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REVIEW ARTICLE

Progress of continuously rotating detonation engines

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Abstract Continuously rotating detonation engine (CRDE) is a focus for concern in the field of aerospace propulsion. It has several advantages, including one-initiation, high thermal efficiency and simple structure. Due to these characteristics, it is expected to bring revolutionary advancements to aviation and aerospace propulsion systems and now has drawn much attention throughout the world. In this paper, an overview of the development of CRDE is given from several aspects: basic concepts, applications, experimental studies, numerical simulations, and so on. Representative results and outstanding contributions are summarized and the unresolved issues for further engineering applications of CRDE are provided.

1. Introduction

Combustion is the sequence of exothermic chemical reactions between a fuel and an oxidant accompanied by the production of heat and conversion of chemical species. It is an important process in propulsion systems. Through chemical reactions, it converts the chemical energy of fuels into the heat and then the kinetic energy of the working medium to provide thrust.

Combustion can be performed in two different modes: deflagration and detonation. When the state of premixed combustible mixtures is changed, two Rayleigh lines of different slopes and one Hugoniot curve will be obtained, as shown in Fig. 1 (*P*-pressure, *V*-specific volume, *A*-initial state, *U*-upper Chapman–Jouguet (C–J) point, *L*-lower C–J point). The initial state of the premixed combustible mixture is at point *A* and it may reach two different states after heat release, depending on the combustion mode. Deflagration makes the gas state reach lower C–J point, while detonation makes it reach upper C–J point. During the deflagration process, the velocity of the combustion wave is of the order of meters per second, the pressure drops slightly and the specific volume expends significantly. Thus deflagration is usually treated as approximately isobaric combustion. For detonation, its propagating velocity can reach the order of kilometers per second. During the combustion process, the combustion wave is tightly coupled with the shock wave, the pressure and temperature increase abruptly,

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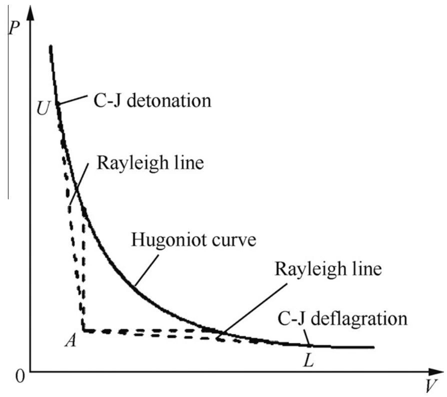


Fig. 1 Rayleigh lines and Hugoniot curve in *P*–*V* diagram.

and the specific volume decreases slightly. Thus detonation is often considered as approximately isochoric combustion. Obviously, the heat release of detonation is faster, the entropy increase of detonation is smaller, and the thermal efficiency of detonation is higher than that of deflagration.

Conventional aviation and aerospace engines, such as piston, turbine, turbofan, and ramjet engines, are usually based on deflagration. After one hundred years of development, it has become more difficult to achieve further improvements in such deflagration-based engines in terms of high efficiency. Since 1940s, more and more researchers have begun to focus on detonation-based engines to achieve higher thermodynamic efficiency of propulsion systems. Three kinds of detonation-based engines are most studied. They are standing detonation engine (SDE), pulse detonation engine (PDE) and continuously rotating detonation engine (CRDE).

In an SDE, detonation waves are positioned in the combustion chamber, normal or oblique to the wedge. Fuels are injected from the upstream of the inlet and then mixed with the supersonic air flow. After the pre-compression and pre-heat of shock waves, the combustible gas in the combustion chamber is detonated. Then the detonation products, after expansion, exhaust from the chamber to provide thrust.[1] SDE seems feasible in principle and it can avoid some bottlenecks that exist in the research of scramjet engines. However, it has encountered many technical problems in practical applications. For example, SDE can only work with the inflow of high Mach numbers (5–7). Due to its harsh restrictions on the flow conditions, detonation waves could not exist in the chamber stably for long duration and therefore the engine is easy to shut down.

PDE is most studied in the last three decades. It has four working processes, including fuel filling, detonation initiation and propagation, exhaust and scavenging. The thrust of PDE results from the pressure difference between the products, which are of high pressure, and the environment. In addition, the counter-acting force from the supersonic working medium also produces thrust. At present, the fundamental principles of PDE have been fully studied and experimental techniques have also been very mature. The high-frequency operations of dozens or even two hundreds hertz have been realized, and further research of PDE is focused on the increase of its effective thrust.[2–6] However, the entire operation of PDE is intermittent and periodic. It requires high-frequency initiations and each initiation needs high energy. Further, the thrust generated by PDE now is small. The problem is rooted in the working process of the engine itself. During the whole running process, the fuel filling and purging processes, which occupy 45% of the whole time, generate no thrust.[6]

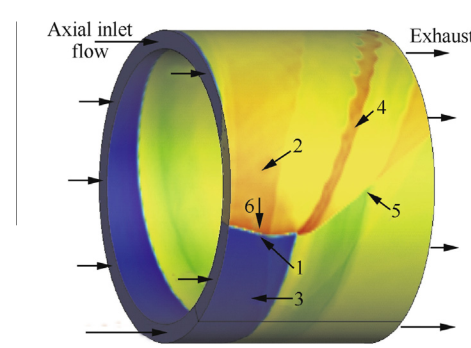
In recent years, the most popular detonation-based engine is CRDE. It is also called rotating detonation engine (RDE) or continuous detonation wave engine (CDWE). It is of obvious advantages, compared with conventional engines or the other two detonation-based engines. Thus it is expected to bring technical revolution to current aviation and aerospace propulsion systems. In this paper, a survey of the development of CRDE is provided. The basic concepts and future applications are first introduced. And then significant achievements in both experiments and numerical simulations are presented. In the last part, challenges that CRDE meets and needs to overcome are discussed.

