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Review

Analysis of Development Trends for Rotating Detonation Engines Based on Experimental Studies

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Abstract: Rotating detonation engines (RDEs), which are Humphrey cycle-based constant-volume combustion engines, utilize detonation waves to attain higher efficiencies compared with conventional constant-pressure combustion engines through pressure gain. Such engines have garnered significant interest as future propulsion technologies, and thus, numerous research and development initiatives have been launched specific to RDEs in various forms. This paper presents a survey of research and development trends in RDE operating systems, based on experimental studies conducted worldwide since the 2010s. Additionally, a performance comparison of RDEs developed to date is presented.

Keywords: detonation; rotating detonation engine; propulsion system; performance

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1. Introduction

Most engines used in conventional aerospace propulsion involve Brayton cycle-based constant-pressure combustion. However, there is growing interest in Humphrey cycle-based constant-volume combustion engines owing to their higher thermal efficiency attributed to pressure gain, compared with Brayton cycle engines [1,2]. A performance comparison between the Humphrey and Brayton cycles (Figure 1) shows that the Humphrey cycle exhibits considerably higher thermal efficiency than the Brayton cycle due to a larger pressure ratio and reduced entropy generation. Consequently, pressure gain combustion (PGC)-based propulsion engines are being actively researched worldwide owing to their potential to enhance thermal efficiency.

PGC-based propulsion engines can be divided into resonant pulse combustors and wave rotors leveraging deflagration at subsonic speeds and pulse detonation engines (PDEs), standing detonation engines (SDEs), and rotating detonation engines (RDEs) using detonation at supersonic speeds. Among deflagration-based PGC engines, resonant pulse combustors operate using pulse jets and are mainly applied in gas turbine combustors. These engines offer increased thermal efficiency compared with conventional Brayton cycle-based propulsion engines. However, establishing and maintaining resonant operation remain challenging tasks [3]. Wave rotors control the flow of fluid through multiple channels in an axially rotating drum, with PGC combustion occurring within the combustion chamber. Wave rotors also offer increased thermal efficiency. However, the engine design process is complex [4,5]. Overall, the development of practical PGC propulsion systems based on deflagration is challenging due to the complexity of the operational and design processes, prompting research into the development of systems based on detonation. Among such frameworks, PDEs achieve detonation through deflagration-to-detonation transition (DDT) in a long conduit through a cycle of propellant supply, combustion, exhaust, and purge. However, despite their increased thermal efficiency, PDEs require continuous ignition, and their inherent low-frequency operation renders it challenging for a single engine to generate consistently high thrust [6]. SDEs leverage a wedge to generate a normal, oblique detonation wave that is distributed uniformly within the combustor.

As PGC-based propulsion engines, SDEs are highly efficient but can only operate at high Mach numbers (Mach 5–7). Moreover, stabilizing the detonation remains a major technical challenge [7]. RDEs utilize a detonation wave that propagates continuously along the walls within the combustor. RDEs have the advantage over PDEs and SDEs of being able to generate continuous thrust under simple operating conditions, with the engine operating continuously from a single ignition. Consequently, RDEs are the most actively researched among PGC-based propulsion engines and considered to have the highest potential for commercialization. Many recent studies conducted in developed countries have been aimed at introducing RDEs to combustors of various engines, such as rocket, gas turbine, and ramjet engines.

Voitsekhovskii et al. [8] in Russia first explored RDEs in the 1960s, and until the late 2000s, basic research was conducted to confirm their operability and to observe the characteristics of the internally propagating detonation wave. Since the 2010s, these engines have been increasingly applied to combustors in real engine systems. Furthermore, in the 2020s, successful flight tests of aircraft and rockets with RDEs were reported. In the process of developing RDE operating systems, various practical performance data, such as optimal combustor and injector geometries and propellant-specific performance, have been obtained through experimental studies. The analysis of these results is expected to be invaluable for the development of propulsion systems using RDEs in the future. Therefore, this work is aimed at examining the experimental research and development trends of RDE operating systems, considering studies conducted in various countries worldwide since the 2010s. Research conducted by universities, companies, and research institutes in major countries is investigated and summarized, and a comparative analysis of research and development trends is performed.

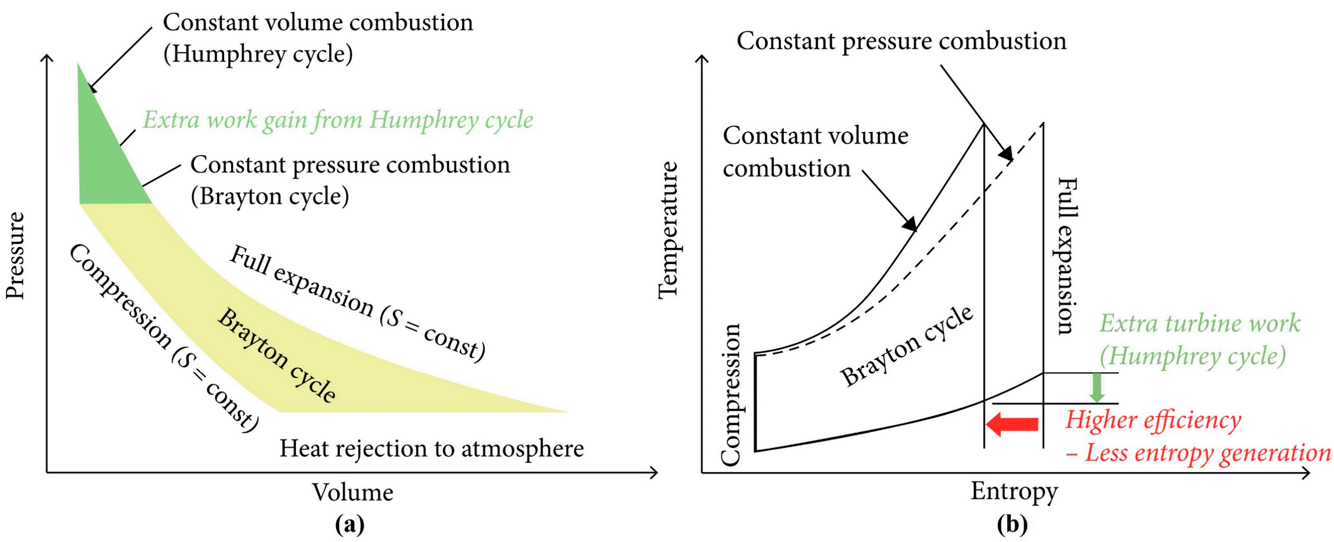


Figure 1. P-V (**a**) and T-S (**b**) diagrams of ideal Humphrey and Brayton cycles [9].

2. RDE Research and Development by Country

2.1. United States

Since the University of Michigan built a small RDE and conducted experimental research in the 1960s [10], interest in using RDEs has grown since the mid-2000s, and collaborative research among universities, research institutes, and companies has been actively conducted since the 2010s. In the United States, universities have primarily focused on basic research, while companies have engaged in research and development in cooperation with universities, aiming for the practical operation of RDEs. Research institutes have explored the performance of RDEs and reported successful ground testing of engine systems.

In particular, universities have focused on the propagation characteristics of the detonation wave within RDEs. In 2010, the University of Texas at Arlington built two annular-type models with swirl injection applied separately for the fuel and oxidizer and conducted experiments [11]. As shown in Figure 2, swirl injection was introduced, along with water cooling. The results confirmed that detonation could occur without a pre-detonator and that swirl injection plays an important role in ensuring the stability of the detonation wave.

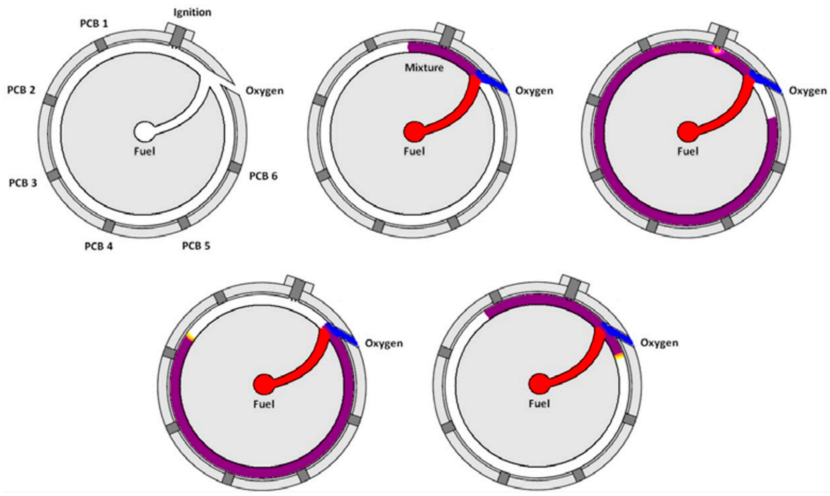


Figure 2. Schematic of the initiation cycle of a swirled-flow RDE [11].

The Air Force Institute of Technology (AFIT) conducted experiments using a 3 in diameter RDE provided by Pratt & Whitney and a 6 in diameter RDE built in-house [12–16]. Russo et al. [12,13] conducted experiments under normal air (volume fraction: 21% oxygen, 79% nitrogen) and enriched air (volume fraction: 23% oxygen, 77% nitrogen) conditions in an annular-type model with a 3 in outer diameter to explore the minimum fuel flow conditions required for detonation to occur. The results indicated the stoichiometric RDE ignition limit for enriched air with a fuel flow rate of 10.6 g/s. Moreover, the velocity of the detonation wave was noted to increase with increasing fuel flow rate and decrease with decreasing g ($=\dot{m}_{tot}/S_c$) under enriched air conditions. Shank et al. [14,15] fabricated an annular model with a 6 in outer diameter and conducted tests with the gaseous hydrogen (GH_2)/gaseous oxygen (GO_2) configuration. By observing the detonation wave generation through high-speed camera imaging and comparing the experimental results with those from a conventional 3 in model, the authors showed that detonation wave generation did not depend on the mass flux and that the equivalence ratio served as a reliable indicator of the operating limit. Tellefsen et al. [16] applied an RDE to the combustor section of a JetCat P-200 gas turbine (JetCat, Ballrechten-Dottingen, Germany) to characterize its performance in turbine applications. The specific power was improved when RDE was applied, compared with conventional constant-pressure combustion, and the addition of nozzles slowed the detonation wave as it became unstable, thereby increasing the variation in combustion pressure. Later, in 2024, Keller et al. [17] conducted a small-scale annular-type RDE experiment with the advantages of portability, efficiency, and low noise. Ethylene-oxygen, which has a small cell size and can generate detonation even at low mass flow rates, was used as a propellant for stable detonation formation at a small size with a 28 mm chamber diameter and 2 mm channel gap. The experimental results showed that the operational detonation frequency of 31 kHz was achieved, which was above the design target of 20 kHz (human hearing threshold), but the wave speed was 1100–1400 m/s (approximately 52% of CJ value).

