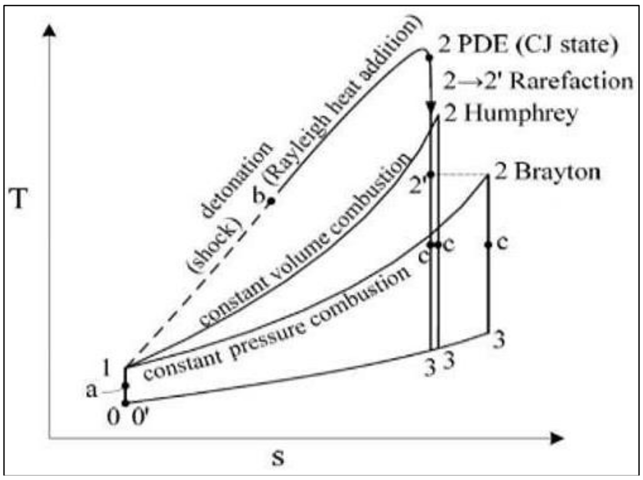


Fig. 5. *Comparison of Brayton, Humphrey and ZND cycles [16].*

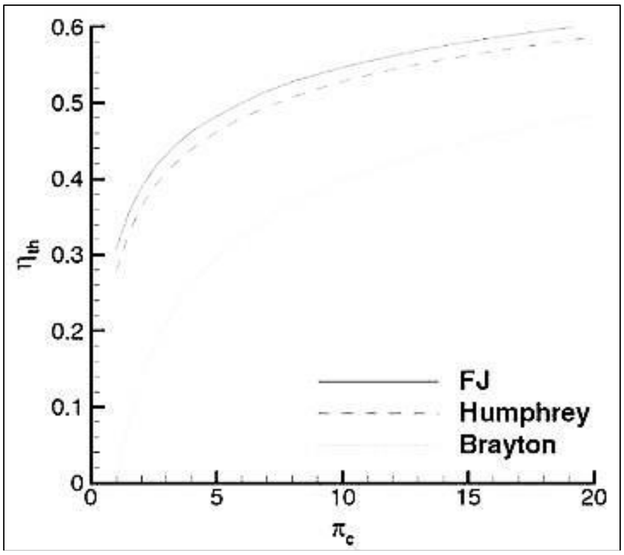


Fig. 6. *Thermodynamic energy conversion coefficient at various compression rates in compression [16].*

When switching from combustion at constant pressure cycle (Brayton cycle) to combustion at constant volume cycle (Humphrey cycle), the thermodynamic efficiency rises by about 20%. At compression rate of 5, the thermodynamic efficiency of Brayton cycle is 36.9% for hydrogen, and 31.4% for methane. When switching to Humphrey cycle, the thermodynamic efficiency is 54.3% for hydrogen and 50.5% for methane [7].

COMBUSTION CHAMBER DESIGN

The combustion chamber of CRDE (Continuous rotating detonation engine) is usually a coaxial cylinder, as shown in Figure 7. The head end is closed but drilled with a large number of micro-nozzles or slits to inject fuel and oxidant into the chamber. In experiments, the detonation wave in the chamber is usually initiated by a pre-detonator attached tangentially to the chamber.

The length of the combustion chamber can be shortened, because the combustion zone is shorter than that in the deflagration mode and does not need a mixing with secondary air flow. The shorter the chamber, the lower the mass of the engine.

In RDC (Rotating detonation combustors) and their similarities to rocket instabilities, by Anand et al [8] types of combustor design annular, hollow and disk chamber were studied:

Annular

In annular design some of the important parameters which are crucial to the wave formation and stability were studied by Zhou and Wang. The parameters studied were as follows.

Width

Maintaining a constant diameter of the inner wall, while increasing the channel width was found to produce a curvature on the detonation front and additional reflected shocks from the outer wall (Figure 7). For the largest channel width, the detonation front is very weak at the inner wall due to decompression caused by the convex surface, which results in the production of expansion waves.

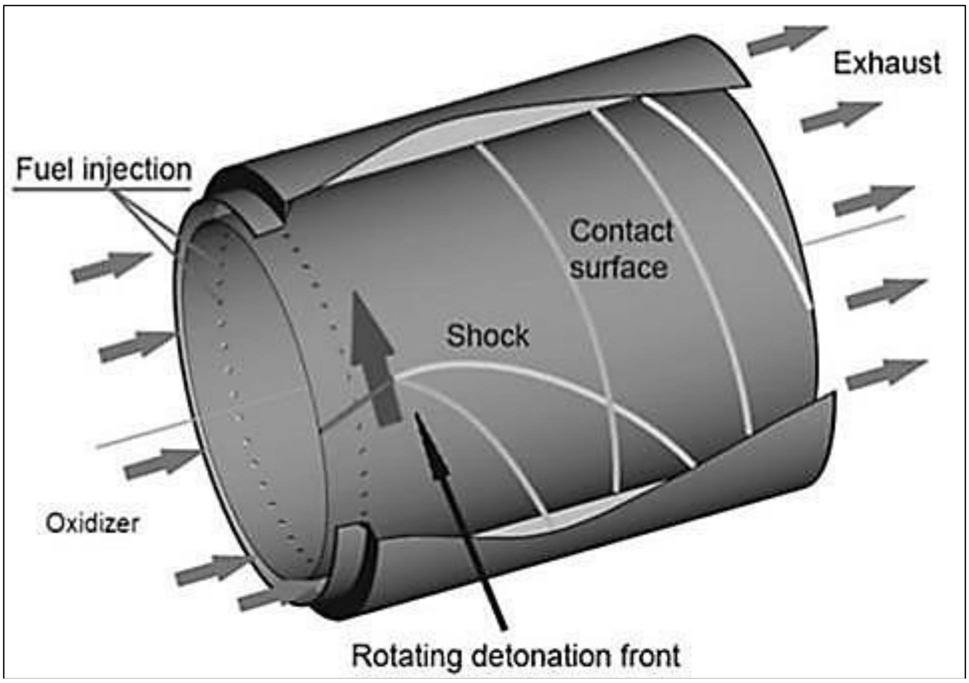


Fig. 7. *Combustion chamber schematic [17].*

The outer wall produces a stronger detonation region near it since it compresses the wave. Note that the outer portion of the wave also travels at a faster linear tangential velocity than the inner portion (it is a product of a constant angular velocity and radius). These effects result in considerably smaller cell sizes near the outer wall and enlarged cells by the inner wall. This was attributed to the reflection of shock waves, not only from the outer wall, but also from the inner wall, a process implied to be caused due to the product gases not fully exiting the chambers with larger diameter. Though shock waves are produced at increased width, the stability does not decrease, on contrary it increases because at less width comparable to the detonation cell width, boundary losses are more. Also increased plenum recovery as the time takes for the wave to propagate increases with the increase in diameter. This would entail enough time for the injector elements to recover and allow proper propellant flow. These effects are inferable from the data of Kindracki et al. [18].