2. Basic concepts and future applications of CRDE

2.1. Basic concepts

The combustion chamber of CRDE is usually a coaxial cylinder, as shown in Fig. 2. The head end is closed but drilled with a large number of micro nozzles or slits to inject fuel and oxidant into the chamber. In experiments, the detonation wave in the chamber is usually initiated by a pre-detonator attached tangentially to the chamber. While working, one or more detonation waves lean on the head end and propagate in the circumferential direction. Behind the detonation wave, burnt products are of high temperature and high pressure. Through a series of expansion waves, these burnt products flow out of the downstream exit almost axially to provide thrust. In addition, there is an oblique shock wave and a contact surface in the flow field. During the propagating process of the detonation wave, combustible mixtures are continuously injected into the chamber. They form a triangle combustible mixture layer and are combusted by the detonation wave.

In comparison with other detonation-based engines, CRDE has several inherent advantages. First, it needs only one-time initiation. Once started, detonation waves will continuously rotate. Secondly, due to the self-sustaining and self-compression of detonation waves, combustible mixtures can be compressed



1—Detonation wave 2—Burnt products 3—Freshpremixed gas
4—Contact surface 5—Oblique shock wave
6—Detonation wave propagation direction

Fig. 2 CRDE propagation schematic structure.

inherently. Thus CRDE can produce a large effective thrust at low pressure ratio. Besides, the propagation direction of detonation waves is independent of the inflow and outflow directions, preventing the intermittent thrust. Detonation waves are enclosed in the combustion chamber to produce efficient working medium. It avoids the tremendous energy loss caused by the ejection of detonation waves. Moreover, CRDE can work stably within a wide range of inflow velocity. Thus it also allows for a wild range of the flow rate of combustible mixtures.

2.2. Future applications

Based on the characteristics of CRDE and industrial needs, predictable propulsion systems will be rotating detonation rocket engine, rotating detonation ramjet engine and rotating detonation turbojet engine, as shown in Fig. 3. They can be applied to various types of rockets, missiles, near space aircraft, military aircraft, unmanned aerial vehicles and so on.

Rotating detonation rocket engine is the simplest kind of CRDE. The early research of CRDE is based on gaseous fuel rocket engine model. Currently, rotating detonation rocket engine of liquid fuel has been successfully realized in Russia, Poland and other countries. The existing mature technologies of rocket engines can be efficiently transferred to the rotating detonation rocket engine. This favors the engineering applications of such kind of CRDE.

Compared with conventional ramjet, rotating detonation ramjet engine is not so sensitive to the inflow and can work stably in a wide range of flight conditions. Thus, the working range of ramjet will be widened in future, if detonation waves take the place of the deflagration waves in conventional ramjet.

The rotating detonation waves can also be applied in turbojet engines. Rotating detonation turbojet engine can produce a large effective thrust at low pressure ratio. This will reduce the number of compressors in conventional turbine engines and then reduce the demanding requirements of the turbine manufacturing process. The resulting combustion chamber is smaller, simpler, and of higher thrust/weight ratio. Due to the characteristic of detonation waves, the performance of such engines will be increased greatly as well.

3. Development of CRDE

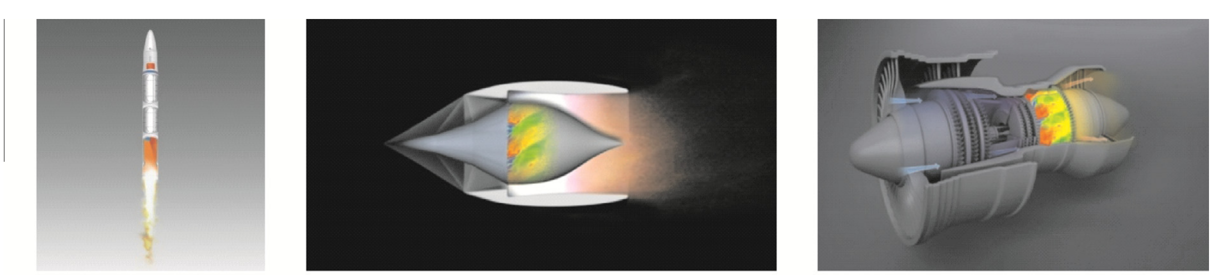
3.1. Experimental studies

The basic concept of continuous detonation waves was proposed by Voitsekhovskii in 1960.[7,8] He experimentally achieved a short-lived continuous detonation wave in a disk-shaped chamber, using premixed acetylene and oxygen. The schematic of the experimental setup is shown in Fig. 4(a). Premixed combustible mixtures were injected into the chamber along the inner cylinder of the disk. Burnt products exited from the chamber along the outer wall of the disk. Rotating detonation waves continuously propagated in the chamber. Based on the motion-compensated technology, a propagating and rotating detonation with six heads was observed, as shown in Fig. 4(b). This experiment was considered as the first fundamental step in the history of CRDE.

