Chapter

A Theoretical Review of Rotating Detonation Engines

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Abstract

Rotating detonation engines are a novel device for generating thrust from combustion, in a highly efficient, yet mechanically simple form. This chapter presents a detailed literature review of rotating detonation engines. Particular focus is placed on the theoretical aspects and the fundamental operating principles of these engines. The review covers both experimental and computational studies, in order to identify gaps in current understanding. This will allow the identification of future work that is required to further develop rotating detonation engines.

Keywords: rotating detonation engine, detonative engines, propulsion, detonation shock waves, spin detonation engine

1. Introduction

1.1 Background

Detonative combustion is a potential propulsion method for aerospace systems, offering high efficiency and low mechanical complexity. In comparison, deflagration is generally considered easier to control and has therefore dominated both experimental and real world engine applications. Research into detonation engines has been limited due to the lack of the necessary tools required to design and analyse such systems [1, 2]. As such, practical development of detonation engines, notably the pulsed detonation engine (PDE) and the rotating or rotational detonation engine (RDE), has been limited [3]. Nevertheless, the application of detonation engines for propulsion is very promising, already proving to be compact, whilst providing highly efficient thrust generation [3–7]. This supersonic thrust could be utilised independently as a rocket engine, or as part of a gas turbine system. Interest in the development of RDE technology has grown and the challenges of utilising a more thermodynamically-efficient cycle have become better understood [8, 9].

Combustion can occur at both subsonic and supersonic velocities, known as deflagration and detonation, respectively. Deflagration is typified by a regular flame, which propagates at less than the speed of sound. The heat release may be used to expel the resulting products, generating thrust. Deflagration has been used in a broad range of applications to produce power. However, in theory, deflagration lacks the thermodynamic efficiency of a detonation system, which is a system where combustion is initiated suddenly and "propagates utilising most, if not all, of the heat from combustion in an incredibly rapid shock wave" [10]. The heat generated by the exothermic chemical reaction sustains the shock wave. The concept of using detonation as a propulsion source has been proposed since the 1840s [11], but no substantial work had been completed until the 1950s when the development of models and concepts for a more lightweight and compact engine began [12]. The mechanisms that drive the detonation engine were not well understood at that time, so much of the research over the following decades was centred on the theoretical development of the engine.

As the name implies, the pulse detonation engine (PDE) has been proposed for propulsion using detonations [12, 13]. In a PDE, a detonation chamber is filled with a fuel/oxidiser mixture, which is subsequently detonated. The accelerating detonation propels the exhaust from the chamber, thereby generating thrust. The chamber is then re-primed with fresh reactants, and re-detonated. With sufficiently high cycle speeds, large amounts of thrust may be generated in a small engine [14, 15]. This type of engine has been found to be particularly efficient [3, 16, 17].

Development of the concept of a rotating detonation engine (RDE) began as a result of further work into detonative propulsion. This engine type is characterised by one or more detonation waves contained within an open-ended annular chamber. A fuel/oxidiser mixture is fed into one end of the chamber, and the detonation wave consumes these reactants azimuthally, expelling reactants from the open end of the annulus. In some literature, this type of engine may also be referred to as a continuous detonation wave engine (CDWE) or a spin detonation engine [6].

Early research into rotating detonations was conducted in the 1950s [18], with attempts to document the structure of detonation shock waves, including those in spinning detonations, with further developments through the 1960s [1]. Subsequent research has been conducted into the effects of geometry, rotation characteristics, spiralling of the wave, and other variables [6, 19–22]. Another advancement in general detonation research is improvements in deflagration to detonation transitions (DDTs), leading to a greater understanding of the consumption of fuel in the chamber [23–25]. Further work has developed prototype RDEs to measure the thrust of small-scale units as a baseline for larger model behaviour, utilising the results from experimental work to verify theoretical results, and to generate new results [26–30].

In this review, several aspects of RDEs will be examined, starting with a brief comparison of RDEs and PDEs. This will be followed by further exploration into RDE operation, and methods of analysing RDEs, both experimentally and with numerical modelling. Finally, there will be an overview of areas still requiring further work.

1.2 Thermodynamic cycles

The majority of gas turbines that operate with a deflagration follow the Brayton (B) cycle: an isobaric (constant pressure) process, as shown in **Figure 1** [31]. In contrast, a detonation is almost isochoric (constant volume) and may be modelled with the Humphrey (H) cycle, or, preferably, with the Fickett-Jacobs (FJ) cycle, which models detonation [3, 31]. The H cycle assumes that combustion occurs in a fixed volume, resulting in a pressure spike as the products expand. Differentiation between the H and FJ cycles in **Figure 1** can be seen through the state changes of 2–3′ for the H cycle and 2–3″ for the FJ [31]. This pressure spike decreases the volume of combustion for FJ while remaining constant for H. The next phase (FJ 3″–4″, H 3′–4′) is similar for the two cycles, with the FJ cycle expanding further before reaching atmospheric pressure. Both then undergo a constant pressure compression through cooling back to the initial state 1. As seen in **Figure 1**, the FJ cycle is more

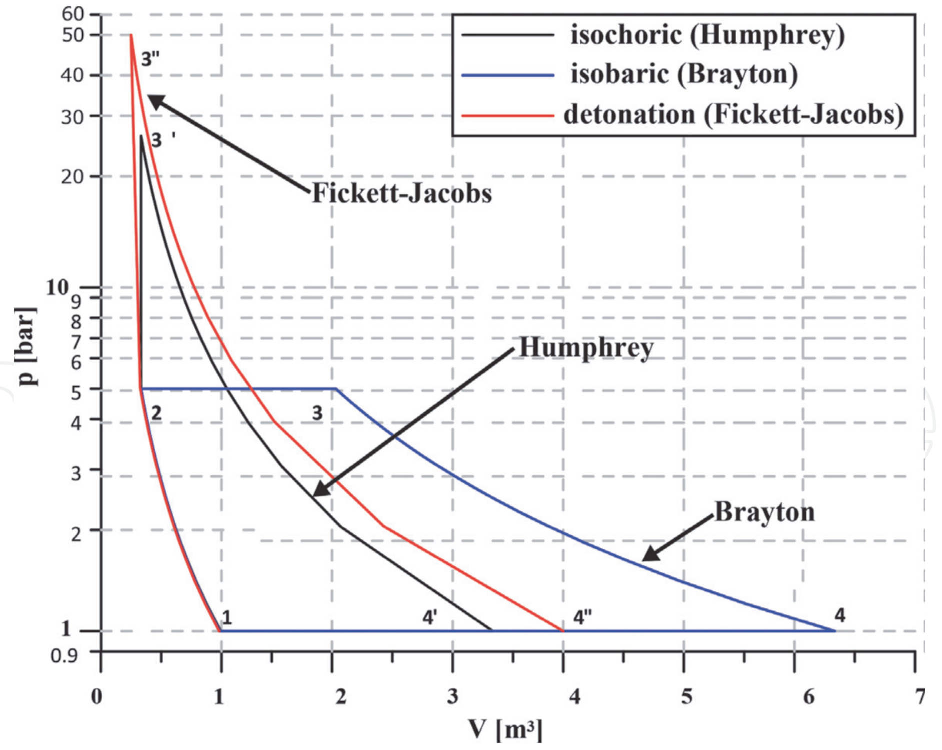

Figure 1.
Thermodynamic cycles: Humphrey, Brayton, and Fickett-Jacobs. Adapted from Wolański [31].

volumetrically efficient than the B cycle, and involves a higher pressure gain than the H, indicating that for the same initial isochoric compression, the FJ cycle is the more efficient of the three. This is supported by the thermodynamic efficiency equations for each of the cycles [31]:

$$\eta_B = 1 - \frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}} \tag{1}$$

$$\eta_H = 1 - k\frac{T_1}{T_2}\frac{\left(\frac{T_{3'}}{T_2}\right)^{\frac{1}{k}}}{\frac{T_{3'}}{T_2} - 1} \tag{2}$$

$$\eta_F = 1 - k\frac{1}{\left(\frac{p_3}{p_1}\right)^{\frac{k-1}{k}}}\frac{\left(\frac{T_{3''}}{T_2}\right)^{\frac{1}{k}} - 1}{\frac{T_{3''}}{T_2} - 1} \tag{3}$$

where η_B, η_H, and η_F are the thermal efficiencies of the Brayton, Humphrey, and Fickett-Jacobs cycles, T is temperature, p is pressure, k is the ratio of specific heats, and the numerical subscripts denote the position on the plot in **Figure 1** [31]. A substitution of the relevant temperatures, pressures, and specific heat ratios into the above equations indicate the higher thermal efficiency of the FJ cycle. Additionally, the thermal efficiencies of various fuels under each of these thermodynamic cycles have been calculated and reported in **Table 1**, further supporting the use of the FJ cycle when exploring detonation cycles as a high efficiency combustion method.

1.3 Pulsed detonation engines

In a PDE, such as that shown in **Figure 2**, a detonation chamber is filled with a fuel/oxidiser mixture and then ignited. The deflagration of the reactants accelerates,

Fuel	Brayton (%)	Humphrey (%)	Fickett-Jacobs (%)
Hydrogen (H_2)	36.9	54.3	59.3
Methane (CH_4)	31.4	50.5	53.2
Acetylene (C_2H_2)	36.9	54.1	61.4

Table 1.
Calculated thermodynamic efficiencies for various fuels under different thermodynamic cycles [26].

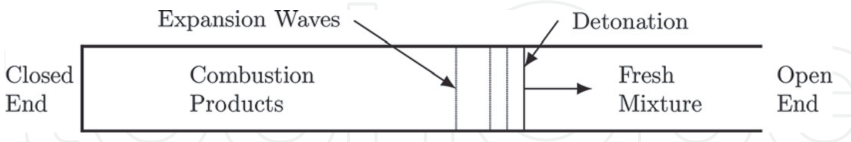

Figure 2.
Labelled schematic of a PDE. Adapted from [15].

and through a deflagration-to-detonation transition (DDT), generates a shock wave. The products are accelerated from the end of the chamber, carried by the detonation front, generating thrust [30, 31]. For each cycle, the chamber must be purged and then refilled with fresh fuel/oxidiser mixture and then detonated again, limiting the maximum practical frequency of operation to an order of 100 Hz [32]. This results in poor efficiency when scaled to high thrust levels as the discontinuous thrust cycles may not be fast enough to approximate the continuity required for propulsion purposes [32–35]. In some designs, it is also necessary to purge the chamber with an inert gas due to some residual combustion products remaining stagnant in the detonation chamber that interfere with the next detonation cycle. This process further restricts the operating frequency to approximately 50 Hz [3, 16].

In order to provide a more compact device, obstacles may be placed in the chamber to accelerate the DDT, but these reduce the specific impulse (I_{sp}) [31, 33]. Specific impulse can be defined as the change in momentum per unit mass of propellant used. An alternative approach is to remove the requirement for repeated DDT transitions, and hence the efficiency loss, by sustaining the detonation reaction. This approach leads directly to the concept of an RDE, which should provide a method of utilising the H or FJ cycle, in a much more compact form.

1.4 Rotating detonation engines

An RDE, such as the one shown as a cutaway in **Figure 3**, consists of an annular combustion chamber, into which fuel and oxidiser, either premixed or non-premixed, are fed through a series of orifices [3, 26, 36]. Each fuel/oxidiser mix requires a slightly different orifice geometry for optimal operation, so some devices have an adjustable injector plate [37, 38].