Length

Longer RDC lengths tended to cause stronger shock trains through the annulus, with a corresponding increase in the strength of the Mach wave reflecting from the width provides higher stability by repeated peak pressures.

Diameter

When diameter increases the stability increases as there is increased inner wall. Interesting, here, the shock train got shorter, despite getting stronger, as opposed to the cases with increased diameter. These effects were explained to be the effect of product gas expansion—lack of complete exit from the annulus causes significant secondary and tertiary shock structures (Figure 8).

This was proposed to be a negative effect, as the strongest part of the detonation front is by the outer wall, which would mean that the annular RDC would produce a more efficient burning of the reactants since the filling height is highest near the wall. On the other hand, because of the removal of

Hollow

The same parameters that define the annular Combustion design and stability also apply for hollow chambers, however, here, there are the additional parameters owing to the removal of the inner wall. In a hollow RDC, curvature of the rotating detonation front, radially, is unavoidable as seen in Figure 9.

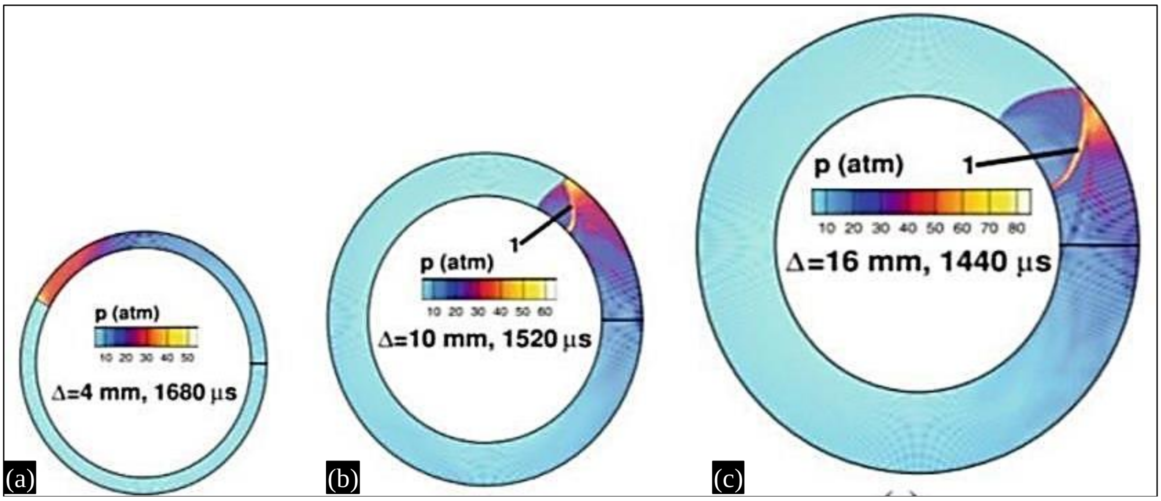


Fig. 8. *Radial pressure profiles of rotating detonation wave through three annulus widths at constant inner diameter (a) 4 mm, (b) 10 mm and (c) 16 mm, waves [8].*

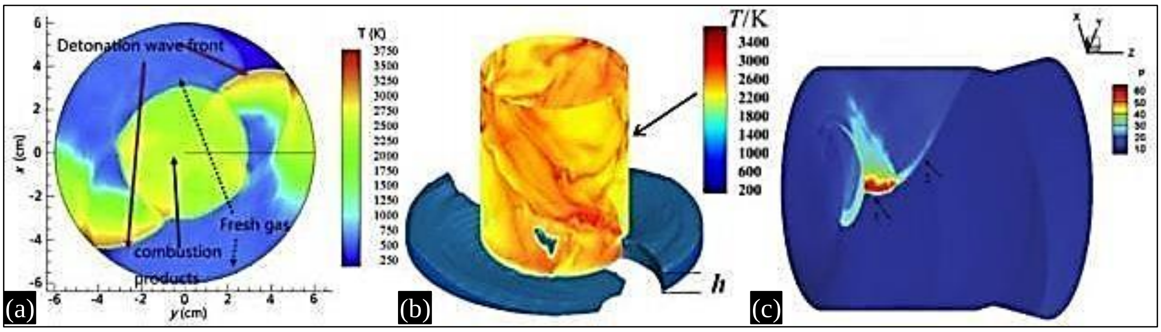


Fig. 9. *(a) "Looking into" view of a hollow RDC with two detonation waves traveling counter clockwise [8], (b) reactants fill region (blue) and central deflagrative burning formed in a hollow RDC when there are two waves [8], and (c) rotating detonation wave shape in a hollow RDC with de Laval nozzle at the exit [8].*

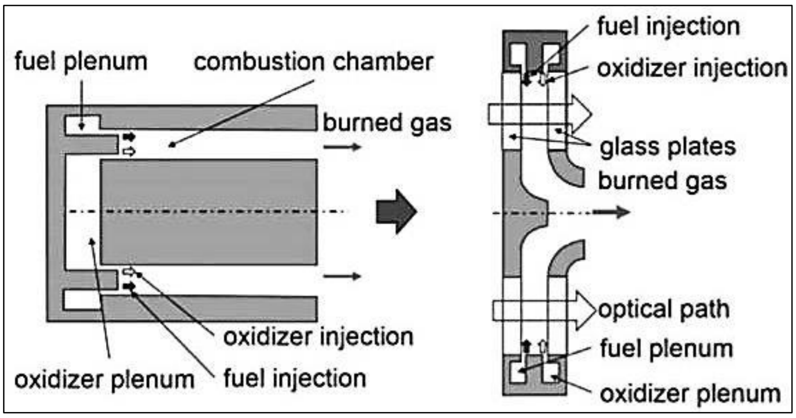


Fig. 10. *Difference in construction between annular (left) and disk (right) RDC [8].*

Due to the compressibility of the concave surface of the outer wall, the outer portion of the wave moves twice as fast as the inner tail part and the tail terminates towards the center, which causes deflagration combustion at the axial region radially.