Afterward, theoretical analyses and preliminary experimental research of the application of rotating detonations to rocket propulsion were first conducted by Adamson and Olsson[9] and Nicholls et al.[10] They pointed out that the new concept engine was expected to be applied to the rocket propulsion systems, although there were many questions to answer. In the experiments, Nicholls et al.[10] used an injection system in line with liquid rocket engines and tested several fuel–oxygen mixtures (including hydrogen, methane, acetylene and others). However, the detonation waves extinguished after one cycle and they could not stabilize for long duration. They pointed out that the injection pattern, advance ignition, flow control and other factors played a key role in the formation of a continuous detonation in experiments.

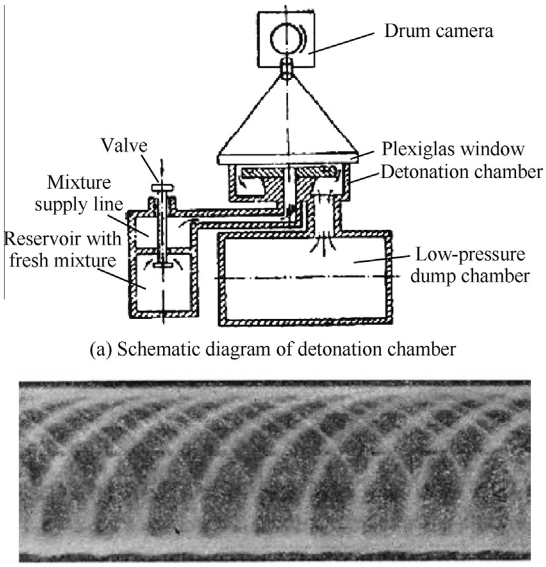
These early experimental researches mainly focus on the feasibility and initiation of detonation waves. Motion-compensated pictures are usually obtained to reveal the flow structure of continuous detonation waves. Long duration operations have not been achieved. Due to the limitations of measurements and numerical simulation, the propagating mechanism of stable detonation waves is less understood. In the following twenty years, little attention has been paid to the development of CRDE and few publications relate to CRDE.

In recent years, extensive experiments of CRDE have been carried out in the Institute of Hydrodynamics by Bykovskii et al.[11–13] in Russia. They achieved continuous liquid and gas fuel detonations of multi-cycle in combustors of different shapes under different injection systems. The basic geometric configurations are shown in Fig. 5[11]. The tested fuel included acetylene, hydrogen, propane, methane, kerosene, gasoline, benzene, alcohol, acetone and diesel. The oxidant was air or gaseous oxygen and in some cases, liquid oxygen. Without tail nozzle, the specific impulse of CRDE using kerosene–oxygen mixtures in experiments was as high as 200 s. In addition, the compensation technique was used to capture the flow filed inside the CRDE combustion chamber. The results of stable rotating detonation waves are shown in Fig. 6[11] (1-fuel and oxidizer injection, 2-annular duct, 3-mixture, 4-detonation



(a) Rotating detonation rocket engine (b) Rotating detonation ramjet engine (c) Rotating detonation turbojet engine

Fig. 3 Applications of CRDE.



(a) Schematic diagram of detonation chamber

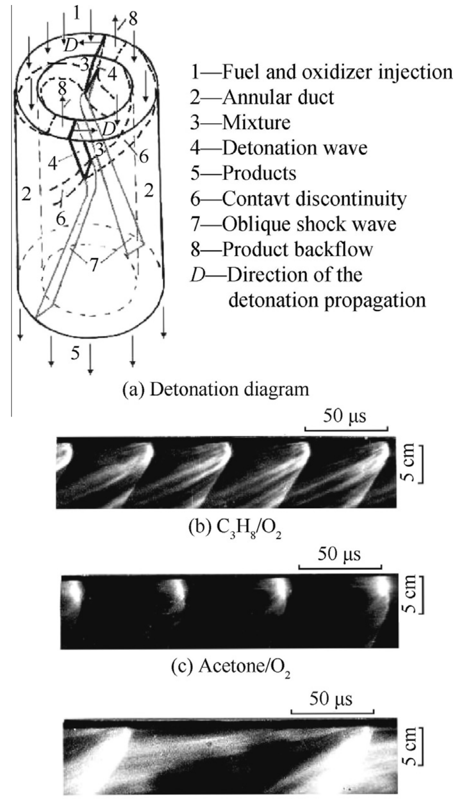
(b) Compensation picture of rotating detonation with six heads

Fig. 4 Experiment by Voitsekhovskii.[8]

wave, 5-products, 6-contavt discontinuity, 7-oblique shock wave, 8-product backflow, *D*-direction of the detonation propagation).

They also proposed empirical laws for the parameters in the chamber design.[11] These parameters were of great significance to achieve stable detonation waves. For example, the critical height of the mixture layer depth h^* ahead of the detonation front was related to the detonation-cell size α as $h^* = (12 \pm 5)\alpha$. The minimum length of chambers was approximated by the equation $L_{\min} = 2h^*$. If the chamber length was smaller than this value, stable detonation waves would not be formed. The radial size of the chamber should not be smaller than one detonation-cell size. When liquid fuel was used, it should not be smaller than the minimum diameter of droplets.

