Chapter 6
Review on the Research Progresses in Rotating Detonation Engine

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Abstract Present paper focuses on the comprehensive survey of Rotating Detonation Engine (RDE) and their research from the basic to the advanced level. In this paper, an abridged archival background of Pulse/Rotating Detonation Engine (PDE/RDE) is briefed. This is followed by a short description of a Continuous Spin Detonation (CSD) and a few essential facts from the prior publications. Furthermore, a summarization of the Continuous Detonation Wave Rocket Engine (CDWRE) concepts is examined. At long last, a detailed numerical investigation and experiment work of RDE is also presented.

1 Introduction

Since the Detonative Propulsion Research has obtained its peak (Hoffmann 1940; Tsuboi et al. 2011; Braun et al. 2010a; Davidenko et al. 2011, 2009a; Zhou and Wang 2012; Eude and Davidenko 2011; Yi et al. 2009a; Naour et al. 2011; Endo et al. 2011), the practical application of such propulsive device is still a question mark (to author's insight). The current focus in utilizing Detonative Propulsion (DP) for air-breathing engines has come across a long journey from the Pulsed Mode (PM) to Continuous Rotating Mode (CRM). Contrary to the pulsed operation that is applicable to the flight Mach (M) number up to about 3–4, the concept of RDE is attractive for M of above 4. Moreover, the PDE designed for flight M exceeding 3–4 increases the complexity and are getting too expensive. By the same token, in use gas turbine engines (Jet Engine (JE)/Turboprop Engine (TpE)/Turbo shaft Engine (TsE)/Radial Gas Turbine (RGT)/Scale Jet Engine (SJE)/Micro-turbine (Mt)) are also having some disadvantages when compared to RDE in terms of both the engineering and materials standpoint. Noticeably, the gas

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turbines has reduced efficiency, increased cost and delayed response to changes in power settings.

The global interest in the development of RDE for aerospace propulsion has led to numerous studies in DP, particularly pertaining to its efficiency. This is evident from the formation of collaborative teams and groups by universities and industries worldwide. During the period of 2005–2008, the Lavrentyev Institute of Technology (LIT) and the Novosibirsk Institute of Hydrodynamics (NIH) in Russia have collaborated in the development of CSD. From 2006 to 2009, the France missile developer and manufacturing company so called Matra BAe Dynamics Aérospatiale (MBDA) joined together with the Lavrentyev Institute of Hydrodynamics of the Siberian Branch of the RAS in developing the CDWRE. The recent speedily numerical investigation of RDE was carried out in many places world-wide. Some of the noteworthy universities and collaborative include Warsaw University of Technology (WUT), Pusan National University (PNU), Aoyama Gakuin University (AGU), Japan Aerospace Exploration Agency (JAXA), N.N. Semenov Institute of Chemical Physics and collaborative work of Air Force Research Laboratory (AFRL) with Innovative Scientific Solution Incorporated (ISSI) and Air Force Institute of Technology (AFIT). The equal effort in numerical research is given to the experimental work of RDE, which is taken care by large number of research organizations in the US and many regions across the big blue marble. Some of them are Aerojet Rocketdyne (AR), Naval Research Lab (NRL), NASA Glenn Research Center, Collaborative work of University of Tsukuba (UoT) with Keio University (KU) and JAXA, AFRL, Peking University (PU), and also the Collaborative work of Nagoya University (NU) with University of Tsukuba and JAXA.

Recently, in 2013, the International Workshop on Detonation for Propulsion (IWDP) (International Workshop on Detonation for Propulsion 2013) was held in Taiwan with the participation of more than 20 experts. Likewise, the 14th International Detonation Symposium (IDS) (Heiser and Pratt 2002) has also contributed for DPR. As the result of these conferences and symposiums, a number of journals and papers have been published. The main goal of this review paper is to provide a full detailed review of RDE for those who are interested in recent accomplishments and thorough knowledge of RDE design concepts.

In order to use the advantages of rotating detonation concept in aircraft engines, there are number of challenges which include both fundamental and engineering problems are yet to be solved. These problems deal basically with low-cost achievement and control of successive detonations in a propulsion device. To ensure the practical use, one needs to improve the (1) thermodynamic scale of cycle efficiency; (2) to reduce the design complexities and geometrical constrains, geometry of the combustion chamber to promote detonation initiation and propagation at lowest possible pressure loss and to ensure high operation frequency; (3) Heat transfer rates and their losses; (4) As the structural components of RDE are subject to repeated high-frequency shock loading and thermal deformations, a considerable wear and tear can be expected within a relatively short period of operation. (5) low-

energy source for detonation initiation to provide fast and reliable detonation onset; (6) cooling technique for rapid, preferably recuperative, heat removal from the walls of (Detonation Chamber) DC to ensure stable operation and avoid premature ignition of Fuel–Air Mixture (FAM) leading to detonation failure; Among the most challenging issue, is the problem of durability of the propulsion systems. The other additional problems include noise and vibration.

The paper is organized is such a way that the reader first gets acquainted with a basic idea of detonation based propulsion in pulsed mode, followed by the advantages and disadvantages of PDE (Sect. 2.1) which lead to the development of RDE. Then, based on the significance, a small description of the thermodynamic cycle analysis of RDE, their advantages and existing problems which restrict the technology to come into practical use is discussed (Sect. 2.2). With that clear knowledge of PDE/RDE, a brief historical background of detonation research is presented (Sect. 3). Then, some of the early Russian work of CSD is given (Sect. 4), which is continued by the France works of CDWRE, their advantages (Sect. 5.1), and their collaborative works are mentioned (Sects. 5.2 and 5.3). A turning point in detonative research by the French scientist is also elaborated in this section. Then a thorough survey of numerical investigation of RDE research around the world has been discussed from early 2007 to recent 2014 (Sects. 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7 and 6.8). Besides, the experimental work of RDE research starting from the late 2011 to up-to-date 2014 has also been discussed (Sects. 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 7.7, 7.8 and 7.9). The investigation is presented in such a manner that the readers can comprehend the full research flow of RDE very easily. And conclusively, there are some novel concepts of utilizing detonative propulsion phenomenon in space application has been discussed (Sect. 8).

2 Fundamentals

Pulse Detonation Engine

Till last decade, PDEs are attractively considerable attention of research because they promised and provided hope for the performance improvements over existing air-breathing propulsion devices, especially at low flight Mach numbers (Heiser and Pratt 2002). Figure 6.1 shows the first pulsed detonation powered aircraft so called Rutan Long-EZ on Jan 31, 2008. PDE uses detonation waves to combust the fuel and oxidizer mixture. Pulsed mode of detonation engine operates in an intermittent cyclical manner that (1) propellant injected from the closed end, then (2) wave propagation and (3) transition in the tube, finally the (4) wave exist tube, (5) exhaust and (6) purge. Figure 6.2 shows the basic PDE cycle operation. Key issues for further PDE development includes efficient mixing of fuel/oxidizer, prevention of auto-ignition and integration with an inlet and nozzle.

Fig. 6.1 First pulsed detonation powered aircraft, Rutan Long-EZ on Jan 31, 2008 (Heiser and Pratt 2002)
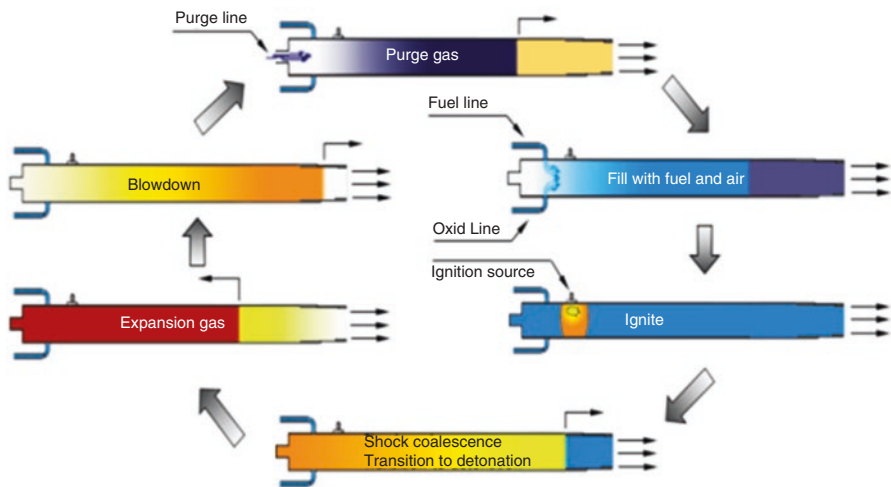
Fig. 6.2 PDE cycle

Historical Background

PDEs have been considered for propulsion for over 70 years. Merely, in the end of the 20th – the beginning of the twenty-first century, most of the Asian (china, Japan, Singapore and South Korea), European (France, Poland, Russia, Belarus) and North American (U.S.A) countries entangled in the research on PDE-based propulsion. PDE typically generate detonative combustion product in order to get high pressure, which in turn converted to thrust performance. It is acclaimed in the 1990's that the

performance improvements of the PDE is relatively appreciable than the existing constant pressure conventional air-breathing propulsion engines (Eidelman et al. 1991, 1990a, b; Eidelman and Grossmann 1992; Helman et al. 1986; Lynch et al. 1994; Lynch and Edelman 1994). Further betterments in the thermodynamic efficiency of PDE cycle has been achieved in the late decades (Bussing and Pappas 1996; Kailasanath 1999). This enhancement insisted the researchers all over the globe to interfere intensely in the PDE research. As an outcome of action, the mechanical valve PDE concept (Bollay 1960; Winfree and Hunter 1999) has been renovated to valveless scheme of PDE's with continuous or intermittent airflow within a combined cycle concept (Roy et al. 2000a). In the same decennium, the two-step detonation initiation method the so-called Predetonator approach for PDE's Detonation Chamber (DC) was introduced (Roy et al. 2003a; Brophy et al. 2001). Concurrent studies were executed to enhance the Deflagration to Detonation Transmission (DDT) by including blockages to benefits the DDT to takes place within the distance of the detonation tube of PDE's (Yu 2001; Conrad et al. 2001). Nevertheless, rampant propellant injection in PDE's is a serious dispute which was rectified by stratified-charge phenomenon by Knappe and Edwards (2002, 2001). Further augmentation of detonation initiation in PDE's was brought by means of shock-booster method (Frolov et al. 2001; Roy et al. 2002a) and shock-implosion method (Roy et al. 2000b). Thrust production in PDE research gets appreciated when Pulse-reinitiation concept (Roy et al. 2000c) and Pulse-blasting concept (Borisov 2002) was acknowledged. Subsequently, much effort was made to examine the Multi-tube PDE's (Roy et al. 2002b, 2003b). Complete description of the research accomplished in detonation based propulsion is briefed and discussed in the survey documents that have been published by Wolanski (2013a) and Kailasanath (2011a). By the time mentioned, some of the expected and imminent perspectives of utilizing these detonative propulsion technologies in rockets/space applications were suggested by Roy et al. (2004), Falempin et al. (2006) and Davidenko et al. (2008, 2009b).

Thermodynamic Cycle Efficiency of PDE

The time independent, thermodynamic cycle analysis of the PDE was presented by W.H. Heiser et al. (2002). The most significant conclusion was drawn from the Heiser method is the thermal efficiency of the PDE cycle, called as 'Zel'dovich cycle' nowadays, or the fraction of the heating value of the fuel that is converted to work that can be used to generate thrust. The cycle thermal efficiency is then used to and all of the traditional propulsion performance measures. The benefits of this approach are the fundamental processes incorporated in PDEs are clarified, quantitative comparisons with other cycles are easily made, the influence of the entire ranges of the main parameters that influence PDE performance are easily explored, the ideal or upper limit of PDE performance capability is quantitatively established and that this analysis provides a basic building block for more complex Zel'dovich cycles. A comparison of cycle performance is made for ideal and real PDE, Brayton, and

Humphrey cycles, utilizing realistic component loss models (Heiser and Pratt 2002). The results show that the real Zel'dovich cycle has better performance than the real Brayton cycle only for flight Mach less than 3, or cycle static temperature ratios less than 3 (Heiser and Pratt 2002). For flight Mach greater than 3, the real Brayton cycle has better performance, and the real Humphrey cycle is an over optimistic surrogate for the real Zel'dovich cycle. The T – s diagram for the ideal Humphrey cycle is presented in Fig. 6.3, together with the Zel'dovich and Brayton cycles. (Heiser and Pratt 2002). It is apparent from a comparative inspection of the three ideal cycles displayed in Fig. 6.3 that the thermal efficiency of the ideal Humphrey cycle is close to, but always somewhat less than, that of the ideal Zel'dovich cycle. Figure 6.4 demonstrates that both the ideal Zel'dovich and Humphrey cycles enjoy a significant cycle thermal efficiency advantage over the ideal Brayton cycle. Significant papers on pulse detonation cycles by Heiser and Pratt and Dyer and Kaemming have been discussed and are often cited by researchers for the comparison of engine cycles (Heiser and Pratt 2002; Dyer and Kaemming 2002). These papers are significant to RDE research by establishing the Zel'dovich cycle as the basis for the PDE and introducing the effects of parasitic losses on the cycle.

Advantages/Disadvantages of PDE

Application of the pulsed detonation mode in the aircraft engines offers significant advantages over the existing conventional engines with constant pressure combustion. The compression effect by the detonation gets rid of the necessity of
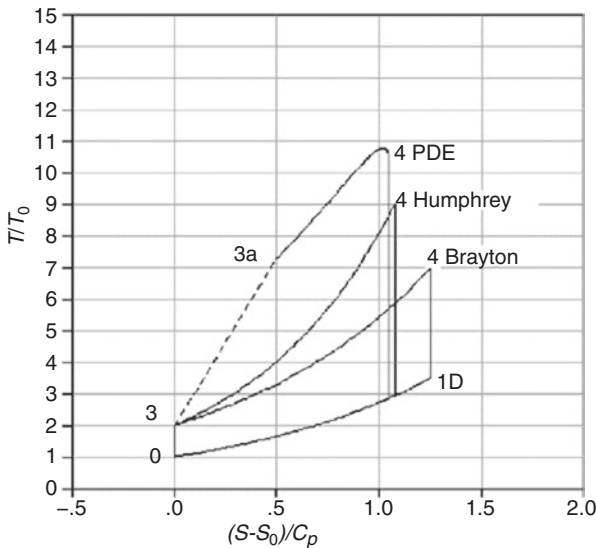
Fig. 6.3 Temperature-entropy diagrams for the ideal Zel'dovich, Brayton, and Humphrey cycles (Heiser and Pratt 2002).