A detonation wave is initiated in the chamber, most commonly utilising a high speed flame that undergoes DDT by the time it enters the chamber [39, 40]. As this wave propagates around the chamber, it consumes the fuel, generating a high pressure zone behind it. This zone expands, and due to the geometric constraints, exits the chamber, generating thrust [35, 41]. An example of a CFD representation of the propagating wave can be seen in **Figure 4** [42]. Behind the wave, fresh fuel enters the chamber at a constant rate, priming that section of the chamber for the wave to continue on the next revolution, thus making a self-sustaining wave as long as fresh mixture is supplied [35, 43]. The detonation waves generally propagate close to the Chapman-Jouguet velocity (discussed in Section 3.2) for each fuel type (typically 1500–2500 m s^{-1}), so the effective operational frequency of current RDEs is approximately 1–10 kHz. Frequency is dependent on the chamber geometry, fuel,

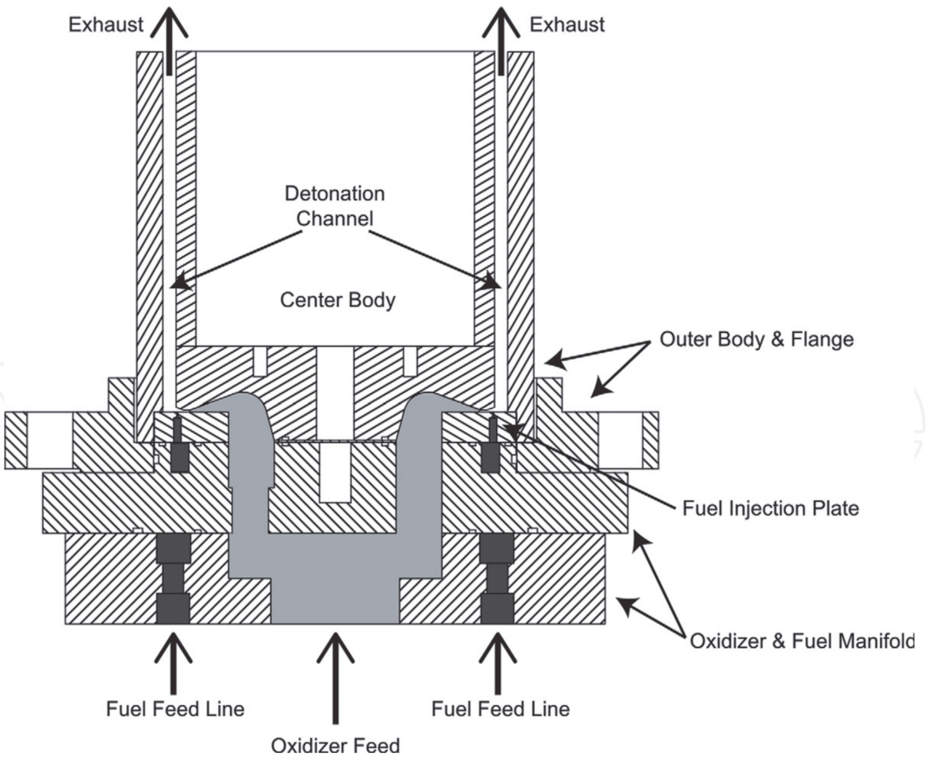

Figure 3.
Cross-section of a typical rotating detonation engine [38].

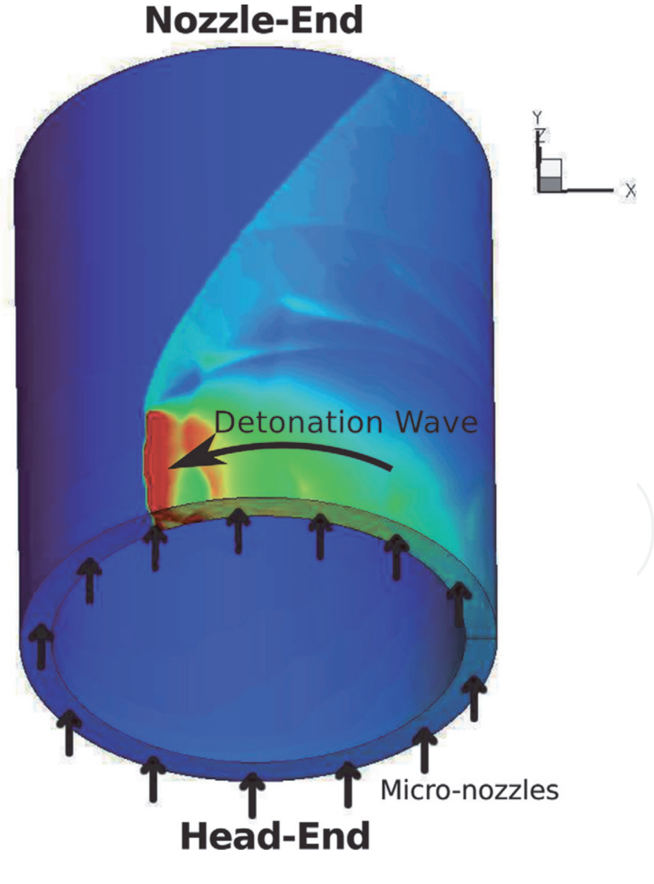

Figure 4.
3D model of the detonation wave propagation in an RDE [42]. The short arrows indicate the flow of fuel/oxidiser into the engine, and the long arrow indicates the direction of detonation propagation.

and thermal and frictional losses [31, 44]. The result is quasi-continuous thrust that approximates a continuous thrust through high frequency rotations, suitable for both direct propulsion applications and in the combustor of a gas turbine [31, 32, 45].

Important areas of RDE research include determining the wave characteristics, geometric constraints, the effects of pressure on the injection characteristics, determining fuel flow properties, and examining the geometry and structure of the detonation wave [3, 4, 30, 31, 41, 42, 44]. Additionally, there has been research into potential applications of detonation engines in which an RDE may be applied, such as air-breathing vehicles and gas turbines [46]. Despite a growing body of work on RDEs, there are still large gaps in current understanding that restrict practical application. Notably, optimising the system for wave stability, ensuring reliable detonation initiation, and ensuring the RDE does not overheat, are significant challenges facing engine development prior to commercial applications. Further development in this area would allow an engine to operate reliably over extended durations, with well-designed chamber and fuel supply.

2. Existing RDE designs

Most experimental RDEs are geometrically similar in design, consisting of an annulus made up of coaxial cylinders [5, 38, 47]. The chamber width, characterised by Δ, sometimes referred to as channel width, varies across designs. Several modular RDEs have been produced for testing various geometric parameters [30, 37, 48, 49]. As will be discussed in Section 4.4, the number of alternative designs to the annulus is limited. An exception is the hollow cylinder model to determine the effects of having no inner wall on the detonation wave as well as the practical feasibility [50].

There is reasonable consistency across published designs in the methods of initiating detonation waves in the RDE. Detonator tubes, in which a high-speed flame is encouraged to transition from deflagration to detonation, have been regularly and reliably used [26, 31, 32, 39, 49, 51]. It has been shown that the success of the detonation tube makes it an excellent initiator, producing a self-sustaining rotating detonation 95% of the time [26].

Like all jet-thrust reaction-based engines, the exhaust from a RDE may be channelled through a nozzle to increase thrust. Outlet and nozzle designs have varied across different RDEs. Many have not attached any nozzle, whilst some have chosen to utilise an aerospike [30, 31, 52]. The use of an aerospike increases performance through higher expansion area ratios, although the increased surface area results in higher heat flux and thus a loss of efficiency from the additional heat transfer [53]. Aerospikes may be directly attached to the end of the reaction chamber [31]. A diverging nozzle was found to increase the specific impulse, although the thrust increase was small, and for angles greater than 10°, the increase with angle was negligible [53]. None have made use of converging or converging-diverging nozzles, because the exhaust is typically flowing at supersonic velocities and thus could be choked through the converging cross-section. This would result in a loss of energy that would decrease the overall efficiency of the system.

A typical RDE, 90.2 mm in diameter, has been tested on a thrust sled [54]. It produced a thrust of 680 N using 176 g s^{-1} of C_2H_4/O_2 propellant at an equivalence ratio of 1.48 [54]. As can be seen from **Table 2**, this is well below that required for typical supersonic flight applications. The specific impulse (I_{sp}) of small scale operational RDEs has ranged from 1000–1200s depending on the fuel/oxidiser source used, though it is often H_2 with air [30, 31, 39, 41, 42]. The measured values of I_{sp} in these small scale RDEs are significantly below computationally predicted range: 3000–5500 s [31, 32]. However, a large scale RDE, discussed in further detail in Section 4, does operate with an I_{sp} of approximately 3000 s [5]. The experimental values for I_{sp} are similar to that of hydrocarbon-powered scramjets, but less than

Engine	Application	Thrust	Thrust to weight
Rolls-Royce Olympus 593	BAC Concorde	38,000 lb (169,000 N)	5.4:1 [55]
Teledyne CAE J402	McDonnell Douglas Harpoon	660 lb (2900 N)	6.5:1 [56]
Pratt and Whitney F135	Lockheed Martin F-35	191,300 N	11.47:1 (dry) [57]
General Electric F414-400	Boeing F/A-18E/F	98,000 N	9:1 [58]
Experimental RDE	None	680 N	3.47:1* [54]

This is the thrust to weight ratio calculated using a pre-weight load cell system.

Table 2.
Thrusts and applications of various engines.

turbojets and ramjets. These low values for small-scale RDEs are likely due to the use of unoptimised designs, and low chamber pressures [31].

RDEs have been found to be successfully operable with a range of gaseous fuels including hydrogen, acetylene and butane, as well as various jet fuels [30, 31]. Air, pure oxygen, and oxygen-enriched air have all be used as oxidisers [31]. Each of these has a variety of advantages and disadvantages, in both performance characteristics, and ease of obtaining, transporting, and storing the oxidiser. Particular difficulty is noted in the transport of gases such as H_2 and O_2 due to the high risk regarding transportation and significant compression of these chemical species [59]. In the case of transporting liquid fuels such as LH_2 and LOx cryogenic units are also required, adding to the already challenging process. The performance characteristics for several of these fuel types will be discussed further in Section 4.4.

The detonation wave velocity in operational H_2/air RDEs has been found to be on the order of 1000 m s^{-1} [30, 39]. In these RDEs, the operational frequencies are on the order of 4000 Hz, which produces quasi-continuous thrust [3, 32]. As wave speed is a key factor in the development of thrust, stable waves with high speeds are ideal for propulsion purposes. Stable detonation waves have reached maximum speeds in the range of 1500–2000 m s^{-1} in most designs using a H_2/air or H_2/O_2 fuel/oxidiser combination (more commonly the former), suggesting that there is open research into whether there is upper limit for detonation wave speed, and subsequently the thrust that may be produced [3, 22, 26, 60]. However, at very high frequencies (19–20 kHz), there may be multiple waves rotating around the annulus [60–62]. Multiple wave modes of propagation appear to be affected by fuel/oxidant equivalence ratio as well as total mass flow rate through the system. The high frequencies are a result of multiple waves travelling at approximately the same speed as the normal single wave. This phenomenon has the potential to provide more continuous thrust, though the higher frequency may limit I_{sp} due to insufficient refuelling of the detonation cell between waves. These wave modes have reliance on factors including fuel injection velocity, critical minimum fill height (discussed further in Section 4.3) as well as the detonation velocity [31]. Due to the inherent instabilities of rotating detonation waves, there are no specific relationships that can be determined between these factors and specific designs, only that they have an influence. Multiple wave fronts have been observed in several different RDE designs, where the general geometry has remained fairly similar [30, 31].

There are several methods of recording data from an operating RDE. Thrust generated may be measured with a thrust plate, and the flow rates of fuel and oxidiser may be measured or controlled within the supply lines [30]. The details of the shock may be recorded with pressure sensors attached to the chamber head, and external cameras [30]. Pressure sensors record the increased pressure generated by the shock, and by using multiple sensors, the detonation wave propagation velocity may be determined. A high-speed camera may be set up to capture the operation of the engine, allowing various parameters to be recorded, including the detonation wave propagation velocity, although this method is limited by spatial resolution, as the channel width can be quite small [30, 39]. A camera may also be used to image from the side, if the outer surface of the annulus is made of a transparent material [63]. Additionally, OH* chemiluminescence may be used to detect, record, and analyse the detonation waves in UV-transparent optically-accessible RDEs [64, 65]. These radicals are indicative of the reaction zone, and so, by analysis of their chemiluminescence, the structure of the detonation can be inferred. Often this detection is done through a quartz side window integrated into the RDE [63]. Peak intensity of the OH* chemiluminescence indicates the location of the detonation front, and so the effects of varying factors such as equivalence ratio and chamber geometries can be documented. Images are often phase-averaged and can by "unwrapped" for comparison to equivalent two-dimensional, "linearised", simulations and designs.

3. Detonation waves

3.1 Shocks

The structure of shock waves in gases was examined in detail by Voitsekhovskii in 1969, including those of shock waves in spinning detonations [66]. These examinations resulted in the first diagram of the structure of a spinning shock wave, and the identification of a number of features, which are identified from the computational model of an RDE shown in **Figure 5** [32]. This model used premixed hydrogen/air as the fuel/oxidiser mixture and has been "unwrapped" into two-dimensions (this approach is described in Section 5.1). Feature A is the primary detonation front; Feature B is an oblique shock wave that propagates from the top of the detonation wave; Feature C is a slip line between the freshly detonated products and older products from the previous cycle; Feature D is a secondary shock wave; Feature E is a mixing region between the fresh premixture and the product gases, where deflagration may occur [67]; Feature F is the region where the injector nozzles are blocked; and Feature G is the unreacted premixture.

In both **Figure 5b** and **Figure 8c** (Section 4.3) the detonation cell structure can be seen, with high pressure zones outlining each cell. These lines of high pressure contain triple points, where the transverse and oblique shocks meet the Mach stem of the detonation wave [68, 69]. The concentrated pressure at these triple points is the point of maximum energy release, and the subsequent pressure spike when two triple points collide generates new detonation cells [68, 70]. While this generation is the main reason behind the propagation of detonation waves, the triple points still require further investigation as to the effects they have on the overall characteristics of a detonation wave [70]. The direction of these triple points can be seen as the white lines in **Figure 8c** with trailing high pressure zones forming the walls of the detonation cells. As the detonation cell width is defined by the geometry of the system and the chemical composition of the detonating fuel, it seems that the triple point velocity and direction must also directly relate to these factors, although limited research has been done to formally connect these points.