With the increasing international cooperation, more and more researchers are involved in the experimental studies of CRDE. Extensive CRDE experiments have been carried out by Wolanski's group[14] in Poland. Different geometries of cylindrical chambers, ranging from 50 mm to 200 mm in diameter, were tested with fuels of acetylene, hydrogen, methane, ethane, propane and kerosene with air, oxygen-enriched air, and oxygen under different injection stagnation pressures and back pressures. Long durations of stable detonation waves



(a) Detonation diagram

(b) C_3H_8/O_2

(c) Acetone/O_2

(d) Kerosene/O_2 (liquid)

Fig. 6 Continuous rotating detonation wave structure in a cylindrical chamber obtained for different mixtures in experimental research by Bykovskii et al.[11] in Russia.

were obtained. The experimental devices and obtained pressure signals of CRDE are shown in Figs. 7 and 8.[14]

Combining experimental data and theoretical analysis, Wolanski et al.[15] proposed an equation to determine the detonation wave number inside the combustion chamber. Subsequently, they built a small model of a rocket engine, tested it and gradually optimized the design. Detonation waves of long duration were obtained and the performance of the engine (thrust and specific impulse) was measured.[15] In cooperation with Japanese researchers, Wolanski et al.[16] also proposed a new concept of Turbocharged CRDE, which was a combination of CRDE and ramjet. They applied for a Japanese patent on CRDE and a similar application was repeated for a US

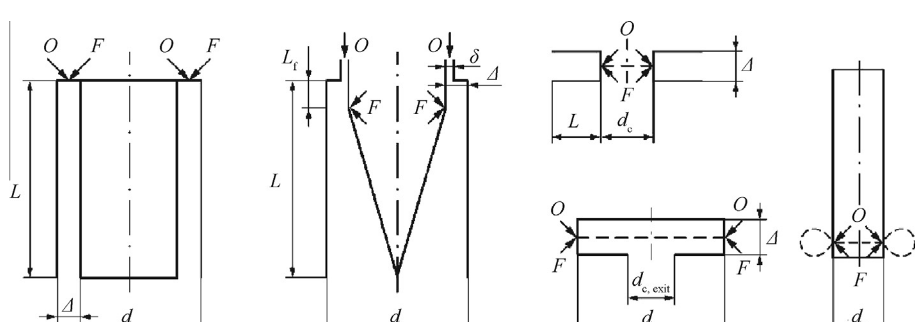


Fig. 5 Basic geometric configurations for continuously rotating detonation studies by Bykovskii et al.[11] in Russia.

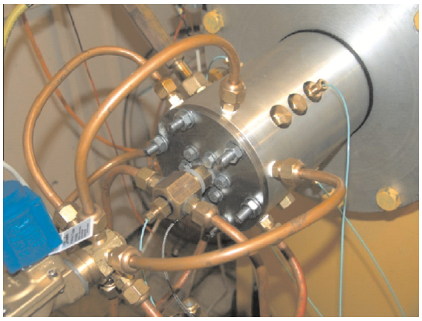


Fig. 7 Experimental devices of CRDE in Wolanski's lab in Poland.[14]

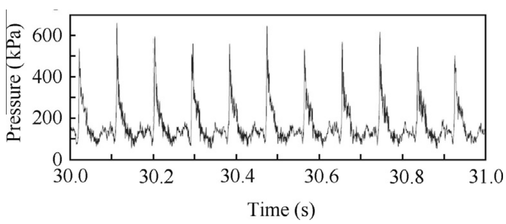


Fig. 8 Experimental pressure signals of CRDE in Wolanski's lab in Poland.[14]

patent. The engine had several advantages, including high thermal efficiency, simple design, low charges and others. They believed that it had a bright prospect.

Lately, Wolanski with Polish Aviation Institute[17] started the research of rotating detonation turbojet engine using gaseous mixtures. They replaced the combustion chamber of the conventional GTD-350 turbojet engine by that of continuously rotating detonation waves. The facility was built and its feasibility was proved. Now, research on optimization of the chamber under different operating conditions is underway.

The research team headed by Wang Jianping at Peking University was the first to conduct experimental studies of CRDE in China. In 2009, they successfully achieved hydrogen/oxygen rotating detonation waves and the propagating velocity was 2041 m/s.[18] Since then, they have carried out extensive researches of CRDE and achieved rapid progress.[19–23] They have tested several combustion chambers of CRDE, and one of them with a pre-detonation tube is shown in Fig. 9.[22]

Hydrogen/air and hydrogen/oxygen rotating detonation waves were obtained as long as 2 s in their group, as shown

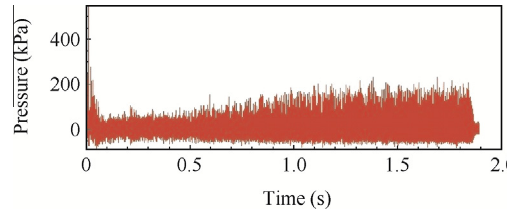
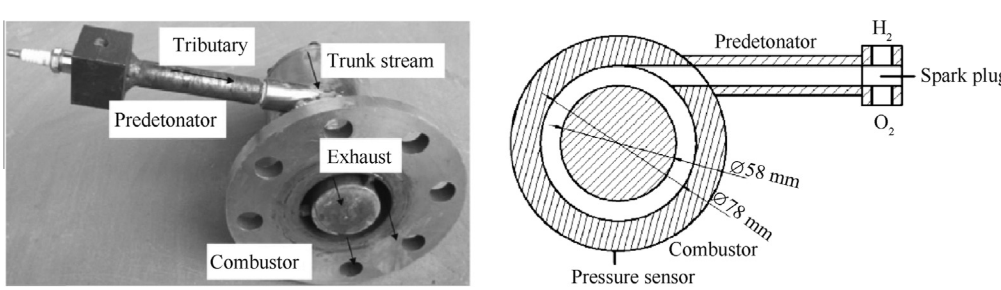


Fig. 10 2 s pressure signals of rotating detonation waves.

in Fig. 10, which is limited by the bearing of the pressure transLducers. They have also observed several interesting phenomena and proposed related explanations. For example, Wang et al.[22] found that a tangential flow of fresh gas from the pre-detonator would lead to a main detonation wave and a few detonation wavelets, and furthermore, slow down the detonation wave. Liu et al.[23] found oscillation phenomenon in pressure peaks and they also proposed a self-adjusting mechanism to explain the phenomenon, as shown in Fig. 11. Now, they are trying to explore the propagating mechanism of stable detonation waves and evaluate the propulsive performance of RDE quantitatively by means of experiments.