**Fig. 6.4** Thermodynamic cycle of PDE (Heiser and Pratt 2002)
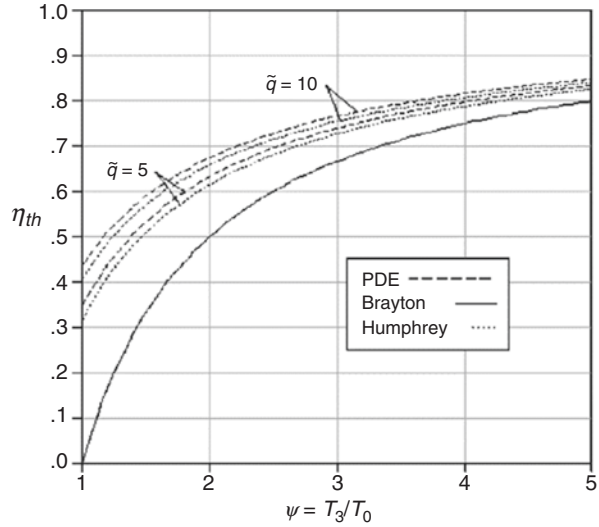
compressor as well as turbine. Moreover, the PDE's are scalable, light-weight with high Thrust/Weight (T/W) ratio. Because of no moving parts, PDE seems to be comparably low cost to acquire and operate with board operating range. In combinations with the existing compressor and turbine system, PDE is expected to provide additional thermodynamic efficiency by the compression effect. In the meanwhile, PDE pose some technical disadvantages. The intermittent operation of PDE at order of 100 Hz is the well-known disadvantage emitting high level of noise and vibration. The system integration of PDE exhibited design problem of unsteady turbine interacting with incoming detonation or shock wave. Also, the high temperature of detonation product gas makes the problem even worse. Since, the turbines rotating at high speed cannot withstand high temperature of the detonation gas, the heat transfer problem of turbine and the cooling of the detonation product gas increase the complexity of the PDE-turbine system.

To avoid the problems associated with the intermittent operation of PDE, they've sought for the continuous detonation operation for propulsion while preserving the potential of higher thermodynamic efficiency by using the detonation moving around the annual chamber, widely called as Rotating Detonation Engine (RDE).

Rotating Detonation Engine (RDE)

RDE, a form of continuous detonation-wave engine, is shown to have the potential to further increase the performance of air-breathing propulsion devices above pulsed or intermittent detonation wave engines. The principle of RDE is based on the
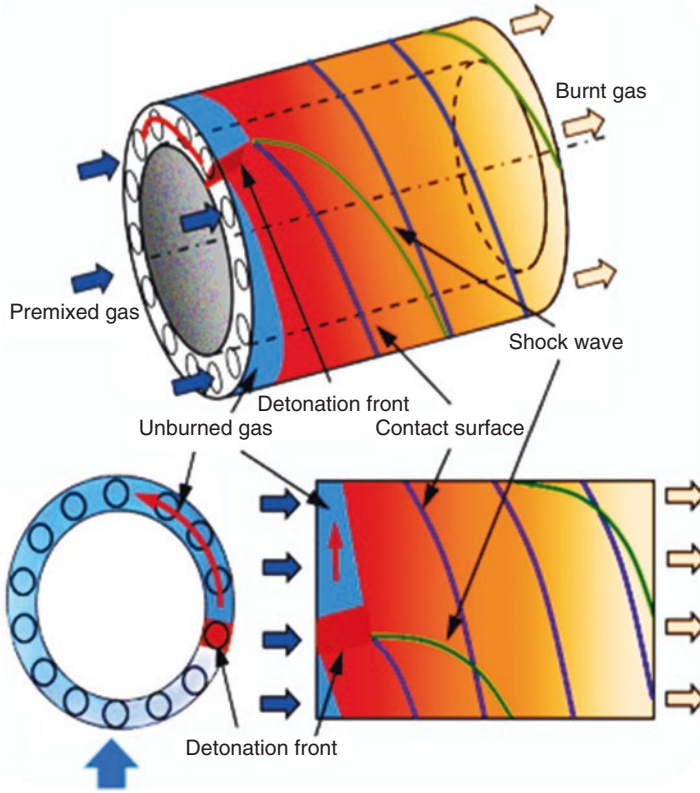
Fig. 6.5 Schematic of rotating detonation engines

creation of direction of tangent Detonation wave travels through disk like path within combustion chamber. Since the detonation wave is moving around the annular chamber at detonation speed the RDE's operation frequency is several kHz, which is same order of magnitude of vibration in ordinary gas turbine. Expanding detonation products from nozzle will produce the thrust. In RDE's, once the detonation is initiated into a combustion chamber containing propellant mixture, then the detonation propagates continuously without any intermission. It is noted, in the mid – 1950's, the efficiency of uninterrupted detonations are quiet impressible than the pulsed or intermittent detonations. From that juncture, rotating detonative propulsion research has drawn attention around the big blue marble. While the PDE poses the loss of thrust by the intermittent operation, RDE could provide better performance than PDE in the same supply conditions. Furthermore, the RDE's geometry is similar to the annular combustion chamber of a conventional gas turbine engine, which makes the system integration much easier with the existing configuration of gas turbine engines (Fig. 6.5).
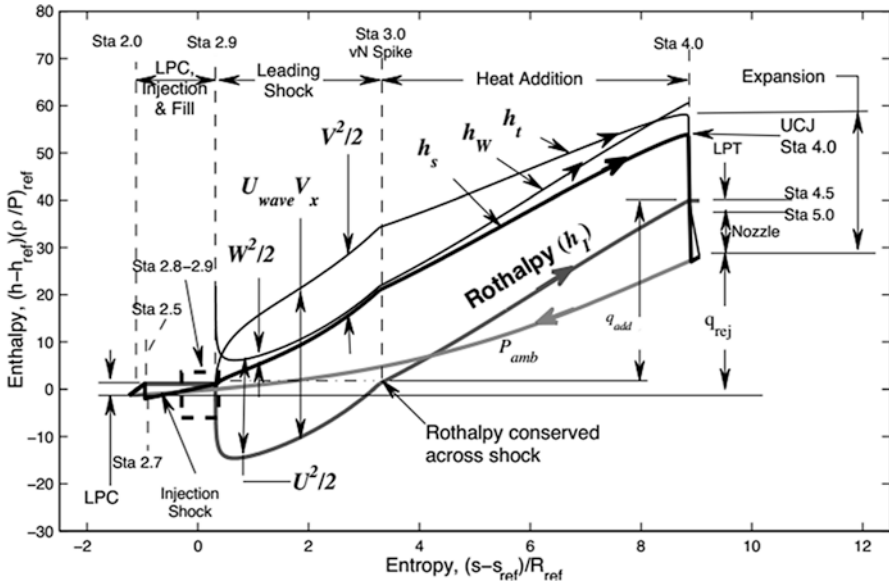
Fig. 6.6 Dimensionless h-s diagram of RDE analytical cycle model (Nordeen 2013)

Thermodynamic Cycle Efficiency of RDE

The thermodynamic efficiency of RDE was recently briefed by Craig A. Nordeen (2013). The general outline of a ZND based RDE cycle has emerged from the studies carried out by Schauer and Lu. Schauer has outlined an evolutionary understanding of the detonation cycle. Lu acknowledged the identification of the ZND cycle in the RDE and notes the differences between the ZND model and the Humphrey cycle (Lu et al. 2011a). The challenge of modeling a RDE is the realization that it is not a pure ZND cycle, but is comprised of a multiplicity of detonation streams, deflagrations and various incidental shocks (Nordeen et al. 2011). Kailasanath acknowledged the significance of multiple streams in the RDE cycle (Kailasanath 2011b).

Braun's approach to the RDE cycle is grounded in the construction of Brayton cycles by constructing the cycle as a single stream from assumed known processes (Braun et al. 2010b, c). The RDE is modeled as a supersonic ramjet. The inlet is isentropic. The significant role of injection losses due to mixing are recognized and modeled as a mass-averaged entropy increase. The detonation is modeled as a rotating wave traveling at the CJ velocity. The wave is assumed to be normal to the azimuthal direction. Expansion is assumed to be isentropic. Energy is used as an approach to analyze performance and identify trends. The performance gap between conventional jet propulsion and scramjet is identified and the RDE proposed as a possible solution. See Fig. 6.6 (Nordeen 2013).

The establishment of the thermodynamic cycle of the RDE as a modified ZND-type cycle is not new, but was disputed. The actual cycle contains multiple processes. Further studies are required to understand the full range of cycle behavior.

Comparison of Cycle Efficiencies of PDE & RDE

| S.No	Pulse detonation engines	Rotating detonation engines
1.	PDE will have unsteady throttling and shock losses associated with the opening and closing of the valves	The RDE will have steady shock and viscous losses from flow through choked injectors
2.	Unsteadiness in the PDE flow has been shown to cause system losses	The RDE does see injection unsteadiness due to the passing detonation, which are expected to be of a small order
3.	The PDE detonation upstream flow velocity is zero	The RDE upstream velocity is non-zero. Non-zero inlet velocity is a source of system inefficiency because of expansion cooling of the inlet flow
4.	The upstream conditions of the PDE detonation are mostly isotropic	The RDE detonation upstream flow is exposed to a gradient of all thermodynamic properties
5.	The PDE exhaust undergoes a "blow down" process. (i.e.,) that is, pressure decreases as flow exits the fixed volume of the detonation tube. Each fluid parcel sees a different expansion process line and thus, generates a different amount of entropy	The RDE flow is continuous

Advantages of RDE

Advantages of application of the continuously rotating detonation (wave) combustion process in all jet engines will results in a very compact combustion chamber, and thus the engines will be shorter, simpler and, due to pressure increase in detonative combustion, will execute higher engine performance. It also seems that RDE will be superior over PDE, since they offer continuous thrust generation and can be applied basically to any Mach number. Also RDE will have a lower mass and will be less expensive (Wolanski 2013b). Such detonation engine has a tremendous improvement in the recent decade. The detailed historical background and briefed survey of numerical and experimental work of RDE is presented below.

3   Archival Background of RDE

Antecedent Effort at the Novosibirsk Institute of Hydrodynamics (NIH)

Pulse detonation has a very long history which was conscientiously surveyed by Wolanski (2013b) and Kailasanath (2011b). As it was done for PDE, specific numerical and experimental studies are being performed to assess some key points for the feasibility of an operational RDE. The first and foremost investigation of a Continuous Detonation Wave Engine (CDWE) was carried out in the mid-nineteenth century by Voitsekhovskii et al. (1957, 1958, 1959, 1960, 1963a, b, 1969) at the Novosibirsk Institute of Hydrodynamics (NIH) in Russia (Figs. 6.7 and 6.8).

Their idea of rotating detonation emerges during the investigation of the instability of the plane detonation wave which leads to the formation of intense transverse disturbances. Voitsekhovskii et al. records a rotating detonation with six heads using Dynafax camera in a disk-shaped combustion chamber. He found that in a circular tube, in the presence of single-head spin, the transverse velocity coincides closely with the value $1.84c$ predicted by the acoustic theory. He also mentioned that a region of very high temperature and pressure – a transverse wave – localized in the neighborhood of a detonation tube wall, is known to exist in spinning detonation.
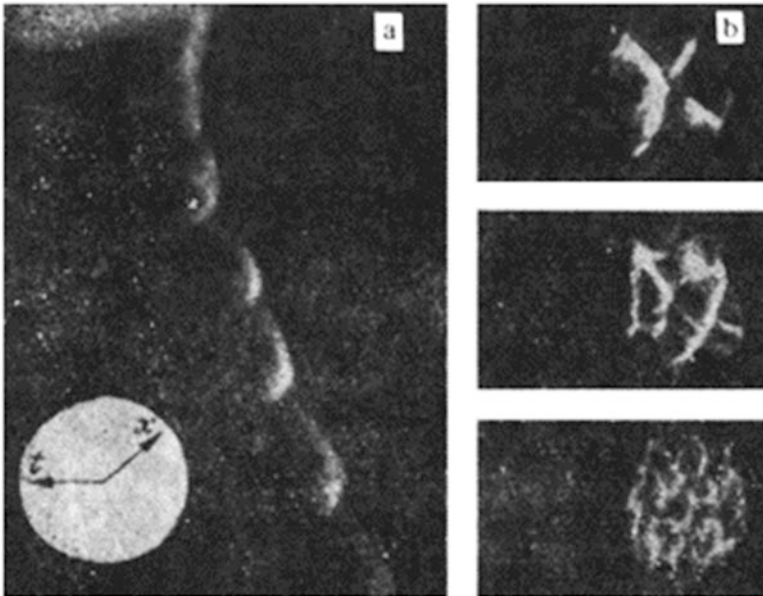
Fig. 6.7 (**a**) Transverse waves in a convergent cylindrical detonation recorded by the total compensation method (**b**) at the wave front in a circular tube (Voitsekhovskii et al. 1969)
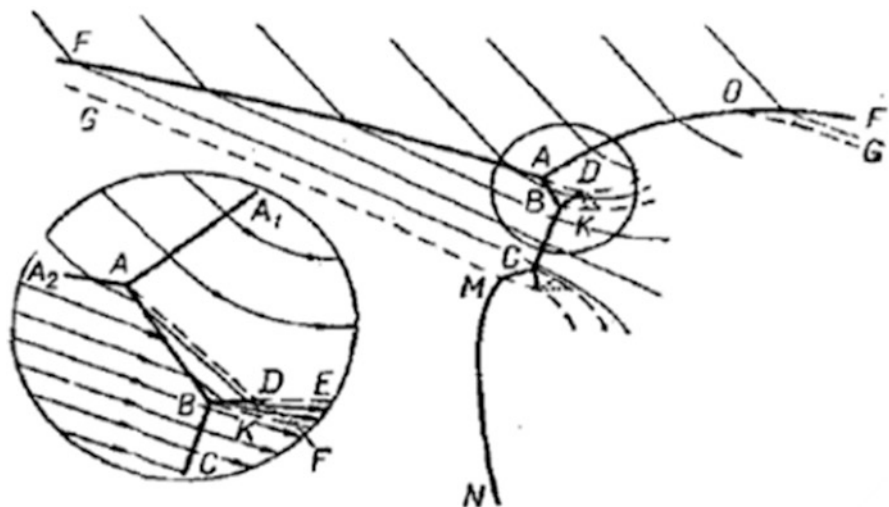
Fig. 6.8 Structure of the first: *BC* transverse wave, *AA1* jog in the primary front, *AA2* primary wave, *AB, BD* jumps coordinating the flow behind the transverse wave and the jog, *ADE, BK'F* contact (Voitsekhovskii et al. 1969)

The rotational frequency of the spinning head is the same as that of tangential acoustic oscillations. He also investigated the feasibility of a CDWE and favorably achieved stationary spinning detonation in the consecutive year (Voitsekhovskii et al. 1969).

Bi-directional Detonation Waves

Mikhailov's work was deliberated as the basics for studying the internal physics of continuous detonation in an annular channel (Voitsekhovskii et al. 1963b). This is followed by the researchers in the U.S. to develop a continuously rotating detonative propulsion engines for rocket applications. Nicholls et al. (1966, b, 1957) from the University of Michigan (UoM) was the first to undergone the feasibility studies of a rocket motor and established a simplex detonation wave. His theoretical examination was appreciated and lengthened additionally to bi-directional detonation waves which revealed the explicit notion of comprehending the RDE concept. Experiments were conducted in a small-scale annular rocket motor and he believed that the injector pattern with the consequent high turbulence level, premature burning, and limited mass flow characteristic was a major part of the difficulty.

The key factors affecting feasibility of the Rotating Detonation Wave Engine (RDWE) were deemed to be performance potential, heat transfer to the wall, the detonation characteristics at very low temperatures and elevated pressures.