Channel width-dependent dimensional constraint, it would be possible to attain detonations in mixtures, which were otherwise non-detonable.

Evidence for this is seen in ethylene-air powered annular RDEs of Wilhite et al. [19] and Andrus et al. [20].

It is yet to be quantified if this increased strength of detonations is worth the trade-off of having vast regions of deflagration burning. One method to overcome this is to provide an air stream through the center of the device.

Disc

Disc combustion chambers as shown in Figure 10 consist of an inner and outer wall and the air flow is radially inwards or outwards. One or more rotating detonation waves are formed between the straight walled confines of the disk-shaped combustor, and the burned products are expanded through the central axis. As pointed out by Huff et al. [21], a constant cross-sectional area for flow field as required in a disk-shaped chamber, to prevent choking of flow is obtained by increasing the channel width continually, while shortening the radius.

Experimental studies so far on disk RDCs have noted considerably higher velocity deficits—more so than in an annular RDC from the ideal C-J speed, most times never exceeding 80% of the isobaric sound speed in the medium of propagation [21]. This shape or design also has higher plenum disturbance and there for less efficient waves.

INITIATION AND WORKING

Initiation

Detonations can be initiated in one of two ways: (i) direct detonation [8] and (ii) deflagration-to-detonation transition (DDT) [22, 23]. Direct detonation method imparts a very high energy into the mixture normally using a spark so that the shock waves are formed initially accompanied by reaction front (detonation). DDT is the most accepted and viable method in which deflagration waves are accelerated to supersonic speeds causing detonation. The device that uses DDT is called a "pre-detonator" which is essentially a miniature PDE that is oriented in a way (either directly into the combustor or facing into it tangentially) that would deposit a blast wave into the RDE. After the instance of the blast wave injection (or the first instance of a high peak pressure event inside the previously cold-flow RDE), there is always a visible period of chaos. This duration is called the "onset time". Since this process requires a certain run-up length for the deflagration wave to accelerate, causing compression waves to form upstream of it, which then finally transforms into a detonation wave, different mixtures require different tube geometries to induce DDT. The following Figure 11 plots the pressure curve over distance in a DDT tube [8].

Flame acceleration ending in a detonation event is widely conceded to be caused due to the Zeldovich mechanism (or the shock wave amplification by coherent energy release—SWACER) [9]. From the pressure time-trace diagram, the formation of the initial compression wave from the accelerating flame is seen at about 0.05 m, which eventually leads to a DDT event at a time of about 0.16 m with a 70 atm pressure peak, finally stabilizing to a stable detonation wave. Figure 12 shows an experimental device of CRDE in Wang's lab in Perking University, China [3].

Working

As the name suggests, rotating detonation engines generates thrust by detonating the propellant mixture through a rotating detonating wave: a shock wave energized by a reaction front. In the combustion chamber the closed head end consists of a large number of micro-nozzles or slits to inject fuel and oxidant into the chamber. The detonation wave in the chamber is usually initiated by a pre-detonator attached tangentially to the chamber.

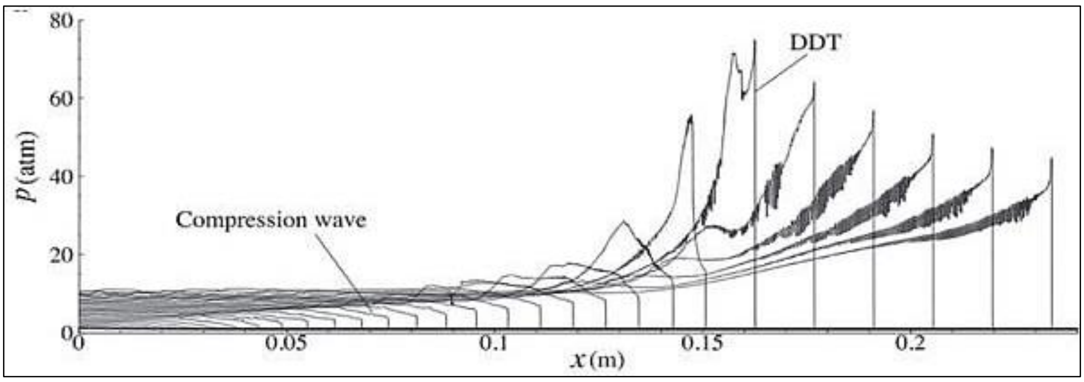


Fig. 11. *Pressure versus distance plot showing DDT [9].*

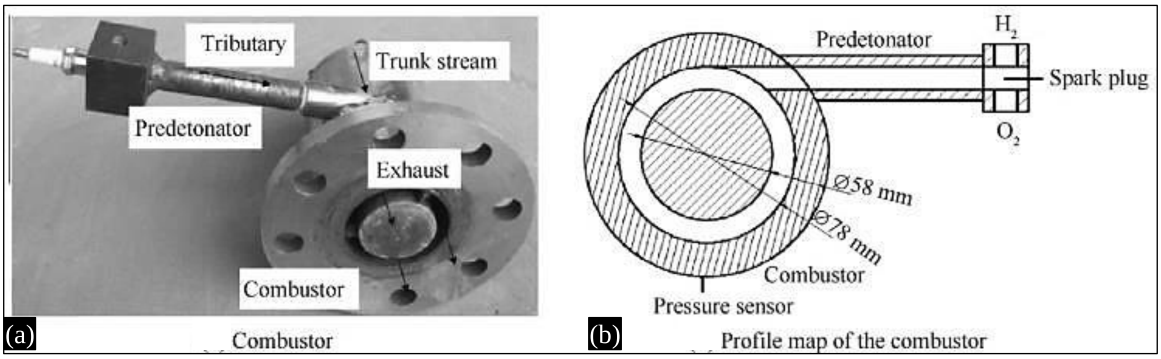


Fig. 12. *Tangential pre-detonator installed RDE [3].*

Table 2. *Specific impulse for different fuel mixtures [18].*

Fuel/oxidizer	Dcj	m·f(kg/s)	Force (N)	Isp (s)	Isp (s)
Hydrogen/air	1810	0.0271	1300	4860	5410
Ethylene/air	1710	0.0712	1390	1990	2260
Ethane/air	1610	0.0526	1310	2540	2860
Propane/air	1720	.0678	1390	2080	2360
Ethylene/oxy	2220	0.268	1840	700	820
Ethane/oxy	2110	0.198	1780	920	1050
Propane/oxy	2210	0.191	2000	1010	1200

