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# Rotating Detonation Wave Propulsion: Experimental Challenges, Modeling, and Engine Concepts (Invited)

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**Rotating detonation engines (RDEs), also known as continuous detonation engines, have gained much worldwide interest lately. Such engines have huge potential benefits arising from their simplicity of design and manufacture, lack of moving parts, high thermodynamic efficiency and high rate of energy conversion that may be even more superior than pulse detonation engines, themselves the subject of great interest. However, due to the novelty of the concept, substantial work remains to demonstrate feasibility and bring the RDE to reality. An assessment of the challenges, ranging from understanding basic physics through utilizing rotating detonations in aerospace platforms, is provided.**

## I. Introduction

THE primary form of chemical energy conversion for jet and liquid rocket propulsion comes from the deflagration of fuel with air and oxygen, respectively. Despite this longstanding approach in relying on deflagration, there has been interest from the late 17th and early 18th centuries in exploiting the rapid energy release from detonations for propulsion or as a power source.[1a] This interest actually predates the early scientific interest in detonations associated with coal mine explosions.[7] However, most of the early interest in detonation-based propulsion did not result in practice and many concepts were fanciful, such as the space gun for delivering a bunch of adventurers to the Moon in Jules Verne's 1865 novel *De la terre à la lune* (From the Earth to the Moon).[b] It was not until the 1940s/50s that serious thought was placed into the development of compact and lightweight, detonation-based propulsion devices.[10,11]

Much of the early efforts were focused on fundamental, experimental observations of detonation phenomena, with particular attention paid to detonation initiation and deflagration-to-detonation transition (DDT). As far as the authors are aware, there were few practical engine demonstrators during this period, if at all. The possibility of practical propulsion and power generation systems was even met with skepticism.[12,13] An interesting example of a detonation-based propulsion design from this era was a patent awarded posthumously to Goddard, the father of American rocketry.[14]

Heightened interest in a particular form of detonation engines, namely, the pulse detonation engine (PDE), began around 1990.[15] This interest culminated in a flight demonstration on January 31, 2008, of a heavily-modified Long EZ aircraft and continues to this day.

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[a] Rankine published a paper in 1866 entitled "On the Theory of Explosive Gas-Engines" ([2], article XXVII, pp. 464–470) which predated even the theory associated with him and Hugoniot[3,4] and the subsequent development of the Chapman–Jouguet theory[5,6] to take into account the heat release from the chemical reaction.

[b] Concepts on using solid explosives persist.[8,9]

Different research threads led to the rotating detonation engine (RDE).[c] As the name implies, the RDE utilizes one or more detonation waves that circle around an annular chamber for energy conversion. In one instance, a type of combustion instability was found in rocket combustion chambers where waves rotated around the chamber's cylindrical walls.[17–19] Another phenomenon observed is a spinning detonation front.[20–26] This spinning detonation front was studied extensively by a group of Soviet/Russian investigators.[27,28] The feasibility of these waves for propulsive applications was apparently first studied by Voitsekhovskii and coworkers[29,30] at the Lavrent'ev Institute of Hydrodynamics (LIH), Novosibirsk, Russia. Additional early investigations were conducted by investigators at the University of Michigan.[31–33] Special mention should be made of the subsequent, prolific effort of Bykovskii and coworkers at LIH toward RDE development.[34] This single reference does not do justice to the comprehensive studies of different geometries involving centrifugal, centripetal or "spinning" waves,[d] gaseous and liquid fuels, air or oxygen as an oxidizer, ways of introducing fuel and oxidizer, and various other parameters that showed the versatility of RDEs and their potential for propulsion and power-production devices. This huge body of work has influenced the present development of RDEs and, in fact, Bykovskii and coworkers still continue to make significant contributions.

A possible RDE configuration is shown schematically in Fig. 1 while an unwrapped schematic of the rotating detonation wave is shown in Fig. 2. Reactants are fed either separately or premixed into an annular combustor from the bottom. A detonation wave and possibly multiple waves rotate in the annulus just at the exit of the injector arrays, consuming the reactants feeding continuously from the bottom. The high pressure is then reduced to the inlet pressure after passage of the detonation wave which allows the reactants to again feed into the annulus, thereby allowing chemical reactions to continue to sustain the detonation wave. The reactants penetrate a certain distance into the annulus which roughly marks the end of the detonation wave. Further away, the detonation wave degenerates into a blast wave. This structure has previously been called a combined detonation-shock wave[35,36] or detonation wavelet. The figure shows a postulated contact surface burning due to the hot environment exceeding the autoignition temperature. Figure 2 shows penetration of the hot, high pressure products just downstream of the detonation wave into the injector. A complex wave interaction is set up, dependent on the properties of the reactants and products, as well as on the geometry of the injector. Preliminary indications are that such a scheme can be operated safely.[37]

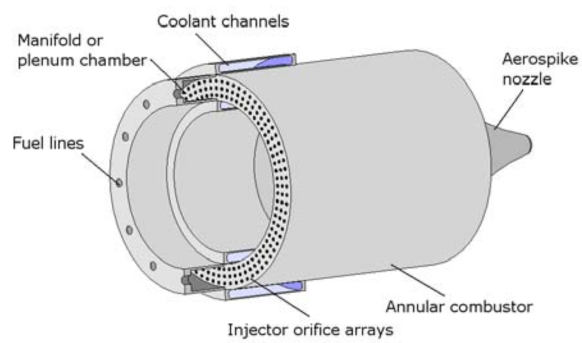



**Figure 1. Schematic of conceptual RDE.**

The high-enthalphy product is then accelerated through a nozzle. Due to the high speed of rotation of the wave around the annulus, the equivalent frequency is also very high, being in the 1–10 kHz range. Perhaps either due to the high frequency that produces an apparent detonation continuous process or due to the ability to continuously feed reactants into the combustor, such an engine is also called a continuous detonation engine (CDE).

The way that the detonation waves are initiated, sustained and stabilized are not well reported even with the recent upsurge of RDE studies. Many other significant features are also not well reported. For example, not much is known as to why the wave rotates around the annulus instead of just flaming out toward the exit and also as to why the wave prefers one direction and not another after ignition.

The extremely rapid combustion of an RDE, compared to that of a PDE or of a conventional propulsion

[c]A review of early work leading to RDEs can be found in [16].

[d]While the term "spin detonation" is used synonymously with "rotating detonation," it may be noted that this terminology should not be confused with spin instability that may occur at a detonation front even though observations of this phenomenon led to the RDE concept.