Unfortunately, continuous operation of the model motor was never realized, so that important questions such as nozzle performance, actual over-all performance, and detonation in heterogeneous mixtures remain unanswered. A survey of propulsive detonation research studies in the late 1950's were briefed by Oppenheim et al. (1963). Further expedite evolution in RDE research were struggled by virtue of the existent heat transfer complications in rotating detonation wave however simultaneous research in heat transfer was bestowed by Sichel et al. (1998a) and Edwards et al. (1970) (Figs. 6.9, 6.10 and 6.11).
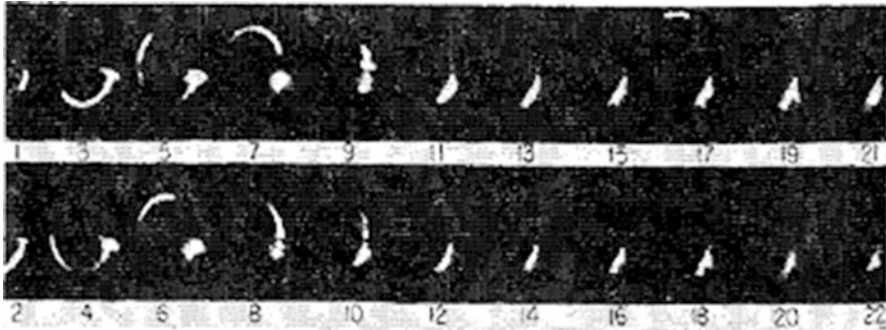
Fig. 6.9 Photographs from typical methane-O2 test using Beckman & Whitley camera (Nicholls et al. 1966)

Fig. 6.10 Cross-sectional view of rotating detonation wave motor (Oppenheim et al. 1963)
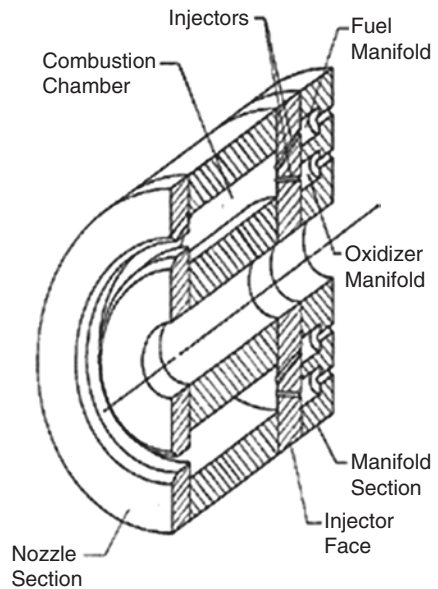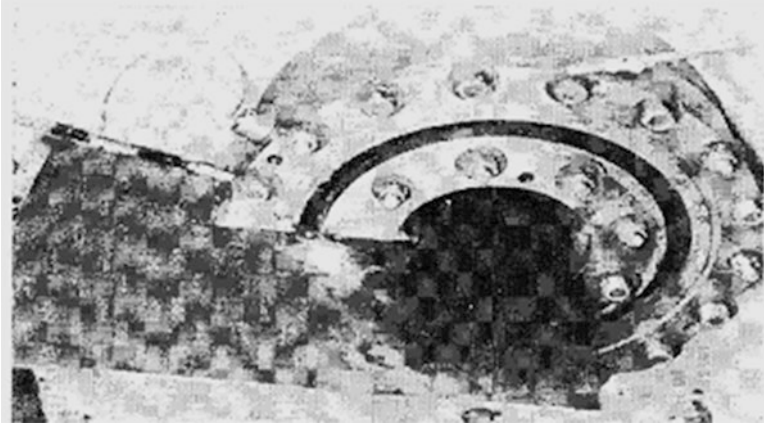
Fig. 6.11 Photograph showing diaphragm holder in annular motor (Nicholls et al. 1966)

Rotating Detonation in Liquid Rockets

Continues work of performance analysis of the rotating detonation waves in liquid rocket engines was carried out by Adamson et al. (1967). In 1973, theoretical calculation of a two-phase detonation in a rotating detonation in liquid rocket motor by Shen and Adamson (1973) is considered as the first and initial step in developing a theoretical analysis of a rotating detonation waves. Different research threads led to the RDE. In one instance, a type of combustion instability was found in rocket combustion chambers where waves rotated around the chambers cylindrical walls (Lu et al. 2011b). Clayton and Rogero (1965) found a rotating detonation like wave concept during a destructive liquid rocket resonant combustion mode. The pressure-wave-to-chamber wall intersection is found to curve in the direction of wave rotation with the nozzle end of the intersection leading the injector end substantially. The wave-to-injector-face intersection extends into the central area of the face, although the wave becomes weak in this area. Although the obtained results are not purported to provide the hypothesized detonation phenomenon, they added insight to the nature of the destructive wave. Figure 6.12 illustrates the triple wave pattern achieved by streak photography along with a tape record of pressure (Ar'kov et al. 1970). Edwards from the advanced research lab group, England has identified the main problem which has been successfully overcome by a gas dynamic valve system whereby differential feed pressures are used for the fuel and oxident to provide a buffer of fuel free oxident between the hot products of the previous wave and the incoming reactive mixture (Ar'kov et al. 1970). Ar'kov et al. discussed some few basic facts related to the effect of High Frequency Instability (HFI) on the combustion chamber, as well as to the nature of the phenomenon caused by the transverse detonation waves itself (Edwards 1977). They proposed that the overloading of a chamber by increasing the fuel atomization, rate of supply, etc. is tantamount to

Fig. 6.12 Symmetrical waves moving in liquid rocket motors (Edwards 1977)
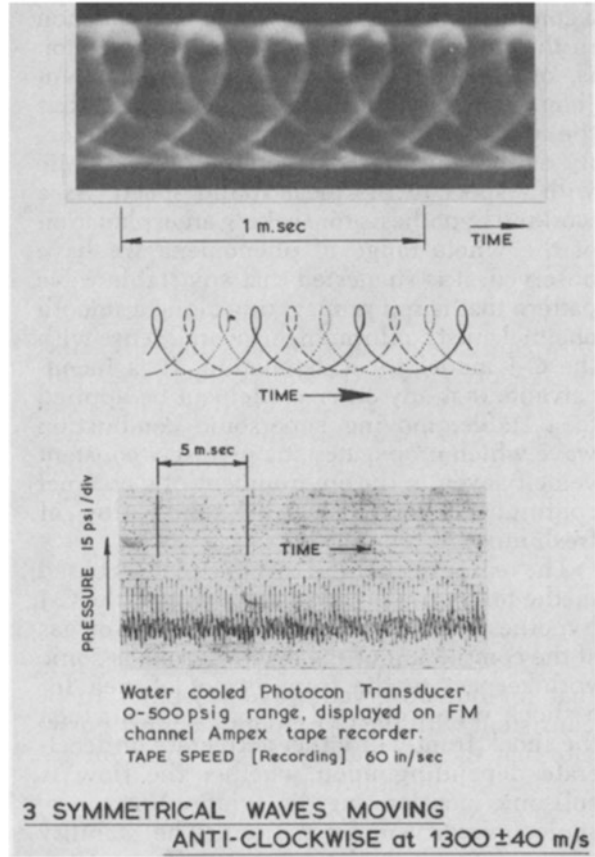

moving away from limit conditions. Moreover they have also mentioned that the most effective means would apparently be the use of transverse waves for burning of fuel. It could ensure a more complete combustion in chambers of reduced dimensions, since the shock waves produce further atomization of fuel droplets and reduce ignition arrests.

4   Continuous Spin Detonation (CSD)

First Mathematical Modeling of Spinning Detonation

In the very beginning of the twenty-first century, the Russian researchers at the Lavrentyev Institute of Technology (LIT) was working on the 2D unsteady mathematical modeling of a continuously spinning detonation wave in a supersonic flow
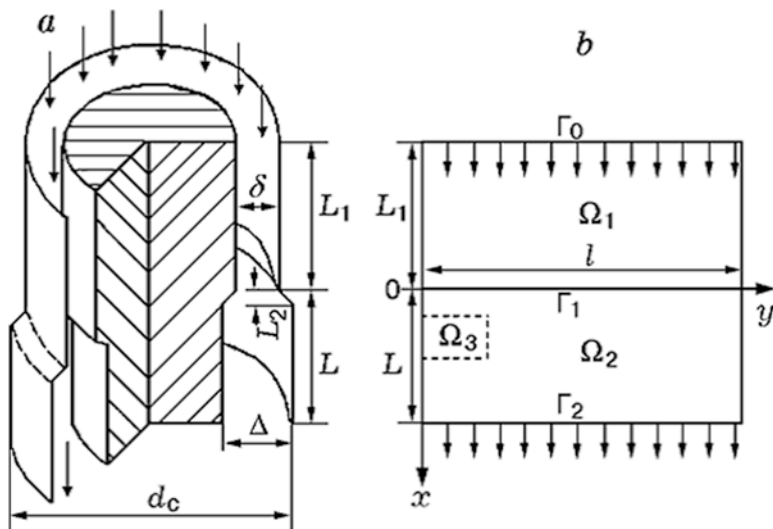
Fig. 6.13 Sketch of an annular detonation and domain of the numerical solution of the problem (Zhdan 2008)

in an annular cylindrical combustor. Their work was supported by the Russian Foundation for Basic Research and by the Foundation of the President of the Russian Federation for Supporting the Leading Scientific Schools. For the first time, the possibility of a continuous spin detonation with a supersonic flow velocity at the diffuser entrance is demonstrated numerically by Zhdan et al. (2008, 2007). It was found that the Mach number of the incoming supersonic flow is restricted for the case ($1 < Mo \leq 3$) of combustion of a H2–O2 mixture in an annular cylindrical combustor. Continuous spin detonation is not realized for $Mo > 3$. Figure 6.13a shows the sketch of an annular combustor (Fig. 6.13a; combustor diameter d_c, combustor length L, and annular channel width Δ ($\Delta > \delta$)) and Fig. 6.13b shows the domain of the numerical solution of the problem (cut section of the annular domain and unfold it into a rectangular domain $\Omega = \Omega1 \cup \Omega2$, which is shown in Fig. 6.13b.)

Dynamics of Transverse Detonation Waves

In Russia, the collaborative work of LIT with NIH has much contribution in the development of RDE (Bykovskii et al. 1980, 1994, 1997, 2004, 2005a, b, 2006a, b, 2008, 2009, 2011). The regime of CSD combustion of a $C_2H_2 – O_2$ mixture in a radial circular channel was employed for the first time by Bykovskii et al. in 2004. The detonation chamber was a coaxial channel; air was delivered into the chamber from a circular collector through a circular slit. At the same time, C_2H_2 was

delivered into the chamber through a spray nozzle supplied with in-pair counter-flow channels. The entire process was photographed through the longitudinal windows of the detonation chamber by a photo-chronograph with a falling drum. Figure 6.14 shows the clear image of the transverse detonation waves in $C_2H_2 - O_2$ mixture (Bykovskii et al. 2004). Bykovskii et al. (2005a) studied the structure of Transverse Detonation Waves (TDW) by varying the flow rates of components of the mixture, width of the slot for oxidizer injection, point of fuel injection, and initial ambient pressure. The losses of the total pressure in the flow in oxygen-injection slots and in fuel-injector orifices are estimated. Bykovskii and Zhdan reported the controlled CSD of various fuels in liquid-propellant rocket motors. Later, a method for continuous photographic recording of the CD process with a microsecond resolution has been developed (Bykovskii et al. 2006a). It has been demonstrated experimentally, theoretically, and numerically that a transonic transition occurs in the flow in the CD process if the cross-sectional area of the chamber is unchanged. They concluded that in the case of high-quality mixing, the TDW velocity and structure are extremely stable in a wide range of the ratios of propellant components and in the examined range of pressures in the chamber. Figure 6.15 shows the photographic
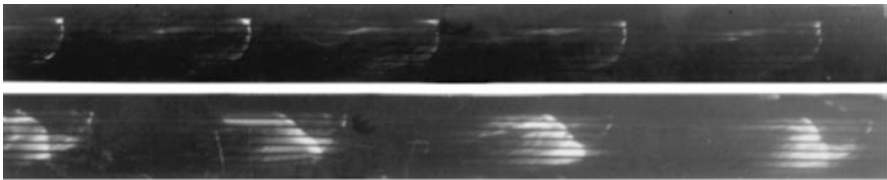
Fig. 6.14   show the clear image of the transverse detonation waves in C2H2-O2 mixture (Bykovskii et al. 2006a)

a) Spin

b) Pulsed
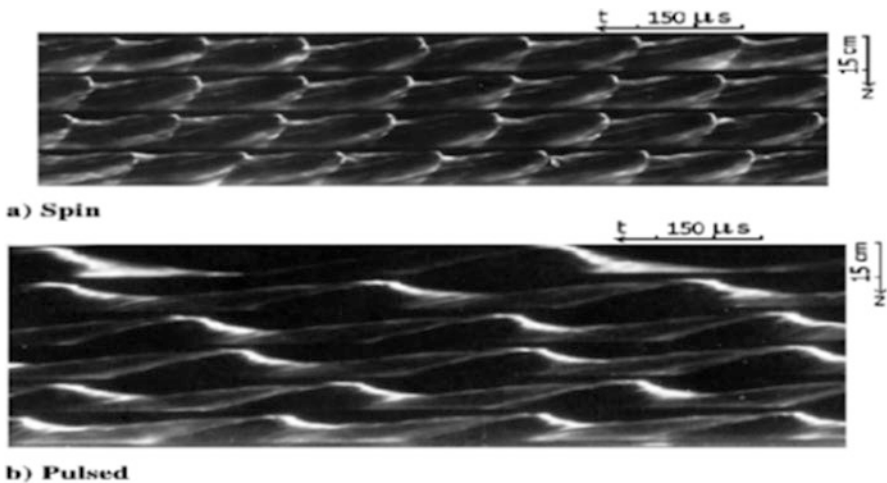
Fig. 6.15   Photographic record of detonation modes in the C2H2-O2 mixture between annular cylindircal (**a**) and expanded duct (**b**) chamber (Bykovskii et al. 2006a)
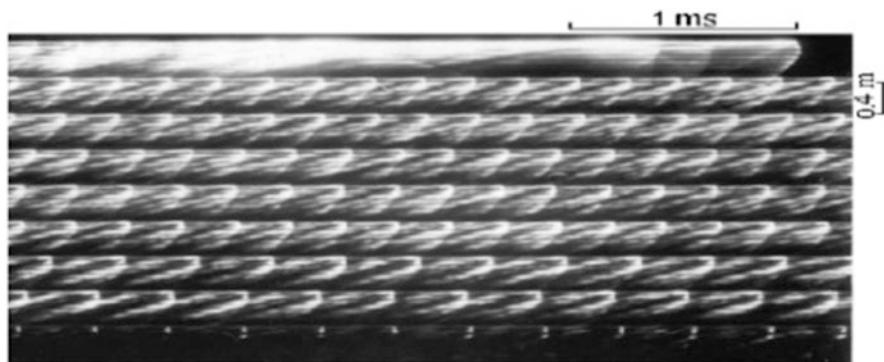
Fig. 6.16 Fragments of TDW photographic records in H2-air mixture (Bykovskii et al. 2006a)
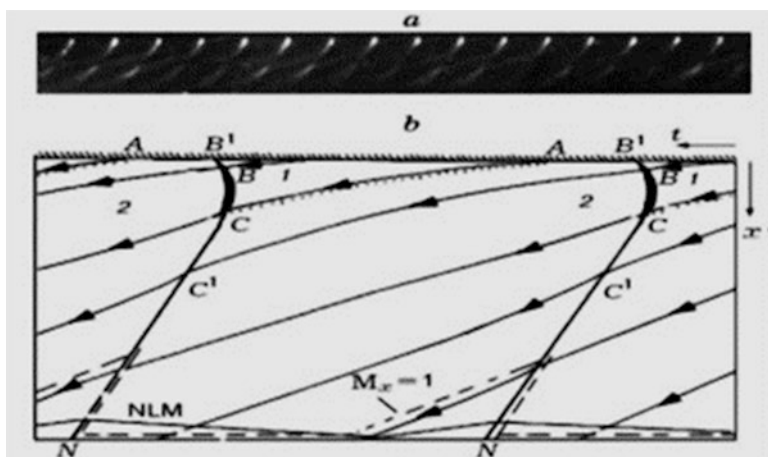

Fig. 6.17 Zoomed-in fragments of the TDW photoraphic records (**a**) and generalized structure of the waves and the flow in the TDW vicinity in the wave-fitted system (**b**): NML is the neutral Mach line (Bykovskii et al. 2008)

record of detonation modes in the $C_2H_2 - O_2$ mixture and Fig. 6.16 shows the Fragments of TDW photographic records in H2 – air mixture (Bykovskii et al. 2006a). Similarly, for the first time, the recent work includes a comprehensive numerical and experimental study of CSD of a $H_2 - O_2$ mixture in annular combustors by Bykovskii et al. (2009). A comparison with experiments reveals reasonable agreement in terms of the detonation velocity and pressure in the combustor. The calculated size and shape of detonation fronts are substantially different from the experimental data. A zoomed-in fragment of the TDW records is shown in Fig. 6.17a ($\varphi = 1$), and the general structure of the waves and the flow in the TDW vicinity in the wave-fitted system is illustrated in Fig. 6.17b.