While working, one or more detonation waves are generated on the head end and propagate in the circumferential direction. The no of waves referred as the modes of detonation, depends mainly on the equivalence ratio and the mass flow rate [24]. Behind the detonation wave, burnt products are of high temperature and high pressure. Through a series of expansion waves, these burnt products flow out of the downstream exit almost axially to provide thrust. In addition, there is an oblique shock wave and a contact surface in the flow field. The contact surface depicts the boundary of the exhaust gases of the previous front and the current front. During the propagating process of the detonation wave, combustible mixtures are continuously injected into the chamber. They form almost a triangle combustible mixture layer and are combusted by the detonation wave. Figure 13 shows a schematic structure of propagation of a single rotating wave mode inside the chamber.

THRUST AND SPECIFIC IMPULSE

Thrust is the propulsive force that pushes the rocket forward. Thrust produced per kg of the fuel, in air breathing engines or propellant (fuel +oxygen) in case of rocket engines is called specific impulse.

$$Isp = F/m^{*}go$$

Where, m* is the mass flow rate of propellant. Specific impulse is a measure of how efficient an engine using a fuel can produce thrust. Specific impulse Isp obtained from the combustion of rotating detonation engines are found to be comparable to other rocket engines and at times far greater than them. Following were the results of 2D simulations of RDE using various fuel oxygen/air mixtures conducted by Kailasanath and D. Schwer [25]. The 4th and 5th columns represent the experimental and theoretical specific impulses respectively (Table 2).

The values considered were for ambient conditions assumed to be in vacuum. Remarkably the specific impulse value of fuel/oxygen mixtures had reached a maximum value of 1070 for propane oxygen mixture. The values of Isp for fuel/air mixtures are high cause the equation only consider the mass of fuel. Another numerical simulation study on thrust performance listed the dependence of thrust and specific impulse on stagnation pressure, micro-nozzle area ratio (ratio of throat area to exit area of inlet nozzle), and mass flow rate [11]. The Figures 14, 15 and 16 show the results of their experiments. The time-averaged thrust per cycle is found to be proportional to the mass flow rate.

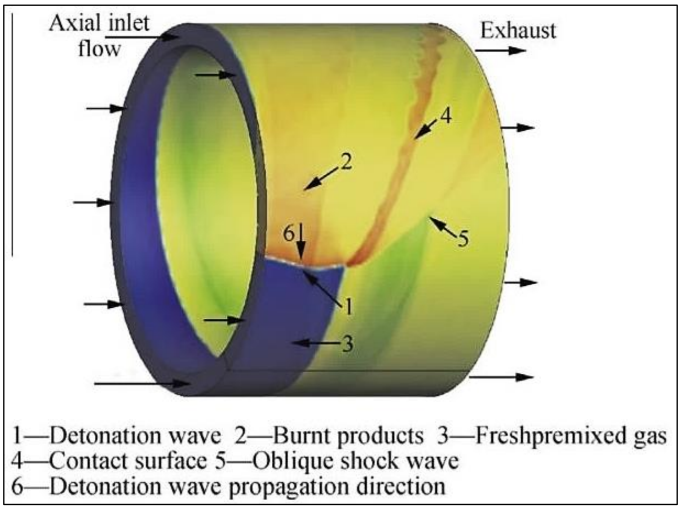


Fig. 13. *Schematic structure of propagation of RDE [3].*

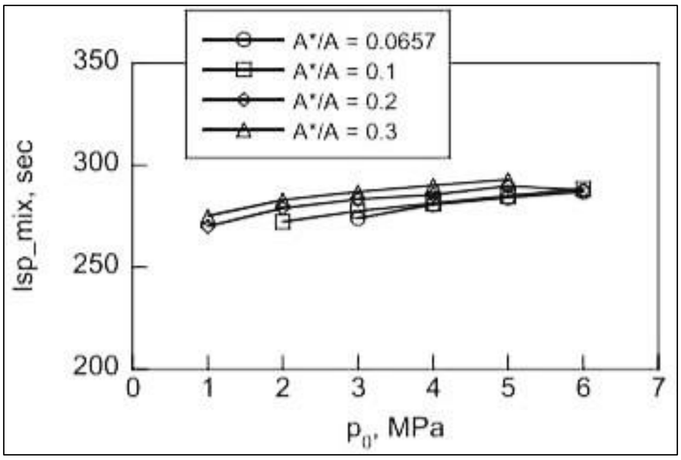


Fig. 14. *Effect of micro-nozzle area ratio and Po [11].*

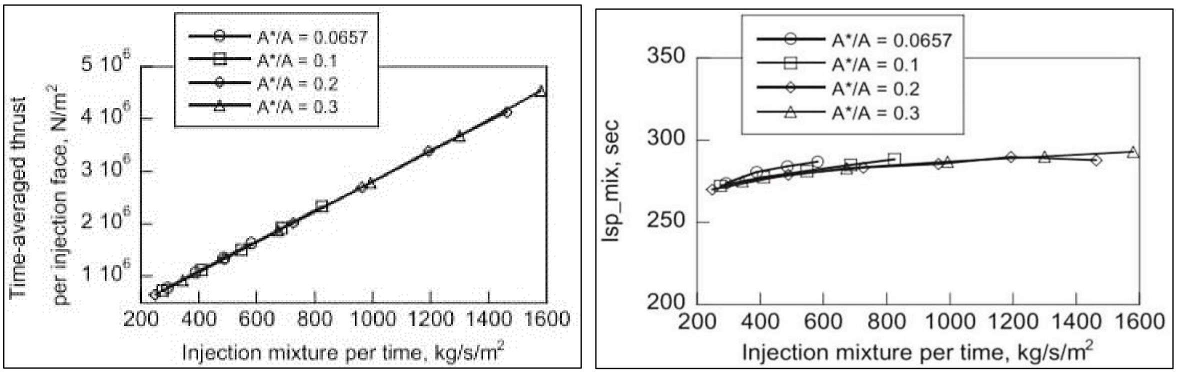


Fig. 15. *Effect of A*/A and Po on thrust and specific impulse [11].*

Since the mass flow rate m depends on the stagnation pressure Po and the micro-nozzle area ratio A*/A., Hence, it can be concluded that two important parameters, such as A*/A and Po, can be replaced by one parameter: the mass flow rate. This correlation is the same as that of the conventional rocket engine.