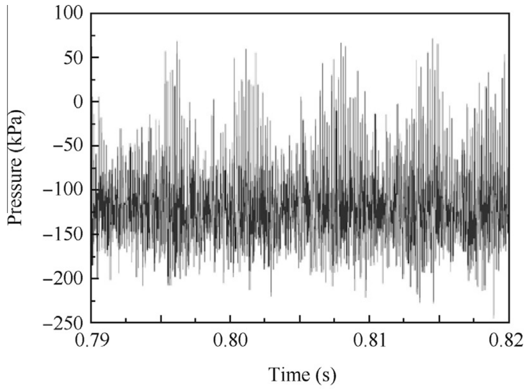
In recent years, many countries are also interested in the prospect of CRDE and have funded the research in this area. This makes CRDE develop from conceptual phase to the stage of engineering applications. MBDA-France in Europe performed some theoretical and experimental studies.[24] They designed a full-size model of the engine and performed ground test.[25] In 2011, MBDA-France announced a concept of Perseus supersonic missile system, they noted, "The new continuous detonation ramjet engine has greatly enhanced the performance of the supersonic missile" [26]. They compared the new missile with the BrahMos missile. It was estimated that the new missile could reduce the launch mass from 3000 kg to 800 kg and decreased the body length from 8.4 m to 5 m. They also announced that Perseus supersonic missile was expected to enter the force in 2030.

Center National de la Recherche Scientifique (CNRS) in France performed experimental researches of CRDE at Laboratory of Combustion and Detonation (LCD).[27] The schematic diagram of the combustion chamber and experimental devices are shown in Fig. 12. They obtained stable pressure signals measured by the pressure transducer. Using the high-speed camera, several detonation waves were observed in the combustion chamber, as shown in Fig. 13. They also pointed out that the number of detonation waves adjusted itself automatically to the mass flow of propellants. As the mass flow

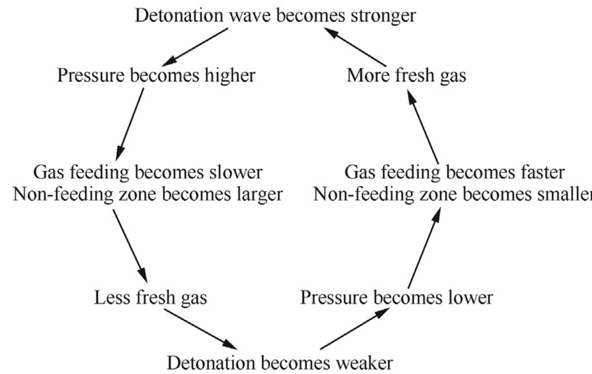


(a) Combustor (b) Profile map of the combustor

Fig. 9 Experimental devices of CRDE in Wang's lab at Peking University in China.[22]

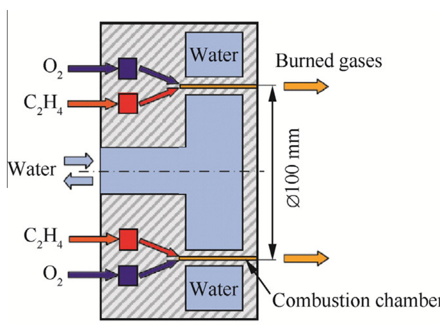


(a) Oscillation phenomenon in pressure peaks

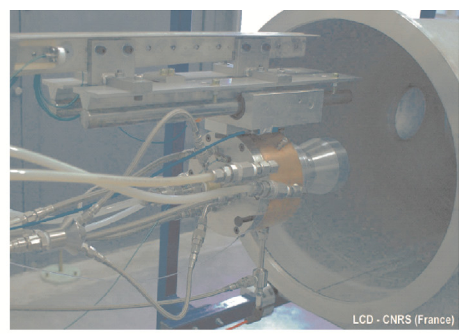


(b) Self-adjusting mechanism

Fig. 11 Experimental result and analysis by Liu in Peking University.[23]



(a) Schematic diagram of combustion chamber



(b) Experimental devices

Fig. 12 Experimental schematic diagram and devices at CNRS in France.[27]

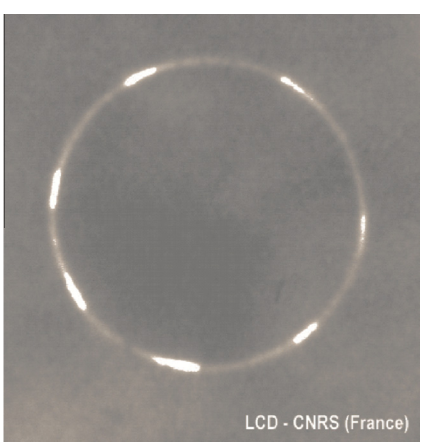


Fig. 13 Rear-view of CRDE with high-speed camera at CNRS in France.[27]