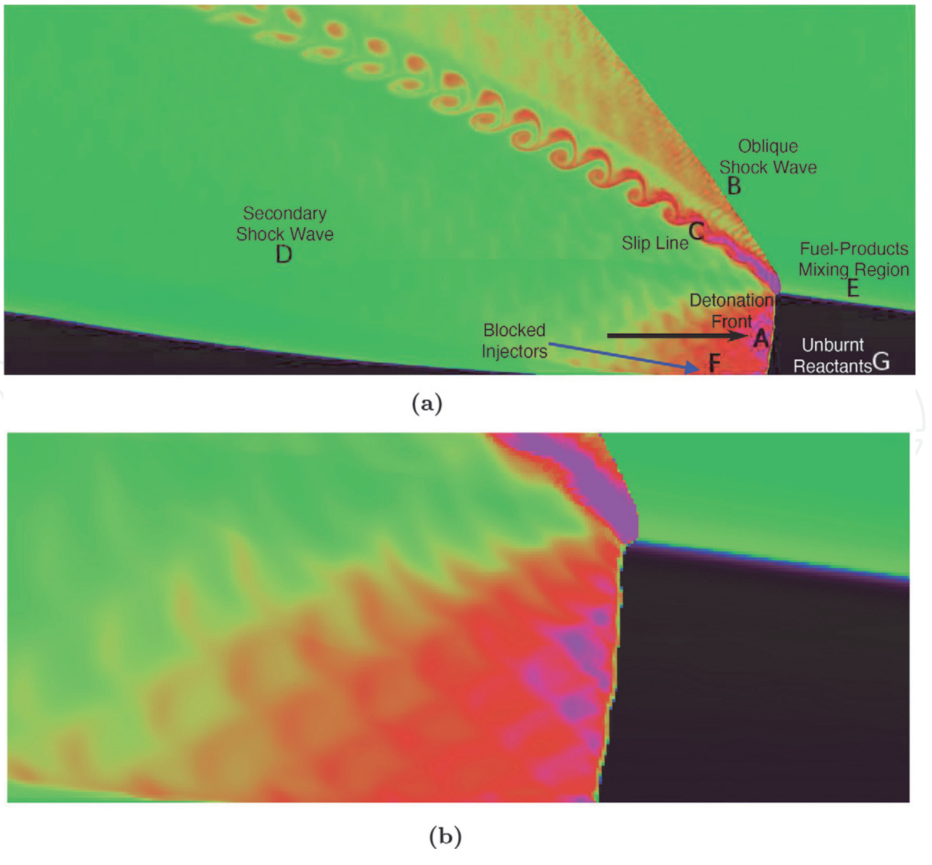

Figure 5.
Pressure contour indicating the cell structure of a detonation wave in an RDE with a premixed supply, taken from a computational modelling study [32]. (a) Pressure contour indicating the full structure of detonation in an RDE, "unwrapped" into two dimensions. Feature A is the detonation wave, Feature B is the oblique shock wave, Feature C is the slip line between the freshly detonated products and products, Feature D is a secondary shock wave, Feature E is a mixing region between the fresh premixture and the product gases, Feature F is the region with blocked injector nozzles, and Feature G is the unreacted premixture. The arrow denotes the direction of travel of the detonation wave. (b) A close-up image of the detonation front.

In an RDE, the detonation wave remains attached to the base of the annulus, as illustrated in **Figure 5b** and in **Figure 6** [3, 6, 71]. This is due to the continuous fuel/oxidant supply [3, 71], as a premixture or allowed to mix in the chamber ahead of the detonation wave [32, 39]. There is also some evidence that stable, lifted waves may also be possible if there is insufficient mixing between the fuel and oxidant

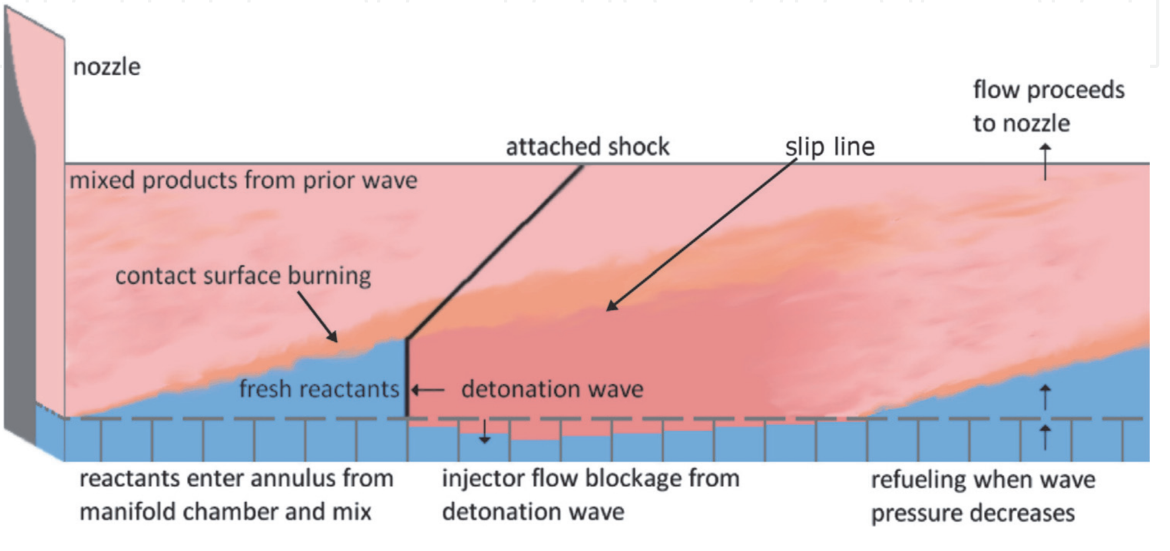

Figure 6.
Diagram showing the general structure of the detonation in an unwrapped RDE [3].

[27, 44]. The propagating detonation wave combusts the reactants [32, 39] which generates a region of extremely high pressure immediately behind the wave. This pressure is on the order of 15–30 times higher than the pressure ahead of the detonation, preventing flow through the injectors [3]. The high pressure zone expands in a Prandtl–Meyer fan, allowing fresh fuel and oxidiser to enter the chamber [35]. This expansion propels the mixed products axially along the engine, generating thrust. In addition to the primary shock, an oblique shock and a secondary attached shock are also generated (Features B and D in **Figure 5a**).

At the interface between the premixed reactants and the combustion products, there is a significant difference between the conditions of the unburnt fuel/oxidiser mixture and the products. This causes some deflagration along the slip line, as shown in **Figure 6**, generating Kelvin-Helmholz instabilities, which vary the detonation propagation velocity [3, 22, 72, 73]. This decrease in the propagation velocity results in an increase in the pressure, disturbing the oncoming shock wave and forcing the sonic flow directly behind the shock wave to undergo supersonic flow acceleration [74]. As shown in **Figure 6** there is a section of injector flow blockage that occurs as the wave passes the fuel array. The high pressure front from the shock wave causes stagnation of the injector flow, or even back-flow which, if not handled, could cause catastrophic failure of the system [3, 6, 36]. This back-flow is a strong reason as to why the fuel and oxidants should not be premixed in practical systems or experimental investigations as it can result in flashback.

3.2 Shock initiation

The Chapman-Jouguet (CJ) condition can be defined as the requirements for the leading shock of a detonation to not be weakened by the rarefactions of the upstream detonation products [75]. This sonic plane then acts to allow the supersonic expansion of the detonated gases to occur without disturbance by rarefactions downstream of the flow [75]. The CJ condition can be used to approximate the detonation velocities in three-dimensional models but is better suited to a one dimensional analysis with an infinitesimally thin detonation front [76]. Despite this, it is used in most instances of numerical modelling as a guide as to whether the wave is performing as expected for the given parameters of the RDE [4, 6, 27, 31, 32, 42, 75, 77]. Chapman and Jouguet's theory only applies to kinetic energy, disregarding the chemical energy of the reacting species, and hence, the Zel'Dovich-von Neumann-Doring (ZND) model is used as a more complete representation of the shock, taking into account the finite chemical reaction area directly upstream of the leading shock [3, 21, 45, 75, 78–80].

There are two methods which may be used to initiate the detonative shock in an RDE—directly in the chamber, or indirectly via a high speed flame in a deflagration to detonation transition (DDT) tube [26, 31, 39, 49, 51]. These tubes are very similar in structure to a PDE. Directly initiating the detonation in the chamber via commercial spark plugs has been found to be generally unreliable, with only a 40% success rate for shock initiation when using CH_4 in O_2 [26]. Particular difficulty is noted in ensuring the detonation travels in the desired direction [26, 32]. In contrast, indirect initiation via a DDT tube has had a 95% success rate for the same fuel/oxidant combination [26, 31]. The indirect method involves using a detonator tube that can be set up in any orientation relative to the chamber, although tangential is favoured for initiating the detonation direction. Initiation is then caused by a small volume of a highly detonative mixture being ignited by spark plugs before DDT occurs, thus initiating the RDE. Perpendicular initiation can also be used, but this often results in the development of two detonation waves that rotate around the chamber in opposite directions [31]. Collision of these opposing waves usually destabilises the system as the waves weaken and reflect back in the direction of origin [31]. Desired direction also appears to be affected by initial total pressure and ignition distribution around the fuel plenum [27, 81]. For a desired single wave direction and propagation, tangential initiation is the most suitable method. Although slightly less compact due to the initiator tube, this may be reduced by placing obstacles in the tube to accelerate the DDT, or by using a more detonative fuel than that used in the primary process [31, 48, 62, 82, 83]. Using an initiator tube, however, may produce small wavelets ahead of the main detonation front, which, if present, reduce the detonation propagation velocity by up to 60% [84]. Once the main detonation is running, the interface between the initiator tube and main chamber must be closed off prior to the shock completing a revolution of the chamber [84]. Additionally, there may be a slight delay, on the order of milliseconds, between the detonation exiting the DDT tube and the commencement of full RDE operation in order to purge the spent reactants from the DDT process [85]. This delay seems to only be transient with no large effects on shock structure or stability, and the excess products are expelled along with the rest of the exhaust [85].

3.3 Instabilities

Three-dimensional modelling has shown that increasing the width of the channel—whilst maintaining the equivalence ratio, injection pressure, chamber length, and injector configuration—increases the detonation velocity, but the transverse shock wave ceases to be aligned with the radial direction [22, 27, 86]. As can be seen in **Figure 7**, the point of contact with the inner wall begins to lead the detonation wave as the channel width increases [22]. This phenomenon generates reflected shocks from the outer annulus wall, which may produce instabilities in the primary shock. It has been suggested through qualitative observation, however, that the effect of upstream reflected shocks on the shock structure may only be minimal [39, 87]. Once the channel becomes sufficiently wide, as shown in **Figure 7c**, the shock wave detaches from the inner wall, briefly forming a horseshoe shape against the outer wall [22]. This allows significant amounts of fuel to pass through the engine without combusting, and produces large instabilities and fragmentation in the detonation wave, which causes the structure to collapse [22]. These lead to a significant loss of performance, and secondary detonations in the exhaust [22]. It has been noted that increasing the channel width also results in increased variance of I_{sp}, and that, combined with high fuel flow rates, leads to the formation of secondary waves, which in turn leads to hotspots and choking the fuel supply

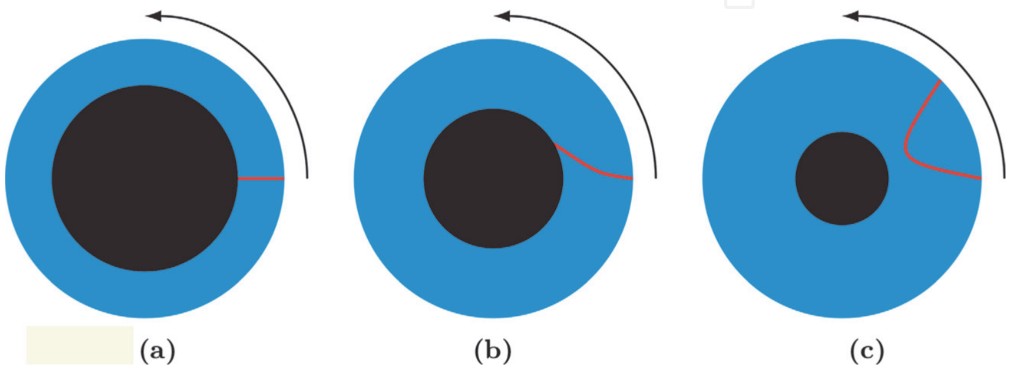

Figure 7.
Schematic of three different RDE designs showing the effect of varying the channel width on detonation structure. Arrows show detonation wave propagation direction. The red line is detonation wave, indicative only. Based on research from [22]. (a) Narrow channel, (b) mid-sized channel, and (c) wide channel.