Numerical simulations on the thrust performance and Isp for different modes of propagation (single wave, multi wave, longitudinal pulse detonation) were conducted by N. Tsuboi et al. [10]. From their results, the specific impulse for the one-waved RDE was found to be approximately 10% larger than that for two-waved RDE, although the difference of the thrust between the one- and two-waved RDEs is small. They also plotted the time averaged thrust for either of the modes and found it almost independent of no of detonation waves.

Figure 16 shows that Isp for the 2D RDE is approximately 10 s larger than Isp for the 3D RDE except for high stagnation pressure. Isp for both the 2D and 3D RDEs is actually greater than Isp of a conventional rocket engine.

Effect of Nozzles

The numerical simulations on the effect of a conic aero spike nozzle on thrust performance were done by a team from Kyushu Institute. Their studies give the comparison of Isp values for the open and choked configurations of the aero spike nozzle (Figure 17). The mass flow rate was found to increases with increase in the micro-nozzle stagnation pressure. The observations indicate a 30 s improvement of the Isp for a mass flow rate from 500 to 1300 kg/s/m^2 for the open flow and by 22s for the choked flow. In terms of performance, for a given mass flow rate and a constant equivalence ratio, the choked aero spike improves from 4 to 7% of the specific impulse. They explained it as: using the choked nozzle increases the chamber time averaged static pressure by 50–60% as compared with the open nozzle leading to a higher pressure thrust through the nozzle, thus improving the Isp (Figure 18).

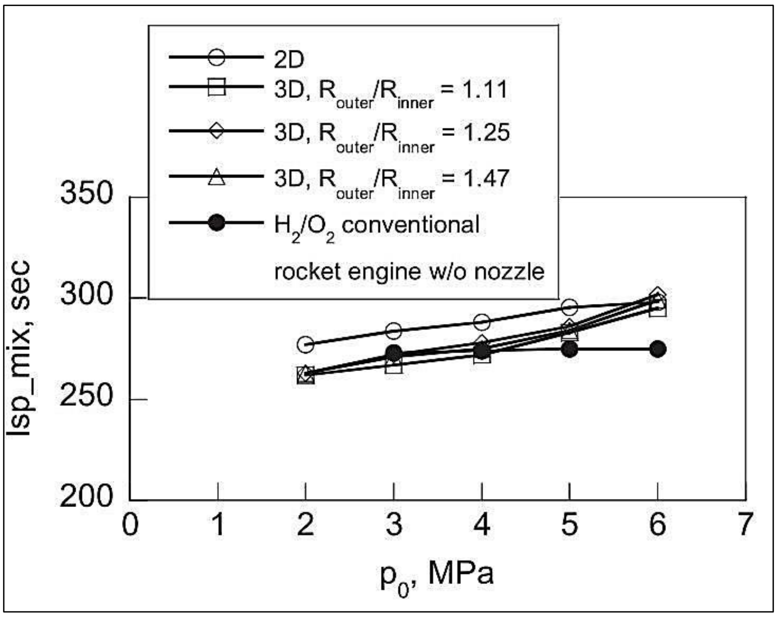


Fig. 16. *Comparison of Isp 2D, 3D RDE and conventional rocket engine. (without nozzle) [11].*

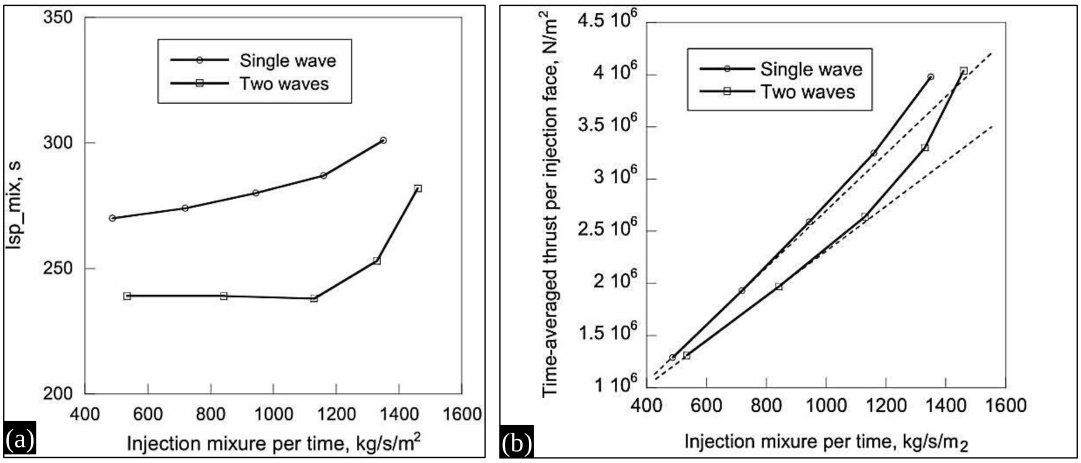


Fig. 17. *Effect of no. of detonation waves on Isp and thrust [26].*

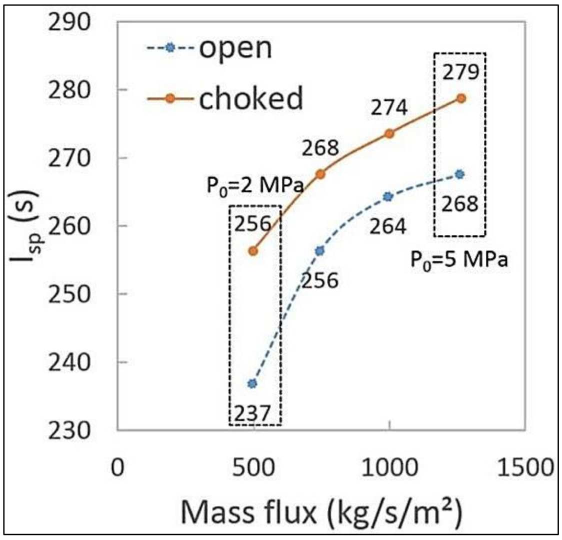


Fig. 18. *Specific impulse against mass flux, for H_2/O_2 mixture.*

Similar simulations were done on convergent divergent nozzle by another team of students of the same institute. Table 3 gives a comparison of averaged Isp during five cycles after the steady RDE is obtained [13]. Table 3 also includes the calculated Isp for a H_2/O_2 rocket engine with and without the nozzle, assuming a chemical equilibrium state under a vacuum environment. They obtained the CD nozzle improves Isp for approximately 90 sec. (33%) larger than that without the CD nozzle. Isp for RDE with the CD nozzle is actually greater than Isp of a conventional rocket engine (with similar configurations).