In 2015, the University of Cincinnati [18] conducted experiments using an air-breathing RDE designed based on the model by Shank et al., 2012 design [14]. Hydrogen and ethylene fuels were used to assess the occurrence of detonation and characteristics of the exhaust plume as a function of the equivalence ratio. In the case of detonation, a dome-shaped exhaust plume was observed, as shown in Figure 3.

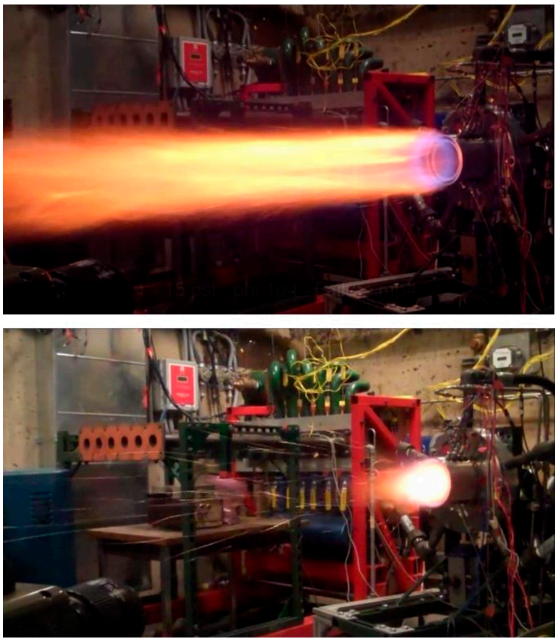


Figure 3. Deflagration exhaust plume (**top**) and detonation exhaust plume (**bottom**) [18].

Walters et al. [19] from Purdue University conducted experiments with RP-2/gaseous oxygen propellant in an annular-type model with a detonation channel having a 228 mm outer diameter and measured the heat flux at combustion pressures up to 17 bar. Embedded thermocouples were used to obtain temperature data and calculate the heat flux. Experiments were performed under flow conditions of 0.77–3.49 kg/s and equivalence ratios of 0.97–1.73, and the calculated average heat fluxes were used to estimate the heat load on the combustor portion of the RDE and nozzle throat of the constant-pressure combustor. Although calculations based on thermocouple time constants may be error-prone, the heat load on the RDE was noted to be smaller than that on the nozzle throat of the constant-pressure combustor. Kubicki et al. [20] conducted experiments using a hypergolic liquid propellant in an annular-type model incorporating a detonation channel with a channel gap of 0.25 in and outer diameter of 3.7 in. Hydrogen peroxide and trigylme were used as the fuel and oxidizer, respectively, and sodium borohydride was used for hypergolic ignition. The experiments confirmed that the detonation wave rotated at a speed of 2220 to 2417 m/s under an equivalence ratio of approximately 1.7 and flow rate of approximately 793.79 g/s.

In 2020, the University of Central Florida conducted experiments using hydrogen/oxygen propellants in an annular-type model with a 76.2 mm outer diameter detonation channel and 5.1 mm channel gap, modeled after the Edwards Air Force Base RDE [21]. High-speed chemiluminescence imaging was used to quantify the velocity and number of detonation waves. Experiments were performed at equivalence ratios of 0.95 to 1.7 and total flow rates of 294.84 to 526.17 g/s, and five detonation waves were observed to rotate. The detonation wave velocities were measured to be in the range of 2272 to 2326 m/s, with higher velocities measured for equivalence ratios of 1.1 to 1.3.

Researchers have developed a racetrack-shaped RDE model to observe and understand the detonation process optically [22–25]. The University of Michigan [22,23] developed a racetrack-shaped RDE designed to operate in the same combustion mode as a circular 6-inch RDE and performed OH-PLIF imaging, as shown in Figure 4. The experiments showed how the buffer region (composed of pure fuel and devoid of OH) separated post-detonation products from fresh reactants and identified parasitic and commensal combustion, providing insight into the details of the reacting flow field. At the University of Alabama [24,25], a racetrack-shaped model consisting of an annular section with an inner diameter of 4 in and a straight section with a length of 4 in was fabricated and tested. The liquid propane/gaseous oxygen configuration was used as the propellant, and detonation wave velocities ranging from 975 to 1075 m/s were measured under flow rates of 276.7–639.6 g/s and equivalence ratios of 0.67–2.21. The detonation wave velocity was maximized at stoichiometric ratios of 1.75 to 1.8.

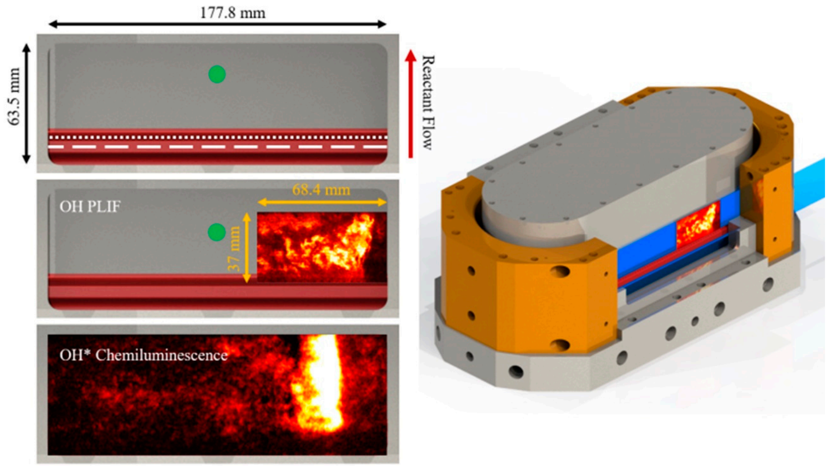


Figure 4. Racetrack-shaped RDE model with schematic of the laser sheet arrangement. The green dot denotes the location of a high-speed pressure transducer used for synchronization of the OH PLIF images [23].

Various companies have collaborated with universities and institutions to perform research and development on diverse aspects. For example, SwRI, in collaboration with the University of Central Florida, used particle image velocimetry (PIV) and tunable diode laser absorption spectroscopy techniques to evaluate the performance of a diffuser in the combustor [26]. Hydrogen fuel and air were used as the propellants. The computational analysis confirmed that the diffuser delivered exhaust gas with minimal total pressure loss, and the computationally simulated diffuser design was modeled and tested. Figure 5 shows the 10 cm annular-type model geometry used in the experiment and a photo of the combustion experiment obtained using the PIV technique.

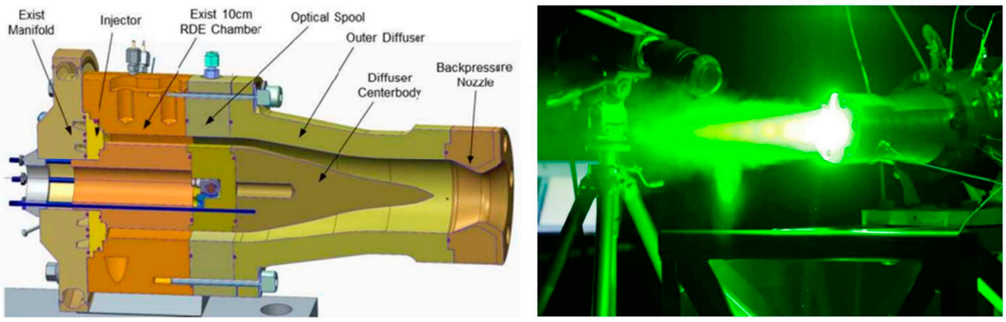


Figure 5. RDE test model (**left**) and RDE hot fire test with PIV sheet laser (**right**) [26].

From 2010 to 2018, Aerojet-Rocketdyne conducted experiments using various models for the development of rocket and air-breathing RDEs [27]. More than 1350 tests were conducted in collaboration with DARPA and various universities. Tests were conducted on various annular-type models with diameters ranging from 100 to 430 mm, as well as models with aerospike nozzles. The results showed that the detonation wave velocity increased when the plasma ignition system was used, compared with the non-plasma ignition system. In addition, combustion experiments with liquid fuels such as JP-8 and

JP-10 were conducted. Aerojet-Rocketdyne has reported that it will continue to study injectors and diffusers for the 13.2 in diameter model in the future.

Laboratories in the United States have conducted research primarily to evaluate the performance of RDEs. The Air Force Research Laboratory (AFRL) conducted experiments using an RDE model provided by Pratt & Whitney (East Hartford, CT, USA). Thomas et al. [28] conducted experiments using an annular-type model with a 3 in diameter detonation channel and channel gaps of 2, 6, and 10 mm with different center body diameters. The hydrogen/air configuration was used as the propellant, and experiments were conducted to predict the size and initial pressure of the detonation cell, albeit without success. Rankin et al. [29,30] performed experiments under various conditions using a combustion chamber wall made of quartz to visualize the detonation wave using OH* chemiluminescence and a steel wall to measure static pressure. The experiments were conducted using an annular-type model with a channel width of 7.6 mm, a 153.9 mm outer diameter detonation channel, and a 138.7 mm outer diameter center body, using hydrogen/air as the propellant. The flow rates of the fuel and oxidizer, equivalence ratio, injector geometry, and diameter and number of injection slots and holes were varied to observe the characteristics of the detonation wave. Figure 6 shows a photo of the model with a quartz outer wall.

Figure 6. Optically accessible RDE model [29,30].