[42, 62]. This is likely due to the increase in size of the interface area producing greater Kelvin-Helmholz instabilities, resulting in larger variances in the detonation velocity [42].

It has been found that using a fuel-rich mixture produces stable waves with high detonation velocity and efficiency [80, 88]. Higher mass flow rates have also been attributed to increasing the chance of a stable wave being formed [6, 89]. Additionally, it has been shown that the equivalence ratio has a strong influence on the effectiveness of detonation and the stability of the system [80]. Detailed investigation has shown that the stability of the system is improved with increased equivalence ratio, but indicated a maximum equivalence ratio of 1.27, before the detonation wave became short-lived and transient, which is unsuitable for practical purposes [60]. Whether this is a universal limit, or a limit of that particular investigation is unclear, and requires further research. Furthermore, the findings indicated that lower equivalence ratio influences the number of wave fronts produced, with stoichiometric seeming to be a transition point to a stable one wave propagation mode [60, 86, 90]. It is interesting to note that for lean mixtures, the initial channel pressure needs to be higher for a stable detonation to propagate [88].

4. Factors influencing the design of RDEs

4.1 Fuel

The wave propagation velocity varies with the fuel/oxidiser combination. A variety of mixtures have been tested in a detonation tube of an RDE, with their wave propagation velocities and wavefront pressures shown in **Table 3**, which is indicative of their varying performance in an RDE. It should be noted that the pressure, energy and specific impulse in **Table 3** are determined with a detonation tube, and provide a numerical comparison between each fuel/oxidiser combination. Hydrogen/oxygen mixes have been ideal for modelling purposes due to the simple chemistry involved, and are often used in experimental work due to the predictable behaviour. Additionally, the high detonation propagation velocity and wavefront pressure of hydrogen makes it a suitable fuel for real applications. Another common fuel choice is methane, due to the satisfactory propagation velocity and specific impulse in testing [31]. As mentioned in Section 2, the theoretical I_{sp} is still greater than that of a standard turbojet propulsion system, irrespective of fuel selection [91].

Fuel mixture	Detonation speed (m s^{-1})	Wavefront pressure (atm)	ΔH_r(MJ kg^{-1})	I_{sp}(s)
Hydrogen/oxygen	2836	18.5	8.43	289.39
Hydrogen/air	1964	15.5	3.48	200.41
Ethylene/oxygen	2382	31.9	5.23	243.06
Ethylene/air	1821	18.2	2.85	185.82
Ethane/oxygen	2257	29.0	4.87	230.31
Ethane/air	1710	15.8	2.49	174.49
Propane/oxygen	2354	34.2	5.18	240.20
Propane/air	1797	17.5	2.80	183.37

Table 3.
Fuels, wave propagation velocities and pressures, heat of combustion (ΔH_r), and specific impulse I_{sp} [36].

Transportability of fuel, and maintenance of fuel lines, are deciding factors in determining which fuels can be used. These issues are especially important for aerospace applications. Gases such as H_2 and O_2 are particularly volatile and reactive, hence can be difficult to transport in the large quantities needed for use in an RDE. Therefore, gaseous fuels and non-air oxidisers are challenging and largely unsuitable for real world applications [5]. However, H_2 does have a high heat of combustion that is not matched by liquid hydrocarbon fuels. Jet fuel, kerosene, octane and other long-chain hydrocarbons provide a practical alternative to the H_2/O_2 mixture though. High volumetric energy density as a result of liquid state, as well as greater ease of transportability makes these hydrocarbons a more feasible fuel choice.

There are several issues regarding fuel choice that deserve further discussion. In particular, the use of cryogenic fuels for cooling the engine is a beneficial approach, increasing thermal efficiency, as well as reducing the thermal load on other components such as mounting systems [3]. Another advantage is a higher volumetric energy density that comes from the compression of normally gaseous fuel sources. Testing of liquid oxygen (LOx) and gaseous or liquid hydrogen (GH_2/LH_2) fuel/oxidant systems for viability has been performed, but implementation in real world scenarios is challenging [92, 93]. Liquid hydrocarbons require further investigation to demonstrate their effectiveness in producing thrust through detonation [30], particularly because of the need for flash vapourisation to avoid multiphase effects in the mixing process [30, 51].

4.2 Injection

An axial fuel injection process through a circumferential orifice plate was consistent across most simulations and real world models as an injection scheme [5, 6, 22, 26, 30, 32, 36, 38, 39, 41, 42, 42, 52, 61, 62, 82, 86, 88, 92, 94–99]. Further research is required into fuel blockage effects due to the high pressure of the shock wave, with particular emphasis on the effects of increasing fuel pressure to alleviate blockage and increase overall engine performance [100]. In the majority of numerical and physical models, such as **Figure 3**, fuel and oxidiser are injected through an orifice place around the annulus, allowing them to continually feed the propagating detonation wave. Typically, the fuel and oxidiser are fed in separately, and allowed to mix in the chamber [26]. This design is also used in most numerical models, although some have used premixed fuel/oxidiser as a simplified boundary condition. Almost all physical designs have been built without a premixed fuel/oxidant injection scheme due to concerns with flashback [99]. In a premixed design, the shock wave may propagate into the injection plenum, carrying with it the reaction front. With sufficient pressure though, typically 2.3–3 times the chamber pressure, this can be avoided [32].

Investigation into flow characteristics of a turbulent inflow have shown that there are specific zones within the chamber which favour different forms of combustion: some zones favour deflagration, and others favour detonation [101]. The larger deflagration zones created reduce the thermodynamic efficiency of the engine, indicating that fuel flowrate influences the reliability of an RDE [101]. It has been suggested that high inlet velocities generate incomplete combustion and hot spots, reducing detonation wave stability and reducing system efficiency, although further research is required [102]. As indicated in Section 3.3, the introduction of instabilities in the flow profile can decrease the efficiency of the engine as well as disrupt the detonation wave itself. Further findings indicate that increasing the fuel injection area, particularly by increasing the number of orifices, results in more efficient pressure gain [86, 97, 99, 103]. This produces a larger expansion wave of the previous combustion reactants, generating higher thrust, without disrupting the flow-field characteristics [98]. However, with lower fuel injection velocities comes an increased risk of flashback. There is, therefore, some optimal fuel injection area for operation which requires further work to verify [98]. Finally, the pressure ratio between the inlets and the engine outlet also has an effect on the I_{sp} of the engine, with pressure ratios of less than 10 showing notable reductions in impulse [32, 72]. Thus, because of these conflicting requirements, injector design is complex and more research is required such that fuel consumption and thrust output are optimised.

4.3 Scalability

Existing RDEs tend to be relatively small, and therefore may need to be scaled up, or arranged in parallel, to produce thrust required for practical applications, such as those listed in **Table 2**. One method of scaling RDEs is to run multiple identical devices in parallel, in a similar manner to that used to run multiple PDEs [34, 104]. However, this would require more complex plumbing, increasing the weight of the overall system, and thus decreasing the thrust-to-weight ratio. However, this solution has not been explored in any depth and its viability is unknown.

In order to make larger RDEs, in-depth research into the geometry of the combustion chamber is required. A number of relationships between the critical detonation wave height and the various dimensions have been identified [27, 30]. Detonation structure, as described in Section 3.1 is composed of small diamond shaped detonation cells that make up the front. The widths of these cells are dependent on the energy of the detonation (related to the fuel in use) as well as the available geometry for detonation. In this way, the equivalence ratio can be a large determining factor [30, 105, 106]. Critical minimum fill height is the minimum mixture height required for a detonation wave to propagate through a given fuel/oxidiser mixture. It has been found that the critical minimum fill height, h^*, and the minimum outer wall diameter, $d_{c_{min}}$, are related to the detonation cell width, λ, by

$$h^* \propto (12 \pm 5)\lambda \tag{4}$$

$$d_{c_{min}} = 28\lambda \tag{5}$$

and the minimum channel width, Δ_{min} is related to the h^* by

$$\Delta_{min} \propto 0.2h^* \tag{6}$$

Finally, the minimum axial length of an RDE, L_{min} is related to the actual fill height, h, by

$$L_{min} = 2h \tag{7}$$

although lengths under 2–3 times the minimum result in reduced efficiency due to incomplete combustion [27]. However, in simulations, it has been suggested that for low inlet-nozzle pressure ratios the wave the wave height grew with the chamber length, reducing the I_{sp}, of the engine [42]. For high pressure ratios, no such reduction was indicated [42]. **Figure 8** indicates the physical representations of the above variables.

There is not yet any theoretical data for λ, but there are multiple models which may be used to predict the value under various conditions [78]. It is known that more highly reactive mixtures, such as H_2/O_2, have lower λ values, and so have minimum

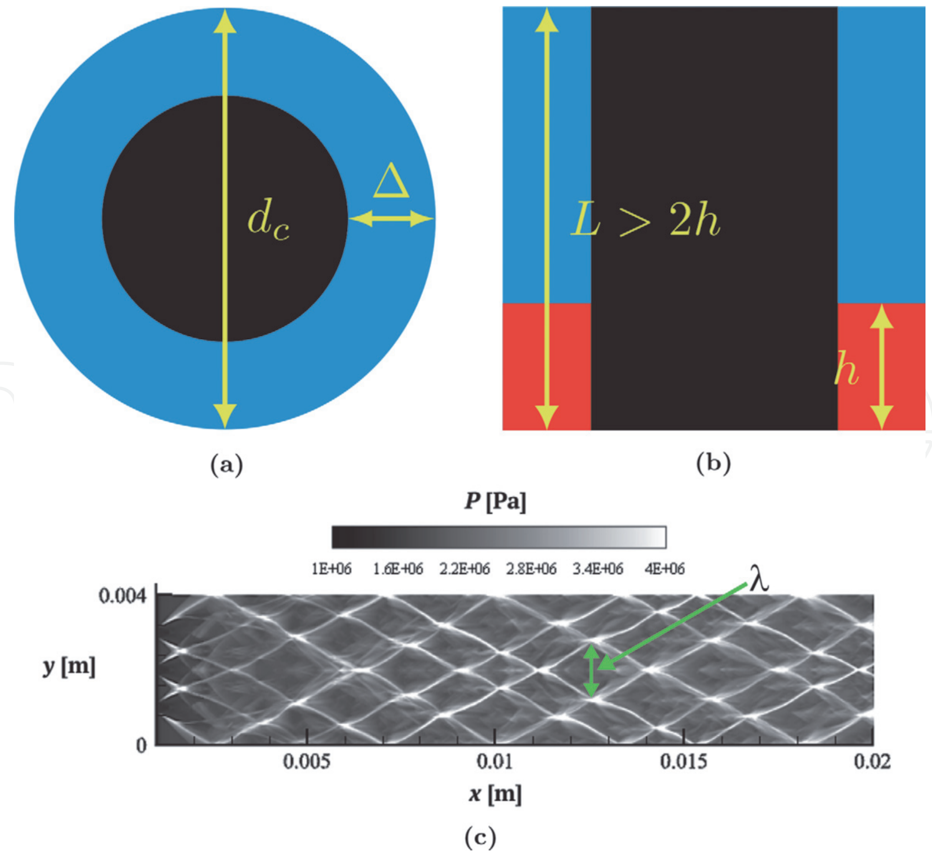

Figure 8.
Geometric parameters of an RDE. The red area is the area filled by the fuel/oxidiser mix in which the detonation propagates. (a) Top view, (b) side view, and (c) detonation cell width adapted from [79].

chamber diameters on the order of 40–50 mm. Liquid hydrocarbons, such as kerosene and jet fuel, combusting in air, have reactions with higher λ, so, when Eq. (5) is applied, the minimum chamber diameter is calculated to be 500 mm [3].

Modelling a large-scale RDE presents a challenge due to increasing computational requirements with increasing size, so limited work has been done in this area. Nevertheless, a larger scale experimental RDE has been demonstrated [5]. This RDE had an outer chamber diameter of 406 mm, and a channel width of 25 mm, and an air inlet slit that could be varied across the range 2–15 mm [5]. It produced a consistent thrust of 6 kN with a combined fuel/oxidiser flow rate of 7.5 kg s^{-1}, whilst also producing an I_{sp} at 3000 s, consistent with the computational models noted in Section 2 [5, 31]. This is approximately four times the physical size, ~40 times the consumption of combined fuel/oxidiser, and ~12 times the thrust of other RDEs noted in Section 2 [46, 54]. Although still producing low thrust compared with conventional jet engines, such as those listed in **Table 2**, it is also half the diameter of the modern engines [57, 58]. Furthermore, 6 kN would be more than sufficient thrust for use in a Harpoon missile [56], and this RDE shows that they are capable of being scaled beyond small sizes.