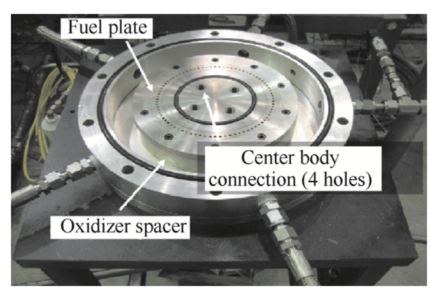
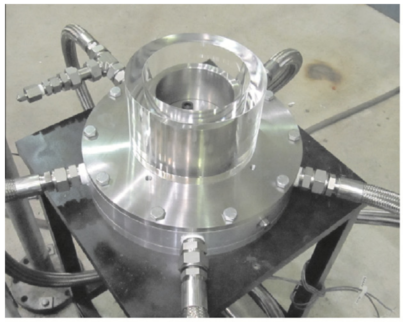


Fig. 14 Experimental facilities of CRDE and its combustion chamber at AFRL in USA.[28]

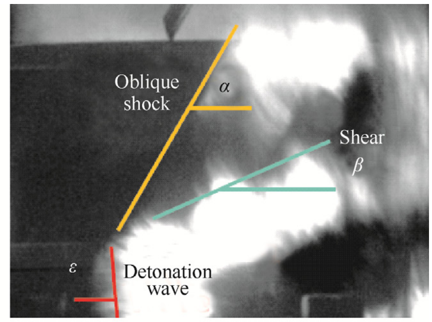
increased, there were more detonation waves in the combustion chamber.

Several groups in USA are also carrying out experimental studies of CRDE. Air Force Research Laboratory (AFRL) cooperates with Universities to research CRDE.[28–30] The combustion chamber is still coaxial cylinder, as shown in Fig. 14. They performed experiments in chambers of different sizes. Hydrogen/air and ethylene/air were used. The engine was tested at a wide range of flow rates and equivalence ratios. The high-speed camera used in experiments captured images of multi-detonation wave in the combustion channel. Pressure signals were traced and the detonation velocity was calculated. In addition, an optically accessible CRDE, with the quartz tube as the outer wall of the chamber, was developed to make basic measurements of an operating CRDE flow field. With the high-speed camera, the basic flow structure of the rotating detonation and its entire propagating process were determined.[31] The optically accessible CRDE and the obtained flow field are shown in Fig. 15.

Since 2010, Pratt and Whitney Rocketdyne (PWR) has been investigating the behavior of a CRDE using modular



(a) Optically accessible CRDE device



(b) Flow field structure

Fig. 15 Experimental device and result in AFRL.[31]

hardware.[32] Continuous detonation was achieved for long duration with multiple propellants and engine geometries. The longest test was 6.95 s. Based on experimental data, the combustion chamber was optimized. High-speed camera and pressure transducer were used to understand detonation wave behavior. The experimental facilities of CRDE is shown in Fig. 16.

CRDE experiments have also been carried out by GHKN/Aerojet in USA.[33] In their cooperation, Aerojet tested CRDE and invested in test facility. The experimental facilities of CRDE at GHKN are shown in Fig. 17. Currently, their research is still at the early stage. Experimental researches of CRDE have also been done at Texas State University in USA. The injection and ignition processes were focused on in experiments. They effectively controlled the propagating direction of detonation waves in ignition process.[34]

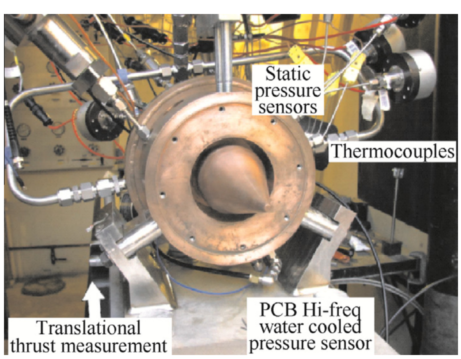


Fig. 16 Experimental facilities of CRDE at PWR.[32]

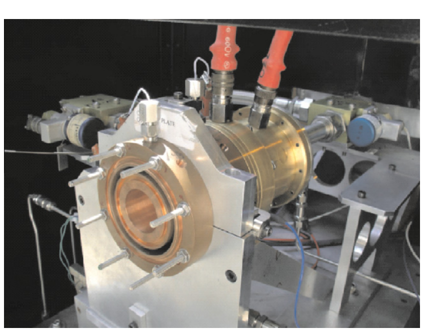


Fig. 17 Experimental facilities of CRDE at GHKN.[33]

Liu et al.[35,36], from National University of Defense Technology in China, have tested the feasibility of CRDE experimentally. In their experiments, a pre-detonation tube was used to ignite the engine. It was found that there existed a time gap between the initiation and the formation of stable detonation waves due to the exhaust process of the pre-detonation tube. Thus deep understanding of the initiation is needed to enhance the stability of detonation waves. In experiments, they achieved continuously rotating detonation waves of long duration, and the corresponding pressure signals are shown in Fig. 18. Zheng et al.[37], from Nanjing University of Science and Technology in China, also realized hydrogen/air rotating detonation waves. The equivalence ratio was 0.93, and the tested velocity of detonation waves is from 1518.5 to 1606.1 m/s. Peng et al.[38], also from Nanjing University of Science and Technology in China, did ignition experiments on rotating detonation engine with the slot-orifice impinging injection method. It was found that the success rate of rotating detonation wave initiation was up to 94% with automotive spark plug.