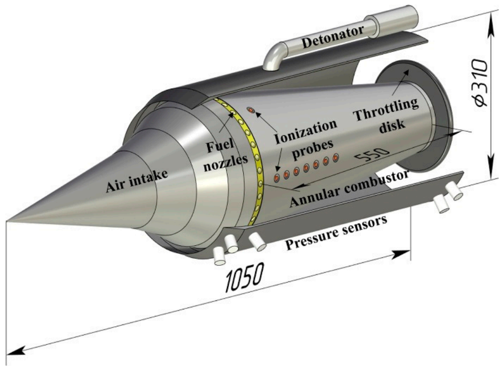
The experimental results showed that at low flow levels (0.15 kg/s), the detonation wave height (length of the detonation wave in the direction of the nozzle exit) increased with the flow rate of the oxidizer (0.32 to 0.61 kg/s), while the detonation wave height decreased and the number of waves increased from one to two when the oxidizer was supplied at a higher flow rate (0.86 kg/s). Experiments with injector geometry variables showed that the detonation wave front tended to become more concave as the diameter of the oxidizer injection slot increased under the same flow conditions. When the number of holes in the fuel injector with the same hole area decreased from 120 to 80, the number of detonation waves changed from one to two. In addition, in experiments with a low oxidant flow rate (0.15 kg/s), oxidant injection slot with a smaller diameter, and fewer holes in the fuel injector, two counter-rotating detonation waves and their interactions were observed. Static pressure measurements showed periodic changes in oxidizer plenum pressure as the diameter of the oxidizer injection slot increased, and wave speeds of 1160–1740 m/s (60–90% of Chapman–Jouguet (CJ) detonation speed) were found depending on the experimental conditions. Fotia et al. [31,32] conducted experiments using an annular-type model with a 6 in outer diameter detonation channel. Hydrogen and ethylene were used as the fuel, with air as the oxidizer, and the performance variations in the presence and absence of an aerospike nozzle and different nozzle throat sizes and detonation channel widths were examined. When the aerospike nozzle was used, performance metrics such as the specific impulse, specific thrust, and normalized corrected specific impulse ($= I_{sp}P_{0,Ref}/P_0$) increased when the nozzle throat size was reduced. Moreover, the normalized corrected thrust ($= FP_{0,Ref}/P_0$) increased as the combustion channel width increased. This outcome indicated that changing the geometry of the RDE could enhance the thrust production efficiency, leveraging the dynamic characteristics that change along the flight profile. In addition, experiments with ethylene/air were conducted to compare the normalized corrected thrust with hydrogen/air, specific impulse, and specific thrust in the PDE with hydrogen and ethylene. The results showed that the normalized corrected thrust of the hydrogen/air case was higher than the ethylene/air case. Furthermore, the specific impulse by fuel was found to be similar to that reported in prior studies using PDE and RDE. Hargus Jr. et al. and Bennewitz et al. [33,34] performed over 500 experiments on an annular-type model with a detonation channel having a 3 in (76.2 mm) outer diameter and 0.2 in (5 mm) channel width using methane/oxygen propellant. Various shapes of the center body were considered to change the internal geometry of the combustor, and the RDE operation characteristics under different nozzle constriction ratios (ratio of combustion chamber area to nozzle throat area) and combustion channel lengths were determined. The results showed that the maximum thrust was approximately 1334 N, and the maximum specific impulse by mixture was approximately 250 s. The thrust increased with the nozzle constriction ratio, and detonation wave speeds of 50–70% of the CJ velocity were observed. The length of the combustion channel did not considerably affect the performance, with detonation wave speeds of 70–75% of the CJ velocity and fewer detonation waves propagating in the counter direction. In 2021, the National Energy Technology Laboratory conducted experiments on an annular-type model with a detonation channel having a 152.4 mm outer diameter and 7.62 mm channel width for gas turbine application [35]. Hydrogen/air was used as the propellant, water cooling was applied, and NO_x emissions from hydrogen and natural gas–hydrogen blends were compared. The results showed that the amount of NO_x in the natural gas–hydrogen blend was approximately 5 to 15 ppm higher than that for hydrogen fuel.

NASA conducted a design verification test totaling 10 min, as shown in Figure 7, for a 2023 deep space mission [36]. The rotating detonation rocket engine (RDRE) model incorporated a GRCop-42 copper alloy developed in-house using additive manufacturing based on 3D printing technology to increase the engine thermal performance. During tests, the RDRE generated more than 4000 lbf of thrust for about a minute at an average chamber pressure of 622 psi. The team is now engaged in follow-up research to develop a reusable RDE with a thrust of 10,000 lbf.

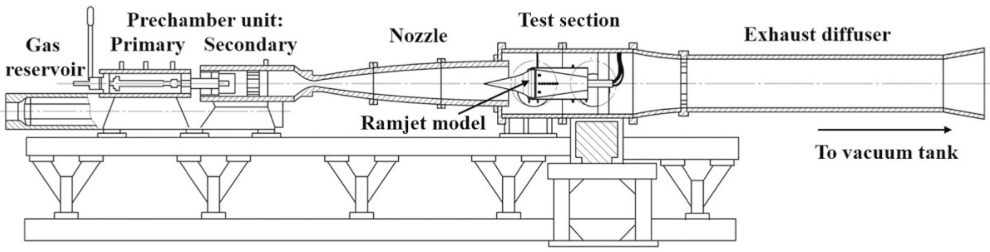
Figure 7. NASA RDE hot fire test [36].

2.2. Russia

As mentioned in the introduction, research on RDE was pioneered by Voitsekhovskii et al. [8]. In Russia, the Lavrentyev Institute of Hydrodynamics (LIH) led the research. Frolov et al. [37,38] at the Semenov Institute of Chemical Physics conducted experiments on the detonation ramjet model in short-duration (pulsed) wind tunnels, Transit-M and AT-303. The wind tunnel and detonation ramjet model used in the experiments are shown in Figure 8. The Transit-M wind tunnel is designed to perform aerodynamic tests in the Mach number range of 4–8 using a nozzle with a cutoff diameter of 300 mm. The AT-303 wind tunnel is designed to perform tests over a wide range of Mach numbers from 5.7 to 20 with a cutoff diameter of 400 mm. The detonation ramjet model includes an inlet and annular expander that decelerates the supersonic flow through three oblique shock waves, with the outer cowl having a diameter of 284 mm and the combustor having an outer diameter of 310 mm. The Transit-M wind tunnel was used to conduct experiments at an air temperature of 290 K and Mach numbers of 4–8, using hydrogen as the fuel. The maximum specific impulse by fuel was 3600 s, and a maximum thrust of approximately 2200 N was achieved [37]. Later, the same detonation ramjet model was used to conduct experiments in the AT-303 wind tunnel at a temperature of 1500 K and Mach number of 5.7. The maximum specific impulse based on fuel was 3300 s, and a maximum thrust of about 1500 N was determined [38]. In addition, a large-scale annular-type RDE was built and tested using liquid fuel [39]. The detonation channel outer diameter was 406 mm, length was 310 mm, and channel width was 25 mm. Hydrogen/air and hydrogen–liquid propane/air mixtures were used as the propellants. The experimental results showed that the hydrogen/air propellant did not generate a detonation wave when the hydrogen pressure was 0.52 MPa, and the hydrogen–liquid propane/air propellant did not generate a detonation wave when the hydrogen pressure was 0.24 MPa. Additionally, continuous detonation combustion did not occur at low velocities of the detonation wave (600–650 m/s). Since then, research has been ongoing to achieve continuous detonation combustion for propane/air propulsion without hydrogen addition. Since then, Ivanov et al. [40] have designed and experimented with a new type of hydrogen-fueled detonation ramjet for cruise flight speeds of Mach 2. The experiments were carried out in a pulsed wind tunnel with free jet Mach numbers 2.0 and 1.5, and the results confirmed stable continuous detonation combustion of hydrogen at both Mach numbers, with the maximum thrust and fuel-based specific impulse at each condition being 650 N and 1610 s for M = 1.5, respectively, and 860 N and 1630 s for M = 2.0, respectively. Subsequently, a detonation afterburner (DA) for continuous detonation combustion of TS-1 aviation kerosene was developed, fabricated, and tested for the first time [41]. Longitudinally pulsating detonation mode (LPD) and spin detonation (SD) mode were observed, and the static pressure inside the DA was measured, and it was found that the specific fuel consumption was 30% lower and the specific thrust and thrust boosting coefficient were 30% higher compared to the conventional afterburner at the same chamber pressure. The Russian rocket engine company NPO Energomash established the "Detonation Liquid Rocket Engine" laboratory in 2014, and in 2016, they successfully conducted a liquid propellant RDE test using liquid kerosene and oxygen [42]. At a supply pressure of 40 bar, a 6% higher specific thrust was obtained compared with deflagration combustion. Moreover, this experiment (Figure 9) was the first to confirm the feasibility of RDE with liquid propellants.



(**a**)



(**b**)

Figure 8. Detonation ramjet model (**a**) and short-duration wind tunnel "Transit-M" (**b**) [37,38].

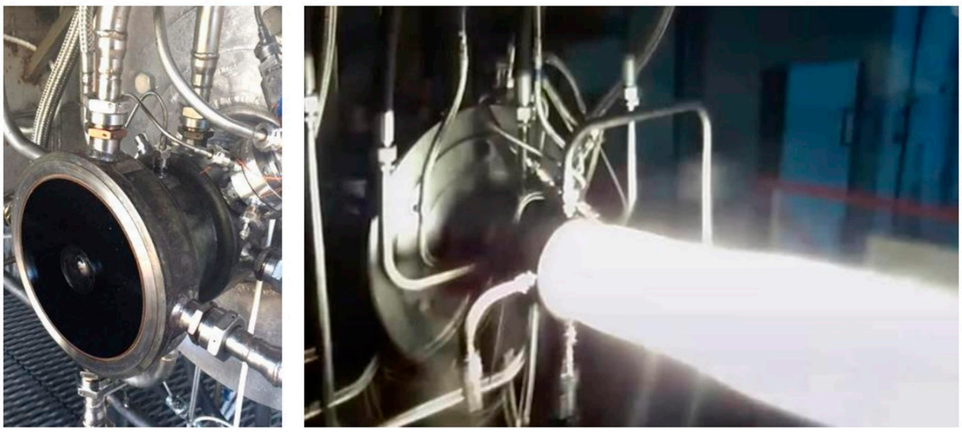


Figure 9. Prototype of the Ifrit Rotating Detonation Engine and its tests [42].