4.4 Alternative designs

The design used in most simulations and experimental work is a coaxial cylinder structure [3, 27, 31, 35]. This simple geometry is advantageous for both modelling and manufacturing. Design variations including using nozzles, aerospikes such as that shown in **Figure 9**, or an entirely hollow cylinder, have been utilised in several RDE designs [5, 52].

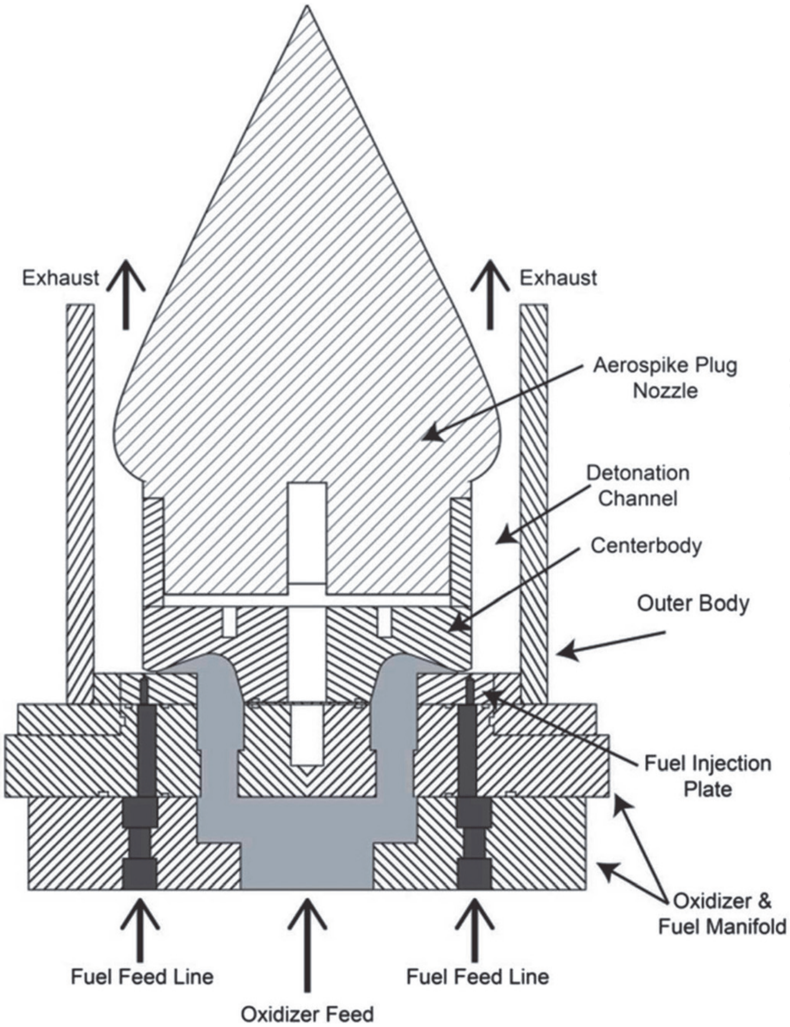

Figure 9.
Example of an aerospike nozzle configuration [52].

Alternative chamber geometries have been largely limited to adjustments in the diameters of the chamber [4, 42], including with different sized engines [15, 31, 39, 54]. Other work has been conducted on a single RDE with interchangeable outer wall sections [22, 30]. As noted in Section 2 and Section 3, both of these factors influence the stability and the performance of RDEs. The effect of varying the length of the chamber on the detonation propagation has been investigated, which led to the previously mentioned requirement that the chamber be at least twice, and preferably four to six times, the fuel fill height [4, 96].

Hollow RDEs, dubbed "centrebodiless" designs, have been tested with two different designs [50, 61]. One design was identical to a conventional RDE 100 mm across, but the inner cylinder terminated parallel to the fuel/oxidiser injectors [61]. In this design, tested with 169.7 g s^{-1} of CH_4/O_2 at an equivalence ratio of 1.154, it was found that the detonation was unstable [61]. The fuel and oxidiser were free to move into the space usually occupied by the centre body, and thus insufficiently mixed to sustain a stable detonation [61]. However, when the same geometry was tested with 253.3 g s^{-1} of CH_4/O_2 at an equivalence ratio of 0.665, the mixture became sufficiently mixed to sustain a stable four-wave detonation structure [61]. Another design was completely hollow, allowing oxygen-enriched air to be pumped through the centre of the chamber, and fuel was supplied around the edge [50]. In this design, stable detonations, operating at $\sim$8000 Hz were achieved at an equivalence ratio of $\sim$0.4 [5-]. However, this design required that the molecular ratio of nitrogen-to-oxygen in the oxidiser be approximately two for detonation. Nitrogen-to-oxygen ratios of $\sim$2.5 produced deflagration, and a ratio of 3.75—approximately standard air—led to the RDE self-extinguishing [50]. Nevertheless, the need for oxygen enrichment introduces additional cost and challenges for practical RDEs in propulsion applications. It was also noted that the oxidant flow provides an outward pressure that acts like a wall but carries no extra weight, and even adds a small amount of thrust as the air is expelled [50]. Both designs can be looked at as successful proofs of concepts, and potential first steps in simplifying the geometry of an RDE, with the latter being potentially useful in applications such as after-burners [50, 61]. However, this concept has not been explored with pre-heated reactants, such as those which would be present in an afterburner.

The attachment of turbines to RDEs has been proposed [8, 9, 31, 32, 45]. It has also been noted that there is a secondary shock propagating from the detonation, which exits the outlet of the chamber [32]. However, turbine blades are sensitive to shocks. As such, the effect of the secondary shocks on the blades of potential turbines must be investigated. It is worth noting that an experimental PDE array has been tested with an attached turbine, in the form of an automotive turbocharger [31]. In that case, a buffer chamber was inserted between the PDE and the turbine [31], and such a technology may be suitable for RDEs.

5. Modelling and development tools

5.1 Planar and three-dimensional modelling approaches

Computational fluid dynamics (CFD) modelling is a powerful tool for the analysis of rotating detonations prior to, or in tandem with, experimental systems. The majority of numerical studies have aimed to provide in-depth understanding and details of the detonation structure [22, 41, 62, 67, 72, 94, 107, 108] or assess the physical and modelling factors influencing performance [32, 67, 73, 109].

Computational models of the azimuthal detonations in RDEs may use full three-dimensional geometries [20, 22, 67, 94, 95, 107, 110] or simplified, two-dimensional geometries [6, 32, 41, 43, 62, 72, 73, 108, 109, 111–114]. The former, higher-fidelity, approach can incorporate complex geometric and flow features, although require $\sim$ 10,100 million numerical cells for high fidelity large-eddy simulations (LES) or direct numerical simulations (DNS) [22, 94, 95, 112]. These may subsequently result in considerable computational expense in conjunction with detailed turbulence and combustion chemistry. In contrast, by assuming that the channel width is much smaller than the diameter, the annulus geometry may be "unwrapped" [108] and treated as a planar flow [41]. The azimuthal detonation repeatedly travels through the domain using periodic boundaries (i.e. the outflow from one side feeds into the other side). Such a model was shown previously in **Figure 5a** [32], where the detonation is travelling left-to-right and the two vertical edges of the image are the periodic boundaries. This can be seen by noting the height of the unreacted premixture region (Feature G) at each side of the figure. The stationary geometry shown in **Figure 5a** [32] shows a full, two-dimensional, unwrapped RDE geometry, and allows the detonation to freely—and repeatedly—propagate through the domain. It may, in some cases, be beneficial to examine the detonation in its own frame, by matching the domain velocity to the negative of the detonation speed; however, this requires significant trial-and-error as the detonation speed cannot be accurately approximated as the CJ velocity for this purpose [108].

Two-dimensional modelling of RDEs assumes that the flowfield along the centre of the channel is representative of shock and deflagration structure across the entire width. Consequently, this inherently assumes slip-wall conditions and that the detonation-front is normal to the two-dimensional geometry. In the unwrapped two-dimensional geometry, all fuel is injected axially from one edge (the bottom edge in **Figure 5a** [32]) and is exhausted through the opposite edge (the top edge in **Figure 5a**) [6, 32, 72, 111]. It therefore follows that all exhaust products must leave the domain axially, due to conversation of angular momentum. This was confirmed in early two-dimensional modelling, which found that the density-averaged azimuthal velocity was less than 3% of the axial velocity [41]. Such a criterion could be extended to assessing whether a three-dimensional model, at some fixed radius within the channel, could be treated as an unwrapped planar domain.

Detonation wave curvature, imperfect mixing, three-dimensional turbulent structures and transverse shocks are features reported in three-dimensional computational modelling [22, 67, 79, 94, 107] and experimental studies [62]. These features arise from the effects of channel size [22], discrete injectors [79] and interactions between transverse waves and walls [62, 79]. These features are inherently three-dimensional and cannot be captured using planar, periodic models, and require more complex computational geometries.

5.2 Boundary conditions in computational models of RDEs

Fuel/oxidiser inlets may be modelled as simple points, lines, surfaces or complex, discrete injectors. The latter may be treated as a series of inlets in two-dimensional models, assuming upstream micro-mixing [109, 112]. Differences in the injector configuration can lead to differences in detonation pressure [112], or lifted flame behaviour in the event of poor mixing in a partially premixed system [109]. The study which observed the latter phenomenon, however, was undertaken using the Euler equations, which may affect the fidelity of modelled mixing (discussed later in this section), and a simplified induction parameter model (described in Section 5.4) [109], although this has also been observed experimentally in C_2H_2-fuelled RDEs [115].

Inlet boundary conditions in premixed models, are often defined by inlet throat-to-nozzle-exit ratios. These, and the set upstream pressure, control whether the inlets are blocked, subsonic or choked and are chosen to range from 0.1–0.2 [6, 109, 110, 112], although ranges as large as 0.07–0.3 have shown little effect on I_{sp} [73]. More complex fuel injector geometries have been assessed through three-dimensional modelling [94], demonstrating the effects of the complex detonation/deflagration interactions on imperfect mixing, however, neither instantaneous (fuel or air) plenum pressures nor detonation wave-speeds could be correctly predicted.

5.3 Turbulence modelling in RDE simulations

Rotating detonation engines have often been numerically modelled using the compressible Euler Equations [6, 20, 32, 41, 43, 62, 72, 95, 108, 110–112]. The Euler equations conserve momentum, mass and energy, but do not account for viscosity, following the assumption that the detonation structure dominates viscous dissipation. Viscous effects may, however, be incorporated into numerical studies of RDEs through the use Reynolds-averaged Navier Stokes (RANS) modelling [107, 113], LES, LES-RANS hybrids such as [improved] delayed detached eddy simulations (IDDES) [67, 94], or DNS [22]. Of these approaches, Euler, IDDES and DNS studies [22, 41, 67] have all been able to capture Kelvin-Helmholtz instabilities in the unreacted/reacted and the post-shock mixing layers (see **Figure 5a** as an example), using sufficiently small element sizing in both two- and three-dimensional models.

The grid required to resolve large structures in RDE mixing layers is dependent on the size of the geometry. Elements of 200 μm have been shown to predict shear layer instabilities using either Euler equations or IDDES in an RDE with a mid-channel diameter of 90 mm [67] and an ∼140 mm inner diameter RDE required axial and azimuthal elements smaller than 200–300 μm to capture the structures in a DNS study [22]. In contrast, Kelvin-Helmholtz structures were not observable in models of a 1 mm outer diameter RDE with computational elements larger than 1.25 μm [73]. In all cases, these minimum azimuthal element sizes are ≲0.21% of their respective mid-channel diameters, suggesting a minimum relative element size relative to geometry. These element sizes are not, however, proportional to the CJ induction lengths which are ∼200–300 μm for stoichiometric H_2/air mixtures near 300 K [116, 117], compared to ∼50 μm H_2/O_2 [117].

Both viscosity and species diffusion have been stated as critical features in non-premixed models of RDEs, promoting the use of IDDES or LES in modelling studies [67]. In contrast, a negligible dependence of detonation velocity or I_{sp} was reported in DNS of a partially-premixed "linearised" model [114] (refer to Section 5.5 for more on these models). Despite this, it is crucial to note that Euler equation models significantly over-predicted deflagration upstream of the detonation in the premixed numerical RDE model [67], whereas the mixture upstream of the shock in the linearised model is completely unreacted [114, 118]. This warrants further study on the differences of these modelling approaches on detonation interactions with non-premixed fuel/air injection into post-combustion gases. This is further complicated by the suggestion that the absence of viscous dissipation and diffusive mixing in the Euler equations could enhance perturbations driven by baroclinic vorticity generation which is, in turn, promoted by wrinkling in the deflagration upstream of the detonation.