3.2. Numerical studies

Because of the properties of detonation waves which are of high velocity, high temperature and high pressure, it is difficult to obtain the detailed flow field and physical or chemical parameters of CRDE. In the early numerical research of CRDE, detailed and large-scale calculations of detonation waves were not performed, since computer power at that time was significantly less than today's computers and also because

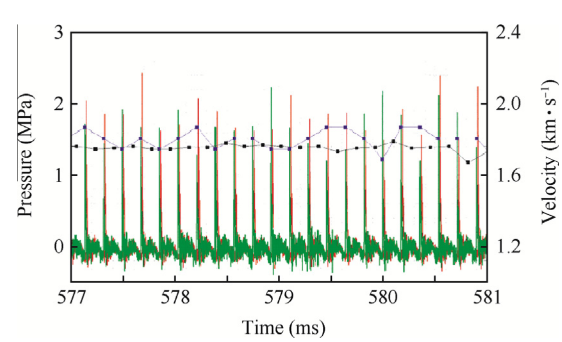


Fig. 18 Experimental results of CRDE at National University of Defense Technology.[35]

the shock-capturing schemes was not as high as today's. Thus, many simplifying assumptions had to be made. Despite of all these limitations, Shen and Adamson[39] performed calculations of CRDE combining both theoretical and numerical methods, and the basic structure of rotating detonation waves was revealed, as shown in Fig. 19.

Numerical simulations of CRDE in different geometries and for different initial conditions offer a very good tool not only for better understanding of the mechanisms controlling the detonation propagation process in complex geometries but also for optimizing the geometry and fuel and oxidizer feed parameters for the experimental design of CRDE. In recent years, detailed simulations of the flow field structure in the combustion chamber of CRDE have been performed due to the increasing computing power and the rapid development of the program parallelization. Now, numerical simulation has been a powerful means to assist and guide experimental research.

Zhdan et al.[40,41] in Russia performed early theoretical analysis and 2D numerical simulations of continuously rotating detonation waves. The obtained flow fields qualitatively coincided with the experimental results, as shown in Fig. 20 ($l = \pi d_c'$, l = 8 cm, d_c'-diameter of the combustion chamber). However, the calculated detonation velocity was only 80% of the theoretical Chapman–Jouguet (C–J) value. Due to the simple numerical methods and coarse meshes, only rough flow field structures were obtained.

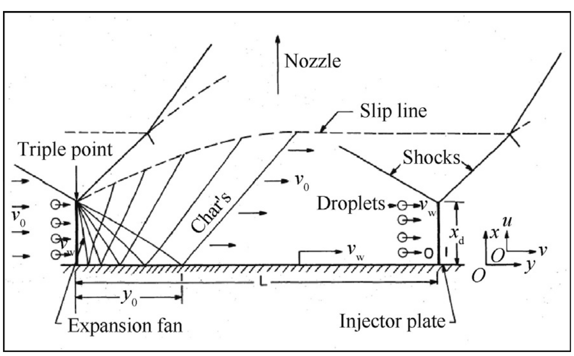


Fig. 19 Basic flow structure of CRDE by Shen and Adamson.[39]

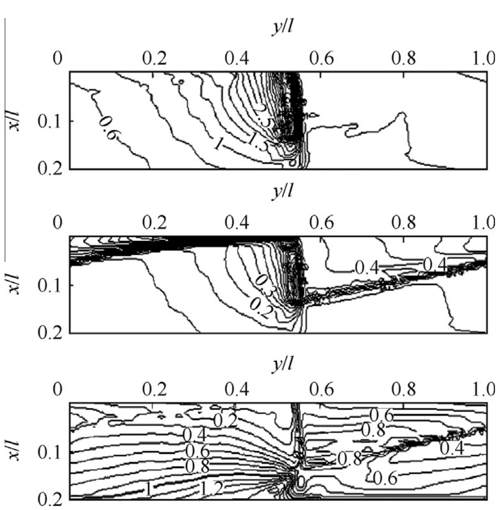


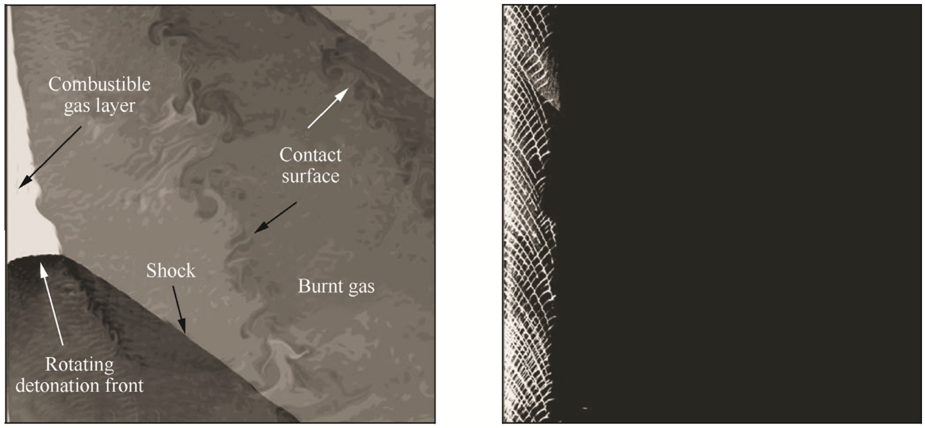
Fig. 20 Numerical results by Zhdan et al. in Russia.[40]

Hishida et al.[42] in Japan, using two-step reaction chemical model, obtained detailed structures of the detonation flow field by assuming the 3D cylindrical chamber to be a 2D plan without variation in radical direction and with periodic boundary conditions in circumferential direction, as shown in Fig. 21. They obtained the cellular pattern of the rotating detonation wave on the computed smoke-foil record. For the first time, they analyzed the Kelvin–Helmholtz instability existing on the interface of the injected combustible. The propulsive performance of CRDE was also computed, and the specific impulse was as high as 4700 s.