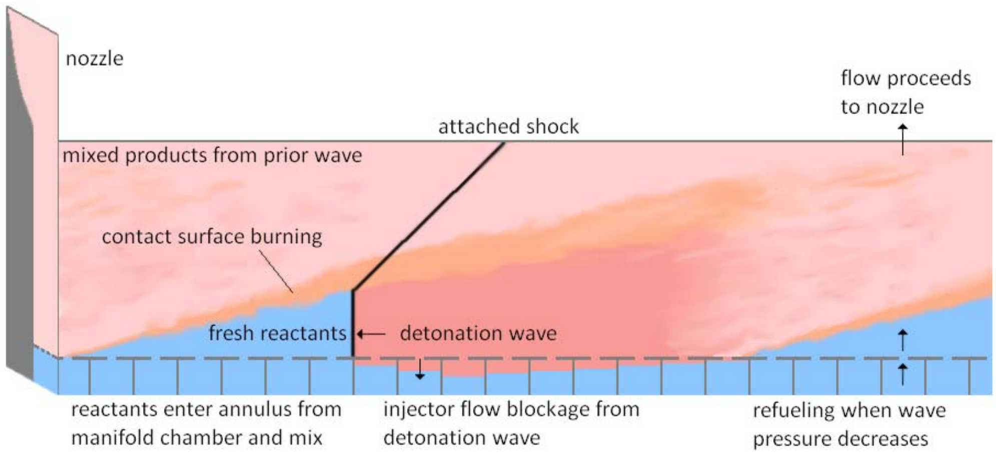



**Figure 2. Schematic of rotating detonation wave structure.**

system, yields many advantages. The most important advantage of the rapid energy release is high specific power output potential performance gains to yield as high thrust-to-weight ratio and high volumetric efficiency, all of which makes RDEs attractive as part of a future aerospace propulsion system. If one is to measure engine performance by the speed of the combustion front, then the performance of detonation engines far outstrips those based on deflagration. Moreover, the higher frequency of operation of RDEs compared to PDEs, likely less than 100–200 Hz for the latter, ensures the advantage of the former based on this performance benchmark. The high power output ensures a compact design which can lead to paradigm shifts in aerospace vehicle design. But this high power output also leads to some challenges as will be discussed further. The equivalent high frequency of RDEs of 1–10 kHz ensures smooth flow, with the possibility of simpler valving and avoiding the valving problems of PDEs due to their intermittent operation. The ability to operate without valving or with simple valving schemes apparently makes it easier to integrate the RDE into various aerospace platforms.

Due to the perceived similarities between PDEs and RDEs, it will be beneficial to consider these, as well as differences, briefly. Some of the similarities and differences between PDEs and RDEs are highlighted in Table 1. As their name suggests, both PDEs and RDEs rely on detonations for energy conversion. In the former, detonation waves propagate in the axial direction, usually downstream, although upstream propagating schemes have been proposed as well. In RDEs, the detonation waves travel circumferentially in an annular chamber. These different propagation modes provide the fundamental differences between the two schemes.

Since direct initiation requires an exorbitant amount of energy, PDEs are expected to utilize DDT enhancement devices to shorten the length of the detonation tube. For estimation purposes, the DDT length is $\mathcal{O}(0.1\text{–}1)$ m long for a variety of fuel and oxidizer mixtures, regardless of the type of DDT enhancement device. This length and a certain minimum diameter to ensure that detonation cells form yield a constraint on the minimum volume that needs to be filled with reactants and to have the products purged. Purging is considered a necessary process to rid the tube of high-temperature products to prevent the fresh reactant from premature deflagrative combustion. The fill and purge processes are time consuming and, together with other processes, limit the cyclic frequency of PDEs optimistically to 100–200 Hz. Also, due to the cyclic nature of the PDE, each pulse requires the reactants to be ignited, as in an internal combustion engine. This repetitive ignition at high frequency puts a heavy demand on the entire ignition system.

On the other hand, RDEs are fed continuously and configurations examined thus far indicate that they are self purging. (See §II.D for a further discussion of purging in the context of contact surface burning.) Therefore, the time requirements for feeding and purging are diminished or nonexistent. Further, the DDT

Table 1. **Qualitative similarities and differences between pulse and rotating detonation engines**

| Feature | Pulse detonation engines | Rotating detonation engines |
|---|---|---|
| DDT device | Likely needed | Likely unnecessary |
| Purge | Likely needed | Likely unnecessary |
| Frequency | < 100–200 Hz | 1–10 kHz |
| Ignition | One per pulse | Once at start |
| Flow unsteadiness | Yes | Reduced |
| Vibration | Yes | Reduced |
| Acoustics | Noisy | Noisy |
| Scalability | Yes* | Unknown |
| Fuel type | Gaseous and liquid | Gaseous and liquid |
| Oxidizer | Air and oxygen | Air and oxygen |
| Heating | High | High |
| Integration with turbomachinery | Yes | Yes |
| Different vehicle platforms | Yes | Yes |

*To within limits

length is satisfied by accelerating the flame around the annulus as a starting transient. Once the fully-developed detonation wave is established, such a wave will sustain itself so long as it is supplied with reactants. Thus, DDT enhancement devices may not be required as DDT can be achieved through cycling the wave around the circumference. Based on this principle, such an arrangement allows for a more compact design, axially and radially, than a PDE. Finally, since the detonation wave in an RDE is sustained once it is established, only an initial ignition is needed to start the wave, unlike the repeated ignition of PDEs. This difference conveys another advantage to RDEs in a simplifed ignition system design, reduced weight and bulk, and increased life of the igniter.

Next, the unsteadiness of PDEs is thought to affect the air induction and exhaust processes. There is concern of unstart in a Mach 5 inlet although careful design appears to be able to address this.[38] Experimental studies at Mach 2.1–2.5 appear to confirm that the flow oscillation did not unstart the inlet.[39,40] On the exhaust end, there is concern on the structural integrity of turbine blades due to the repeated impingement of high-pressure waves, as well as on the performance of nozzles in a fluctuating flow.[41,42] Associated with the unsteadiness are issues of vibration and acoustics. The high stress levels from the propagating detonation waves may cause fatigue[43,44] although this has not been well investigated. Moreover, a unique thudding noise probably best described as a very loud jackhammer noise is produced by the PDE. This has led to a proposal to use a miniature PDE as a helicopter emulator.[e] In contrast, the RDE produces a loud roar with no distinct thudding. While it appears that standard stress and acoustic amelioration techniques may be satisfactorily applied for RDEs, there are no reports thus far in the open literature of such efforts.

Amongst the similarities, both PDEs and RDEs can utilize a variety of fuels. They have been tested with air or oxygen. However, there is a longer track record in the use of hydrocarbons, including liquid ones, for PDEs, as well as with air. It is also apparently possible to integrate PDE and RDE cores with turbomachinery. Of note is that both PDEs and RDEs are not self aspirating. A simple approach to overcome this is to incorporate a low-pressure fan ahead of the core should self-aspiration be a requirement. While it is generally claimed that PDEs are scalable, there are limits to miniaturization, stemming from the DDT

[e] "DARPA steps up air vehicle activity," Flight International, 26 April 2005, online http://www.flightglobal.com/articles/2005/04/26/197138/darpa-steps-up-air-vehicle-activity.html accessed June 16, 2011.

requirement. It appears that RDEs can be scaled through a wider range of sizes. Despite this, since tests have used small engines of about 10 cm diameter, the scalability to larger sizes remains to be demonstrated. For example, Falempin et al.[45] considered an RDE with a diameter of 2.15 m.

PDEs have been proposed for a variety of airbreathing and rocket applications, ranging from low-speed to the hypersonic regime. Similar claims can be made for CDEs. In fact, since there is no need to temporarily contain the reactants in a detonation chamber, the CDE appears to be eminently suited for launch vehicles.[16,45–47]

The brief review above shows that the novelty of RDEs introduces some unique challenges, ranging from an understanding of the basic physics of the detonation and blast wave propagation in a narrow channel through integrating them into a propulsion system, despite an earlier phase of development 50 years ago. Due to the relative paucity of research in RDEs, the focus of this paper is primarily to consider what efforts are required to bring RDEs into reality, ranging from fundamental scientific investigations to systems studies. The paper is organized as follows:

- Section II discusses gaps in fundamental knowledge that need to be filled that will lead to increased confidence in utilizing rotating detonation waves for propulsion and power production,
- Section III discusses the development of the hardware components and test techniques,
- Section IV discusses the integration of the RDE core into practical propulsion systems.