Table 3. *Comparison of Isp with and without nozzle [22].*

	without nozzle (sec)	**with nozzle (sec)**
3D RDE	275.7	363.2
Chemical equilibrium	274.3	328.6

The experimental studies by Frolov S.M. on RDE powered by natural gas and oxygen gave successful results as it produced a specific impulse of 270 s at a mean combustor pressure of 32 atm. This performance, in terms of specific impulse, is noted to be about the same as that of the RD 170-A engine, but at a mean chamber pressure of 61 atm, leading to the conclusion that an RDE is more energy efficient since it produces the same impulse at half the chamber pressure, which suggests a prospective decrease in turbo pump unit sizes.

Experimental thrust stand testing of a rotating detonation engine had been conducted at the Detonation Engine Research Facility of the U.S. Air Force Research Laboratory [12] where the combustor exit has been coupled to various bluff body and aerospike nozzle configurations. A schematic of the test stand is given in Figure 19. They considered four different nozzle configurations which included two variations on a bluff body exhaust and two on aerospike nozzles as shown in the Figure 19. The values of thrust and specific impulse are not comparable to H_2/O_2 mixtures, as the equation considers only mass of air (for specific thrust) or mass of fuel (for specific impulse).

$$F_{sp}=F/m^*_{air} \quad I_{sp}= F/m^*_{fuel}g_o$$

Using H_2/air as propellant, the nozzle configurations were compared at a mass flow rate of 1.14 kg/s over a range of equivalence ratios. Incremental improvement of performance in specific thrust was observed with change in each configuration from even bluff body to choked aerospike (Figure 20).

The performance increase obtained through reducing the exit area of the detonation channel by 20% is shown in the following Figure 20 in which the measured performances of both the open aerospike and choked aerospike nozzles are given for two mass flow rates and a range of equivalence ratios. They observed that specific impulse decreases with increasing equivalence ratios. It was also noted that the performance observed for the aerospike nozzle at the higher mass flow rate of 1.14 kg/s is similar to that of the choked aerospike configuration at the lower 0.76 kg/s condition.

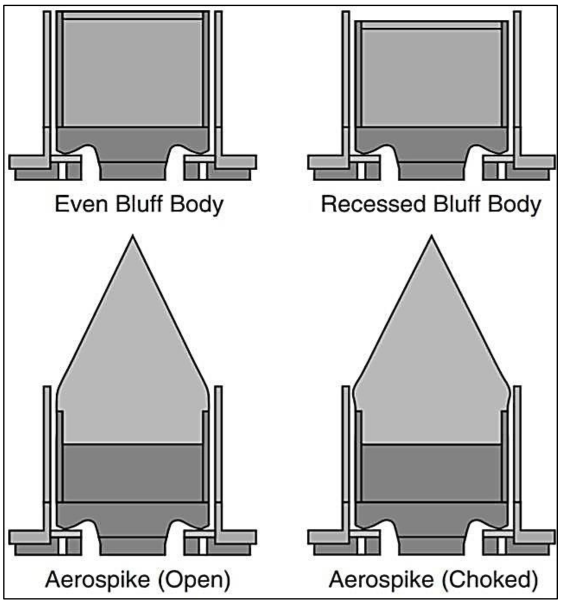
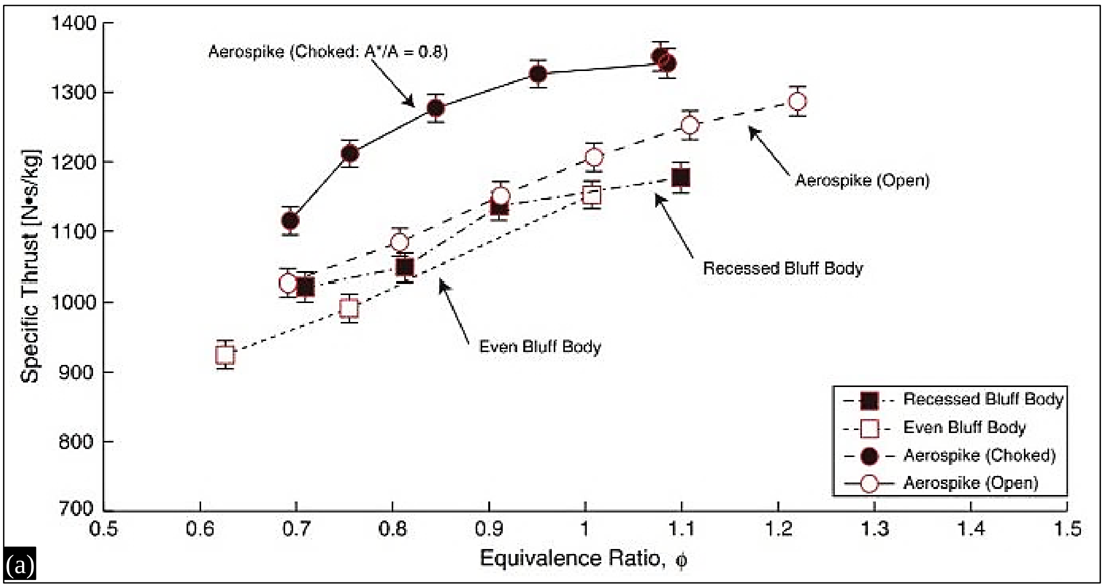


Fig. 19. *Schematic of various experimental nozzle configurations used at US Air force research laboratory [12].*

As expected, the values of specific thrust increases at the expense of fuel efficiency. The increase in equivalence ratio with increasing mass flow rate increases the thrust delivered but with an increase in fuel consumption. Though the above experiment was conducted using H_2/air mixture, the configuration and the trends displayed in the results can be well correlated to that of H_2/O_2 mixtures.