5 Continuous Detonation Wave Rocket Engines (CDWREs)

What Is CDWRE

The main principle difference between CDWREs and currently existing rocket engines is an annular shape instead of a cylindrical combustion chamber. The working of CDWREs (Lentsch et al. 2005) includes, (i) fuel is injected continuously from one end; (ii) a detonation wave is initiated, which keeps rotating and turns into a multi-wave regime; (iii) finally, the detonation products are expelled on the opposite side of the injector plate. The conceptual sketch of such an engine is shown in Fig. 6.18 (Adamson and Olsson 1967). The primary advantages of CDWRE is significantly shorter combustion chamber without throat leading to a lower engine mass, higher chamber lifetime, increase in specific impulse, reduced sensibility, only starting ignition and higher chamber reliability (Lentsch et al. 2005).

First Experimental Verification of CDWRE

In the very beginning of the twenty-first century, the Laboratoire de Combustion et de Détonique (LCD) in Poitiers, financed by Centre National d'Etudes Spatiales (CNES) and Centre National de la Recherche Scientifique (CNRS), started the experimental research to evaluate the feasibility of rotating detonation rocket engines. This is considered as the first ever step in experimental verification of CDWRE in Western Europe and around the big-blue marble (Lentsch et al. 2005). Even though, only preliminary information's and qualitative data was obtained in the start, the main goal of the CDWRE study is to fully demonstrate the new engine
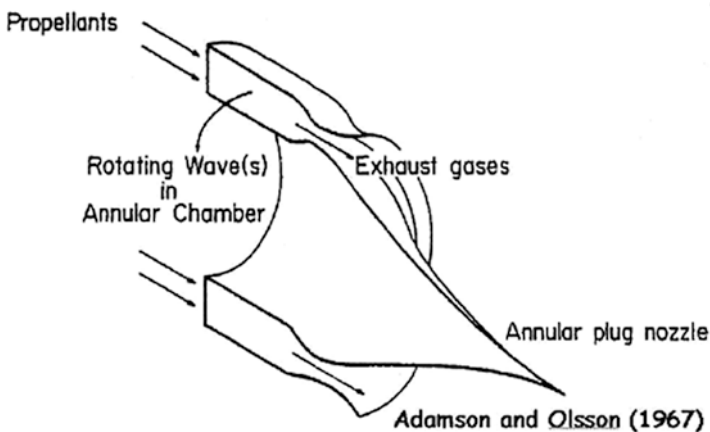

Fig. 6.18 Concept of CDWRE (Adamson and Olsson 1967)
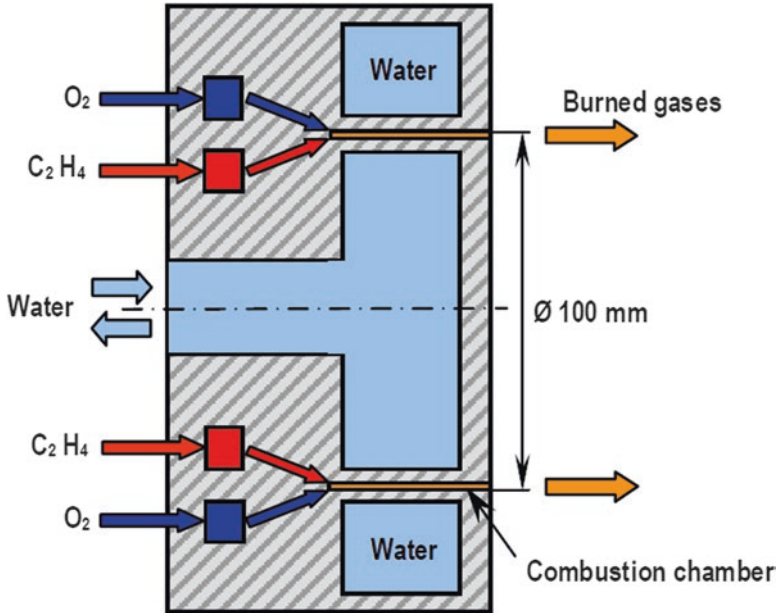
Fig. 6.19 First experimental work in LCD, France (Lentsch et al. 2005)

concept with sub-systems such as the propellant injection system, ignition system, etc. Figure 6.19 (Lentsch et al. 2005) shows a schematic cross section of the annular combustion chamber.

Collaborative Studies of MBDA with Lavrentyev Institute of Hydrodynamics (LIH)

Recently in French, both Falempin group in MBDA & Bykovskii group in LIH worked together in designing an operational CDWRE usable for the upper stage of a space launcher has been performed taking into account all engine/airframe integration issues in order to optimize the benefit of detonation wave engine (Falempin et al. 2006). Then, specific experimental works have been undertaken to address some key issues like noise generated by a CDWE operating at several kilo-Hertz, heat fluxes (intensity, areas) and cooling strategies, composite materials (Carbon/Silicon Carbide) compatibility, engine thrust vectoring capability (Falempin et al. 2006). Some preliminary simulations were performed using FLUCEPA code and found that this code was sufficiently robust to deal with the large pressure and velocity gradients found in a detonation front without the need to use mesh adaptation.

Fig. 6.20 Detonatio propagation in an annular chamber 10, 20 and 30 ms after ignition (Falempin et al. 2006)
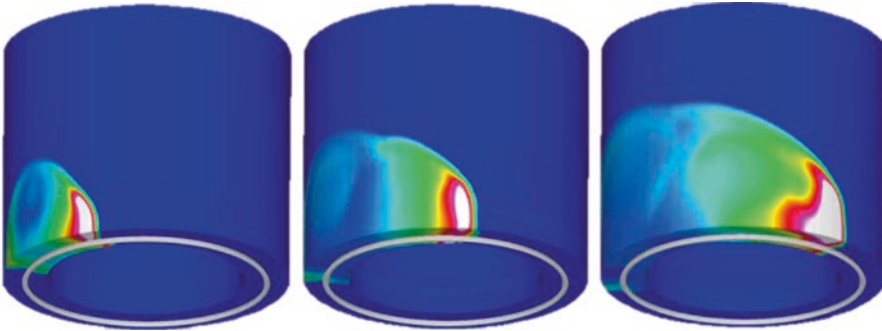
Falempin et al. (2008) has proposed that compared to a PDE, the CDWE design allows an easier operation in reduced-pressure environment and an increase in engine Mass Flow Rate (MFR) and T/W ratio. Figure 6.20 shows the detonation propagation in an annular chamber 10, 20 and 30 ms after ignition. It was found, increasing specific MFR increase both lean & rich ignition limits of the engine and it was possible to start TDW at low combustion chamber pressure in a wide range of Equivalence Ratio (ER) (Falempin et al. 2006). One of the peculiarities of a CDWE is that the number of detonation waves inside the chamber is not constant and is a function of the combustible mixture, the combustion chamber geometry and the MFR (Falempin et al. 2006).

Meticulous research of both numerical and experimental studies of the CDWRE for space application was carried out by Davidenko et al. (2008, 2009b, 2011). He simulated a 2D Euler model of a CDWRE combustion chamber to investigate the effect of geometrical and injection parameters on the internal process and performance (Davidenko et al. 2009b). Furthermore he also carried out experimental studies to investigate the liquid oxygen breakup and vaporization in a helium flow as well as detonation initiation and propagation in a spray of liquid oxygen/gaseous hydrogen.

Some of the late existing challenges in experimental and numerical modeling of the rotating detonation wave propulsion and engine concepts were briefed by Lu et al. (2011c). Lu et al. have been simulated a more realistic environment of a rotating detonation in an annular chamber without any major drop in performance. The structure and cooling capability of the engine itself appears to have limited many of the tests by creating auto-ignition conditions and causing the rotating detonation to fail. Many recent investigations such as turbulence, non-uniform mixing, wall curvature, have addressed and there has been steady progress with understanding how they relate to an efficient RDE design (Lu et al. 2011c).

6   Recent Numerical Investigation of RDE (Fig. 6.21)

Stability and Sensitivity Analysis

In Japan, the Nagoya University (NU) and the Aoyama Gakuin University (AGU) in collaboration with Warsaw University of Technology (WUT) and Japan Aerospace Exploration Agency (JAXA) have involved in the sensitivity analysis of RDE with a detailed chemical kinetics model. Hayashi et al. (2009) proposed that the flow properties such as inlet pressure, Mach and T have a significant effect on rotating detonation device performance. Milanowski et al. (2007) have numerically stabilized a rotating detonation propagating at nearly C–J velocity on a 2D simple chemistry flow-model. Under purely axial injection of a combustible mixture, the rotating detonation is proven to give no average angular momentum at any cross section. Figure 6.22a, b shows the pressure profiles at 300 K and at two reservoir pressures; (a) 1.5 MPa and (b) 1.3 MPa. Figure 6.22c, d shows the T profiles in a RDE. In the Fig. 6.22, the T profiles give the rotating detonation structure more drastically and when the initial reservoir pressure is lower than the critical value, the detonation collapses that its front leaves from the inlet wall (Hayashi et al. 2009). Both experimental and theoretical analysis of the stability of RDE with different velocities consisting of two coaxial cylinders was carried out by Fujiwara et al. (2009). Further optimization study of RDE systems was undergone by Yamada et al. (2010) in 2010. The main aspects of their detonation study includes rotating detonation limits and specific impulse in doubled computational area and increased ignition energy, and they proposed that the lower detonation limit gets the computational area effect, but the upper one does not (Yamada et al. 2010).
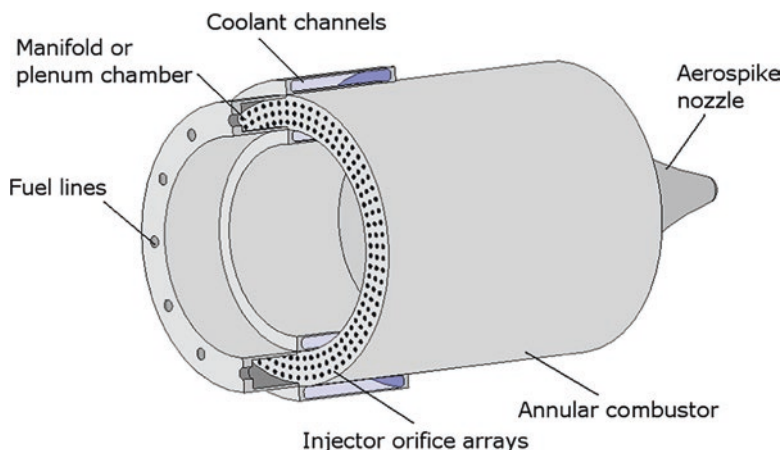
Fig. 6.21 Numerical modeling of the rotating detonation wave propulsion (Lu et al. 2011c)
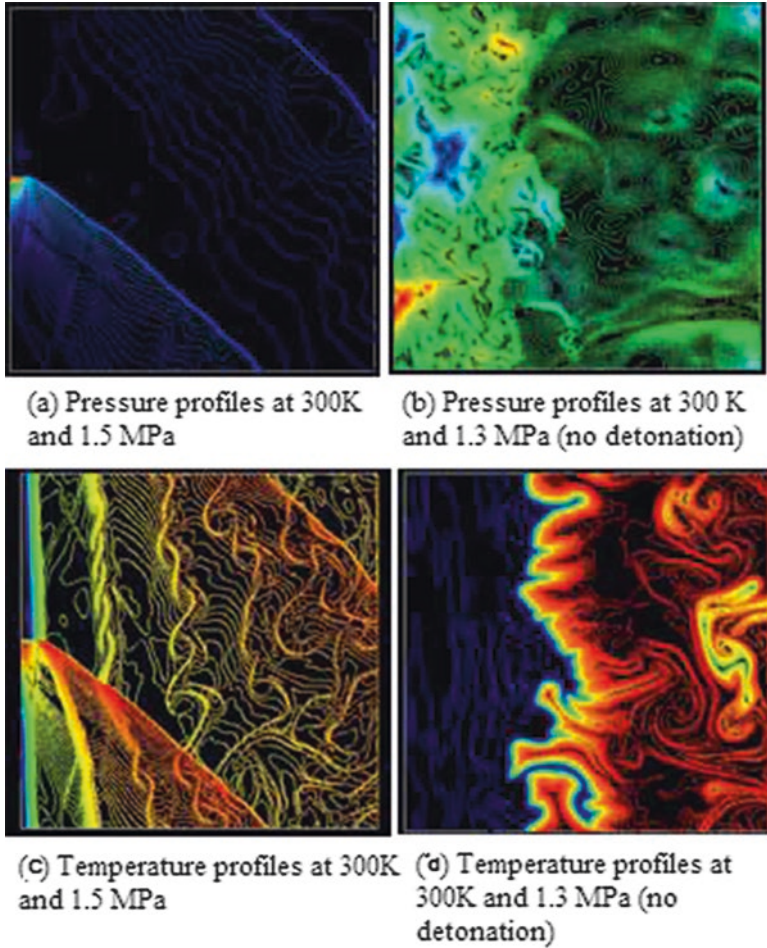
Fig. 6.22 (**a**, **b**) show the pressure profiles at 300 K and at two reservoir pressures; (**a**) 1.5 MPa and (**b**) 1.3 MPa. (**c**, **d**) show the temperature profiles in a RDE (Hayashi et al. 2009; Milanowski et al. 2007; Fujiwara et al. 2009; Yamada et al. 2010)

Propulsive Performance Analysis

There have been some attempts to experimentally and numerically analyze the propulsive performance of RDE by Daniau et al. (2005), who experimentally measured the thrust in a small rocket chamber. Another performance analysis study was carried out by Hishida et al. (2009), who numerically studied 2D RDE with a 70% argon-diluted hydrogen and oxygen mixture. Recently, propulsive performance of a rotating detonation based propulsion systems was carried out by Yi et al. (2009b, 2011). It was found that the propulsive performance is strongly dependent on the

mass flow rate of an injected mixture but it is weakly dependent on the axial chamber length and the number of detonation waves. However, the effect of geometric parameters is insignificant on the engine performance (Yi et al. 2009b).