Although the Euler equations cannot account for viscous effects, such as wall shear-stress and heat transfer, these have a small, but non-negligible, effect (∼7%) on predicted I_{sp} compared to IDDES modelling including non-slip, isothermal walls in premixed RDE models [67]. The appropriate selection of wall boundary conditions will therefore likely prove to be an important factor in RDE development, with different thermal treatments significantly changing the fraction of fuel burnt upstream of the detonation wave [67]. Neglecting these physical features, results in decreased deflagration away from the detonation wave, with adiabatic walls most significantly over-predicting combustion outside of the detonation wave [67]. Despite this, detonation wave-speeds were reasonably insensitive to wall temperatures in the range of 500–800 K in the same study, and consistently over-predicting experimentally measured detonation wave-speeds [94], although temperatures significantly exceeding the autoignition temperature (up to the adiabatic wall temperatures ∼2000 K) were not assessed.

Incorporating viscosity and thermal wall-effects into IDDES simulations requires significant computational resources. One such study required a computational mesh of ∼100 million computational elements, included multiple chemical species and reactions, with numerical time-steps of 30 ns [94] and is similar to an earlier study using approximately one-third of the number of cells which required ∼ 35,000 CPU-hours to solve [67]. Several cases in an earlier study, however, required ∼9 million CPU-hours to produce a final solution due to the use of time-steps of 2 ns [67]. In addition to IDDES studies, viscous and diffusive effects may be accounted for in unsteady RANS modelling [107] and facilitate the inclusion of detailed chemistry (see Section 5.4) with significantly lower computational overhead than IDDES or DNS. Such RANS models cannot, however, capture the turbulent fluctuations in the instantaneous flow-field, although there is evidence that they may be able to provide sufficient accuracy for parametric studies of mixing, detonation wave structure and loss mechanisms in RDEs [119, 120]. The interactions between detonations, deflagration and viscous and thermal wall-effects add further complexity to producing RDE models which can accurately reproduce experimentally measured engine characteristics, although the computational resources may currently prohibit broad parametric studies using high fidelity modelling approaches.

5.4 Chemical kinetics and interaction models

The majority of numerical RDEs works to date targeted H_2/air and H_2/O_2 systems [6, 20, 22, 41, 62, 72, 73, 79, 94, 95, 111, 112, 118, 121, 122], given their relatively simple chemistry in comparison with both small and large hydrocarbons. Nevertheless, limited data are also available for linearised CH_4/air and C_2H_4/air systems [114].

The simplest approach to describe the chemistry is that of a one-step irreversible reaction [6, 43, 62, 95, 108, 109]. This assumption has been widely used to numerically investigate various aspects of fully premixed canonical RDE cases and useful insights have been gained [6, 32, 95]. However, it is well known that such a simplification is not able to accurately quantify many detonation responses of interest (e.g. upstream deflagration phenomena [109], triple shocks structure [79, 116]), mainly due to the sensitive Arrhenius nature of the reaction rate to temperature variations. Also, the use of *ad hoc* correlations of the experimental data with adjustable kinetic parameters (e.g. reaction order, activation energy) are only valid for a limited range of the system and thermodynamic parameters [116].

Simplified approaches to chemical kinetics may employ a one-step reversible reaction [20, 62] or a two-step mechanism [22, 41] to describe the chemistry within a system. In particular, for the one-step case, the forward reaction rate is calculated using the classical Arrhenius equation with the reaction rate constants tuned from a reference case while the backward reaction rate is calculated from the assumption of local chemical equilibrium [20, 62]. This approach has been validated against detailed chemistry for a 1D model [20]. For canonical 2D premixed RDEs, a one-step reversible reaction is not able to accurately capture the post-detonation temperature while it is able to predict both the experimental pressure and velocity fields [20]. In addition, it was also found that this approach can be successfully implemented to describe stratification effects in three-dimensional non-premixed RDE systems [62].

For the one-step case, a number of two- and three-dimensional premixed RDE simulations employ an induction-time parameter model (IPM) to compute the chemical source terms [6, 32, 43, 109]. The IPM has shown reasonable accuracy for the prediction of detonation wave propagation in premixed systems [108], as the induction time is derived from the same configuration as the CJ wave-speed [116]. In addition, it is computationally inexpensive as a global induction parameter allows for release of energy over a finite period of time. Nevertheless, the IPM lacks the flexibility to accurately describe the physics occurring in more realistic non-premixed systems [94]. The thermodynamic properties of the single product species employed in this model are dependent upon the equivalence ratio of the fuel/air mixture. Therefore, this approach cannot easily handle the spatially varying local equivalence ratio occurring in a non-premixed system [116]. This model also lacks the capability to capture the low-pressure heat release and the change in equilibrium chemistry of post-detonation products. Finally, this method requires *a priori* calculation of the CJ induction time, but the computed detonation velocities in detailed simulations can be significantly higher than that of CJ velocity [94]. If this approach is extended to a two-step reaction model (consisting of an induction reaction followed by an exothermic recombination reaction), two progress variables are obtained and need to be solved in lieu of individual species concentrations. This approach is termed two-parameter progress variable, and it has been successfully applied for premixed systems [22, 41]. Nevertheless, the variation of the two source terms is extremely sensitive to the choice of the constants adopted [22]. Global chemistry has also been implemented through the well-known PDF method [107], although this approach is generally used for detailed chemistry in combustion processes [123].

Finite-rate kinetics and the associated kinetic mechanisms are needed to capture complex phenomena such as near-limit propagation leading to quenching of the detonation wave [116]. This is mainly because the use of a one-step reaction precludes the influence of chain-branching-termination mechanisms that are invariably multi-step in nature. In this regard, an advanced approach is the induction-length model, which concerns determining the induction length for adiabatic propagation and using it to estimate global detonation parameters such as the cell size of steady propagation and the wave curvature at quenching [116]. This study showed that at least a four-step mechanism is required to achieve acceptable predictions in CJ detonation.

Models of RDEs using H_2/air, H_2/O_2, CH_4/air and C_2H_4/air mixtures have employed detailed chemistry and simplified configurations [68, 72, 73, 79, 111, 112, 114, 118, 122], although only limited studies are available in comparison with simplified (one- or two-step) chemistry, given the relatively large computational expense required and the current computational resources. A set of 8–9 chemical species and 18–21 elementary reactions are generally employed for H_2 systems [72, 112], while 21–22 species and 34–38 reactions are used for simple hydrocarbons systems [114]. These studies highlighted that the use of detailed chemistry is needed to accurately predict the energy-release pattern in RDEs and complex characteristics, including re-ignition, number of triple points and transverse waves [68].

5.5 Linearised model detonation engines

A linearised model may be constructed to simulate the operation of an RDE [79, 124]. These models, shown in **Figure 10**, are known as linearised model detonation engines (LMDEs). In this model, fuel is fed into the chamber, and a transverse

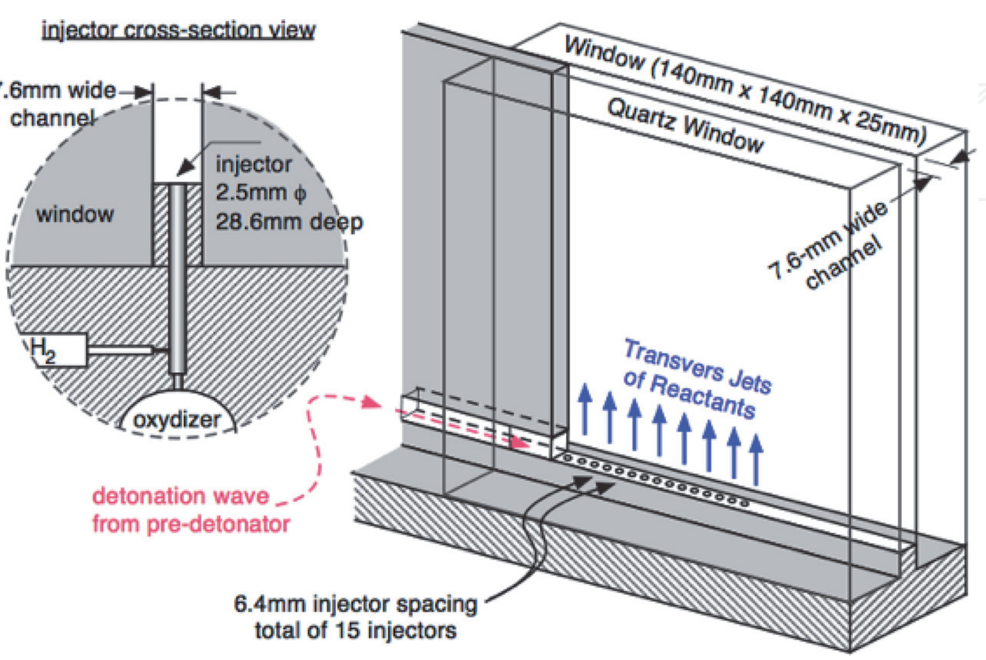

Figure 10.
An example linearised model detonation engine [79].

shock wave propagates through it. This occurs in much the same manner as in an RDE. However, the chamber is rectangular, and so the detonation only makes a single pass through the chamber [79, 124]. Both computer models and practical experiments have been run in three different modes, all using fresh supplies [79, 125]:

- The chamber is pre-filled with premixed fuel/oxidiser, and then the detonation is initiated.
- The chamber is pre-filled with an inert gas, then premixed fuel/oxidiser is injected and the detonation is initiated simultaneously.
- The chamber is pre-filled with oxidiser, then fuel is injected and the detonation is initiated simultaneously.

LMDEs have been used to characterise the detonation process, by allowing both sides of the chamber to be imaged through quartz walls, or the density field imaged through the use of the Schlieren technique [79, 126]. It has been found that the critical fill height of an LMDE is about 10λ, which is consistent with Eq. (4) for RDEs [27, 126]. It has been found that the presence of background gases, such as the inert gas used to pre-fill the chamber, strongly affected the detonation process, causing the reaction zone to slightly trail the detonation wave [125]. This produced fluctuations in the wave velocity, adversely affecting the detonation propagation [125]. This would seem to be consistent with mixing of detonated and undetonated reactants producing Kelvin-Helmholtz instabilities in an RDE, as noted in Section 3.1 [3, 22, 72, 73]. It was also found that low pressure zones in an LMDE attenuate reflected shocks [124]. This suggests that, should a shock wave be reflected off an irregular feature in an RDE’s annulus, then the shock would not serve as a significant source of thermodynamic loss [124].

Computer modelling of an LMDE indicated that the propagation of a detonation wave was not affected by the turbulence caused by in-chamber mixing of fuel and oxidiser [118]. However, the presence of this turbulence did cause the reaction zone to trail the detonation wave [118]. A model of an LMDE was also used to test the result of applying different back pressures, such as might occur if a nozzle or a turbine was attached to an RDE [114]. This indicated that increased back pressure also increased the detonability of the fuel mixture, but also restricted the acceleration of the products, which, in some cases, led to the production of tertiary shock waves to sufficiently compress the flow to match the exit plane conditions [114]. However, as noted previously in Section 2, nozzles have very limited benefit [53], and, as noted in Section 4 the effect of secondary and tertiary shocks on a turbine may be problem.

6. Future outlook

Rotating detonation engines have the potential to provide a significantly more efficient combustion cycle than deflagration-based engines. The application of this technology to turbines promises to increase the thermodynamic efficiency of these engines to previously unattainable levels. Additionally, RDEs as a standalone engine hold significant promise for both air-breathing and air-independent rocket propulsion. However, there exists a large body of research and development work still-to-be undertaken, including:

- Nozzles have been shown to have limited benefit to the thrust generated by RDEs. However, varying the angles of the walls of an RDE, either independently or together, may simulate the effect of a nozzle to provide a slight benefit to performance. It remains unknown what effect such modifications to the conventional cylinder might have.

- Comparisons of thrust to weight ratios between experimental RDEs and conventional rocket engines show similar values, indicating that an RDE could represent a method of propulsion in space. This has not been widely explored as an option, and would benefit from experimental work in vacuum conditions or microgravity conditions.

- It has been suggested that there may be a maximum equivalence ratio at which an RDE will operate, but further investigation is required to determine if this is a universal limit, and identify ways to lower the limit.

- Triple points appear to have significant effect on the propagation of the detonation wave but little work has been done on determining the constraints, besides chemical composition, on the formation of stable and consistent triple points as well as the effect of those parameters on other characteristics of the triple points such as peak pressure and propagation direction. Findings would be beneficial in terms of properly defining the parameters that affect λ as well.

- Very few studies have provided a mathematical relationship between the detonation cell width and the geometry requirements of the chamber. More supporting work to help refine and verify or dispute the relationships that have been established needs to be done, so that in the future, specialised design needs can be catered for through knowing the geometry and cell width of fuel types.

- Varying the channel width has been noted to affect the stability of the detonation wave in an RDE. As such, this is likely to affect the performance of such devices. Further research is required to determine what the optimal width would be for different design requirements.