# II. Fundamental Processes

The know-how gained from developing PDEs is definitely beneficial toward the development of RDEs since both engine concepts share similarities. This section reviews what may be considered to be fundamental physics issues that are crucial to RDE development. While these may not be unique to RDEs and they do not necessarily represent showstoppers, proper understanding of these issues will lead to strategies for mitigating adverse effects or for exploiting favorable ones.

It should be noted that there is complex coupling between gasdynamics, thermodynamics, structures, materials and so forth in RDEs, giving rise to a large number of governing parameters.[34] Despite the complexities, the primary concerns here are to establish one or more detonation waves that circle the annular detonation chamber; to ensure that the waves are stable, sustainable and controllable; and to prevent them from degenerating into deflagration waves. Presently, as available in the open literature, RDE demonstrators have been tested for short durations of less than a second to a few seconds. In some instances, the tests were limited due to severe heating and in others due to the detonation wave degenerating into a deflagration. Thus, adequate understanding of the fundamental physics peculiar to RDEs is needed to ensure that these engines can operate reliability over a broad range of conditions.

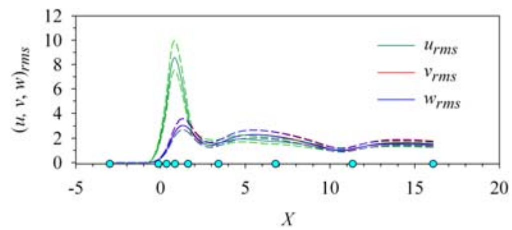
## A. Fuel/Oxidizer Mixing

Good mixing is a requirement of all combustion processes. In practice, the mixing must happen rapidly and in a short distance. These requirements are exarcerbated by the high flow rates of RDEs, the rapid combustion and possible erratic behavior of the detonation wave due to mixture nonuniformity. Configurations shown in the open literature generally have nozzles that separately inject oxidizer and fuel into the detonation chamber, this arrangement being apparently capable of mixing the reactants.[34] On the other hand, Braun et al.[48] proposed an arrangement where the fuel and oxidizer are fed separately into a mixing chamber through swirl vanes which help with the mixing. The mixture is then fed into the detonation chamber. Other than helping with the mixing, the vanes impart a swirl to the mixture which initiates the direction of the detonation wave. Even though the arrangement appears to be a two-step process, the continuous nature of the engine remains and the arrangement should be able to maintain a high flow rate with appropriate pressurization. However, potential problems may occur and these are discussed in Section III.

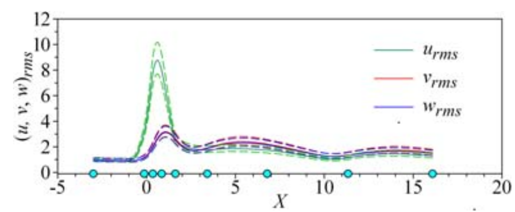
## B. Detonation–Turbulence Interaction

There is every likelihood that the reactants being introduced ahead of the detonation wave is turbulent. How the turbulence affects the stability of the detonation wave is not understood. Recently, studies have been initiated to gain fundamental insight into detonation–turbulence interaction.[49,50] These studies introduce a parameter $N = L_{1/2}/\lambda$, the ratio of the detonation half-length and a turbulence lengthscale, here being the Taylor microscale.

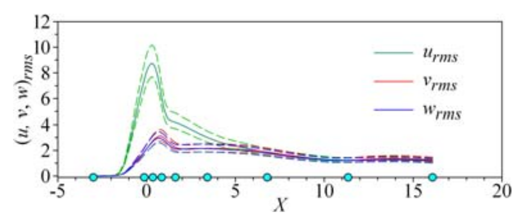
Figure 3 shows the distribution of the rms of the axial and crosswise velocity components upon passage of a detonation wave at Mach 5.5 based on mean upstream conditions. The upstream conditions for the three respective cases are quiescent, an isotropic turbulent velocity field and a turbulent temperature field. The figure shows that the axial rms velocity component spikes to about nine times a baseline value upon passage of the detonation wave. The crossplane velocity components maintain their isotropy. The flowfield, based on the rms of the velocity fluctuations, reverts to isotropy, with the entropic forcing requiring the longest distance. Moreover, the unsteadiness remains to the end of the computational domain. These are preliminary results and the question of whether the incoming turbulence can destabilize the detonation wave remains to be answered.




(a) Unforced.




(b) Vortical forcing.




(c) Entropic forcing.

**Figure 3. Time-averaged rms values of the Cartesian velocity components. The abscissa $X = x/L_{1/2}$ for the unforced case and $X = x/\lambda_0$ where $\lambda_0$ is the Taylor microscale of the upstream turbulent field for the forced cases. Dashed lines indicate the 95 percent confidence level.**

## C. Hot Spots

It is known that the detonation wave front is unstable. The lead shock and transverse wave system intersect at triple points from which shear layers emanate.[51] "Hot spots" have been observed in the vicinity of the triple points under conditions of high activation energy. These hot spots appear to be related to shear-layer instability. Of concern in RDE development is whether hot-spot formation is increased due to detonation–turbulence interaction. Also of concern is the related issue of whether these hot spots can destabilize the subsequent detonation wave.

A fundamental observation on shear-layer detonation coupling is that shear layers are convective amplifiers of fluctuations, meaning that they do not create their own (intrinsic) structures. So, how are the turbulent eddies that support hot spots generated? Massa et al.[49,50] identify two mechanisms that excite the shear layers. The first mechanism is the acoustic feedback from the detonation intrinsic instability, which yields a distinct peak in the post-shock velocity spectra. The second one is the advection of entropy (temperature spottiness) and vortical (solenoidal velocity field) waves from the free-stream, which are distorted by the lead shock, and support the continuous broadband part of the spectra.

## D. Contact Surface Burning

A PDE typically includes a purge process that scavenges the detonation tube of hot exhaust gases which also helps to cool the tube. Such a process is missing in an RDE. Thus, Fig. 2 postulates contact surface burning due to contact between the reactants and the hot exhaust products from the passage of the previous detonation wave. Such premature burning is evident as a luminous front in streak photographs shown in Refs. 34 and 52.

Despite the successful demonstration of RDEs, there remains concern that contact surface burning may destabilize the detonation wave or cause the detonation to degenerate to a deflagration. From a practical standpoint, contact surface burning presents a performance loss. A possible method to prevent contact surface burning is to introduce an inert buffer between the reactants and the hot products, similar to the purge in a PDE. However, this procedure adds complications.

### E. Shear-Layer Instability

This pertains to the shear layer downstream of the detonation/shock wave intersection and not the shear layers from the triple points mentioned in §II.C. For example, the detailed computations of Nordeen et al.[53] reveal a substantial shear layer with a high stagnation enthalpy and temperature that persists for a long distance downstream. In the cited study, the shear layer trajectory is inclined steeply away from the azimuthal direction so that it will not interfere with the formation of the next detonation wave. Nonetheless, one can imagine certain conditions in which the shear layer may be inclined closer to the azimuthal direction. This shear layer may possibly destabilize the next wave system, depending on their proximity. Moreover, Nordeen et al.[53] reported post-detonation temperatures of 3000 K and similar values in the shear layer. Whether these hot regions promotes shear-layer instability remains to be understood.