The injection system is modeled with three different injection conditions, depending on the left-wall pressure as follows. In Fig. 6.23a, the detonation wave is
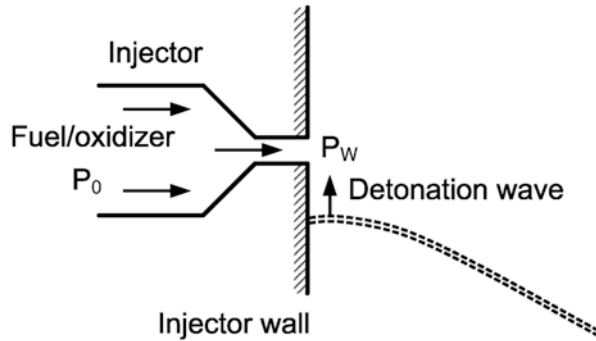
Fig. 6.23 Injector conditions (Yi et al. 2009b)
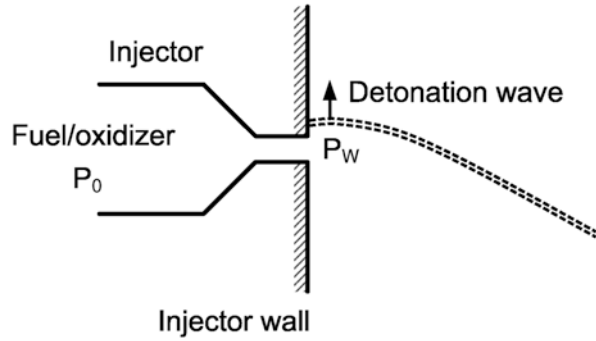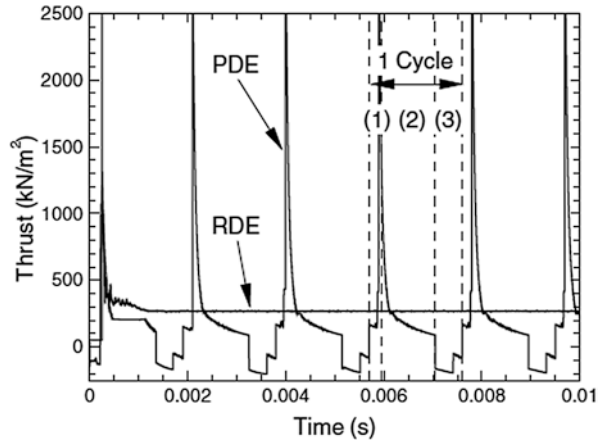

a) No injection: $p_w \geq p_0$
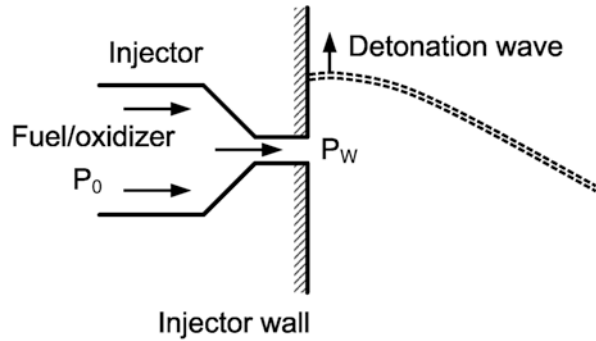
b) Subsonic injection: $p_0 > p_w > p_{cr}$

c) Sonic injection: $p_w \leq p_{cr}$

Fig. 6.24 Temporal evolution of thrust for performance calculation (Yi et al. 2009b)

located just in the front of an injector so that the wall pressure (p_w) is greater than the injection total pressure. In Fig. 6.23b, the wall pressure is less than the injection total pressure, but greater than the critical pressure (p_{cr}) obtained at a choking condition. In Fig. 6.23c where the detonation wave propagates far from or before the injector, here the p_w is less than the p_{cr}. It was demonstrated that the CRDE produces a total impulse higher than that of a single-tube PDE and the nozzle effect is not significant, compared with that of PDE (Yi et al. 2009b). Further effects of nozzle shape, angle and length on the propulsive performance of CRDE is numerically investigated in a 3D annular chamber with the one-step chemical kinetics of a H2/air mixture by Yi et al. (2011). They concluded that the RDE has the negligible nozzle effect on the propulsive performance, compared with that for PDE. Figure 6.24 gives the temporal evolution of thrust per unit area, indicating that because of purging and filling processes in the PDE operation, it is difficult to obtain high operating frequency, resulting in lower thrust. Figure 6.25 gives the temporal evolution of total impulse per unit area, indicating that the total impulse of the RDE linearly increases with time, but the PDE shows the discontinuous behavior in the total impulse, which is caused by a sudden increase in the thrust.

Heat Transfer Analysis

Recently, the Semenov ICP (Frolov et al. 2012) in Moscow has developed an efficient computational tool for transient 3D numerical simulation of RDC (Rotating Detonation Chamber) which has the capacity to solve various RDE issues such as chamber design, thermal management, operation control and conjugate heat transfer and fluid – structure interaction.

Resolution Study of RDE

Recently, Tsuboi et al. (2013) have involved in simulating 2D and 3D RDE by using a recent H2/O2 full chemistry model to estimate (1) the shock structure (2) Thrust performance and (3) Effect of resolution. They concluded that the Specific Impulse (Isp) with the diverging nozzle increases more than that without the nozzle, and also the time-averaged thrust with the diverging nozzle also increases more than that without the nozzle. Figure 6.26 gives the two different resolution study of a flow filed by using 2nd order MUSCL scheme.
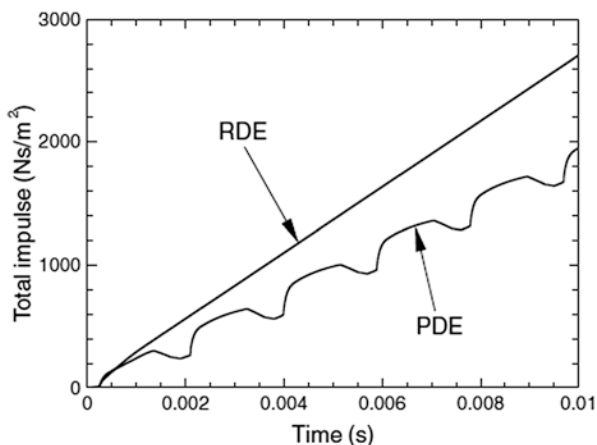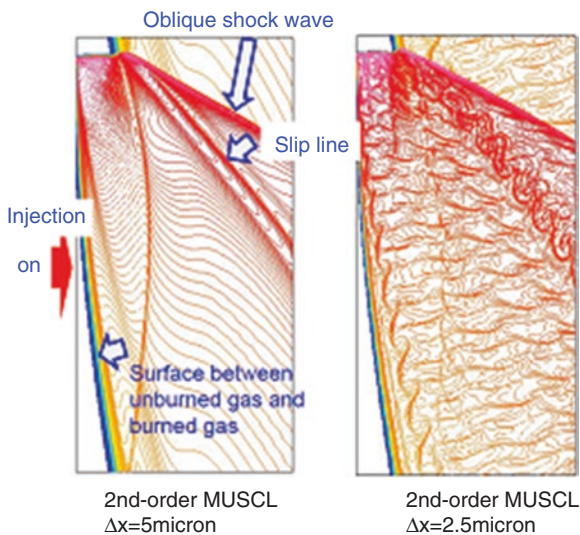

Fig. 6.25 Temporal evolution of impulse for performance calculation (Yi et al. 2009b)

Fig. 6.26 Resolution study (Tsuboi et al. 2013)

Particle Tracking Analysis of RDE

In Peking University (PU), Zhou and Wang (2012) carried out a 2D and 3D particle tracking analysis and concluded that the particles' paths only have a small fluctuation along the azimuthal direction (About 8% of circumference of chamber) (Zhou and Wang 2012). Flow particles are injected into the combustion chamber, burned by the detonation wave or the deflagration wave, and then rapidly ejected almost along the axial direction to generate great thrust. When the flow particles encounter the detonation wave or the oblique shock wave, their paths are deflected. When the flow particles encounter the deflagration wave or the contact surface, their paths are not deflected. 3D path's fluctuant trend along the azimuthal direction is coincident with 2D path; 3D path's deflection is gentler than the 2D path. Figure 6.27 shows

Fig. 6.27 Particle Tracking Analysis of RDE (Zhou and Wang 2012)
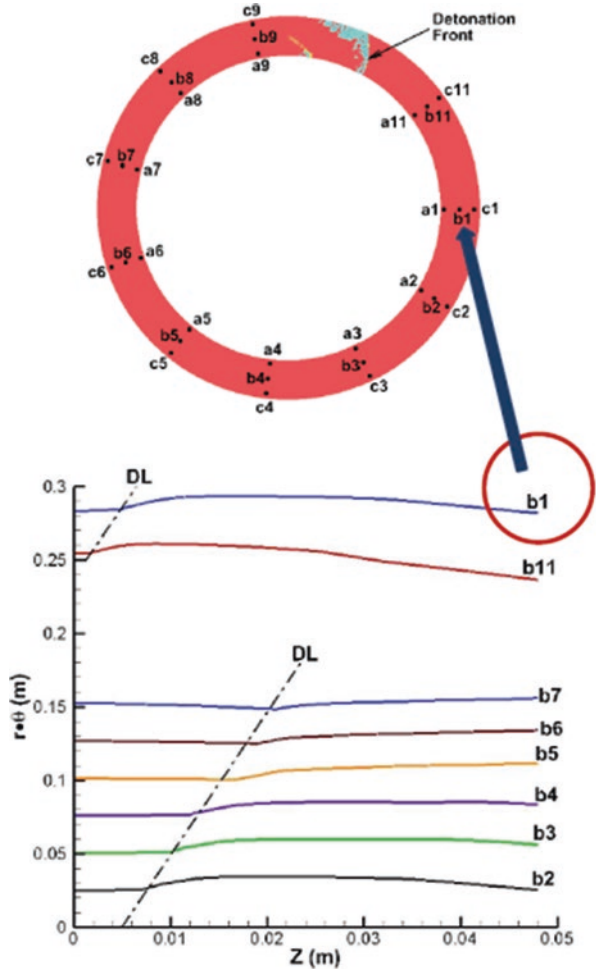
the 3D particle tracking technique utilized for particle path analysis. Moreover in thermodynamic point of view, Zhou and Wang (2012) have also proposed that the (1) 3D's p-v and T-s diagrams are consistent with 2D results; (2) they are all consistent with the Ideal ZND Model perfectly; (3) the maximum pressure in the 3D p-v diagram is higher than the 2D p-v diagram; (4) entropy increment in the 3D T-s diagram is slightly smaller than the 2D; (5) The mass flux and specific impulse of RDE increase with the stagnation pressure p_0 of inlet flow.

Recent Numerical Investigation at NRL

Very recently, time-accurate calculations of 2D and 3D RDE models was studied to using time-step-splitting and FCT (Flux-Corrected Transport) algorithm by Schwer and Kailasanath (Schwer and Kailasanath 2010, Schwer et al. 2011; Schwer and Kailasanath 2011; Kailasanath and Schwer 2013) at Naval Research Laboratory in U.S.A. It was found that the specific impulse was dependent on pressure ratio, whereas the mass flow and propulsive force were primarily dependent on the stagnation properties of the inlet micro-nozzles. Figure 6.28 shows a typical wave-structure within the RDE. In Fig.6.28, (A) Detonation Wave, (B) oblique shock wave, (C) slip line between freshly detonated products and older products, (D) secondary shock wave, (E) mixing region between fresh premixed fuel-air gases and detonated gases, (F) region with blocked injection micro-nozzles, and (G) unreacted pre-mixed fuel-air mixture injected from the micro-nozzles. In NRL, investigation on the effect of different engine sizing parameters on MFR, performance, and thrust of RDE is carried out. Some of the clear-cut understanding of the internal physical behavior of the combustion chamber of RDE is ongoing in the NRL. Recent RDE studies includes flow-field description, stagnation/back pressure effect, engine sizing effect, 3D effect, simulation of specific rigs, injection/inflow effects and preliminary fuel-air effects. Results indicate that for many of the above parameters, the
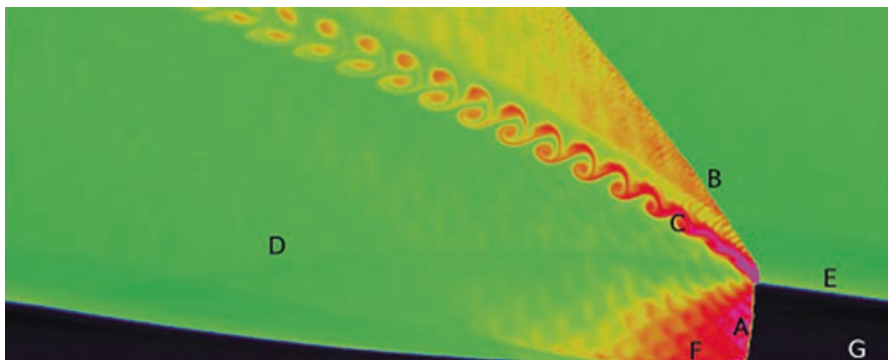
Fig. 6.28 Temp. solution as chamber length is increased (Schwer and Kailasanath 2010)

characteristics of the engine scale in predictable ways for high plenum pressures. A subsequent examination by Nordeen et al. (2014) confirms the operation of the Euler equation in a 3D numerical simulation and is consistent with the modified ZND model.