- It is established that RDE chambers need to be at least twice as long as the fuel fill height, and increasing the length four to six times the fill height improves the efficiency. However, depending on the ratio of inlet pressure to nozzle pressure, such a length increase may also result in reduced I_{sp}. Further research is required to determine an appropriate balance of these effects, and the effect chamber length has on other design parameters.

- So-called "centrebodiless" designs have been explored, and proposed for use in afterburners. However, they have not been modelled or tested with heated high velocity air, as would be typically found at the outlet of a conventional jet engine, so their potential performance remains unknown.

- It has been demonstrated that the thrust produced by RDEs scales non-linearly with engine size, but they are not yet approaching the size required to replace most existing gas turbines. It remains unknown if an RDE can be scaled up sufficiently to provide the thrust levels offered by contemporary gas turbine engines.

- It has been suggested that a turbine could be attached to an RDE. However, the effects of the various shocks on a turbine have not been explored. In particular, the oblique shock (Feature B in **Figure 5a**) has been shown to propagate out of the chamber, and is likely to have significant effect on the viability of using a turbine.

- The invsicid Euler equations have been demonstrated to over-predict deflagration in three-dimensional computational models of premixed RDEs, even with the use of detailed chemistry. Their validity in non-premixed RDE configurations, with deflagration upstream of the detonation and the potential to produce lifted detonation waves, still requires rigorous assessment.

- Viscous and thermal wall-effects in RDEs have significant effect on RDE performance characteristics, and may be essential in accurately reproducing experimentally measured values. Understanding of the appropriate numerical modelling approaches of these effects, however, is still immature, owing to the computational resources required for sufficiently fine resolution of near-wall grids.

- The computationally predicted wave-speeds and plenum pressures in RDEs are significantly different to those measured experimentally. It has been proposed that this could be partially due to baroclinic vorticity, resulting from interactions between detonation waves, fresh reactants, deflagration reaction-zones and post-combustion products, although this is yet to be analysed in detail in either full RDEs or linearised models.

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References

[1] Cullen R, Nicholls J, Ragland K. Feasibility studies of a rotating detonation wave rocket motor. Journal of Spacecraft and Rockets. 1966;**3**(6): 893-898

[2] Eidelman S, Grossman W, Lottati I. Review of propulsion applications and numerical simulations of the pulsed detonation engine concept. Journal of Propulsion and Power. 1991;**7**(6): 857-865

[3] Lu FK, Braun EM. Rotating detonation wave propulsion: Experimental challenges, modeling, and engine concepts. Journal of Propulsion and Power. 2014;**30**(5):1125-1142

[4] Bykovskii FA, Zhdan SA, Vedernikov EF. Continuous spin detonation of hydrogen-oxygen mixtures. 2. Combustor with an expanding annular channel. Combustion, Explosion, and Shock Waves. 2008;**44**(3):330-342

[5] Frolov S, Aksenov V, Ivanov V, Shamshin I. Large-scale hydrogenair continuous detonation combustor. International Journal of Hydrogen Energy. 2015;**40**(3):1616-1623

[6] Schwer D, Kailasanath K. Numerical investigation of the physics of rotating-detonation-engines. Proceedings of the Combustion Institute. 2011;**33**(2): 2195-2202

[7] Kailasanath K. Review of propulsion applications of detonation waves. AIAA Journal. 2000;**38**(9):1698-1708

[8] Heiser WH, Pratt DT. Thermodynamic cycle analysis of pulse detonation engines. Journal of Propulsion and Power. 2002;**18**(1):68-76

[9] Wintenberger E, Shepherd J. Thermodynamic cycle analysis for propagating detonations. Journal of Propulsion and Power. 2006;**22**(3): 694-698

[10] Yi T-H, Lou J, Turangan C, Choi J-Y, Wolański P. Propulsive performance of a continuously rotating detonation engine. Journal of Propulsion and Power. 2011;**27**(1):171-181

[11] Rotaru C, Mihăilă-Andres M, Renard P. New constructive solutions for aircraft turbojet engine combustion chamber. Journal of Military Technology—MTA Review. 2013;**23**(4): 219-230

[12] Nicholls JA, Wilkinson HR, Morrison RB. Intermittent detonation as a thrust-producing mechanism. Journal of Jet Propulsion. 1957;**27**(5):534-541

[13] Dunlap R. A preliminary study of the application of steady-state detonative combustion to a reaction engine. Journal of Jet Propulsion. 1958;**28**(7):451-456

[14] Wu Y, Ma F, Yang V. System performance and thermodynamic cycle analysis of airbreathing pulse detonation engines. Journal of Propulsion and Power. 2003;**19**(4):556-567

[15] Kailasanath K. Recent developments in the research on pulse detonation engines. AIAA Journal. 2003;**41**(2): 145-159

[16] Bussing T, Pappas G. An introduction to pulse detonation engines. In: 32nd Aerospace Sciences Meeting and Exhibit. 1994. p. 263

[17] Eidelman S, Yang X. Analysis of the pulse detonation engine efficiency. In: 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 1998. p. 3877

[18] Voitsekhovskii BV. The spin detonation. Doklady Akademii Nauk. 1957;**114**(4):717-720

[19] Yetao S, Meng L, Jianping W. Continuous detonation engine and effects of different types of nozzle on its propulsion performance. Chinese Journal of Aeronautics. 2010;**23**(6): 647-652

[20] Yi T-H, Turangan C, Lou J, Wolański P, Kindracki J. A three-dimensional numerical study of rotational detonation in an annular chamber. In: 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. 2009. p. 634

[21] Nakayama H, Moriya T, Kasahara J, Matsuo A, Sasamoto Y, Funaki I. Stable detonation wave propagation in rectangular-cross-section curved channels. Combustion and Flame. 2012; **159**(2):859-869

[22] Katta VR, Cho KY, Hoke JL, Codoni JR, Schauer FR, Roquemore WM. Effect of increasing channel width on the structure of rotating detonation wave. Proceedings of the Combusion Institute. 2019;**37**(3): 3575-3583

[23] Lee S-Y, Watts J, Saretto S, Pal S, Conrad C, Woodward R, et al. Deflagration to detonation transition processes by turbulence-generating obstacles in pulse detonation engines. Journal of Propulsion and Power. 2004; **20**(6):1026-1036

[24] Eidelman S, Grossmann W. Pulsed detonation engine experimental and theoretical review. In: 28th Joint Propulsion Conference and Exhibit. 1992. p. 3168

[25] Sorin R, Zitoun R, Desbordes D. Optimization of the deflagration to detonation transition: Reduction of length and time of transition. Shock Waves. 2006;**15**(2):137-145

[26] Kindracki J, Wolański P, Gut Z. Experimental research on the rotating detonation in gaseous fuels–oxygen mixtures. Shock Waves. 2011;**21**(2): 75-84

[27] Bykovskii FA, Zhdan SA, Vedernikov EF. Continuous spin detonations. Journal of Propulsion and Power. 2006;**22**(6):1204-1216

[28] Bykovskii FA, Zhdan SA, Vedernikov EF. Continuous spin detonation of fuel-air mixtures. Combustion, Explosion, and Shock Waves. 2006;**42**(4):463-471

[29] Suchocki J, Yu S-T, Hoke J, Naples A, Schauer F, Russo R. Rotating detonation engine operation. In: 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2012. p. 119

[30] Russo RM. Operational characteristics of a rotating detonation engine using hydrogen and air [MA thesis]. Air Force Institute of Technology; 2011

[31] Wolański P. Detonative propulsion. Proceedings of the Combustion Institute. 2013;**34**(1):125-158

[32] Schwer D, Kailasanath K. Numerical investigation of rotating detonation engines. In: 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2010. p. 6880

[33] Schauer F, Stutrud J, Bradley R. Detonation initiation studies and performance results for pulsed detonation engine applications. In: 39th Aerospace Sciences Meeting and Exhibit. 2001. p. 1129

[34] Helman D, Shreeve R, Eidelman S. Detonation pulse engine. In: 22nd Joint Propulsion Conference. 1986. p. 1683

[35] Braun EM, Lu FK, Wilson DR, Camberos JA. Airbreathing rotating detonation wave engine cycle analysis.

Aerospace Science and Technology. 2013;**27**(1):201-208

[36] Schwer D, Kailasanath K. Fluid dynamics of rotating detonation engines with hydrogen and hydrocarbon fuels. Proceedings of the Combustion Institute. 2013;**34**(2): 1991-1998

[37] Shank J, King P, Karnesky J, Schauer F, Hoke J. Development and testing of a modular rotating detonation engine. In: 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2012. p. 120

[38] Fotia M, Kaemming TA, Hoke J, Schauer F. Study of the experimental performance of a rotating detonation engine with nozzled exhaust flow. In: 53rd AIAA Aerospace Sciences Meeting. 2015. p. 631

[39] Rankin BA, Codoni JR, Cho KY, Hoke JL, Shauer FR. Investigation of the structure of detonation wave in a non-premixed hydrogen air rotating detonation engine using mid-infrared imaging. Proceedings of the Combustion Institute. 2018:3479-3486

[40] Shank JC. Development and testing of a rotating detonation engine run on hydrogen and air [MA thesis]. Air Force Institute of Technology; 2012

[41] Hishida M, Fujiwara T, Wolański P. Fundamentals of rotating detonations. Shock Waves. 2009;**19**(1):1-10

[42] Schwer D, Kailasanath K. Numerical study of the effects of engine size in rotating detonation engines. In: 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2011. p. 581

[43] Zhdan SA, Bykovskii FA, Vedernikov EF. Mathematical modeling of a rotating detonation wave in a hydrogen-oxygen mixture. Combustion, Explosion, and Shock Waves. 2007; **43**(4):449-459

[44] Nordeen CA, Schwer D, Schauer F, Hoke J, Barber T, Cetegen B. Thermodynamic model of a rotating detonation engine. Combustion, Explosion, and Shock Waves. 2014; **50**(5):568-577

[45] Zhou R, Wu D, Wang J. Progress of continuously rotating detonation engines. Chinese Journal of Aeronautics. 2016;**29**(1):15-29

[46] Wolanski P. Application of the continuous rotating detonation to gas turbine. Applied Mechanics and Materials. 2015;**782**:3-12

[47] Kindracki J, Kobiera A, Wolanski P. Experimental and numerical research on rotating detonation in a small rocket engine model. International Congress of Diesel Engines. 2009:392-400

[48] St. George AC, Driscoll RB, Munday DE, Gutmark EJ. Development of a rotating detonation engine facility at the university of cincinnati. In: 53rd AIAA Aerospace Sciences Meeting. 2015. p. 635

[49] Yang C, Wu X, Ma H, Peng L, Gao J. Experimental research on initiation characteristics of a rotating detonation engine. Experimental Thermal and Fluid Science. 2016;**71**:154-163

[50] Stoddard W, St. George AC, Driscoll RB, Anand V, Gutmark EJ. Experimental validation of expanded centerbodiless RDE design. In: 54th AIAA Aerospace Sciences Meeting. 2016. p. 128

[51] Kailasanath K. Research on pulse detonation combustion systems: A status report. In: 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. 2009. p. 631

[52] Rankin BA, Fotia ML, Naples AG, Stevens CA, Hoke JL, Kaemming TA, et al. Overview of performance, application, and analysis of rotating detonation engine technologies. Journal of Propulsion and Power. 2016;**33**:131-143

[53] Yi T-H, Lou J, Turangan C, Khoo BC, Wolański P. Effect of nozzle shapes on the performance of continuously-rotating detonation engine. In: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition. 2010. p. 152

[54] Kato Y, Gawahara K, Matsuoka K, Kasahara J, Matsuo A, Funaki I, et al. Thrust measurement of rotating detonation engine by sled test. In: 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference. 2014. p. 4034

[55] Aircraft Design Group. Data on Large Turbofan Engines. Available from: http://adg.stanford.edu/aa241/propulsion/largefan.html. Leland Stanford Junior University. 2001. Available from: https://web.archive.org/web/20010223235152/http://adg.stanford.edu/aa241/propulsion/largefan.html

[56] Leyes RA, Fleming W. The History of North American Small Gas Turbine Aircraft Engines. AIAA; 1999. 998 pp

[57] Pratt & Whitney. F135 Engine. 2018. Available from: http://newsroom.pw.utc.com/download/me_f135_engine_cv_pcard.pdf

[58] General Electric Aviation. F414 Turbofan Engines. 2014. Available from: https://www.geaviation.com/sites/default/files/datasheet-F414-Family.pdf

[59] Niaz S, Manzoor T, Pandith AH. Hydrogen storage: Materials, methods and perspectives. Renewable and Sustainable Energy Reviews. 2015;**50**:457-469

[60] Liu S, Lin Z, Liu W, Lin W, Zhuang F. Experimental realization of H_2/air continuous rotating detonation in a cylindrical combustor. Combustion Science and Technology. 2012;**184**(9):1302-1317