2.3. France

RDE studies in France were mainly conducted by the company MBDA France, in collaboration with LIH, Russia. Le Naour et al. [43] performed experiments on an annular-type model with a 100 mm outer diameter detonation channel and 10 mm channel width. The model was composed of a copper/zirconium alloy to ensure long burn times without a cooling system, and gaseous hydrogen/gaseous oxygen was used as the propellant. The maximum test time was 5 s, and the maximum thrust was approximately 338.5 N (equivalent thrust in vacuum). In 2017, an annular-type large-scale RDE model with an outer diameter of 330 mm was developed and tested for application in turbofan and ramjet engines [44]. The experiments were performed at the MBDA ramjet test facility, which can supply a high flow rate of 60 kg/s of air at a total pressure and temperature of up to 15 bar and 750 K, respectively. The experimental facility is shown in Figure 10. The fuels used were hydrogen and a hydrogen–kerosene mixture. The experimental results indicated that the detonation region stabilized at higher mass flow rates and temperatures, and the velocity of the detonation wave decreased when kerosene was injected in the experiments with the hydrogen–kerosene mixture.

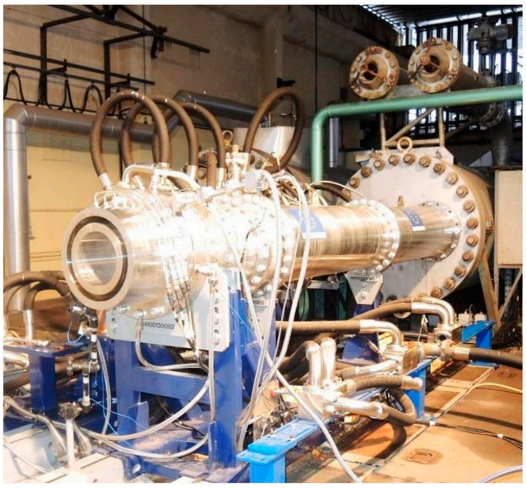


Figure 10. CDWE connected to the ramjet facility [44].

2.4. Germany

In Germany, research on RDEs has been conducted since the late 2010s, led by the Technical University of Berlin. Bach et al. [45,46] performed several experiments using an annular-type model with a detonation channel having a 90 mm outer diameter and 7.6 mm channel width. In 2019, an experiment was conducted to examine the influence of the inclination of guide vanes on the detonation wave propagation direction. In this experiment, a nozzle guide vane was introduced, and the geometry of the rotating detonation combustor (RDC) and guide vane is shown in Figure 11 [45]. The results showed that the detonation wave was more likely to travel in one direction when a non-inclined instrumented guide vane (IGV) was applied, whereas the presence of an inclined IGV with an angle of 8.6° increased the probability of detonation wave propagation in the counterclockwise direction. In 2021, experiments were conducted to determine the effect of changing the combustor geometry and operating conditions on pressure gain [46]. The outlet area and injector area were varied, as shown in Figure 12, and experiments were conducted under mass fluxes of 50 to 300 $kg/s{\cdot}m^2$. The results confirmed that when the outlet area was constant and the injector area increased, the pressure gain increased with the decrease in injection loss. Conversely, when the injector area was constant and the outlet area increased, the pressure gain decreased. Moreover, the pressure gain was noted to increase continuously with the increase in the mass flow rate. Using the same experimental model, Bluemner et al. [47] observed the longitudinal operating mode as a function of combustor length and outlet geometry. The results showed that this mode was achieved only for a combustor length ($= L/\pi D_m$) of 0.435 when the ratio of outlet area to combustor area was 75%. The mode was also observed in the combustor length range of 0.435 to 0.6 when the ratio of outlet area to combustor area was 50%. However, after stabilization, the operating frequency was constant for a given combustor length regardless of the outlet area, consistent with the longitudinal acoustic resonance frequency of the combustor annulus.

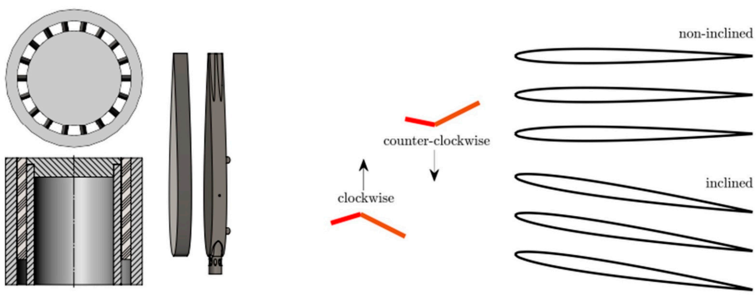


Figure 11. Schematic of test setup [45].

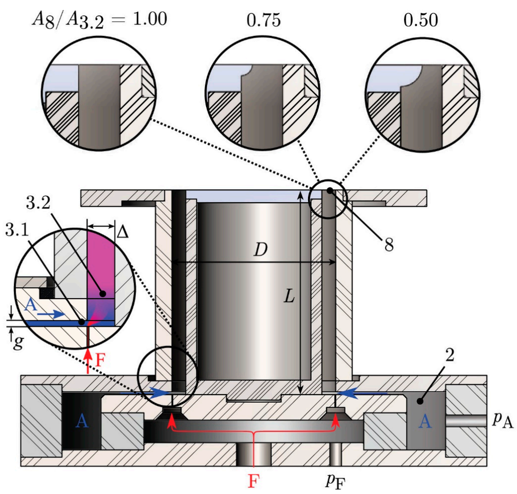


Figure 12. RDE model of the Technical University of Berlin [46].

2.5. Poland

In Poland, the Warsaw University of Technology and its research center, the Institute of Aviation, have been actively conducting RDE research. In experiments conducted at the Warsaw University of Technology, detonation waves were observed in an annular-type model with a 168 mm outer diameter detonation channel, using liquid kerosene/air as the propellant [48]. The kerosene was heated, and small amounts of gaseous hydrogen as well as liquid isopropyl nitrate (IPN) were added to promote mixing and evaporation of the liquid fuel. The experiments confirmed stable detonation wave formation when kerosene and air were heated, and the speed of the rotating detonation wave was reduced by 20–25% when a heterogeneous mixture was used.

The Institute of Aviation has attempted to apply RDEs to gas turbine, ramjet, and rocket engines [49–53]. In 2018, combustion experiments were conducted with a model combining a GTD-350 turbojet engine and an RDC to test the application of RDEs in gas turbine engines [49]. Jet-A1 was used as the fuel, and the combustion performance was noted to be improved by 5–7% when trace amounts of gaseous hydrogen were added to the fuel.

In 2021, a turbojet-shaped RDC with a 225 mm outer diameter detonation channel was fabricated, and combustion experiments were conducted to explore stable detonation wave formation in liquid fuel–air propellant application [50]. Jet-A and gasoline were used as fuels, preheated to approximately 160 °C, with air heated to approximately 100 °C. Wave speeds of 1170 m/s and 1110 m/s were measured under stoichiometric conditions using Jet-A fuel and gasoline, respectively, with the detonation wave lasting approximately 4 s. In 2019, an annular-type rocket-ramjet combined RDE with a 130 mm diameter detonation channel and 3.5 mm channel width was built and tested for the application of RDEs in ramjet engines [51]. Gaseous methane (GCH_4)-gaseous oxygen was used as the propellant, and the experiments were conducted under equivalence ratios of 0.58–0.81. The experimental results confirmed that stable detonation occurred at equivalence ratios of 0.66 to 0.81, and the thrust was measured to be approximately 200 N. At subsonic conditions, the thrust and specific impulse of the combined RDE were up to 40% better than those of the conventional rocket RDE with the same propellant.

For this rocket engine, annular-type, disk-shaped, and cone-shaped RDEs were fabricated (Figure 13) to conduct experiments with different geometries and compare their performance [52,53]. The propellant, liquid propane-liquid nitrous oxide, was pressurized with helium to ensure supply. The results showed that the cone shape had the highest thrust of 250–270 N with an Isp of approximately 200 s. Building upon these results, in 2022, Kawalec et al. [53] launched a small rocket utilizing a cone-shaped liquid propellant-regeneratively cooled RDE rocket engine. Figure 14 shows an image of the small rocket and experiment. The engine was operated for approximately 3.3 s and reached a maximum altitude of ~450 m and maximum velocity of ~95 m/s during the flight time of 20.3 s.

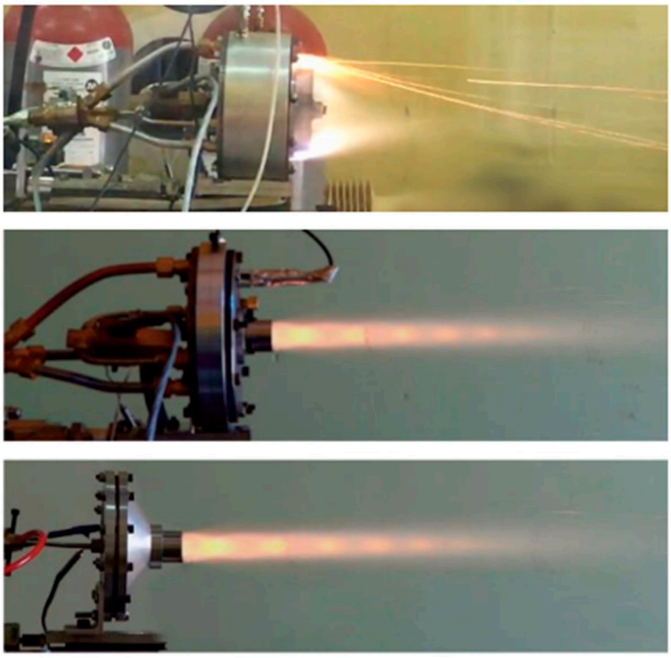


Figure 13. Annular-type cylindrical RDE (**top**), disk-shaped RDE (**middle**), and cone-shaped RDE (**bottom**) [52].

Figure 14. Liquid propellant-based RDE rocket [53].

2.6. Japan

Japan has been conducting RDE research since the mid-2000s when Fujiwara et al. [54] collaborated with Warsaw University of Technology in Poland. RDE research in Japan has been driven by the Japan Aerospace Exploration Agency (JAXA), mainly in collaboration with Nagoya University and Keio University. Notably, Japan was the first in the world to demonstrate an RDE in a space environment.