The Euler constant of integration or rothalpy (Relative total enthalpy) and the wave velocity were extracted from the simulation data by means of a linear regression. Figure 6.29 shows the 2-D time-accurate simulation temperature with time-averaged streamline and Fig. 6.30 shows the time-averaged rothalpy. A complex relationship is suggested by regression fit with area ratio squared. But, a 2nd order relationship is not inconsistent with physics of RDE flow.
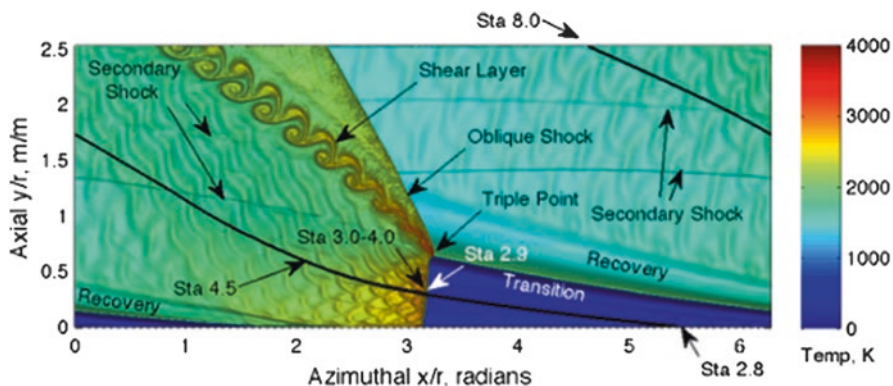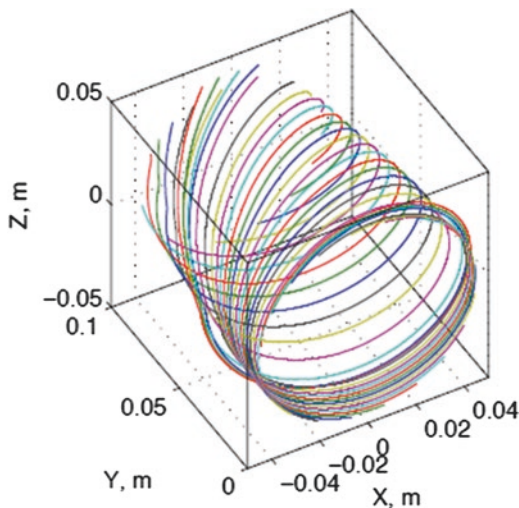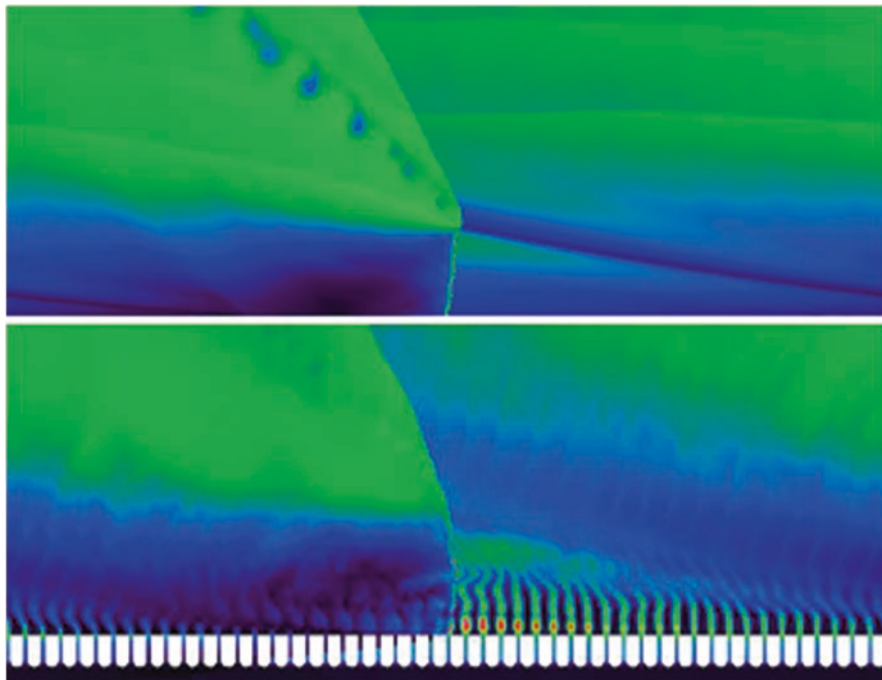

Fig. 6.29 2-D Time-accurate simulation temperature with time-averaged streamline 18 (Tsuboi et al. 2013)

**Fig. 6.30** Time-averaged rothalpy (Tsuboi et al. 2013)

Fig. 6.31 Mach number comparison for ideal injectors (*top*), and 2D injectors (*bottom*) (Kailasanath and Schwer 2011)

RDE injection process is critically important to the stability and performance of the RDE. This has allowed the researchers in NRL to do a variety of parametric studies on the effect of plenum pressure, back pressure, and engine geometric parameters (Kailasanath and Schwer 2011). Figure 6.31 shows the Mach number comparison for ideal injectors (top), and 2D injectors (bottom). The results show that the RDE simulation is very sensitive to how these injectors are modeled; but, the more stable ideal injection approximation still provides valuable information on the influence of different parameters on overall performance. The current work examines the flow field, exhaust flow characteristics for low pressure RDEs and include 3D effects & effects of an exhaust plenum (Kailasanath and Schwer 2014). Figure 6.32 shows the Maximum pressure over one cycle for 3D RDE simulation with no exhaust plenum. Further investigation should also be done to find if an appropriate boundary condition fix can be made to 2D simulation results to bring them into agreement with the much expensive 3D + EP results. In addition to the milestones, Schwer et al. (2014) took the efforts to develop a new code, Propel, for simulating complex engine designs. Their work also compares 2D & 3D solutions using Propel for a detonation tube and baseline RDE with current RDE simulation
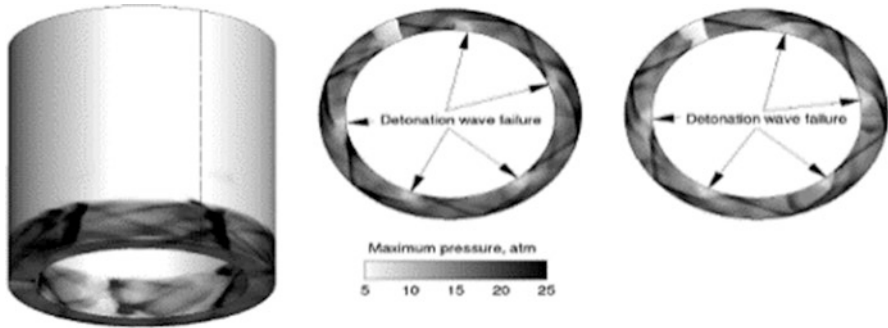
Fig. 6.32 Maximum pressure over one cycle for 3D RDE simulation with no exhaust plenum (Kailasanath and Schwer 2011)
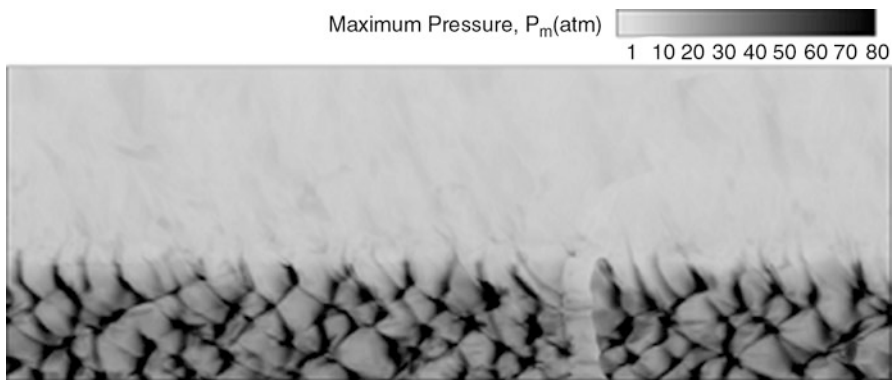

Fig. 6.33 Unrolled pressure maximum plot for inner walls with 2D propel (Schwer et al. 2014)

tool. Figure 6.33 shows the unrolled pressure maximum plot for inner walls with 2D Propel and Fig. 6.34 shows the unrolled pressure maximum plot for outer walls with 2D Propel.

In pursuit of greater thermal and propulsive efficiencies in rockets or gas turbines, a 1D thermodynamic model of RDE is compared to a numerical simulation model with good results by Nordeen et al. (2011). A ZND detonation model is modified to include stagnation properties and account for the velocity vectors that occur upstream of the detonation. Figure 6.35 shows the Static P-V diagram of streamlines & ZND cycle; Fig. 6.36 shows the static H-S diagram with streamlines & ZND cycle and Fig. 6.37 shows the Stagnation P-V Diagram of streamlines & modified ZND cycle. Velocity triangles, commonly used in the gas turbine industry, are shown to be an effective tool for understanding energy transfer in RDE's.
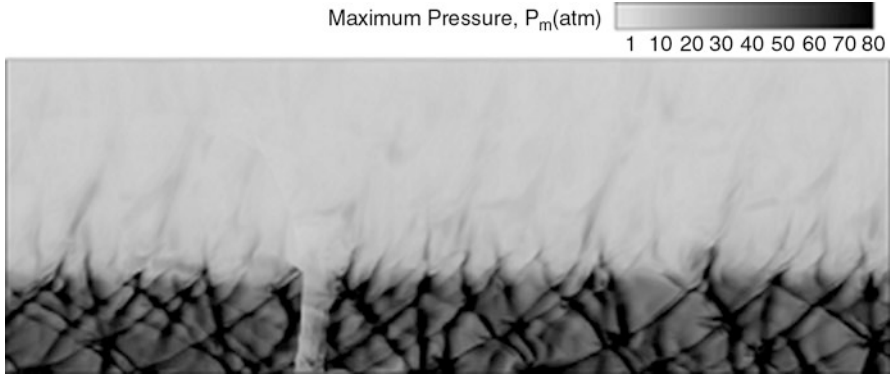
Fig. 6.34 Unrolled pressure maximum plot for outer walls with 2D propel (Schwer et al. 2014)
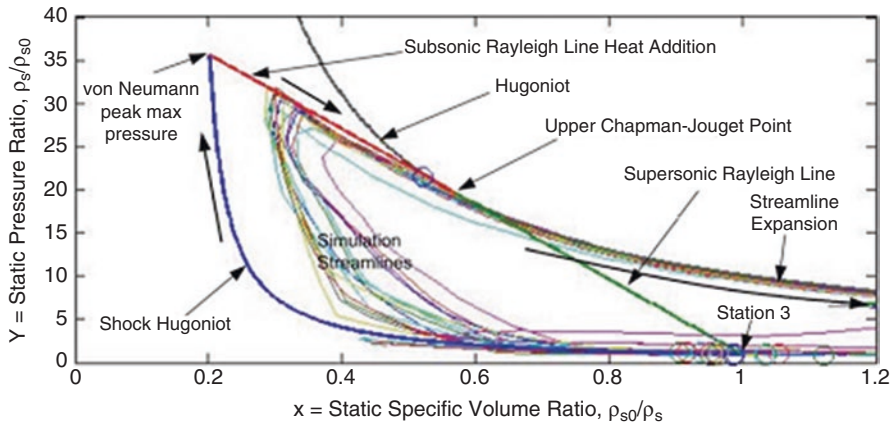
Fig. 6.35 Static P-V diagram of streamlines & ZND cycle (Nordeen et al. 2011)
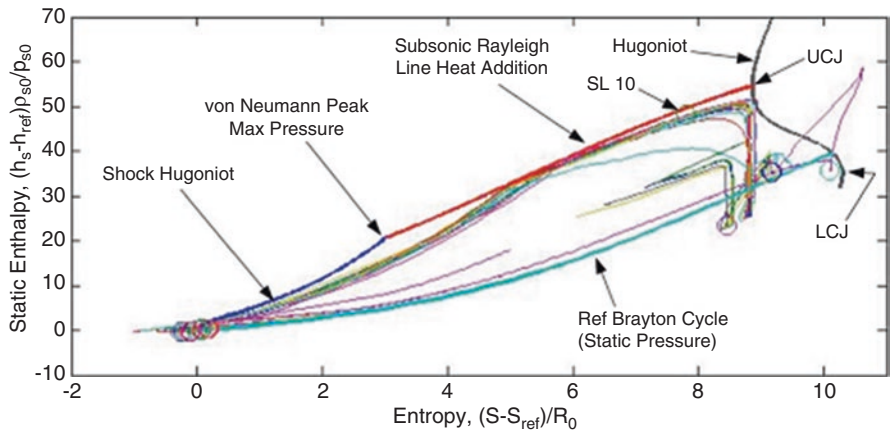
Fig. 6.36 Stagnation P-V Diagram of streamlines & modified ZND cycle (Nordeen et al. 2011)
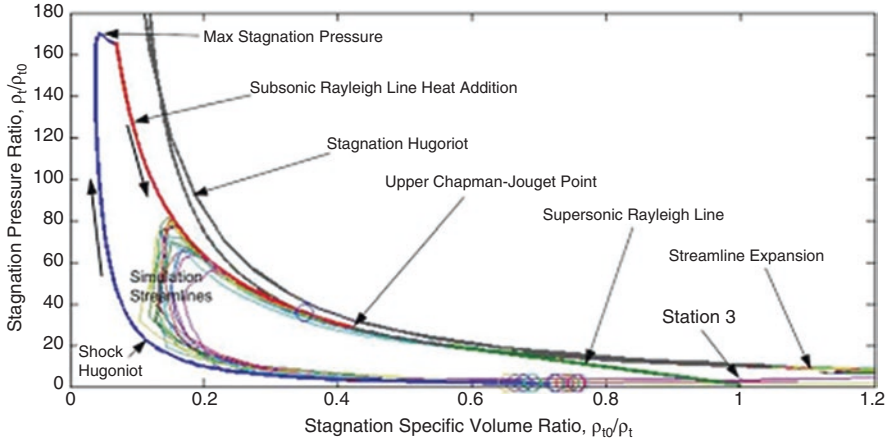
**Fig. 6.37** Static H-S diagram with streamlines & ZND cycle (Nordeen et al. 2011)

RDE Injection and Design Criteria

Premixed operation of an RDE has proven difficult, with the flame igniting the supply upstream of the RDE. As a consequence, much energy has been put toward the design of a mixing system that occurs near or at the inlet of the RDE. Designs utilizing many thin 2D slots have shown some promise, however ignition of the incoming flow due to dead zones behind the plates has occurred.

The current study by Gutmark (2014) aims to investigate more complex three dimensional RDE injection and mixing designs and to reduce the ability to flame-hold, and ensure fewer hot dead zones in the post-detonation refill. Figure 6.38 shows the injection concept (left) with mesh showing refinement near throat (right). Arrows show hydrogen injection direction. Figure 6.39 shows the top and front views of H2 contours from steady operation for 3 different early injection designs during steady operation. The effect of various 3D geometries are studied, including central pintel injection and side wall simple constriction injection, along with modifications to a currently viable experimental design. The simulations have shown a novel RDE design which shows promise, with modification, of successfully repeating a detonation over it with reduced risk of flame-holding, which may result in RDE failure.

RDE Work at NASA

In recent times, NASA has described a semi-idealized 2D RDE simulation which operates in a detonation frame of reference (Paxson 2014) and utilizes a relatively coarse grid such that only the essential primary flow field structure is captured. This construction yields rapidly converging steady solutions and found to be in reasonable agreement with the results of a more complex and refined code. Figure 6.40
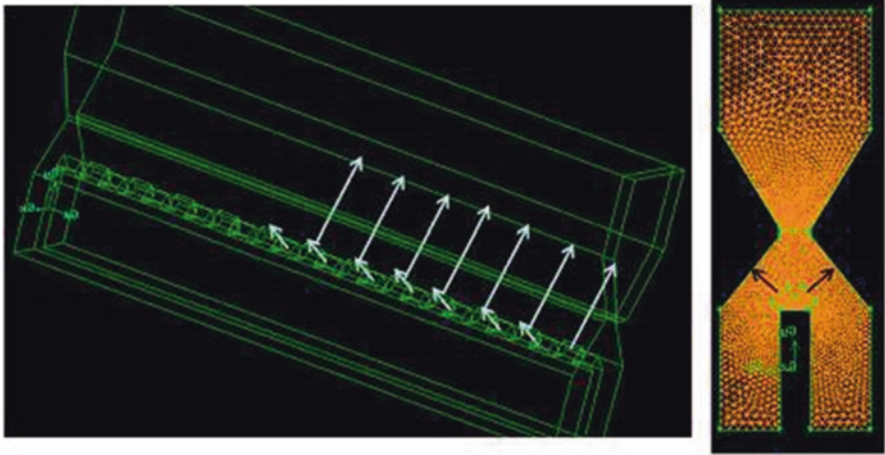
Fig. 6.38 Injection concept (*left*) with mesh showing refinement near throat (*right*). *Arrows* show hydrogen injection direction (Gutmark 2014)
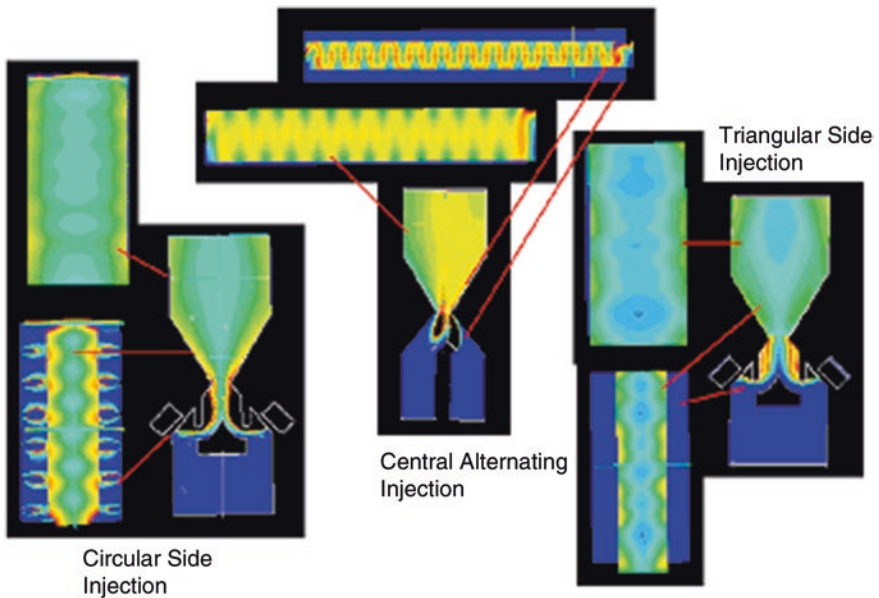
Fig. 6.39 *Top* and *front views* of H2 contours from steady operation for 3 different early injection designs during steady operation (Gutmark 2014)