[61] Lin W, Zhou J, Liu S, Lin Z. An experimental study on CH_4/O_2 continuously rotating detonation wave in a hollow combustion chamber. Experimental Thermal and Fluid Science. 2015;**62**:122-130

[62] 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**:555-582

[63] Naples A, Hoke J, Karnesky J, Schauer F. Flowfield characterization of a rotating detonation engine. In: 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2013. p. 278

[64] Rankin BA, Richardson DR, Caswell AW, Naples A, Hoke J, Schauer F. Imaging of OH* chemiluminescence in an optically accessible nonpremixed rotating detonation engine. In: 53rd AIAA Aerospace Sciences Meeting. 2015. p. 1604

[65] Cho KY, Codoni JR, Rankin BA, Hoke J, Schauer F. High-repetition-rate chemiluminescence imaging of a rotating detonation engine. In: 54th AIAA Aerospace Sciences Meeting. 2016. p. 1648

[66] Voitsekhovskii BV, Mitrofanov VV, Topchian ME. Investigation of the structure of detonation waves in gases. Symposium (International) on Combustion. 1969;**12**(1):829-837

[67] Cocks PA, Holley AT, Greene CB, Haas M. Development of a high fidelity RDE simulation capability. In: 53rd AIAA Aerospace Sciences Meeting. 2015. p. 1823

[68] Oran ES, Weber JW, Stefaniw EI, Lefebvre MH, Anderson JD. A numerical study of a two-dimensional H_2-O_2-Ar detonation using a detailed chemical reaction model. Combustion and Flame. 1998;**113**(1):147-163

[69] Lee JH. Dynamic parameters of gaseous detonations. Annual Review of Fluid Mechanics. 1984;**16**(1):311-336

[70] Kessler D, Gamezo V, Oran E. Gas-phase detonation propagation in mixture composition gradients. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2012;**370**(1960): 567-596

[71] Fujiwara T, Hishida M, Kindracki J, Wolański P. Stabilization of detonation for any incoming mach numbers. Combustion, Explosion, and Shock Waves. 2009;**45**(5). Translation of article originally published in Russian in Fizika Goreniya i Vzryva, 2009;**45**(5): 108-110, 603-605

[72] Hayashi AK, Kimura Y, Yamada T, Yamada E, Kindracki J, Dzieminska E, et al. Sensitivity analysis of rotating detonation engine with a detailed reaction model. In: 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. 2009. p. 633

[73] Tsuboi N, Watanabe Y, Kojima T, Hayashi AK. Numerical estimation of the thrust performance on a rotating detonation engine for a hydrogen-oxygen mixture. Proceedings of the Combustion Institute. 2015;**35**(2): 2005-2013

[74] Sousa J, Paniagua G, Morata EC. Thermodynamic analysis of a gas turbine engine with a rotating detonation combustor. Applied Energy. 2017;**195**:247-256

[75] Dremin ANA. Toward detonation theory. In: Shock Wave and High Pressure Phenomena. 1999. pp. 1-14. ISBN 9781461205630

[76] Vasil'ev AA, Gavrilenko TP, Topchiyan ME. Chapman-Jouguet condition for real detonation waves. Combustion, Explosion and Shock Waves. 1973;**9**(2):268-272

[77] Eto K, Tsuboi N, Hayashi AK. Numerical study on three-dimensional CJ detonation waves: Detailed propagating mechanism and existence of OH radical. Proceedings of the Combustion Institute. 2005;**30**(2): 1907-1913

[78] Yu J, Hou B, Lelyakin A, Xu Z, Jordan T. Gas detonation cell width prediction model based on support vector regression. Nuclear Engineering and Technology. 2017;**49**(7):1423-1430

[79] Prakash S, Fiévet R, Raman R, Burr JR, Yu KH. Numerical study of the detonation wave structure in a linear model detonation engine. In: 2018 Joint Propulsion Conference. 2018. p. 4966

[80] St. George AC, Driscoll RB, Anand V, Munday DE, Gutmark EJ. Fuel blending as a means to achieve initiation in a rotating detonation engine. In: 53rd AIAA Aerospace Sciences Meeting. 2015. p. 633

[81] Yao S, Wang J. Numerical investigation of effects of fuel injection on rotating detonation engine. In: 51st AIAA/SAE/ASEE Joint Propulsion Conference. 2015. p. 4192

[82] Dyer R, Naples A, Kaemming T, Hoke J, Schauer F. Parametric testing of a unique rotating detonation engine design. In: 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2012. p. 121

[83] Naples A, Hoke J, Schauer F. Rotating detonation engine interaction with an annular ejector. In: 52nd

Aerospace Sciences Meeting. 2014. p. 287

[84] Liu Y, Wang Y, Li Y, Li Y, Wang J. Spectral analysis and self-adjusting mechanism for oscillation phenomenon in hydrogen-oxygen continuously rotating detonation engine. Chinese Journal of Aeronautics. 2015;**28**(3): 669-675

[85] Liu S-J, Lin Z-Y, Liu W-D, Lin W, Sun M-B. Experimental and three-dimensional numerical investigations on H_2/air continuous rotating detonation wave. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2012;**227**(2): 326-341

[86] Anand V, George AS, Driscoll R, Gutmark E. Characterization of instabilities in a rotating detonation combustor. International Journal of Hydrogen Energy. 2015;**40**(46): 16649-16659

[87] Zhou R, Wang J-P. Numerical investigation of shock wave reflections near the head ends of rotating detonation engines. Shock Waves. 2013; **23**(5):461-472

[88] Fotia M, Hoke J, Schauer F. Experimental ignition characteristics of a rotating detonation engine under backpressured conditions. In: 53rd AIAA Aerospace Sciences Meeting. 2015. p. 632

[89] Meng Q, Zhao N, Zheng H, Yang J, Qi L. Numerical investigation of the effect of inlet mass flow rates on H_2/air non-premixed rotating detonation wave. International Journal of Hydrogen Energy. 2018;**43**(29):13618-13631

[90] Rankin BA, Richardson DR, Caswell AW, Naples AG, Hoke JL, Schauer FR. Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine. Combustion and Flame. 2017;**176**:12-22

[91] Wolański P. Rotating detonation wave stability. In: 23rd International Colloquium on the Dynamics of Explosions and Reactive Systems. 2011. pp. 1-6

[92] Falempin F, Daniau E. A contribution to the development of actual continuous detonation wave engine. In: 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. 2008. p. 2679

[93] Stechmann DP. Experimental study of high-pressure rotating detonation combustion in rocket environments English [PhD thesis]. Purdue University; 2017

[94] Cocks PA, Holley AT, Rankin BA. High fidelity simulations of a non-premixed rotating detonation engine. In: 54th AIAA Aerospace Sciences Meeting. 2016. p. 125

[95] Shao Y-T, Liu M, Wang J-P. Numerical investigation of rotating detonation engine propulsive performance. Combustion Science and Technology. 2010;**182**(11–12):1586-1597

[96] Davidenko D, Gökalp I, Kudryavtsev A. Numerical study of the continuous detonation wave rocket engine. In: 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. 2008. p. 2680

[97] Liu S-J, Lin Z-Y, Sun M-B, Liu W-D. Thrust vectoring of a continuous rotating detonation engine by changing the local injection pressure. Chinese Physics Letters. 2011;**28**(9):1-4

[98] Schwer D, Kailasanath K. Effect of inlet on fill region and performance of rotating detonation engines. In: 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2011. p. 6044

[99] Schwer D, Kailasanath K. Feedback into mixture plenums in rotating detonation engines. In: 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2012. p. 617

[100] Chang P-H, Leong WK, Li J-M, Teo CJ, Khoo BC. Investigation of channel pressure effect on rotating detonation engine. In: AIAA Scitech 2019 Forum. 2019. p. 2020

[101] Zhou R, Wang J-P. Numerical investigation of flow particle paths and thermodynamic performance of continuously rotating detonation engines. Combustion and Flame. 2012; **159**(12):3632-3645

[102] Massa L, Chauhan M, Lu F. Detonation-turbulence interaction. Combustion and Flame. 2011;**158**(9): 1788-1806

[103] Driscoll R, Anand V, St George A, Gutmark E. Investigation on RDE operation by geometric variation of the combustor annulus and nozzle exit area. In: 9th US National Combustion Meeting. 2015. pp. 1-10

[104] Bussing T. A rotary valved multiple pulse detonation engine. In: 31st Joint Propulsion Conference and Exhibit. 1995. p. 2577

[105] Gavrikov A, Efimenko A, Dorofeev S. A model for detonation cell size prediction from chemical kinetics. Combustion and Flame. 2000;**120**(1–2): 19-33

[106] Pfahl U, Schultz E, Shepherd J. Detonation cell width measurements for H_2–N_2O–N_2–O_2–CH_4–NH_3 mixtures. Technical Report. 1998

[107] Frolov S, Dubrovskii A, Ivanov V. Three-dimensional numerical simulation of operation process in rotating detonation engine. Progress in Propulsion Physics. 2013;**4**:467-488

[108] Paxson DE. Numerical analysis of a rotating detonation engine in the relative reference frame. In: 52nd Aerospace Sciences Meeting. 2014. p. 284

[109] Nordeen CA, Schwer D, Schauer F, Hoke J, Barber T, Cetegen BM. Role of inlet reactant mixedness on the thermodynamic performance of a rotating detonation engine. Shock Waves. 2016;**26**(4):417-428

[110] Wu D, Zhou R, Liu M, Wang J. Numerical investigation of the stability of rotating detonation engines. Combustion Science and Technology. 2014;**186**(10–11):1699-1715

[111] Davidenko DM, Jouot F, Kudryavtsev AN, Dupré G, Gökalp I, Daniau E, et al. Continuous detonation wave engine studies for space application. Progress in Propulsion Physics. 2009;**1**:353-266

[112] Uemura Y, Hayashi AK, Asahara M, Tsuboi N, Yamada E. Transverse wave generation mechanism in rotating detonation. Proceedings of the Combustion Institute. 2013;**34**(2): 1981-1989

[113] Driscoll R, George AS, Gutmark EJ. Numerical investigation of injection within an axisymmetric rotating detonation engine. International Journal of Hydrogen Energy. 2016;**41**(3): 2052-2063

[114] Sato T, Voelkel S, Raman V. Analysis of detonation structures with hydrocarbon fuels for application towards rotating detonation engines. In: 2018 Joint Propulsion Conference. 2018. p. 4965

[115] Bykovskii FA, Vedernikov EF. Continuous detonation of a subsonic flow of a propellant. Combustion, Explosion and Shock Waves. 2003; **39**(3):323-334

[116] Lu T, Law CK, Ju Y. Some aspects of chemical kinetics in chapman-Jouguet detonation: Induction length analysis. Journal of Propulsion and Power. 2003;**19**(5):901-907

[117] Westbrook CK. Hydrogen oxidation kinetics in gaseous detonations. Combustion Science and Technology. 1982;**29**(1–2):67-81

[118] Masselot D, Fiévet R, Raman V. Effect of equivalence ratio and turbulence fluctuations on the propagation of detonations. In: 55th AIAA Aerospace Sciences Meeting. 2017. p. 374

[119] Roy A, Strakey P, Sidwell T, Ferguson DH. Unsteady heat transfer analysis to predict combustor wall temperature in rotating detonation engine. In: 51st AIAA/SAE/ASEE Joint Propulsion Conference. 2015. p. 902

[120] Strakey P, Ferguson D, Sisler A, Nix A. Computationally quantifying loss mechanisms in a rotating detonation engine. In: 54th AIAA Aerospace Sciences Meeting. 2016. p. 900

[121] Falempin F, Daniau E, Getin N, Bykovskii F, Zhdan S. Toward a continuous detonation wave rocket engine demonstrator. In: 14th AIAA/AHI Space Planes and Hypersonic Systems and Technologies Conference. 2006. p. 7956

[122] Asahara M, Tsuboi N, Hayashi AK, Yamada E. Two-dimensional simulation on propagation mechanism of H_2/O_2 cylindrical detonation with a detailed reaction model: Influence of initial energy and propagation mechanism. Combustion Science and Technology. 2010;**182**(11–12):1884-1900

[123] Pope S. PDF methods for turbulent reactive flows. Progress in Energy and Combustion Science. 1985;**11**(2):119-192

[124] Burr JR, Yu KH. Shock in reactive cross-flow under partial confinement. In: International Colloquium on the Dynamics of Explosions and Reactive Systems. 2015. pp. 1-6

[125] Burr JR, Yu K. Detonation wave propagation in cross-flow of discretely spaced reactant jets. In: 53rd AIAA/SAE/ASEE Joint Propulsion Conference. 2017. p. 4908

[126] Burr JR, Yu KH. Blast wave propagation in cross-flow of detonable mixture. In: 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference. 2014. p. 3984