In particular, Nagoya University and Keio University conducted collaborative research with JAXA to assess the performance of RDEs under various conditions and eventually conducted experimental studies for the flight demonstration of an upper-stage rocket engine with an RDE in a space environment [55,56]. Kawasaki et al. [55] evaluated the combustion characteristics of an annular-type RDE with a 78 mm outer diameter detonation channel as a function of the size of the cylinder diameter inside the combustor. The propellant was ethylene-oxygen, and both the fuel and oxidizer were injected from 120 doublet injectors with a diameter of 1 mm. The thrust was measured to be 200–312 N, and the detonation wave velocity was 1780–2380 m/s. Moreover, the thrust increased and wave velocity decreased as the inner cylinder diameter increased. The detonation wave was attached to the inner cylinder surface when the diameter was large, while it was detached from the inner cylinder surface in the case of a small diameter. In 2018, Goto et al. [56] conducted an annular-type RDE combustion experiment with a 78 mm outer diameter detonation channel to verify the flight system characteristics. The propellant was ethylene-oxygen. The fuel was injected through 72 triplet injectors with a diameter of 1 mm, and the oxidizer corresponded to a diameter of 1.4 mm. The experiments yielded a combustion time of 4.4 s, combustion pressure of up to 11 bar, maximum thrust of approximately 291 N, and maximum specific impulse of approximately 206 s. The RDE could then be operated reliably. Subsequently, combustion experiments were conducted to explore the effective injection area for stable operation of the RDE [57]. An annular-type RDE model with a detonation channel having an outer diameter of 78 mm and channel width of 8 mm was used. Ethylene-oxygen and methane-oxygen propellants were used, and a triplet injector was applied. A maximum thrust of approximately 561 N and specific impulse of 257 s were measured, and experiments with fuel injector diameters of 0.8 and 1.0 mm showed that the detonation wave propagated faster in the case of smaller injector diameters. To compare the specific impulse results with those obtained using an indoor stand test, a 100 m-long sled test was conducted, using the same ethylene-oxygen propellant as that for the stand test [58]. An annular-type RDE model with a detonation channel having an outer diameter of 66.9 mm and channel width of 3.2 mm was used. An image of the sled test is shown in Figure 15. The results showed that the thrust was approximately 201 N, and the specific impulse was approximately 144 s, similar to the specific impulse result of the stand test. Based on previous research, in 2021, JAXA successfully demonstrated an RDE rocket engine in the space environment by installing an RDE in the second-stage engine system of the S-520-31 Sounding Rocket, as shown in Figure 16 [59,60]. The propellant was methane-oxygen, the thrust was measured to be approximately 518 N, and the specific impulse was approximately 290 s.

Figure 15. RDE sled test [58].

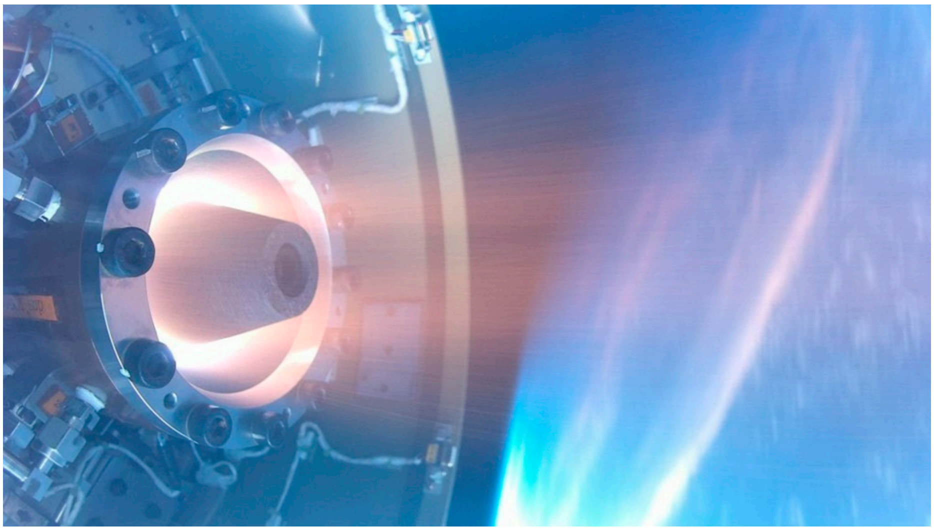


Figure 16. RDE space flight demonstration [60].

Additionally, Japan has been conducting experimental research on cylindrical (hollow)-type RDEs for liquid propellant applications. Yokoo et al. [61] conducted experiments with a cylindrical (hollow)-type RDE model incorporating a detonation channel having an outer diameter of 20 mm, without an internal cylinder in the combustion chamber, using ethylene-oxygen propellant. The experimental results showed that the detonation wave was maintained even without the inner cylinder. The maximum thrust in the experiment was measured to be approximately 108 N, and the maximum specific impulse by mixture was approximately 242 s. Cylindrical (hollow)-type RDEs exhibit a simple structure, are capable of resolving the issue of heat loading within the inner cylinder, and exhibit a specific impulse that is comparable to that of annular-type RDEs. Ishihara et al. [62] conducted combustion experiments to assess the performance of a cylindrical (hollow)-type RDE model with a 20 mm outer diameter detonation channel using liquid ethanol-oxygen propellant. The diameters of the fuel and oxidizer injectors were designed to be small, with values of 0.2 mm and 0.8 mm, respectively, and the collision distance between the fuel and oxidizer was decreased to generate a stable detonation wave. The model is schematically illustrated in Figure 17. In the case of liquid fuel, the thrust was highly dependent on the pressure distribution at the bottom of the combustor. The thrust was measured to be approximately 61 N, and the specific impulse was approximately 195 s. Furthermore, experiments were conducted using a cylindrical RDE to compare thrust performance with conventional rocket engines [63]. By varying the length of the combustor, they found that 94–100% of the theoretical rocket thrust was achieved for a combustor length of 0 mm. This was the same thrust as a conventional rocket with a combustor length of 200 mm. Nakata et al. [64] fabricated a throatless diverging RDE and conducted experiments using ethylene-oxygen propellant in a diverging combustor with a diffusion angle of 5°, starting from a detonation channel with an outer diameter of 20 mm. The geometry of the combustor is shown in Figure 18. Pressure measurements confirmed that the exhaust flow was supersonic even in a diverging combustor without a nozzle throat. To implement cooling by propellant injection, Goto et al. [65] fabricated an RDE that injected propellant from the wall. The authors conducted experiments with a cylindrical (hollow)-type RDE model with a detonation channel having an outer diameter of 24 mm. The increase in heat flux transferred to the wall ranged from 18 to 25% even when the flow rate was doubled through propellant injection from the wall. In 2024, Sato et al. [66] conducted a hollow-type RDE experiment using liquid ethanol and liquid nitrous oxide as the propellants. The vapor quality of nitrous oxide was varied by flash boiling, and the temperature of liquid ethanol and the momentum angle of the propellant were varied to determine the propagation mode of RDE. The experimental results demonstrated the occurrence of a detonation wave under the conditions of a high vapor quality of nitrous oxide, an injector with a high stiffness, a high temperature, and a momentum angle of ethanol. The characteristic exhaust velocity of the detonation mode was found to be lower than that of the deflagration mode due to the lower static combustion pressure. However, exhaust velocity efficiencies of more than 85% were achieved in all combustion tests.

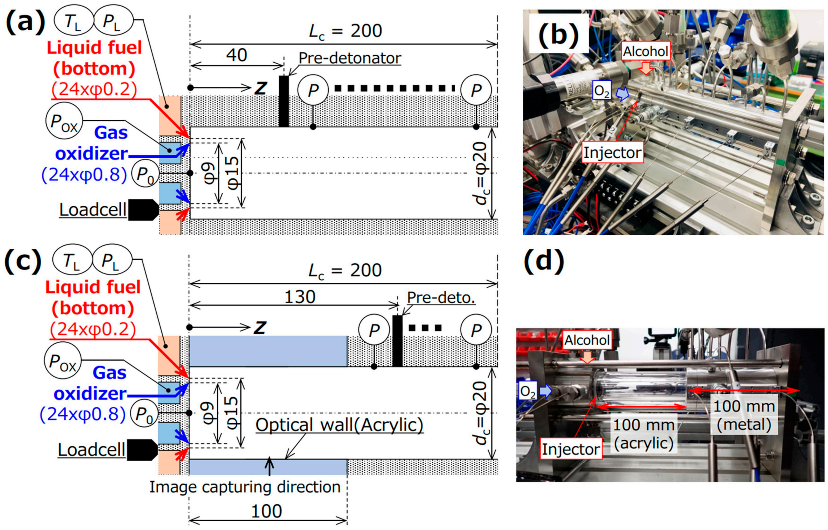


Figure 17. Schematic and overview of the experimental setup of liquid fuel RDE: (**a**) Schematic of RDE with a metal wall, (**b**) overview of RDE with a metal wall, (**c**) schematic of RDE with an acrylic wall, (**d**) overview of RDE with a acrylic wall [62].

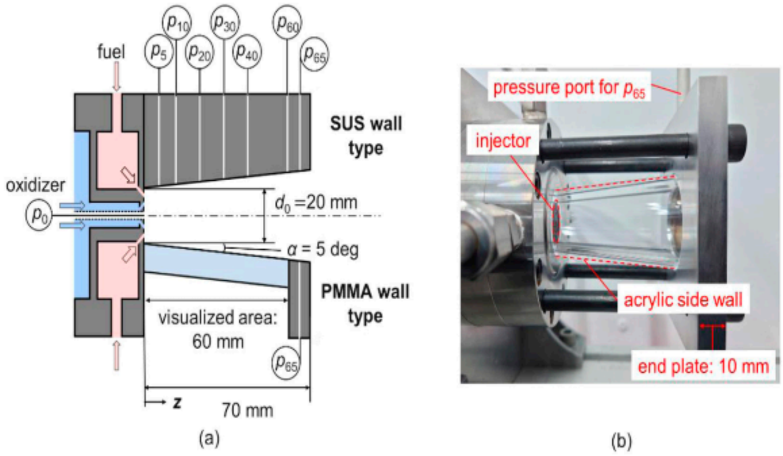


Figure 18. (**a**) Schematic of throatless diverging RDE, (**b**) photo of the RDE for visualization [64].

Japan has also conducted research on other types of RDEs, such as annular and hollow types. In 2016, Nakagami et al. [67] from Nagoya University conducted an experimental study using a disk-type RDE to understand the structure of the detonation wave. They used ethylene-oxygen as the propellant and performed self-luminescence, shadow graph, and Schlieren visualization experiments. The results showed that the detonation wave propagated at a speed of 900–1600 m/s and the propagation process inside the combustion chamber. In 2023, Ishii et al. [68] from Yokohama National University conducted an experiment using a disc-type RDE with a constant cross-sectional channel area. Hydrogen-air propellant was used and the pressure gain was estimated with a developed flow model. The experimental results showed that the wave number increased as the equivalence ratio increased, and that the static pressure and pressure gain in the combustion chamber were high when the wave number was one, regardless of the equivalence ratio.