shows the computed contours of temperature and vortices throughout the annulus of an 'unwrapped' RDE, at steady state. Further, the performance impacts of several RDE design parameters are examined and finally, it is found that the direct performance comparison can be made with a straight-tube PDE and for a particular RDE configuration (Paxson 2014).
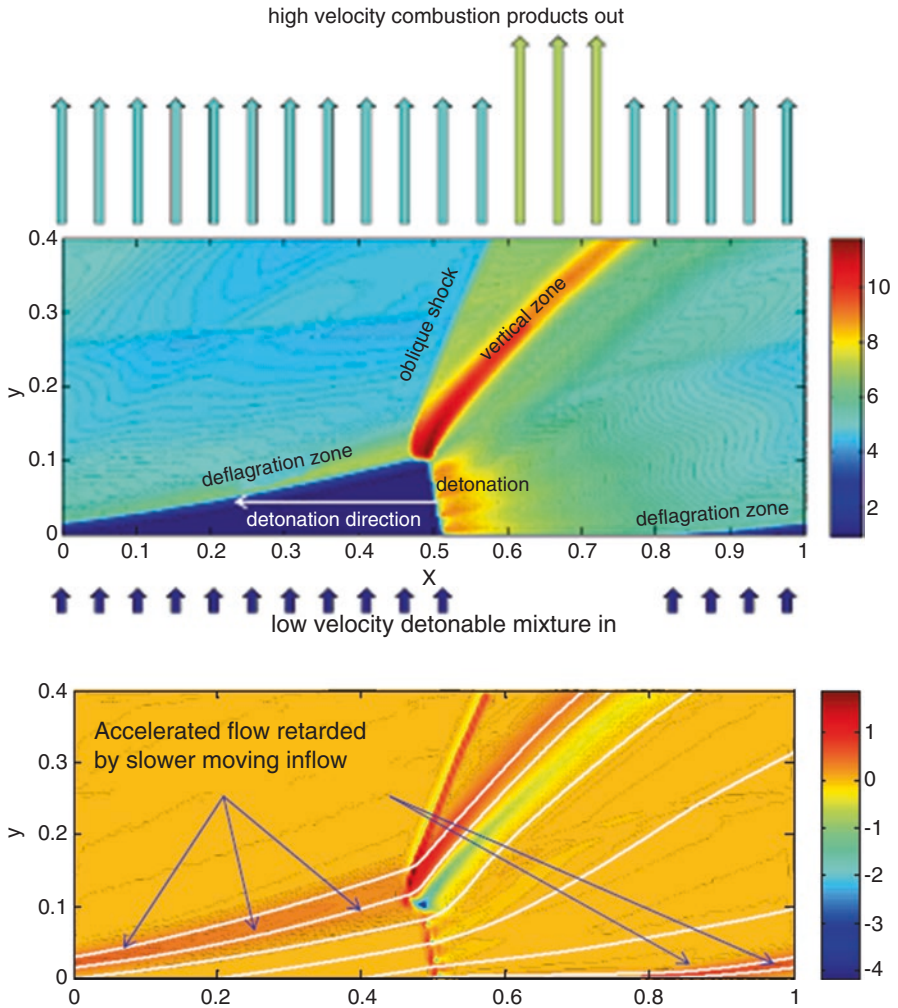
Fig. 6.40 Computed contours of temperature and vorticity throughout the annulus of an 'unwrapped' RDE, at steady state (Paxson 2014)

7   Experimental Work of RDE

Optically Accessible RDE's

Experimental RDE research in AFRL (Air Force Research Laboratory) includes optically accessible RDE's with quartz outer wall having aft end ignition utilizing H_2/O_2 detonation and rig design based on Nicholls and Edwards's research. Figure 6.41 shows the optically accessible RDE manufactured in AFRL (Naples 2011). Moreover, the comparison of experimental result with the obtained

Fig. 6.41 Optically accessible RDE(a) (Naples 2011)

numerical result as shown in Fig. 6.41 (Fievisohn 2012) was made to measure the angles of rough flow structure. They proposed RDE bulk flow looks much steadier to upstream and downstream turbo-machinery – essential for incorporation into turbine engines High speed flow visualization so called chemi-luminescence and RDE heat flux calculations are done in order to conclude that the heat flux increases with increasing wall conductivity (Fig. 6.42).

Integrated RDE's

Uncomplicated design criteria, uninterrupted propellant injection, performance increase and efficiency improvements of the detonation engines so called RDE's enforces the scientists to integrate the detonation technology with air-breathing engines. Recent experimental research on combined small gas turbine with rotating detonation combustion chamber was carried out at the Institute of Heat Energy in Poland by J. Kindracki (2009, 2012). Such a system is shown in Fig. 6.43. Furthermore, AFRL is presently developing a new peculiar engine by implementing Pressure Gain Combustion (PGC) or Constant Volume Engine Cycle (CVEC) approach via RDE. The researchers briefed that the Quasi-steady state outcome from the rotating detonation combustion chamber to the turbine and enormous amount of power density are the substantial advantages of integrating RDE's with gas turbines. However, the bottle-neck challenges of merging RDE's include immense supply of thermal loading, efficient starting, operability betterment, and valving difficulties. Scrupulous investigations are ongoing with the hope to use integrated RDE's in commercial airplanes in nearby future.
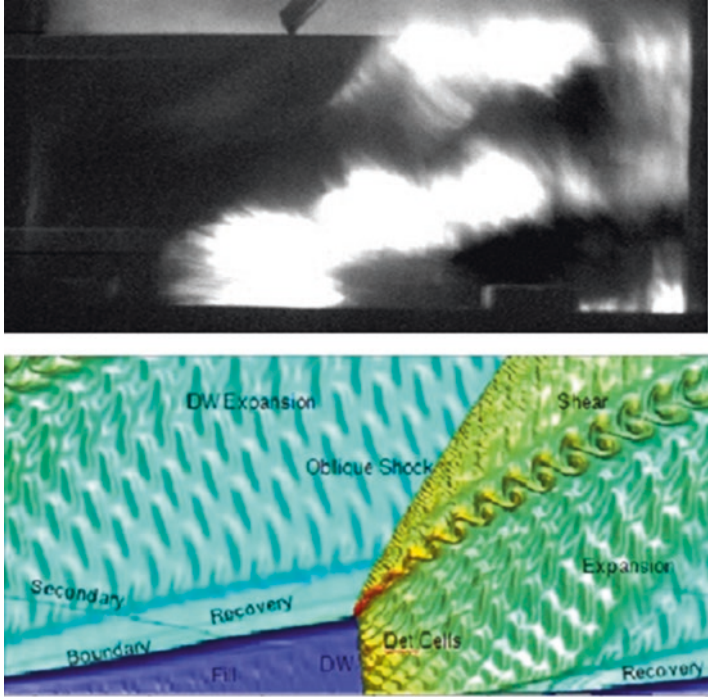
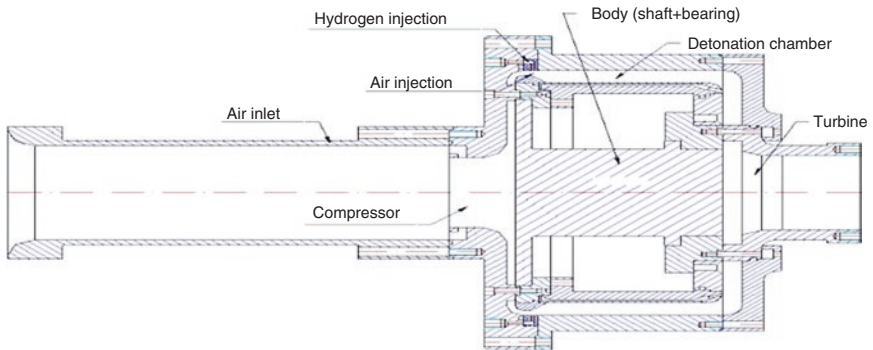**Fig. 6.42** Optically accessible RDE(b) (Fievisohn 2012)

Fig. 6.43 Experimental research on small turbine engine with Rotating Detonation Combustion Chamber (RBCC) (Kindracki et al. 2009)

RDE Research at Poland

A detailed in-depth experimental study of rotating detonation in small rocket engine models were carried out by Wolanski (2011a, b, 2013b) at the Warsaw University of Technology (WUT) in Poland. The experiments clearly showed a possibility of the continuous propagation of rotating detonation in different cylindrical chambers in a wide range of fuel-lean hydrogen air mixtures. Figure 6.44 shows the test stand model of the experimental rocket with RDE and Fig. 6.45 shows the picture of chamber operating under conditions of continuously rotating detonation for hydrogen-air mixture.

Additionally, Wolanski et al. experimental researched to used combined engine between RDE and GTD-350 gas turbine engine. The experiment showed that the continuous rotating detonation could be applied in jet engines. It can be achieved by
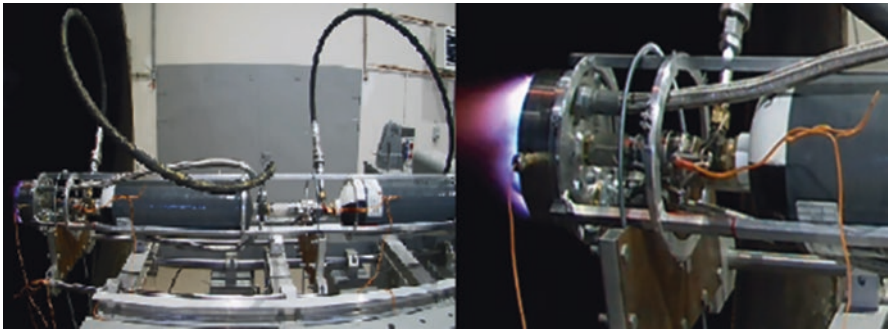
Fig. 6.44 Experimental rocket with RDE on test stand (Wolanski 2011a, b, 2013c)
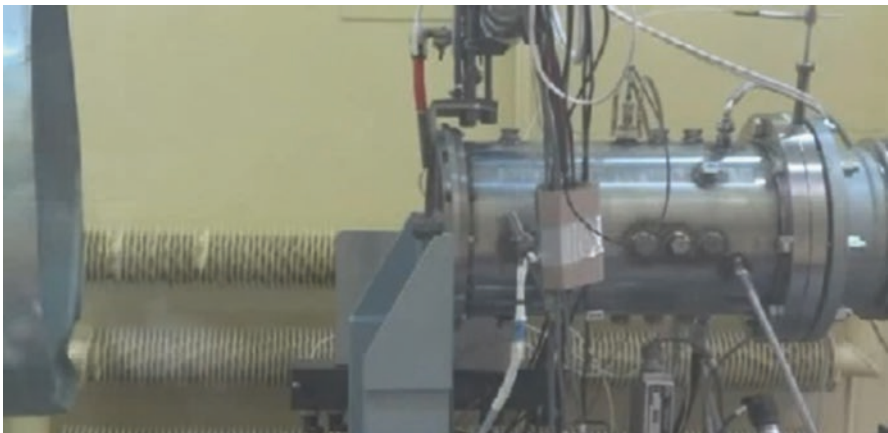
Fig. 6.45 Picture of chamber operating under conditions of continuously rotating detonation for hydrogen-air mixture (Wolanski 2011b)

increasing their efficiency and reducing the weight of the combustion chamber. It was found that it is much easier to get the rotating detonation for fuel-lean and stoichiometric mixtures than for fuel-rich mixtures.

Cooling System of RDE's

Vivid heating of the continuously rotating combustion chamber affects the performance characteristics of the engine as well as leads to structural failure. This kind of heat transfer problems was already discussed by the researchers in 1960's (Siechel and David 1998b; Edwards et al. 1970). However, the recent advancement and solution for novel cooling systems in CRDE were given by the researchers all over the globe. In late 2013, wall cooling and heat release of the wall interaction (Roy 2013) was carried out by the U.S. defense agency. Similarly heat transfer rate in a semi-infinite heat transfer problem and heat flux was given by Wen (2013) in Hong Kong. Wolanski (2013c) in Poland calculated the heat flux distribution in a 16 cooling channel configuration. Figure 6.46 shows the temperature distribution in a cooling channel. Some of the clear-cut understanding of the internal physical behavior of the combustion chamber of RDE was ongoing in the Naval Research Laboratory (NRL) in U.S. Kailasanath and Schwer (2013) in NRL is researching about the flow-field behavior, Stagnation/back pressure effects, injection/inflow effects, exhaust flow effects and preliminary Fuel-Air misting studies of the RDE's.
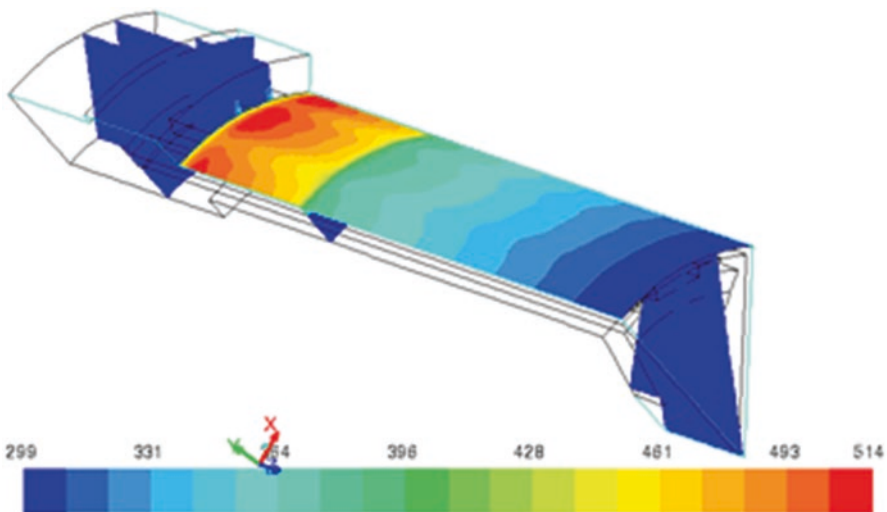
Fig. 6.46 Temperature distributions in a 16 cooling channel configuration (Kindracki et al. 2009)

Visualization and Measurement Techniques of RDE's

The visualization of the flow behaviors and measurement of detonation velocities in RDE's are still remains as a hot topic in detonation research area. Recent study on detonation engine momentum and thrust loss measurement by ballistic pendulum and laser displacement method was presented by Kasahara et al. (Ashida and Kasahara 2014) in Japan. Wolanski (2013c) at the institute of Aviation has briefed a novel measurement technique for investigation on heat transfer characteristics of the gaseous RDE's. Figure 6.47 shows the optical measurement technique developed by Chung (2013). High speed shadow-graphy (Kuznetsov 2013) method was used to optically visualize the inhomogeneity in transparent media and refraction of light rays due to the different in density. Moreover, durability testing system was used recently in Aerospace Science and Technology Research Centre (ASTRC) by Chung (2013) for calibration of flow measurement at high pressure, temperature and compact nozzle conditions.