### F. Detonation Wave Stability

Various investigators have detected multiple detonation wave fronts. Le Naour et al.,[54] citing work from LIH,[55] provided expressions for the number of waves $n$ in terms of the detonation cell size $\lambda$, the diameter of the annular chamber $D$ and the height of the detonation wave $h$. Interpreting their results,

$$n \sim D/h, \quad 1 \leq n \leq 4 \tag{1}$$

The results shown by Le Naour et al. only partly confirmed the scaling expression. From a practical viewpoint, Yi et al.[56] found that the specific impulse is unaffected by whether there is a single front or multiple fronts. While this is reassuring, the creation and sustainment of single or multiple wave forms is a problem of fundamental interest.

### G. Liquid Fuels

Two aspects of liquid fuels pertaining to RDEs are worth addressing, similar to those of PDEs. The first is that there is a desire to use liquid hydrocarbons due to various advantages such as safety, storability and high energy density. Rapid vitiation, atomization and vaporization, perhaps more so than for PDEs, are critical requirements.

The other aspect is the possibility of using cryogenic fuel to cool critical areas of the engine in addition to use of refractory materials. Such a concept is shown in Fig. 1 in a manner akin to existing rocket motors. Similar advantages as in rocket motors accrue.

## III. Hardware Development

Tests reported in the open literature tend to be of short duration including comprehensive tests where the reactants are discharged from tanks with capacities of a few liters at pressures of several bars to tens of bars into a large vacuum tank to simulate a high altitude environment (although a 5 s test was reported[54]). Some of the results showed one or multiple waves traveling at the Chapman–Jouguet velocity. The number of waves was determined by spectral analysis of the pressure record, as well as by photographic analysis of the luminous fronts. In most of these tests, despite attaining CJ velocity, the pressure tended to be below CJ. No satisfactory reasons have been offered on this discrepancy. Due to the short runs, it is difficult to assess the operational performance of RDEs, for example, controllability, structural integrity, etc. In this section, some critical issues regarding hardware development will be discussed. The discussion highlights current trends and identifies some deficiencies in current understanding.

### A. Wave Initiation

Several methods of initiating the rotating detonation wave have been attempted in experimental studies. Some of these initiation methods are straightforward, but the mechanisms behind some successful starts and on the wave direction, are not completely understood. Such was the case with high-frequency pressure oscillations present in early rocket engine testing, where the wave amplitude and speed observed were similar to a detonation wave. Many sources of information exist that describe the history and solutions to dampening these oscillations.[57,58] Small bombs were exploded in liquid rocket engine tests to create a pressure disturbance which was used to ascertain overall stability of the operating parameters. Orienting the bomb blast could control the direction of the wave, but the direction was otherwise random.[59] Note that these tests were for cylindrical, but not annular, combustion chambers. Although the majority of stability data from rocket engine tests are not applicable, there may be some rules that can be essentially reversed and applied to the RDE. First, instabilities can be overcome by injecting the more volatile propellant at a higher velocity. Most RDE studies thus far do not report a difference in fuel and oxidizer injection velocities. Also, a decrease in the nozzle contraction ratio increases the likelihood of high-frequency instabilities. Although some earlier work assumed the engine may be connected to a converging–diverging nozzle,[60] convergence at the end of the annular combustor may in fact be detrimental to the RDE. Bykovskii et al.[61] note that an increase in the chamber pressure as a result of smaller outflow through the contraction will prevent the inflow of fresh reactants.

The simplest means of starting the RDE is to ignite a spark plug,[62] burning wire,[63] or electric detonator and explosive mass[63] in either the channel or one of its side walls. The ignition source causes waves to form, which quickly transition to shock and/or detonation waves. This method is not always successful. For instance, Kindracki et al.[64] note that their automotive spark plug igniter had about a 40 percent repeatability rate after a methane–oxygen mixture was supplied to the combustion annulus. The same engine with an ignition tube and diaphragm had 95 percent repeatability. Thomas et al.[65] and Canteins[16] incorporated predetonator tubes into an engine that should emit a detonation wave into the annulus, a device which has been used successfully with DDT transition in a PDE.[66] Voitsekhovskii[67] ignited the mixture with a spark discharge and discussed that a "special arrangement has to be made to prevent the detonation wave from propagating in more than one direction from the point of ignition." Evidently, Nicholls and Cullen[60] presumed this arrangement was a diaphragm which, in their own work, resulted in a detonation wave initiated in one direction and a weak shock in the other. The detonation wave then dissipated due to an insufficient flow rate and mixing. A detonation wave can also be initiated in one direction by using swirled fuel injection and timed ignition.[48] As the fuel is swirled into the RDE channel, a spark plug is ignited before the entire annulus is filled with a reactive mixture.

These initiation methods are depicted schematically in Fig. 4. All of the engines would be filled with reactants before ignition except for the small uncolored areas in the swirl concept where fuel has not yet mixed with the oxidizer. While initiation of a wave in one direction with an ignition source mounted in the wall or channel has been demonstrated, the performance may not be consistent since there is likely a dependency on the local turbulence and mixing of the reactants as discussed in §II. The use of a diaphragm to stop waves from being formed in both directions also is not practical where restarts may be necessary. The use of a detonation tube connected to the channel appears to be the most straightforward method. If DDT occurs in the tube, then a detonation wave should form in one direction and a rarefaction or weak shock wave will form on the other. A valve could be placed at the end of the tube so it could refill to restart the RDE. It appears possible to incorporate several swirled fuel injectors in one RDE. A disadvantage of a

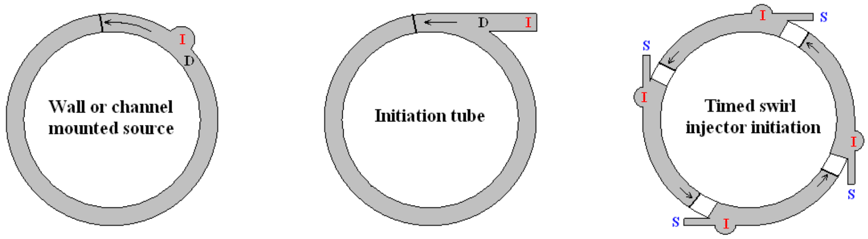



**Figure 4. Schematic depiction of RDE initiation methods. Possible locations of diaphragms, ignition, and swirled injection are indicated by D, I, and S, respectively.**

predetonator is the need for separate carriage of highly energetic materials.

## B. Reactant Injection

Reactant injection strategies in early RDEs were based on rocket injection manifolds where the fuel and oxidizer were separately supplied through arrays of orifices with impinging jets to promote mixing. The main difference between deflagration-based rocket engines and RDEs in terms of fuel injection is that the pressure gain from the detonation wave can disturb or entirely shut off the incoming reactant flow. For example, Voitsekhovskii[67] achieved a prolonged rotating detonation wave using a premix of hydrogen and oxygen. The premix was supplied from a reservoir in the middle of the annulus. While the detonation wave rotated circumferentially, the premix entered from a channel on the inner wall and products exited through another channel on the outer wall into a vacuum tank. Such a configuration could have resulted in flashback to the reservoir, but it appears that the centrifugal force provided a natural counterbalance to the backflow condition.