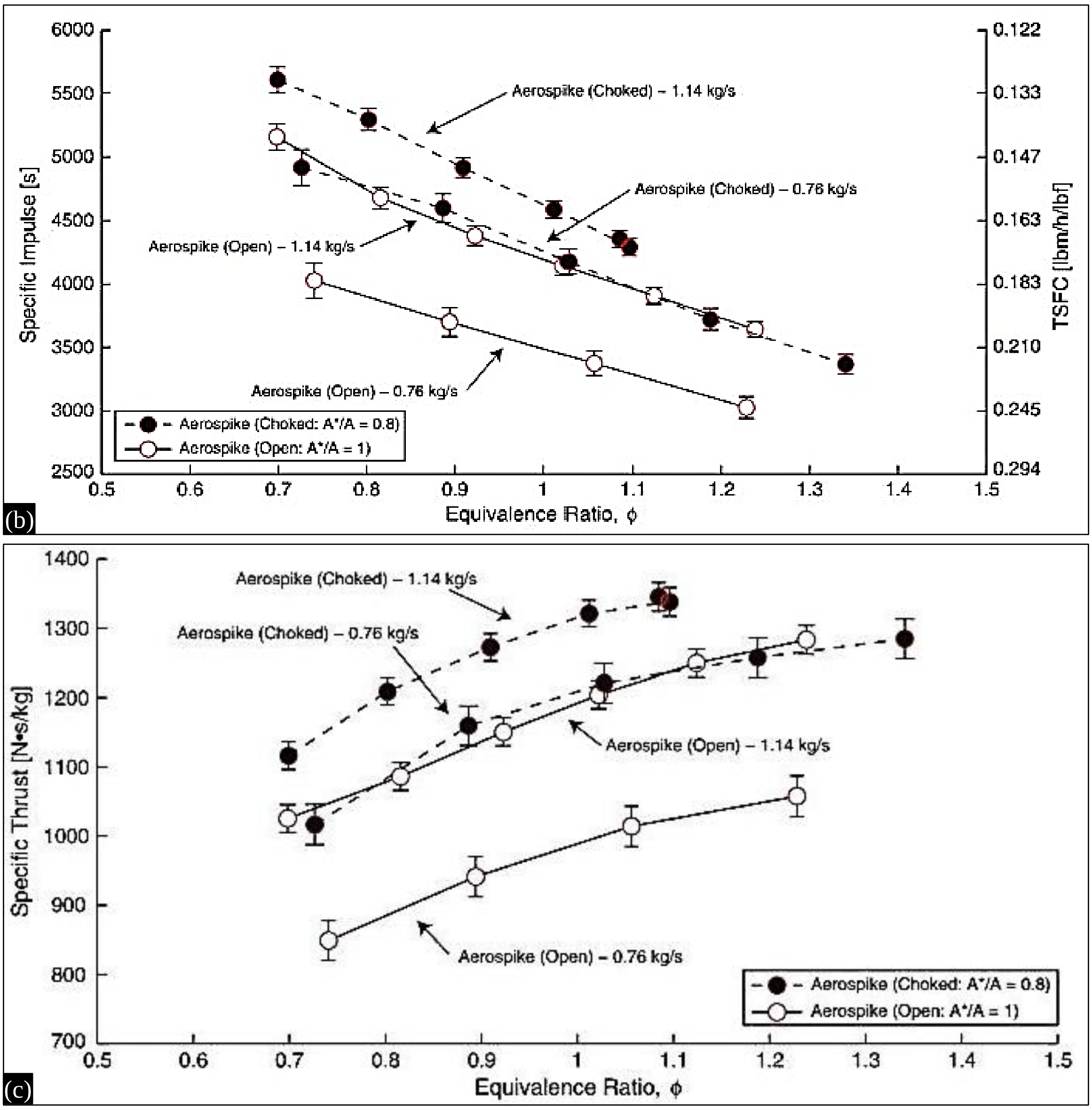


Fig. 20. *(a) Comparison between various nozzle types for specific thrust (Fsp) as function of Equivalence ratio-ø. (b) and (c) Comparison of performance between open and converging aerospike nozzle for (b) Isp and (c) Fsp as a function of ø [12].*

INSTABILITIES

The instabilities observed in rotating detonation engines are similar to that observed in conventional rocket engines. Though the normal operating mode of RDC is to have the rotating detonation inside the chamber, it has been observed by a few studies that at certain geometries and mass flow rates, longitudinal instabilities exist in the chamber producing axial pulsed detonation inside the combustion chamber, (like in the Pulse Detonation Combustor (PDC)), called Longitudinal pulse detonations [8]. LPD is caused most probably due to the same physical process—a high chamber pressure at the exit causing reflected waves moving upstream that eventually detonates a fresh slug of unburnt reactants to cause a detonation that decays into an axially moving shock wave, thereby continuing the cycle. The presence of LPD instability is linked to the backpressure experienced by the RDE, since this phenomenon does not exist when there is no throat at the RDC exit. The presence of this mechanism, however, is found to be dependent on the air injection pressure ratio. LPD occurs when the pressure ratio across the air injection is between 1.4 and 1.854.

Apart from LPD, low frequency transverse instabilities are also observed in the chamber. Another challenge is that the pressure of the incoming flow of mixtures should have same peak potential to do work as that created within the detonation wave [8].

CONCLUSION

The studies, analysis and experiments conducted show that compared to the conventional rocket engines, detonation engines have proven to have higher thermal and propellant efficiency. Rotating detonation engines are found to be more efficient and feasible compared to other detonation engines, owing to better design and higher frequency of combustion. Combustion chamber designs studied show that even though fresh mixture is dispersed more evenly in hollow RDE, it is less efficient due to deflagration burning at the center. Despite disc RDEs have much more velocity deficits. Therefore, apart from the width constraint, annular combustion chamber designs seem best suited. High specific power aside, the detonation engines potentially have other major advantages. Firstly, it needs only one-time initiation. Once started, detonation waves will continuously rotate. Secondly, due to the self-sustaining and self-compression of detonation waves, combustible mixtures can be compressed inherently. Thus, RDE can produce a large effective thrust at low pressure ratio. Since it's a pressure gain combustion, the injection mixtures need not be compressed to higher pressures initially, eliminating the need of turbopump assembly. The same thrust can be obtained from lower pressure ratios compared to deflagration. RDE can also work stably within a wide range of inflow velocity. The rate of heat release, specific impulse and thrust values are higher for certain fuels, still analysis on more feasible fuels and engine modes are yet to be performed. Despite higher temperature of combustion and higher pressure in detonation wave front, faster flow has lesser impact on the engine compared to classical designs. Still instabilities seen in normal rocket engines are present in RDE too, both longitudinal and transverse. Also, the pressure profiles along the radial direction varies drastically which possess safety risks. The solutions for the varying stagnation pressures and combustion instabilities are yet to be developed. The compact configuration of RDE, ability to operate using a variety of propellant mixtures, and work with a lean and rich mixture, outweigh the cons for further studies to carry on.