Long Time Operation Experimental Work of Aerojet Rocketdyne (AR)

Since 2010, AR has been investigating the behavior of a RDE using modular hardware. In 2010, The Power Innovations Group (PIG) at AR successfully conducted over 200 tests of a 4 and 10 cm diameter RDE at Purdue University (PU) and Penn State University (PSU). In 2011, a novel plasma augmentation integrated system (RDE and Turbine engines) (Claflin 2013) was developed by Aerojet Rocketdyne (AR) in California to improve the efficiency of the engine by continuing the air-breathing operation without supplemental oxygen and also to increase the detonation
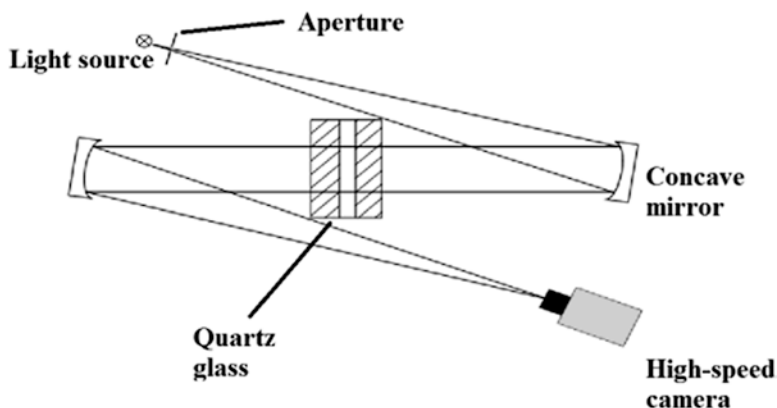

Fig. 6.47 Optical measurement technique (Chung 2013)

velocity. AR is investigating the behavior of RDE for a very long period with lot of experimental testing's using modular hardware, multiple propellant combinations, exchangeable injectors, nozzles and annulus. Figure 6.48 shows the Plasma augmented system developed by AR. In the very recent year it joined with the Defense Advanced Research Projects Agency (DARPA) for developing the high efficient Vulcan exhaust probe (Claflin 2013) to use that for CFD models to generate continuous strong detonation waves and also to sustain the detonation waves in real world scenarios.

High Performance Computing, Incorporated (HyPerComp, Inc.) is currently working on building theoretical and computational model of RDE's. They concluded the continuous detonation behavior of rotating engines is highly dependent on injector behaviors. Figure 6.49 shows the DARPA's recent collaborative projects progress with AR.

In 2013, HyPerComp, Inc. joined with DARPA so called Hypercomp/DARPA program (Claflin 2013) to explore the characteristics of RDE using liquid fuels. The forthcoming work of AR/DARPA includes the optimization of efficient energy conversion and scaling.
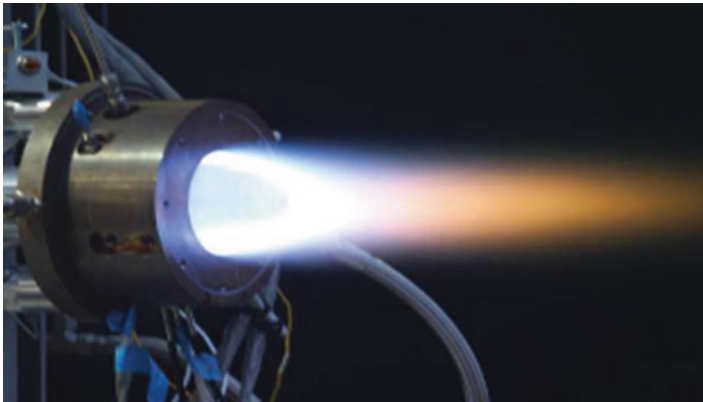
Fig. 6.48 Experimental work at Aerojet Rocketdyne (Claflin 2013)
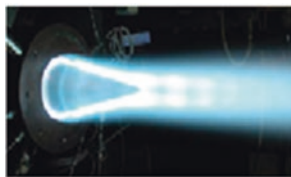
DARPA/Hypercomp Contract Testing   **DARPA Vulcan Exhaust Probes RDE Program**   **DARPA/Hypercomp Liquid Fueled RDE Testing.**

Fig. 6.49 Recent progress in Rotating Detonation Engine development at Aerojet Rocketdyne (Claflin 2013)

RDE's in Space

Recently, Gawahara et al. (2013) taking the advantage of RDE benefits, application to the reaction control system of a spacecraft is expected. Figure 6.50 shows the full schematic photograph of the research stand used for the RDE developmental research and Fig. 6.51 shows the sequence of photographs while the wave front to go around from the incidence of blast. In order to perform internal visualization RDE, and produced a combustor having a straight section the flow channel, and combustion experiments was conducted, and it was confirmed basic combustion characteristics acquisition, the propagation of detonation.

Fig. 6.50 The schematic photograph of the research stand (Gawahara et al. 2013)
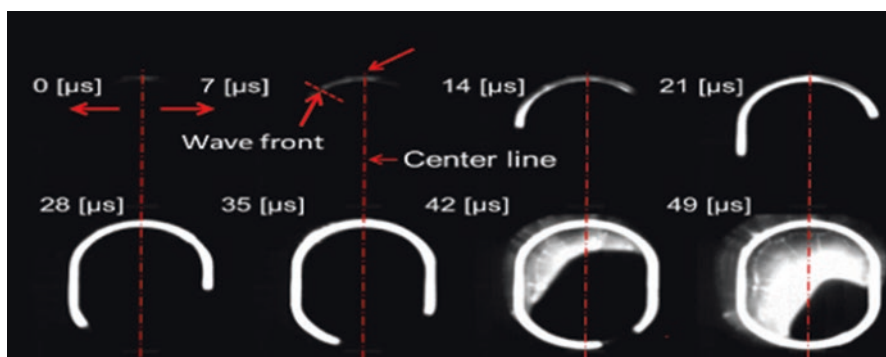
Fig. 6.51 Sequence of photographs while the wave front to go around from the incidence of blast (Gawahara et al. 2013)

RDE Exhaust

Exhaust gas analysis of two RDE's (vertical and horizontal) using Time-Division-Multiplexed Tunable Diode Laser Absorption Spectroscopy (TDM-TDLAS) was carried out by McMahan et al. (2014). These experiments were analyzed to obtain the temperature and H_2O concentration as well as the velo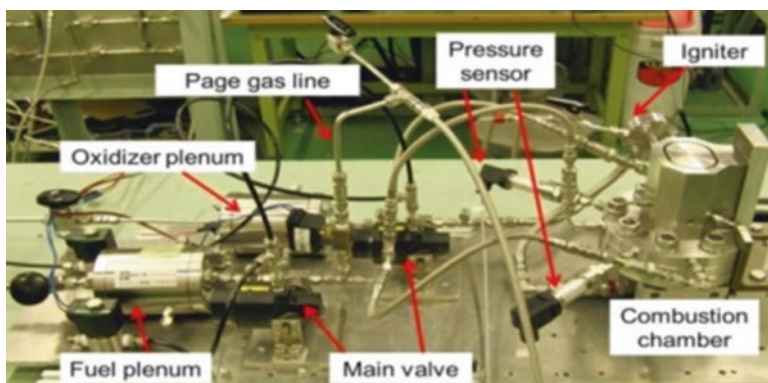city of the exhaust of the RDE. The comparative result shows that after an initial startup region, a steady state operating condition was reached relatively quicker in vertical RDE's then Horizontal RDE's. This may be caused by the difference in flow rates, or it may be that the temperature stabilizes faster than the velocity. Figures 6.52 and 6.53 shows the vertical and horizontal RDE's respectively. The relatively small standard deviation of the temperature and concentration for the steady state region showed that not only the RDE remained steady, but the system taking the measurements could take them repeatedly.

RDE Thrust Measurement

Towards the practical use of RDE's in Rocket Engine, the evaluation of thrust efficiency and the knowledge of combustion under high acceleration or multiple degrees of freedom are essential. Kato et al. (2014) was conducted the RDE thrust measurement experiments by using sled model test in Nagoya University. In order

Fig. 6.52 Vertical RDE (McGahan et al. 2014)
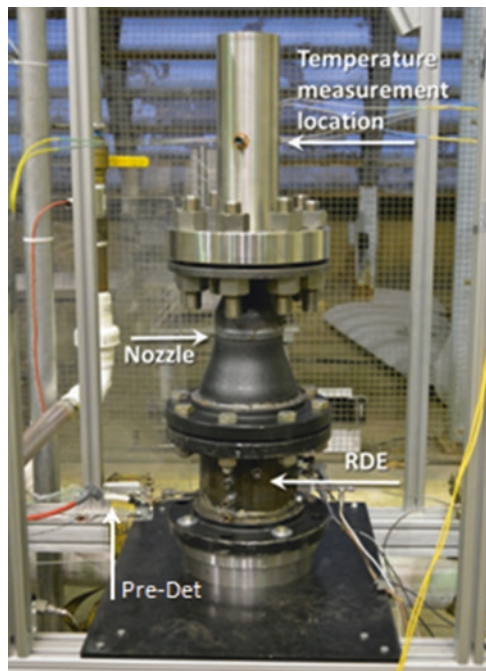
Fig. 6.53 Horizontal RDE (McGahan et al. 2014)

Fig. 6.54 RDE thrust measurement (Kato et al. 2014)

to measure thrust, the test stand with the slide mechanism for noise reduction and exhaust of burned gas was developed. Because of the exhaust chamber pressure, there is a possibility that output large thrust measured by the load cell. Figure 6.54 shows the full photograph of the test stand.

| Rocket-Ramjet (Subsonic) | Rocket-Ramjet (supersonic) | Ramjet (supersonic) |

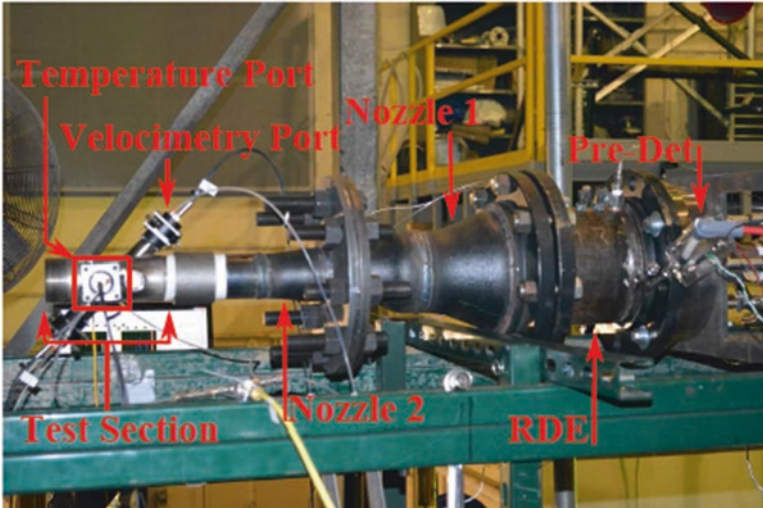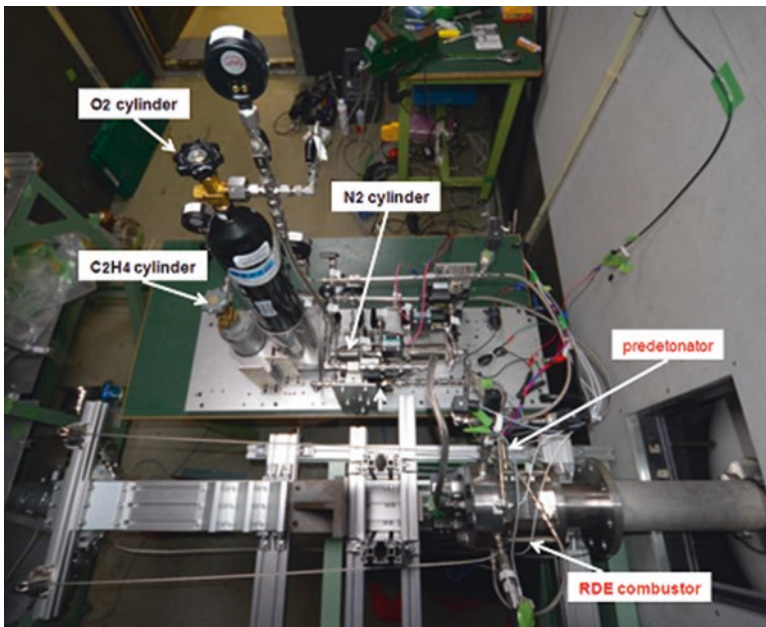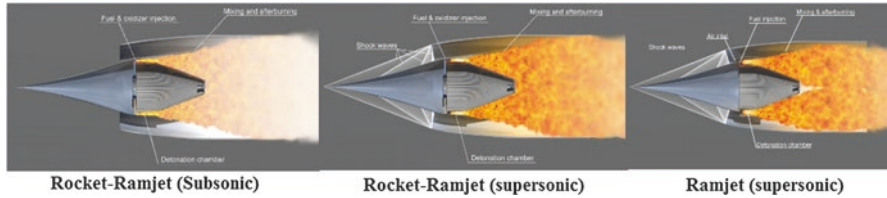**Fig. 6.55** Novel RDE rocket (Wolanski 2013b)

8   Novel Concepts of RDE

Now-a-days among the detonative researchers, liquid propellants are getting quit famous and demanding because of their improved engine performance (Wolanski 2013b; Claflin 2013; Wei 2013). Recently, Wang et al... carried a numerical study of RDE for a circular cylinder without center-body similar to the liquid rocket combustor. (Wang 2012). Integrated RDE based air-breathing propulsion studies are in the stage of advancement. Researchers from Poland (Wolanski 2013b) and U.S. (Kailasanath and Schwer 2013) are progressing to development a small gas turbines with Rocket Booster Combustor Chamber (RBCC) and PGC via RDE's respectively. A suggestion of implementing rotating detonation based engines to space propulsion system has been in ongoing research for several years, since detonative propulsion engines provide a significant rise in engine efficiency over the conventional gas turbine engines.

Poland researchers moved one step forward in integrating RDE's with Rocket engines for space access. Wolanski (2011c) proposed a novel concept of rotating detonation in RBCC. They proposed that the general RDE RBCC engine configuration was not necessarily to be circular. RDE can wrap around any cross section. Figure 6.55 shows the integration of detonative propulsion technology in Rocket-Ramjet engines.

9   Conclusion

A detailed survey of RDE technology is carried out to provide a clear understanding. The recent promising advancement in experimental, theoretical and computational studies of Pulsed or intermittent detonation-wave engines and continuous rotating detonation-wave engines to improve the performance characteristic and cycle efficiency of in-practical gas turbines are also discussed. Moreover, some of the existing crucial problems in detonation technology which holds this propulsion system to enter into practical use are also briefed. Base on the efforts worldwide, detonation based engines would be effectively utilized in both air-breathing and rocket propulsion systems in nearby future.

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