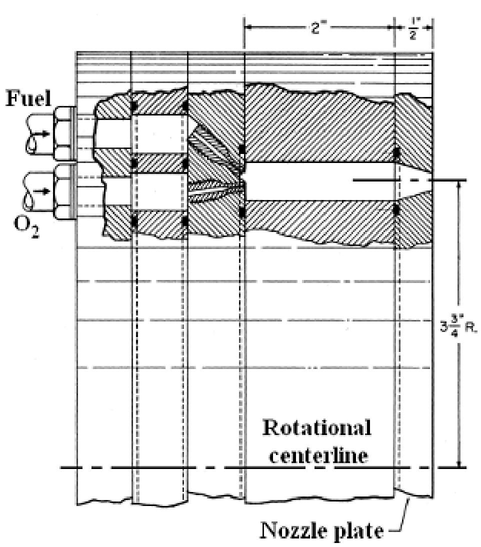



**Figure 5. Impinging fuel–oxygen injection and mixing design from an early RDE study by Nicholls et al.[60]**

The engine developed in the work of Nicholls and Cullen[60] was connected to 2000 psi hydrogen and oxygen storage tanks that provided fuel to a plenum reservoir before injection through orifices with a diameter of about 0.5 mm. The engine contained 72 pairs of orifices placed on the thrust wall, perpendicular to the wave front. Steady rotation of a detonation wave in that engine was not realized because, according to the authors, turbulence of the impinging jets disturbed the detonation wave and the overall flow rate was insufficient.

The initial studies by Voitsekhovskii were progressively developed at the Lavrent'ev Institute of Hydrodynamics that explored different fuels, injection methods, and geometry ratios that led to establishing a stable rotating detonation wave in the annulus. In an engine that used impinging orifices mounted on the thrust wall, Bykovskii and Mitrofanov[62] controlled the incoming reactants by varying the orifice diameters and plenum chamber pressure. Bykovskii et al.[34] noted that the detonation wave pressure can cause reverse flow past the orifices into the manifold, especially if the orifice flow is not choked. At minimum, the manifold pressure should be 2–3 times higher than the annulus pressure. Once the manifold pressure is high enough, many injection methods appear sufficient for sustaining a detonation wave. Typically, the fuel and oxidizer jets are angled towards each other to promote mixing. Injecting the fuel and/or oxidizer through annular slots has also been used in several engines,[16,64] whereby the slot areas are interchangeable. Trial-and-error experimental optimization of the injector orifice/slot areas and impingement angles is likely to continue until mixing in these short timeframes between wave fronts is better understood (probably through combined experimental and computational studies).

Computational models have used a variety of boundary conditions along the thrust wall to simulate fuel injection. Zhdan et al.[68] compared experimental work with a model using injection pressure ratios of 5–15 with a ratio of the injector throat and exit areas. The specific impulse was comparable to a conventional rocket engine. Hishida et al.[69] assumed a negligible injection velocity when the detonation wave pressure is greater than the reservoir pressure. Choked reactant flow is established once the detonation pressure drops to a sufficient level below the reservoir pressure. The maximum injection velocity is 250 m/s while the $2H_2 + O_2 + 7Ar$ wave speed is 1500 m/s. The specific impulse with this inviscid model was 4,700 s. Yi et al.[56] used similar injection velocity boundary conditions for a $H_2$–air engine and report specific impulse and thrust at a flight speed of Mach 1.5. Performance increases up to 3,300 s with injection pressure and the area ratio of the injector throats to the thrust wall. The $H_2$–air engine model discussed by Schwer et al.[70] reports a case with an injector pressure ratio of 10. With injection boundary conditions similar to the other models, 13 percent of the injector orifices were blocked while 63 percent were choked when the engine was operating steadily. With a pressure ratio of 20 and sea-level static conditions, the specific impulse rose to 5,500 s. The authors compared this result with a PDE model that reaches 4,100 s.

Recent experimental work by Braun et al.[37] focused on identifying behavior of the plenum (or manifold) section behind the injector orifices using a linear detonation tube. In this study, orifices of different diameters were connected to a plenum cavity operating at a steady-state injection pressure. The propagating detonation wave in the main tube temporarily shuts off the valve flow, but refueling can be rapid and the process can be scaled to an RDE. The time of the backflow condition was found to scale with the injector/detonation wave pressure ratio divided by the frequency of the rotating wave in the RDE. This study supports the validity of using the injector boundary conditions described in computational studies.

Instead of sonic orifices, Zhdan considered a mathematical model of an annular isolator that increases in channel width where the detonation wave is rotating.[71] Such a design allows for supersonic flow of fresh reactants between detonation fronts. However, the detonation wave structure becomes unstable and ultimately fails as the velocity of the incoming flow increases past Mach 3. In terms of the pressure ratio of the reactants and the detonation wave, there appears to be upper and lower limits for RDE operation. The static pressure of the detonation wave should not exceed the manifold/plenum pressure such that a choked backflow condition can occur. If the total pressure of the manifold/isolator orifices or micronozzles exceeds the peak detonation pressure, the wave can become unstable and detach from the thrust wall.

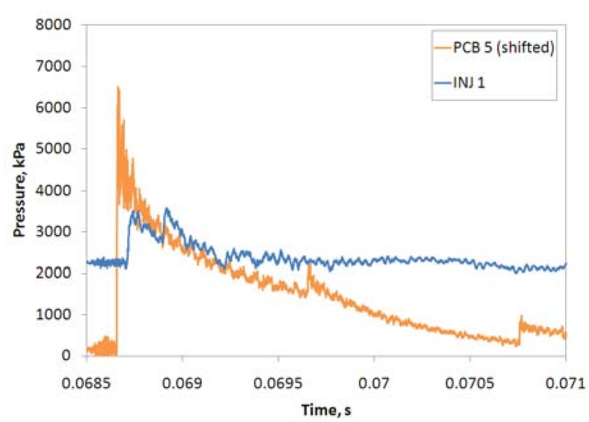



**Figure 6. History of a detonation wave that passes over an injector orifice with backflow followed by refueling.**

Several courses can be pursued in future computational and experimental research regarding RDE fuel injection. First, computational studies must expand to include the injector orifices and the plenum chambers behind them since some amount of temporary backflow or blockage is expected to exist during operation. Such studies will subsequently have to consider several design variables including the ratio of the orifice diameters to the plenum area, contouring of the orifices, and the overall axial length. When the combined area of the orifice diameters is much less than that of the thrust wall, it is evident that RDE performance decreases due to losses associated with the expansion of the reactants into the annulus. A practical issue to consider with this ratio, however, will be the formation of transverse waves in the manifolds themselves and their effect on the backflow dynamics. Pressure ratios between the injector manifolds and the annulus have reached 10–20 for maximum specific impulse in RDEs. These ratios create the possibility of using supersonic, contoured micronozzles to achieve longer jet penetration into the annulus between detonation wave fronts. Contouring may also be used within plenum cavities associated with the orifices to inhibit backflow. These studies will undoubtedly be more computationally expensive and complicated as turbulence and mixing must be addressed. Validation between RDE computations and experiments will be especially useful.