2.7. China

RDE research in China commenced in the 2010s. Although the period of research and development is short, several universities have conducted basic research on RDEs.

The National University of Defense Technology (NUDT) conducted research on an annular, hollow-type RDE and successfully obtained a continuous detonation wave. Liu et al. [69,70] built an annular-type RDE incorporating a detonation channel with an outer diameter of 100 mm and channel width of 5 mm and conducted experiments. Gaseous hydrogen-air propellant was used, and the purpose was to understand the propagation characteristics of the detonation wave under changes in air flow rate at a constant fuel flow rate. The number of detonation waves increased with air flow rate, and the velocity of the detonation wave decreased as the number of waves increased. In 2015, Wei et al. [71] conducted a hollow-type RDE experiment in which gaseous CH_4-O_2 propellant was used. The generation of a continuously rotating detonation wave was investigated by changing the injection conditions of the gas mixture mass flow rate. It was found that stable propagation occurred under conditions of increased injection mass flow rate. Subsequently, Peng et al. [72] conducted a hollow-type RDE experiment with a Laval nozzle. The outer diameter of the chamber was 100 mm, gaseous methane-air propellant was used, and the equivalence ratio and the contraction ratio of the nozzle were varied. The experimental results demonstrated that a continuous rotating detonation wave is generated exclusively when the contraction ratio exceeds 4. Furthermore, the operating range of the equivalence ratio decreased as the contraction ratio increased to 10. In 2024, Fan et al. [73] developed and experimented with the rounded-rectangle hollow-type RDE presented in Figure 19. The non-premixed continuous rotating detonation initiation process was revealed through high-speed Schlieren images, and the initiation time as a function of equivalence ratio was quantitatively analyzed. In 2017, Liu et al. [74] developed a model to confirm the feasibility of a continuous rotating detonation ramjet engine and conducted a free-jet test with a Mach number of 4.5 and a height of 18.5 km. Gaseous hydrogen and ethylene were used as fuel, and the experimental results demonstrated the successful completion of the free jet test using hydrogen. The wave speed was confirmed to be greater than 90% of the theoretical CJ value, and the maximum specific impulse based on fuel was 2510 s. NUDT first proposed the cavity-based annular combustor shown in Figure 20 and conducted research on it [75,76]. It was predicted that flame stabilization in the cavity would facilitate heat release and stable propagation of continuous rotating detonation when using hydrocarbon fuels such as ethylene. The experimental results of Peng et al. [75] confirmed the achievement of ethylene-air CRD in a cavity combustor, an extended operating range, and faster propagation velocity at a stoichiometric equivalence ratio due to the effect of the cavity compared to an annular-type combustor. Subsequently, experiments were conducted by varying the L/D and equivalence ratio in the ethylene-air fuel to find the optimum L/D at which the propagation frequency and pressure were improved [76].

Peking University conducted experimental studies on annular-type and hollow-type RDEs. Wang et al. [77] experimentally observed the variation in detonation propagation characteristics under pre-detonator injection conditions in an annular-type model incorporating a detonation channel with an outer diameter of 78 mm and channel width of 10 mm. Gaseous hydrogen/gaseous oxygen was used as the propellant. The results demonstrated that single and multiple detonation waves were formed when the detonation wave generated in the pre-detonator was introduced in the direction tangential to the axial direction of the combustor internal flow, respectively. Ma et al. [78] conducted experiments to explore the variation in operating characteristics with nozzle throat width and number of injectors in an annular-type model incorporating a detonation channel with an outer diameter of 120 mm and an aerospike nozzle. Gaseous methane/gaseous oxygen was used as the propellant, and the experiments were performed at a maximum thrust level of approximately 400 N. A smaller ratio of the injector area to the nozzle throat area corresponded to a smaller mass flux and more stable detonation. Additionally, the authors proposed a method for comparing the normalized characteristic velocity ($= c^*_{exp}/c^*_{ideal}$), normalized thrust coefficient (= $C_{F,exp}/C_{F,ideal}$), normalized specific impulse (= $I_{sp,exp}/I_{sp,ideal}$), and pressure gain for performance evaluation. Zhang et al. [79] experimentally compared the performance of annular- and hollow-type models, as shown in Figure 21. The outer diameter of the detonation channel of both models was the same, 120 mm, and the channel width of the annular-type model was 15 mm. The ratio (= A_{th}/A_{in}) between the injector area and nozzle throat area was varied for each experimental model. The experimental results demonstrated that the efficiency of the hollow-type RDE was lower than that of the annular-type RDE. However, a high detonation wave success rate was confirmed for the hollow geometry model and large area ratio condition.

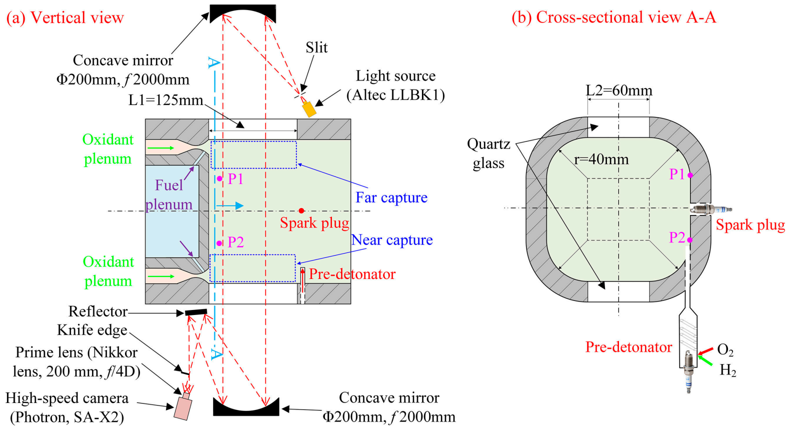


Figure 19. Rounded-rectangle hollow-type RDE [73].

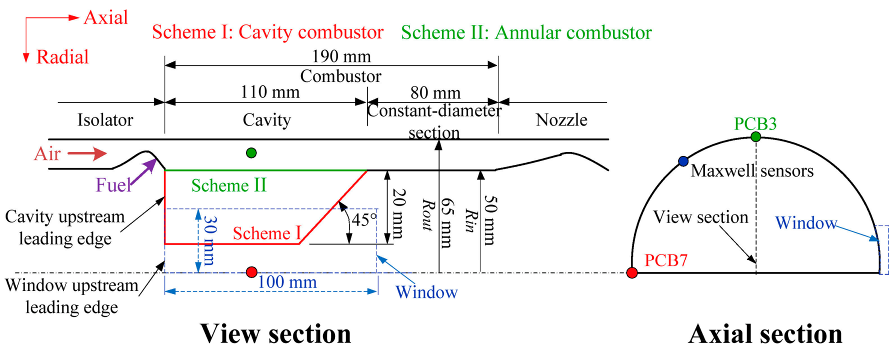


Figure 20. Schematic of cavity-based annular combustor [75].

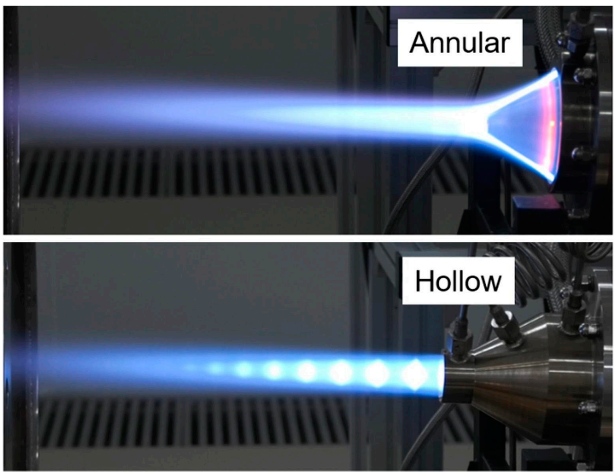


Figure 21. RDE hot fire test [79].

In 2022, Wu et al. [80] conducted a solid fuel RDE experiment using a gas generator. The experiment was conducted by operating an annular-type RDE using gas from solid fuel combustion in a gas generator with a cylinder section diameter of 165 mm. An image of the experiment is shown in Figure 22. The combustion products generated by the gas generator contained 36.5% carbon and 26.83% hydrogen by mass fraction. The detonation velocity was approximately 2625 m/s, an increase of ~20% compared with the detonation velocity under hydrogen-oxygen propellant conditions, and a thrust of 69 N was measured.

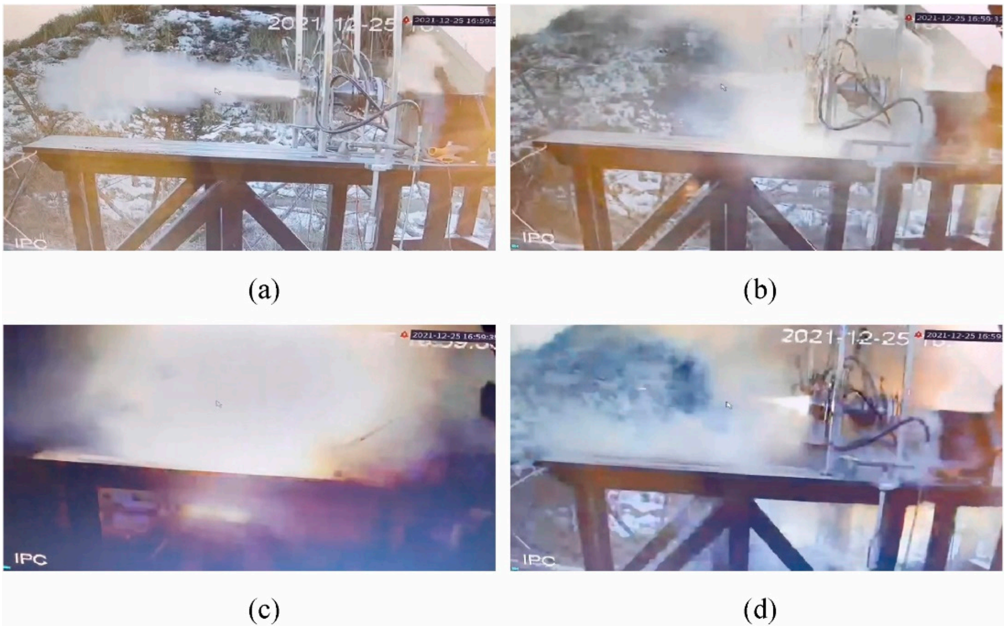


Figure 22. Solid pre-combustion RDE test: (**a**) deflagration, (**b**) DDT process, (**c**) galloping detonation, and (**d**) stable detonation [80].