REFERENCES

[1] Gordon PV, Kagan L, Sivashinsky G. Parametric transition from deflagration to detonation revisited. Planar geometry. Combustion and Flame. 2020 Jan 1;211:465–76.
[2] Peace JT, Lu FK. Performance modeling of pulse detonation engines using the method of characteristics. Aerospace Science and Technology. 2019 May 1;88:51–64.
[3] Zhou R, Wu D, Wang J. Progress of continuously rotating detonation engines. Chinese Journal of aeronautics. 2016 Feb 1;29(1):15–29.
[4] Zheng H, Meng Q, Zhao N, Li Z, Deng F. Numerical investigation on H_2/Air non-premixed rotating detonation engine under different equivalence ratios. International Journal of Hydrogen Energy. 2020 Jan 13;45(3):2289–307.

[5] Voitsekhovskii BV, Mitrofanov VV, Topchiyan ME. Structure of the detonation front in gases (survey). Combustion, Explosion and Shock Waves. 1969 Jul 1;5(3):267–73.
[6] J-M Li, CJ Teo, BC Khoo, J-P Wang, C Wang. Detonation Control for Propulsion. 2018.
[7] Vutthivithayarak R, Braun EM, Lu FK. On thermodynamic cycles for detonation engines. In28th International Symposium on Shock Waves 2012; pp. 287–292. Springer, Berlin, Heidelberg.
[8] Anand V, Gutmark E. Rotating detonation combustors and their similarities to rocket instabilities. Progress in Energy and Combustion Science. 2019 Jul 1;73:182–234.
[9] Merzhanov AG, Sirignano WA, De Luca L, editors. Advances in Combustion Science: In Honor of Ya. B. Zel'dovich. American Institute of Aeronautics and Astronautics. 1997 Jan 1.
[10] Tsuboi N, Eto S, Hayashi AK, Kojima T. Front cellular structure and thrust performance on hydrogen–oxygen rotating detonation engine. Journal of Propulsion and Power. 2017 Jan;33(1):100–11.
[11] N. Tsuboi, Y. Watanabe, T. Kojima, and A.K. Hayashi. Numerical estimation of the thrust performance on a rotating detonation engine for a hydrogen-oxygen mixture. Proc. Combust. Inst.2015; 35(2): 2005–2013. Fotia M, Kaemming TA, Hoke J, Schauer F. Study of the experimental performance of a rotating detonation engine with nozzled exhaust flow. In53rd AIAA Aerospace Sciences Meeting 2015 (p. 0631).
[12] Eto S, Watanabe Y, Tsuboi N, Kojima T, Hayashi AK. 3D Numerical Simulation on Rotating Detonation Engine: Effects of Converging-Diverging-Nozzle on Thrust Performance. 25th ICDERS Leeds, UK. 2015.
[13] Bulat PV, Volkov KN. Detonation Jet Engine. Part 1—Thermodynamic Cycle. International Journal of Environmental and Science Education. 2016;11(12):5009–19.
[14] Wintenberger E, Shepherd JE. Thermodynamic cycle analysis for propagating detonations. Journal of propulsion and power. 2006 May;22(3):694–8.
[15] Wolański P. Detonation engines. Journal of Kones. 2011;18:515–21.
[16] Kindracki J, Kobiera A, Wolański P, Gut Z, Folusiak M, Swiderski K. Experimental and numerical study of the rotating detonation engine in hydrogen-air mixtures. Progress in propulsion physics. 2011;2:555–82.
[17] Wilhite J, Driscoll RB, St. George AC, Anand V, Gutmark EJ. Investigation of a rotating detonation engine using ethylene-air mixtures. In54th AIAA Aerospace Sciences Meeting 2016 (p. 1650).
[18] Andrus IQ, King PI, Polanka MD, Schauer FR, Hoke JL. Design of a premixed Fuel–Oxidizer system to arrest flashback in a rotating detonation engine. Journal of Propulsion and Power. 2017 Sep;33(5):1063–73.
[19] Huff R, Polanka MD, McClearn MJ, Schauer FR, Fotia M, Hoke JL. A disk rotating detonation engine part 1: design and buildup. In2018 AIAA Aerospace Sciences Meeting 2018 (p. 0633).
[20] Rankin BA, Codoni JR, Cho KY, Hoke JL, Schauer FR. Investigation of the structure of detonation waves in a non-premixed hydrogen–air rotating detonation engine using mid-infrared imaging. Proceedings of the Combustion Institute. 2019 Jan 1;37(3):3479–86.
[21] Sosa J, Ahmed KA, Fievisohn R, Hoke J, Ombrello T, Schauer F. Supersonic driven detonation

dynamics for rotating detonation engines. International Journal of Hydrogen Energy. 2019 Mar 15;44(14):7596–606.
[22] L Deng, H Ma, C Xu, X Liu, C Zhou. The feasibility of mode control in rotating detonation engine. Appl. Therm. Eng. 2018; 129:1538–1550.
[23] Schwer D, Kailasanath K. Fluid dynamics of rotating detonation engines with hydrogen and hydrocarbon fuels. Proceedings of the Combustion Institute. 2013 Jan 1;34(2):1991–8.
[24] Jourdaine N, Tsuboi N, Ozawa K, Kojima T, Hayashi AK. Three-dimensional numerical thrust performance analysis of hydrogen fuel mixture rotating detonation engine with aerospike nozzle. Proceedings of the Combustion Institute. 2019 Jan 1;37(3):3443–51.
[25] Frolov SM, Aksenov VS, Ivanov VS, Medvedev SN, Shamshin IO, Yakovlev NN, Kostenko II. Rocket engine with continuous detonation combustion of the natural gas–oxygen propellant system. In Doklady Physical Chemistry. 2018;478(2):31–34.

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