### C. Flow Rates

The high power density also means that flow rates are extremely high. If the flow rates are not sustained, the engine will fail. Numerous related issues arise from this flow rate demand. The flow rate determines the height of the detonation wave $h$ which in turn determines the number of waves rotating around the annulus, per Eq. (1). Fortunately, it appears that the engine performance is not seriously affected by the number of waves.[56]

Le Naour et al.[54] reported combined fuel/oxidizer specific flow rates of about 40 kg/s/m$^2$ although a previous estimate[72] for kerosene/oxygen was higher at 700–1450 kg/s/m$^2$. Empirical strategies may be used to estimate the required flow rate based on engine geometry. For an annulus with a mean diameter $D_m$ and a width $\Delta$, the area is $\pi \Delta D_m$. Using the density $\rho$ of the reactants, the injection velocity may be estimated using the height of the fresh mixture layer $h$ divided by the time between detonation fronts. Thus, an order of magnitude estimate of the mass flux is

$$\dot{m} = \rho A V \sim \rho \pi D_m \Delta h f \tag{2}$$

The specific mass flow rate is

$$\dot{m}_{sp} \sim \rho h f \tag{3}$$

The high mass flux requires consideration of the pumping requirements under different operating conditions, an issue which has also not been addressed. These order of magnitude estimates can lead to several more questions regarding how to design injectors that can maintain the high flow rate. For instance, what estimate can be given for $h$ and can $\rho$ be related to the required injector manifold pressure? Also, how does injector blockage factor into the flow rate estimate? A blockage factor $(1-B)$ can be multiplied with Eq. (2) to relate the percentage blocked to the mass flow rate reduction. This factor can account for the fraction of orifices that are either not supplying reactants or supplying them at a point in the annulus behind the wave front where the manifold pressure is not yet high enough for choked flow. It is simple to use the ideal gas law to estimate the pressure of the reactants. This pressure must be sufficient for the average pressure at the end of the annulus to be high enough to sustain choked flow with given back pressure conditions (as well as the imposition of nozzle requirements if one is used). Additionally, the injector manifold pressure needs to be significantly higher than the reactant pressure in the annulus to achieve the desired mixture height and keep $B$ low to increase power density. As was mentioned earlier, the computational study by Yi et al.[56] shows a reduction in specific impulse as the area of the combined micronozzle throats decreases with respect to the annulus area and lowers the reactant pressure. According to the empirical estimates by Bykovskii et al.,[34] the $h$ requirement for a stable engine can be related to the detonation cell size $\lambda$. Although the experimental uncertainty is about 40%, size estimates for $h$, $\Delta$, and $D_m$ are $8.4\lambda$, $1.7\lambda$, and $28\lambda$, respectively. Using all of these estimates, it appears a first-order flow rate estimate can be made by first selecting the reactants and their initial properties in the annulus such that the exit is choked. Next, the injector geometry and manifold pressure must be able to support the initial annulus pressure and $h$. If the flow rates are not sustained, the engine shuts down rapidly, as has been reported.

### D. Heating

A critical challenge related to the high power density and the compactness of an RDE is the heating. A few studies have revealed high wall temperatures and heat fluxes. For example, one of the test rigs used by the authors showed erosion of the water-cooled nozzle made of copper. Le Naour et al.[54] showed peak wall temperatures exceeding 700 and 1000 deg C for a hydrogen/oxygen and a kerosene/oxygen RDE respectively. Le Naour et al. mentioned that the hottest regions are closest to thrust wall (or, equivalently, the injection nozzles) and the heat flux decreases rapidly away. For the same mixtures, heat fluxes of 12 and 17 $MW/m^2$ were measured with even higher local values. These authors suggested that the proximity of the hot regions to the injection nozzles may be beneficial in vaporizing liquid reactants and in aiding mixing. Le Naour et al. proposed that a C/SiC composite material capable of withstanding temperatures of 1800 deg C even in an oxidizing environment be used for the annular walls of the detonation chamber. These authors stated that the detonation chamber survived short duration tests of about 0.5 s. Further testing under more severe conditions caused damage to the detonation chamber walls. Le Naour et al. also considered that the high temperature environment needs further consideration.

Moreover, it does not appear that high-temperature materials are an adequate solution. This is because the surface can heat up pass the auto-ignition point. It appears that active cooling especially just downstream of the reactant injection region is required. Cooling schemes using liquid fuel can be based on existing rocket nozzle cooling techniques.

### E. Deswirling of Exhaust

Swirl represents a loss of axial momentum. This issue was explored by Nordeen et al.[53] They presented time-averaged pathlines in fixed reference frame. The authors considered the direction of the flow exhausting from an RDE is analogous to that in turbomachinery. The results show that the pathlines near to the inlet are angled at various directions, both upstream and downstream. However, further downstream, the pathlines tended closer to the axial direction. This alignment of the pathlines may obviate the need for deswirling and may impose a minimum chamber length to maximize performance. The possibility of a torque being imparted on the engine due to swirl may not be serious although may need further consideration if the engine is of large diameter or produces a large thrust. In this case, the relatively small torque may become significant.

### F. Ground Testing Summary

Table 2 provides a summary of experimental RDE results in the past few years to reflect the increase in institutions with active research programs. Although not all of the engines tested have significant duration or performance measurements, research efforts at these institutions understandably appear to be ongoing. Diversity and modularity in the geometry, fuel injection methods, initiation methods, and reactants is clearly apparent. Other design parameters like materials, active cooling, and reactant equivalence ratios also have been varied widely throughout these studies. While this table shows that many variations in design parameters (reactant orifices or slits, cylindrical or cylindrical–conic geometry, etc.) lead to successful engine tests, it is thereby difficult to deduce what parameters may cause the engines to fail. Reactant mass flow rates are another parameter worth comparing, but there are also significant variations in these studies since some engines exhausted into vacuum chambers. While there is certainly a minimum flow rate requirement for an RDE as previously discussed, high flow rates alone do not guarantee successful engine tests.

## IV. Cycle Analysis and Systems Studies

Cycle analysis is a necessary aspect in the development of heat engines. For RDEs, such studies are, however, still in their early infancy, even compared to the inroads made with pulse detonation engines. Some of the unresolved issues involve the development of a simple but realistic RDE model for airbreathing or rocket

**Table 2. Summary of recent RDE proposed configurations and tests**

| Authors | Year | Geometry | Fuel Injection | Reactants | Duration | Initiation | $I_{sp}$ |
|---|---|---|---|---|---|---|---|
| Canteins[16] | 2006 | 100–104 mm OD, 2.5–5.5 mm channel, 47.5 or 100 mm length | slots that create impinging jets | $C_2H_4 + O_2$ | 1.5–2 s | detonation tube | 150 s |
| Bykovskii et al.[73] | 2008 | cylindrical, 40 mm OD, 5 mm channel, 100 mm length, truncated cone at exit | impinging jets | $H_2 + O_2$ | 0.4 s | blasting wire | – |
| Bykovskii et al.[74] | 2008 | 17 degree expanding angular channel, 40 mm OD, 100 mm length | impinging jets | $H_2 + O_2$ | 0.4 s | electric discharge | up to 300 s |
| Braun et al.[48] | 2010 | cylindrical, 240 mm OD, 13 mm width, 70 mm length | swirl ports, 0.5–1 $cm^2$ orifice diameters | $H_2 + O_2$ | a few ms | timed swirl injection | – |
| | | cylindrical, 88 mm OD, 79 mm ID, 127 mm length | premix injected axially through slit | $H_2 + O_2$ | a few ms | spark plug | – |
| Bykovskii et al.[75] | 2011 | cylindrical–conic, 306 mm OD, 395 or 510 mm length | Air: 3–23 mm annular slot $H_2$: 0.75–1 mm orifices impinging on air | $H_2$–air | 0.3–0.6 s | Al foil strip blast | – |
| Kindracki et al.[64]* | 2011 | cylindrical, cylindrical–conic, 38 mm ID, 23–50 mm length | Fuel: 0.7–1 mm orifice arrays Oxygen: 0.5–1 mm width interchangeable slit | $CH_4$, $C_2H_6$, $C_3H_8 + O_2$ | 0.15–0.8 s | spark plug, tube-and-diaphragm | 140–180 s |
| Thomas et al.[65] | 2011 | cylindrical, 76 mm OD, 56–72 mm ID, 152 mm length | impinging jets | $H_2$ + air[#] | 0.5 s | detonation tube | – |
| Le Naour et al.[54] | 2011 | cylindrical, 80 mm ID, 100 mm OD, 90 mm length | 190 sets of three-jet impinging injectors | $H_2 + O_2$ | 1–5 s | explosive wire | 310–340 s |