Peng et al. [81] from Nanjing University of Science and Technology conducted experiments on an annular-type model incorporating a detonation channel with an outer diameter of 80 mm and channel width of 5 mm, using a spark plug for direct ignition instead of a pre-detonator. Gaseous hydrogen/gaseous oxygen was used as the propellant. The experiments showed that the ignition success rate was up to 94% even with a conventional igniter. Zhou et al. [82] conducted experiments using an annular-type model incorporating a detonation channel with an outer diameter of 136 mm and channel width of 4 mm using a centrifugal compressor. The rotational speed of the centrifugal compressor with a radial turbine was 11,000 rpm. Gaseous hydrogen/air propellant was used, and the propagation characteristics of the detonation wave as a function of air injector area and operating time were investigated. The experimental results showed that the detonation tended to be unstable as the area of the air injector increases, but a stable detonation wave was formed after a certain operating time. Wu et al. [83] conducted experiments on an annular-type model incorporating a detonation channel having an outer diameter of 88 mm and channel width of 5 mm with a turbine guide vane (TGV). The experiments were conducted using hydrogen fuel in a model with a TGV consisting of 13 turbine blades. The results showed that the velocity of the detonation wave was 1812 m/s (92% CJ) on average, and the combustion pressure was in the range of 10–15 bar. Moreover, a pressure reduction of more than 10% was observed in the case of a mismatch between the propagation direction of the detonation wave and flow turning angle of the turbine blades. In 2022, experiments with cavity-based annular combustor by Meng et al. [84] confirmed kerosene-air rotating detonation, which was feasible under Mach 4 flight conditions using liquid kerosene as fuel and confirmed that the flame in the cavity contributed to the generation of the rotating detonation wave.

In 2024, Nanjing University of Aeronautics and Astronautics conducted liquid kerosene-air RDE experiments under various incoming flow conditions [85]. The experimental results confirmed that under the condition that the detonation wave propagates stably, the wave speed increased and the initiation time decreased as the equivalence ratio increased, but the overall stability decreased. In addition, a long-term experiment of about 4 s was conducted to confirm the reliability of the short-term experimental results.

In 2023, Chongqing University conducted experiments on an annular-type model incorporating a detonation channel with an outer diameter of 106 mm using a straight guide vane (SGV) [86]. GH2/air was used as the propellant, and the SGV was composed of 30 vanes to explore the effect of vane length on RDE performance and the propagation characteristics of the detonation wave. The results showed that the detonation wave speed in the presence of the vane was lower than that without the vane, and the thrust tended to increase with the increase in the length of the guide vane, as shown in Figure 23.

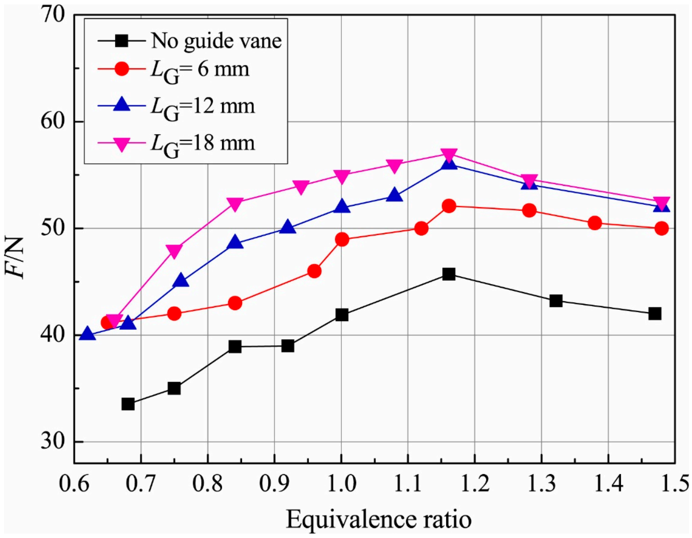


Figure 23. Statistics of RDC thrust [86].

Xi'an Aerospace Propulsion Institute conducted an experiment to verify the practicality of using liquid contact ignition propellants [87]. Liquid nitrogen tetroxide (NTO) and liquid monomethyl hydrazine (MMH) were used as the propellants to verify the generation of detonation waves inside an annular-type model incorporating a detonation channel with an outer diameter of 60 mm and channel width of 20 mm. An impinging-type injector was applied for liquid propellant injection and atomization. The experimental results showed that the number of detonation waves increased with increasing flow rate under the same oxidizer/fuel ratio condition.

3. Research Trend Analysis

Section 2, which summarizes the research and development trends of RDEs, shows that RDEs are being researched and developed worldwide. To compare the performance of these RDEs, Tables 1–7 present the performance metrics by country. The tables include information on engine type, geometry type, engine size, propellant, rotating detonation wave speed, and thrust for RDEs developed in each country, excluding studies without wave speed and thrust information. This section outlines the research trends, presents a performance comparison, and discusses the related issues.

Table 1. Performance characteristics of rotating detonation engines developed in the United States.

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
Texas University	Rocket	Annular	87.6	4.45	GH_2, GC_3H_8	GO_2	4083	-	Braun (2010) [11]
AFIT (Air Force Institute of Technology)	Rocket	Annular	76.2	2, 6, 10	GH_2	GO_2	1013–2818	-	Russo (2011) [12]
	Rocket	Annular	28	2	C_2H_4	GO_2	1100–1400	-	Keller (2024) [17]
	Rocket	Annular	152.4	7.62	GH_2	GO_2	1400–1550	-	Shank (2012) [14]
	Air-breathing	-	76.2	-	GH_2	Air	1200–1600	-	Tellefsen (2012) [16]
University of Cincinnati	Air-breathing	Annular	228	19	GH_2, C_2H_4	Air	1200–1300	-	George (2015) [18]
Purdue University	Rocket	Annular	228	19	RP2	GO_2	-	3000	Walters (2018) [19]
	Rocket	Annular	94	6.35	H_2O_2	$C_8H_{18}O_4$	2220–2479	-	Kubicki (2020) [20]
University of Central Florida	Rocket	Annular	76.2	5.1	GH_2	GO_2	2272–2326	-	Sosa (2020) [21]
University of Michigan	Rocket	Annular (Racetrack)	63.5 × 177.8	-	-	Air	1450	-	Chacon (2018) [22]
University of Alabama	Rocket	Annular (Racetrack)	101.6 (annulus, linear)	7.62	LC_3H_8	GO_2	975–1075	-	Unruh (2021) [25]
Aerojet-Rocketdyne	Rocket Air-breathing	Annular	100–430	-	CH_4, C_2H_2, C_2H_6, H_2, LNG, JP-8, JP-10	Air, O_2	1000 < wave speed	-	(2018) [27]
AFRL (Air Force Research Laboratory)	Rocket	Annular	76.2	2, 6, 10	GH_2	Air	684	-	Thomas (2011) [28]
	Rocket	Annular	228	19	RP2	GO_2	1160–1740	1020	Rankin (2017) [30]
	Rocket	Annular	152.4	-	GH_2, C_2H_4	Air	-	1360	Fotia (2017) [32]
	Rocket	Annular	76.2	5	CGH_4	CO_2	980–2200	1334	Bennewitz (2021) [34]
NASA	Rocket	Annular	-	-	-	-	-	25,800	(2023) [36]

Table 2. Performance characteristics of rotating detonation engines developed in Russia.

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
Semenov Institute of Chemical Physics	Air-breathing	Annular	310	-	GH_2	Air	-	2200	Frolov (2017) [37]
	Air-breathing	Annular	310	-	GH_2	Air	-	1500	(2018) [38]
	Rocket	Annular	406	25	GH_2, GH_2 + LC_3H_8	Air	400–2200	-	(2017) [39]
	Air-breathing	Annular	120	-	kerosene	Air	-	650 (M = 1.5) 860 (M = 2.0)	Ivanov (2021) [40]

Table 3. Performance characteristics of rotating detonation engines developed in France.

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
MBDA France	Rocket	Annular	100	10	GH_2	GO_2	3100 (wave number: 2) 2750 (wave number: 3)	338.5	Le Naour (2011) [43]
	Air-breathing	Annular	330	25	GH_2, GH_2 + kerosene	Air	1000–1400	-	(2017) [44]

Table 4. Performance characteristics of rotating detonation engines developed in Germany.

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
Technical University of Berlin	Air-breathing	Annular	90	7.6	GH_2	Air	1181–1812	-	Bach (2019) [45]
	Air-breathing	Annular	90	7.6	GH_2	Air	355–1773	-	(2021) [46]

Table 5. Performance characteristics of rotating detonation engines developed in Poland.

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
Warsaw University of Technology	Air-breathing	Annular	168	-	Kerosene (add GH_2, LIPN)	Air	1350–1550	-	Kindracki (2015) [48]
Institute of Aviation	Air-breathing	Annular	-	-	Jet-A Jet-A + GH_2	Air	500–2500	-	Wolanski (2018) [49]
	Air-breathing	Annular	225	-	Jet-A Gasoline	Air	1045–1170	-	(2021) [50]
	Rocket-Ramjet combined	Annular	130	3.5	GCH_4	GO_2	-	200	(2019) [51]
	Rocket	Cone, disk, Annular	228	19	C_3H_8	N_2O	1200–1300	250–270	(2022) [53]

Table 6. Performance characteristics of rotating detonation engines developed in Japan.

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
Nagoya University, Keio University, JAXA	Rocket	Annular, Hollow	78	Hollow 8, 16, 24, 60	C_2H_4	GO_2	1780–2380	200–312	Kawasaki (2019) [55]
	Rocket	Annular	78	8	C_2H_4	GO_2	1293–2121	92–291	Goto (2018) [56]
	Rocket	Annular	78	8	C_2H_4 CH_4	GO_2	1213–1648	561	(2021) [57]
	Rocket	Annular	66.9	3.2	C2H4	GO_2	2040 (wave number: 2) 1750 (wave number: 3)	201	(2021) [58]

Table 6. *Cont.*

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
Nagoya University, Keio University, JAXA	Rocket	Annular	-	-	CH_4	GO_2	-	518	(2022) [59]
	Rocket	Hollow	20	-	C_2H_4	GO_2	1209–1333	108	Yokoo (2020) [61]
	Rocket	Hollow	20	-	LC_2H_6O	GO_2	1400–1900	61	Ishihara (2023) [63]
	Rocket	Hollow	20 Diverging angle: 5°	-	C_2H_4	GO_2	1180–1261	133–234	Nakata (2023) [64]
	Rocket	Hollow	40	-	C_2H_5OH	N_2O	1650–1850	280	Sato (2024) [66]
	Rocket	Disk	33.6	-	C_2H_4	GO_2	900–1600	-	Nakagami (2016) [67]
Yokohama National University	Rocket	Disk	76	-	GH_2	GO_2	-	75–400	Ishii (2023) [68]

Table 7. Performance characteristics of rotating detonation engines developed in China.

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
National University of Defense Technology	Rocket	Annular	100	5	GH_2	Air	1605–1790 (wave number: 1) 1329–1475 (wave number: 2)	-	Liu (2016) [69]
	Rocket	Hollow	100	-	GCH_4	GO_2	1500	-	Wei (2015) [71]
	Rocket	Hollow	100	-	GCH_4	GO_2	1767.8	-	Peng (2019) [72]
	Air-breathing	Annular	80	-	GH_2	Air	1725	610–824	Liu (2017) [74]
Peking University	Rocket	Annular	78	10	GH_2	GO_2	2449	-	Wang (2014) [77]
	Rocket	Annular	120	15	GCH_4	Air	1621–1646	14.2–400.4	Ma (2023) [78]
	Rocket	Annular Hollow	120	15 (annular)	GCH_4	GO_2	1200–1650 (Annular) 1700–2700 (Hollow)	10–350 (Annular) 50–380 (Hollow)	Zhang (2023) [79]
	Rocket	Annular	-	-	Burned gas of solid propellant N_2 (36.5%), H_2 (26.83%)		2625	69	Wu (2021) [80]
Nanjing University of Science of Technology	Rocket	Annular	80	5	GH_2	GO_2	1621–1646	14.2–400.4	Peng (2019) [81]
	Air-breathing	Annular	88	5	GH_2	Air	1550–1950	-	Wu (2023) [83]
	Air-breathing	Annular	136	4	GH_2	Air	1380–1530	-	Zhou (2017) [82]

Table 7. *Cont.*

Organization	Engine Type	Geometry	Chamber Size [mm]		Propellant		Wave Speed [m/s]	Thrust [N]	First Author
			Outer Diameter	Channel Width	Fuel	Oxidizer			
Nanjing University of Aeronautics and Astronautics	Rocket	Annular	206	31	Liquid Kerosene	Air	1575–1610	-	Li (2024) [85]
Chongqing University	Air-breathing	Annular	106	5	GH_2	Air	1550–1700	40–55	Zhou (2023) [86]
Xi'an Aerospace Propulsion Institute	Rocket	Annular	60	20	MMH	NTO	1350–1650	-	Xue (2018) [87]

3.1. Summary of Research and Development

Most of the research conducted in each country was preceded by basic research on RDEs. This basic research was aimed at verifying that detonation waves are generated inside the combustor and at exploring the propagation characteristics and stable formation conditions of detonation waves. Pre-detonators, spark plugs, and contact ignition propellants were used to generate detonation waves inside the RDE, and the conditions for stable detonation waves were explored by changing the geometry of the injector, combustor, and nozzle, as well as the propellant supply conditions. To confirm the occurrence of a stable detonation wave, the occurrence and velocity of the detonation wave were verified through direct imaging using a high-speed camera, optical techniques such as OH* chemiluminescence and PIV, and measurements using dynamic pressure sensors and ion probes.

Depending on the engine type, RDEs have been studied as a combustor for rocket and air-breathing engines. In the case of rocket engines, research has been extended beyond the nascent stage to the flight test stage, and prototypes are being developed to apply large-scale RDEs to actual launch vehicles. In addition, research on the application of liquid propellants is actively underway. For the application of RDEs in air-breathing engines, prior research has been focused on gas turbine and ramjet engines. In the case of gas turbine engines, research has been conducted mainly on the operating characteristics of RDEs in turbine applications. Most studies have examined the propagation characteristics of detonation waves and performance changes when a guide vane is applied. Moreover, NOx measurements have been attempted for RDE applications. In the case of ramjet engines, RDE studies have been conducted focusing on rocket-ramjet combinations, or inlets have been introduced to conduct wind tunnel experiments and actual flight tests.

Research has also been focused on the propellant type. As oxidizers, gaseous oxygen or air has been mostly used. In the case of air, studies have also been conducted with varying proportions of oxygen. Gaseous fuels are mainly hydrogen, methane, and ethylene, and liquid fuels include kerosene, propane, and ethanol. Among these fuels, hydrogen and liquid hydrocarbon-based fuels have been applied to air-breathing engines. In studies using liquid hydrocarbon-based fuels, it was confirmed that combustion performance was improved by introducing additional gaseous hydrogen. Gaseous fuels, such as methane and ethylene, and liquid fuels, such as propane and ethanol, have been used primarily for rocket engine applications. In addition, contact ignition propellants or solid fuels have also been studied for possible use in RDEs by examining the generation of detonation waves inside the RDE.

Depending on the type of RDE geometry, studies on annular-type RDEs were initially conducted, followed by studies on hollow-type and disk-type RDEs. Annular-type RDEs have been used as an experimental model for initial research and to determine the feasibility of RDE operation for new propellants, given the facile formation of stable detonation waves due to its internal cylinder shape. Hollow-type RDEs are currently the subject of active research due to their lack of a cylindrical center body, which facilitates cooling and reduces the weight of the engine. It has a similar specific impulse to the annular-type combustor, and Zhang et al. [79] demonstrated a high detonation wave success rate compared to the annular-type in their experiments, although the efficiency was lower. Disk-type RDEs have the advantages of the hollow-type and, at the same time, have the advantage of shortening the length of the combustor, which can further reduce the weight. They are currently being actively researched.

Previous studies have compared the thrust performance of RDEs to constant-pressure combustion systems [16,41,51,63]. The results show an increase in specific power with RDEs compared to constant-pressure combustion [16] and a 30% higher specific thrust with a detonation afterburner compared to a conventional afterburner [41]. The specific impulse is 40% higher than that of a conventional rocket [51], and it has been demonstrated that the same thrust can be generated with a shorter combustor length than a conventional rocket, thus reducing the weight of the engine [63]. These findings indicate that the use of RDEs in rocket and air-breathing propulsion systems has the advantage of reducing the weight of the engine and increasing the thrust performance. Consequently, it is recommended that further research be conducted into the development of future propulsion technologies utilizing RDEs.

3.2. RDE Performance

A comparative evaluation of the performance of RDEs developed so far was performed considering studies conducted in different countries. Tables 1–7 summarize the RDE performance indicators by country. The results demonstrate that although the detonation wave speed has been measured in most cases, thrust has been measured in only a few cases, and the highest thrust among rocket-applied RDE engines has been reported to be 25,800 N in a ground test conducted by NASA [36] in the United States. The thrust range of rocket-applied RDEs in other countries outside of the United States is mostly below 1000 N. RDE studies of air-breathing engine applications have not measured thrust in most cases, and experiments at the Semenov Institute of Chemical Physics in Russia have confirmed thrust levels of up to 2200 N [37]. In terms of engine size, most studies have been conducted with combustor diameters of 400 mm or smaller, with the United States and Russia having conducted studies considering larger engines with combustor diameters of 400 mm or higher [26,39]. Poland [53] and Japan [60] have reported engine demonstrations through flight tests. Poland has conducted flight tests of a small rocket with a cone-type RDE with regenerative cooling. Japan has successfully demonstrated the installation of an RDE on the second stage of a sounding rocket in a space environment. The performance comparison highlights that current RDE research can be divided into two groups: countries that are conducting basic research and development using small-scale RDEs, and countries that have conducted research up to the development stage for application to actual systems.

3.3. Research and Development Issues

Three main issues are being addressed in studies conducted in different countries. The first pertains to RDE geometry optimization. It is crucial to understand the effect of geometric variables on performance while changing the geometry conditions of components such as combustors, injectors, and nozzles to maximize performance. Thus, this aspect has garnered significant research interest. Injectors, in particular, represent a key design variable for efficient combustion when using liquid propellants, as they directly affect the degree of mixing of the fuel and oxidizer.

The second issue pertains to combustion instability. As the detonation wave propagates at supersonic speeds, the flame is unstable and difficult to control. Consequently, it is necessary to continue research on the formation of stable detonation waves and the number and direction of waves.

The third issue, cooling, must be addressed before RDEs can be applied to real engines. As combustion using detonation wave creates an extremely high-temperature environment inside the combustor, it is necessary to consider optimal cooling methods to operate RDEs for extended periods. Current research has been focused on applying cooling methods such as water cooling, regenerative cooling, and propellant injection at the wall. As water-cooling methods have been typically applied for ground tests, it is difficult to apply them to actual engines, and research on cooling methods such as propellant injection and regenerative cooling must be actively conducted to ensure long-term operation when applying RDEs to actual engines.

4. Conclusions

This review was focused on exploring experimental research and development trends on RDEs across various countries. Basic research has been conducted on the propagation characteristics of the detonation wave inside RDEs, the performance of RDEs with different geometries, the characteristics of RDEs depending on the propellant type, and application of RDE cooling. In terms of the development trends of each country, the United States is currently conducting RDE research and development for application to lunar exploration rockets. Russia, France, and Germany continue to conduct research and development for the commercialization of air-breathing RDEs. Poland successfully conducted the world's first flight test of a small rocket using a liquid propellant RDE with regenerative cooling. Japan has successfully demonstrated an RDE rocket engine in the space environment and is continuing research on more advanced liquid propellant RDEs. China claimed to have successfully flight-tested an RDE on a launch vehicle engine with an inlet. According to the RDE research conducted by each country so far, experiments have been conducted on RDEs of various sizes and shapes depending on the application system of the engine, and different thrust levels have been obtained. Among them, the United States has conducted the largest number of thrust experiments, but only Poland, Japan, and China have reported the successful conduction of flight tests.

Through the analysis of research and development trends in each country, the direction of progress and common issues in existing research were analyzed. Issues related to the optimization of RDE geometry, combustion instability, and cooling for prolonged combustion must be addressed for the practical application of RDEs, and the relevant solutions are expected to provide references for future RDE research.

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