*Also a 150 mm OD, 140 mm ID engine with otherwise similar design parameters
[#]$C_2H_4 + O_2$ premix was used in tests about 10 years ago, led to backflash

mode and development of both ideal and real parametric and performance analysis tools. The latter requires an improved understanding of the coupling between the combustion core and the other components that make up a practical engine, such as the inlet and nozzle and any requisite turbomachinery elements. There is also recent interest in a realistic evaluation of thermodynamic losses through exergy analysis.[76] Proper performance metrics for comparing detonation propulsion systems with conventional propulsion systems are also not well developed. Proper metrics should be the specific thrust and the specific fuel consumption. From this perspective, hybrid RDE (or PDE) systems with low pressure compressors can be compared against multi-spool turbofans which develops higher overall compressor pressure ratios. Additionally, with the touted benefit of high power density, comparisons of engine size are also needed. Such a comparison is beneficial in identifying how RDEs/PDEs can be used in existing or new aerospace platforms. In a related effort, Schwer and Kailasanath[77] examined certain aspects of sizing for RDEs only.

### A. Thermodynamic Cycle Analysis

An examination of the modeling of a detonation-based propulsion system using a Humphrey, a Fickett–Jacobs and a Zel'dovich–von Neumann–Döring (ZND) cycle indicates that the last is the most appropriate for capturing the physics.[78] A $T$–$s$ diagram of these three processes is shown in Fig. 7. In other words, the terminology "constant volume combustor" is misleading. The Humphrey cycle as originally proposed is too simplistic and applicable only to a truly constant volume csombustor which a detonation process is not.[1]

Nordeen et al.[53] developed an innovative technique by tracking the properties of a number of streamlines. Unlike PDEs which may be modeled in a quasi-one-dimensional manner using the ZND cycle, RDE flows are highly nonuniform. These authors thereby proposed a modified ZND model. The model utilizes turbomachinery concepts and yields a quasi-one-dimensional thermodynamic model. This model appears promising in its consistency with conventional propulsion analysis techniques. Further, Nordeen et al.[53] remarked that performance comparisons between classes of propulsion systems have not generally taken into account parasitic losses.

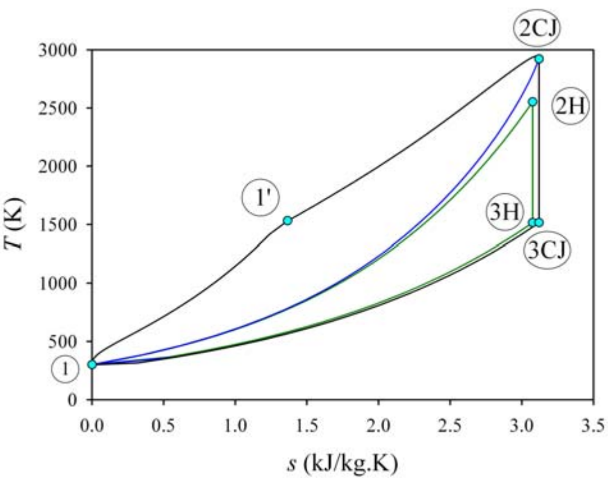



**Figure 7. Ideal Humphrey (1 → 2H → 3H → 1), FJ (1 → 2CJ → 3CJ → 1) and ZND (1 → 1′ → 2CJ → 3CJ → 1) cycle $T$–$s$ diagrams for a stoichiometric hydrogen/air mixture initially at STP.[79]**

The nature of PDEs and RDEs poses several problems for analysis methods commonly applied to Brayton cycle engines. The fact that the Brayton cycle is steady with combustion occurring at a low overall flow speed allows for performance estimates to be made using stagnation properties at each stage. In some cases, an entire analysis can be completed with fewer than ten steps. Some issues such as accounting for real gas effects and efficiencies remain topics of active research.[80] Using only stagnation properties for an analysis of a PDE is troublesome because of the need to fill the detonation tubes during each cycle which is dependent on a velocity calculation. For example, a long filling time for an otherwise efficient PDE cycle can drastically decrease specific impulse. Heiser and Pratt considered this and developed a time-independent procedure for PDE cycle analysis.[81] They found that the specific impulse can reach up to 4000 seconds for realistic component efficiencies and hydrocarbon fuel. These authors remark that the design of a system to exhaust the combustion products to the ambient pressure, thereby maximizing performance, is challenging due to the unsteady nature of the PDE. It is the present authors' opinion that this analysis procedure represents the highest possible performance of a detonation-based engine until practical problems with pressure gain are addressed. Furthermore, it may be applied both to PDEs and RDEs.

Wave rotors, which can be considered true Humphrey cycle, constant volume combustors, use rotary valves to temporarily close off the combustor from the inlet and outlet to sustain pressure gain.[82] Potential applications usually involve ground-based gas turbines and internal combustion engines, although systems for aircraft are possible. When a single detonation tube is coupled with an inlet that shuts as the detonation wave is initiated, specific impulse (including ram drag) for a $H_2$–air engine can reach 4000 s at low flight speeds, but it decreases linearly until there is no net thrust at Mach 4.[83] Consequently, multi-tube engines have been proposed for development since they can result in improved steadiness and performance. A computational study by Ma et al.[84] considered the interaction of three detonation tubes operating with shifted phases that exhausted into an area that preceded a conventional CD nozzle. Although propulsive performance can be increased, complex shock interactions can be created between tubes in different phases. For instance, a detonation wave front exiting one tube may cause a shock wave to enter another tube in the process of filling. Thus, it appears that one of the main challenges with multi-tube PDEs is management of the unsteadiness and wave interaction to minimize stagnation pressure losses. A plenum chamber placed after the compression system and before the tube entrances can assist in refueling the combustors despite downstream pressure gain. Losses are likely to occur as each tube is filled, especially if the plenum chamber is near stagnation conditions and the filling velocity is high. For RDEs, mechanical systems with moving parts to counteract pressure gain effects do not appear compatible and thus the cycle is more susceptible to stagnation pressure losses from the plenum chamber to the annulus that contains the detonation wave(s). Consequently, thermodynamic cycle analysis methods need to move towards accounting for power density and weight to truly compare RDEs and PDEs—no doubt a challenging task at this stage of development. To address factors such as weights and parasitic losses, there is increasing interest in applying exergy concepts to aerospace systems.[76,85]

## B. Systems Studies

The RDE core needs ancillary systems to create a practical propulsion or power production system. As an example, an air induction system needs to be incorporated for airbreathing applications. The airbreathing RDE is also not self-aspirating so that it cannot start from rest. Again, due to the novelty of the RDE concept, there is a paucity of systems-level studies. This review points to some of the potential applications and highlights the need for such studies.

Instead of "constant volume combustor," the terminology "pressure gain combustor" has appeared in the literature lately. The term can be interpreted differently for an RDE as opposed to the intermittent PDE. Note that cycle analysis, as the name suggests, is for one cycle only. Thus, in a PDE which has an unsteady exhaust, an averaging process is typically performed. Consequently, the cycle efficiency of a PDE may be quite high if one does not include parasitic losses. Such an averaging process may not be necessary for an RDE.

### *1. Rocket Motors*

As a pure rocket, the compactness of the RDE opens up new possibilities in aerospace vehicle design. RDE motors can be scaled or combined to provide the thrust required for space access vehicles. Besides increased efficiency, additional benefits that can result in reduced weight and complexity are the addition of an aerospike nozzle and possibly thrust vectoring.[72] An ejector may also be used to increase performance,[86] especially in the case that the RDE exhaust contains a large transverse component. One-dimensional thermodynamic modeling was considered in detail in early work where the annulus was coupled with a CD nozzle, but no appreciable difference was found between RDE and conventional motor performance.[60]

The review by Bykovskii et al.[34] contains a summary of analytical models developed for both constant width and expanding annulus channels. Removing outlet constriction allows the RDE to make use of work generated by the expansion of detonation products, thereby providing a specific impulse advantage over conventional engines. The analytical model is developed by selecting a ratio of the height of the fresh mixture to the annulus circumference, a ratio of the fresh fuel pressure at the entrance to pressure of the products exhausting from the exit, and an angle of the internal flow streamlines with respect to the detonation wave front.[87] By specifying a sonic exit velocity at the end of the constant area channel, the mass flow rate can be deduced and the pressure and specific impulse of the engine become independent of the internal annulus flow. Engines with an expanding channel area have an exhaust Mach number of well over 1.0. The sonic exit velocity assumption is probably conservative. Zhdan et al. state that the flow velocity from a constant area channel is indeed supersonic, and varying the combustor length with respect to the circumference appears to have some effect on the axial velocity as the products expand.[68] A computational model by Yi et al.[56] with an axial injection velocity of up to 500 m/s finds the exit Mach number to be 1.08.

Although there has been considerable progress in understanding the internal flow dynamics of the RDE, less development has occurred with systems studies aimed at optimizing power density. Volumetric efficiency will obviously increase as the channel width increases for an engine with a fixed outer diameter. While a minimum channel width for stable operation has been established, less information exists regarding the maximum width. Using a three-dimensional computational model, Pan et al.[52] showed that the wave is stronger along the outer wall of the annulus. Although the walls sustain the wave as it propagates with constant velocity, it is possible that larger wall separation could result in a non-planar or unstable wave. Nicholls and Cullen[60] show several diagrams and photographs of a detonation wave propagating along a curved section with trailing oblique shocks reflecting off the inner and outer walls. Such behavior will have adverse effects on the injector orifice flow which must be re-established between wave fronts.

Presuming that there is some limit to the channel width for a fixed outer diameter, other methods can be pursued for increasing power density. For instance, it is worthwhile to question if a single annular chamber is optimal for practical RDE systems. An oval or "racetrack" shape can be envisioned which allows the width of the straight sections to be increased with respect to the curves. If a large engine were to be constructed for a heavy hydrocarbon fuel with a large cell size and, thus, a large radius of curvature requirement, more energetic fuel could be injected along the curves to increase volumetric efficiency. In addition to changing the shape, a heavy-lift engine could be built from several concentric channels sharing an aerospike nozzle. The axial length of the channels would have to ensure that the exhaust was uniform such that intra-channel shock interactions would be minimized. Figure 8 depicts these engine shapes.

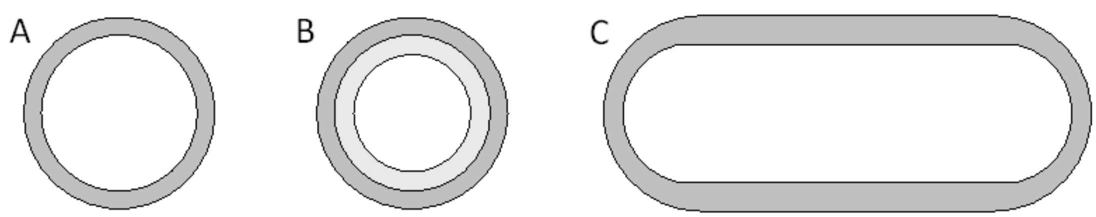



**Figure 8. Depiction of possible RDE shapes, including A) a standard annulus, B) two concentric channels, and C) a racetrack with variable channel width.**

### *2. Airbreathing Engines*

Adding an inlet and nozzle to an RDE appears to be a baseline propulsion system, analogous to the ramjet. Unlike the ramjet, further pressure rise is achieved in the combustor through the rotating detonation process. For low flight speeds, the compressor outlet can be connected to a plenum chamber before air is injected into the annulus. For subsonic applications, the high total enthalpy of the RDE exhaust may yield a low propulsive efficiency.[88] In this case, the RDE may actually be promising for ejector augmentation to reduce the engine's exhaust velocity. If one accepts the analogy between an RDE and a conventional jet engine, then it is easy to conceptualize the RDE as the combustor replacement for turbojets, turbofans and turboprops.

Alternatively, the high total enthalpy makes the RDE suitable for high-speed applications. At supersonic speeds where ram compression is feasible, axial ducts or slots can deliver air directly to the annulus. Braun et al.'s[89] analytical study shows that the detonation annulus can be connected to an axial inlet system where air enters and mixes with fuel between detonation waves. It was found that the interaction between the inlet system and the annulus is the most complex modeling issue to resolve. Thus, an area expansion is utilized such that the average value of the detonation wave pressure distribution created around the annulus is matched with the inlet pressure. An isolator with a slight area increase is envisioned to keep the inlet flow properties constant since the detonation wave continually blocks a portion of the annulus entrance from filling. Although an isolator can support a rise in static pressure, it is strictly used for damping out detonation and shock waves. For a practical engine, a minimum length will be required to damp any waves propagating upstream from the annulus.

Recent literature indicates potential for hybrid and multi-mode engines based on the RDE architecture. Fujiwara et al.[90] noted that the emergence of the RDE concept shows that a stable detonation wave can exist for any non-zero incoming axial velocity. Furthermore, fresh mixture axial velocities greater than the CJ velocity lead to the family of oblique detonation wave engines. Shao and Wang[91] performed a three-dimensional computational study that indeed shows the RDE can transition to a standing detonation wave mode in the annulus as the axial velocity becomes larger than the wave velocity.

## V. Conclusions and Outlook

The prospect of rotating detonation engines is a tantalizing one. At present, there are more questions than answers. Euler solutions indicate that rotating detonation can be established. These fundamental conceptions removes any question on the viability of rotating detonations as a chemical energy conversion technique. However, bringing concept to reality entails the solution of many difficult problems. In practice, the problem is to be able to sustain the rotating detonation wave for a long duration and to be able to control it in some fashion, such as in modulating the wave height. Related to the stability and controllability are the effects of turbulence, nonuniform mixing, wall curvature and other geometrical considerations, contact surface burning, shear layer stability, amongst other fundamental considerations. Turning to more practical issues, the ability to feed the combustor at high rates requires consideration of arrangements to facilitate pumping and mixing, as well as safety issues. The ability of such an engine to provide thrust optimally for different flight conditions, and integration to existing or novel aerospace platforms are further considerations.

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