The research team headed by Wang Jianping, from Peking University in China, has begun both 2D and 3D CRDE simulations since 2007. They were the first who performed both 2D and 3D simulations of CRDE to validate RDE's feasibility and explore its physical mechanism. Thorough and comprehensive researches on RDE have been done from many aspects, including the detailed flow structure, fuel injection limit, nozzle effects, viscous effects, propulsive performance, self-ignition, particle path, thermodynamic performance, shock reflections near the head end, and the generation and propagation process of multi-detonation waves.[43–53]

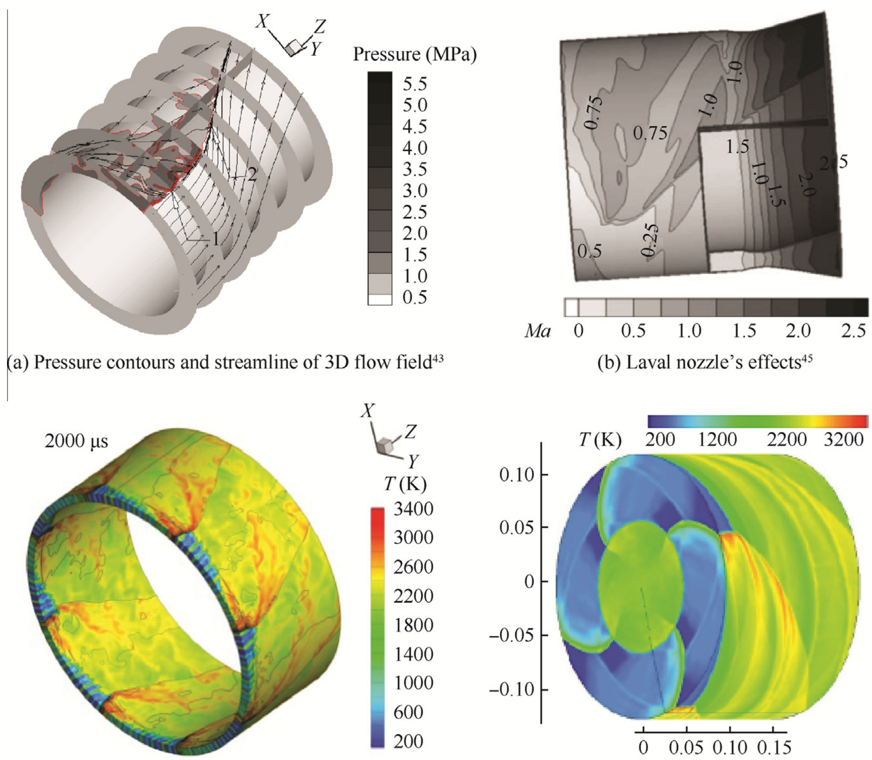
In 2010, Shao et al.[43] have already obtained 3D flow field of CRDE, as shown in Fig. 22(a). Based on 3D simulations, Shao et al.[44,45] verified the unique advantages of continuous detonation waves, that rotating detonation waves can be realized within the range from subsonic to hypersonic injection, and also found that the combustor with Laval tail nozzle had the best performance. Mach number contours in Laval nozzle combustor is shown in Fig. 22(b). Liu et al.[46–48] established different new intake models to analyze their effects on the flow field evolution and the stability of detonation waves. For the first time, they captured the phenomenon of the spontaneous formation of multi-front rotating detonation waves in the combustion chamber of CRDE, as shown in Fig. 22(c). Tang et al.[49] proposed a new model of CRDE without inner cylinder and verified the feasibility of this new model numerically, the flow field of which is shown in Fig. 22(d). If the new model is used in application, it can greatly reduce the difficulties in engine cooling. Zhou et al.[50,51] proposed particle tracking method to track flow particles in the flow field and found that flow particles spurt out the combustor almost axially. They also discussed the corresponding thermodynamic cycle and verified the superior performance of CRDE. Wu et al.[52,53] discussed the stability and restabilization of CRDE, and found that CRDE could finish the main adjustment within two times of the detonation cycle period, demonstrating the high stability of CRDE.

Yi et al.[54–56] in Singapore, using one-step chemical reaction model of H2/Air, performed both 2D and 3D CRDE simulations. They mainly focused on estimation of various design parameters on the propulsive performance of CRDE. These parametric variables included stagnation pressure, stagnation temperature, injection area ratio, axial chamber length effects and the number of detonation waves. It was shown that the propulsive performance of the engine was strongly dependent on the injection conditions, but was weakly dependent on the axial chamber length effects and the number of detonation



(a) Temperature distribution in entire flowfield (b) Smoke-foil record written by triple shocks

Fig. 21 Detailed 2D flow structure of CRDE in numerical results by Hishida in Japan.[42]



(a) Pressure contours and streamline of 3D flow field[43] (b) Laval nozzle's effects[45]

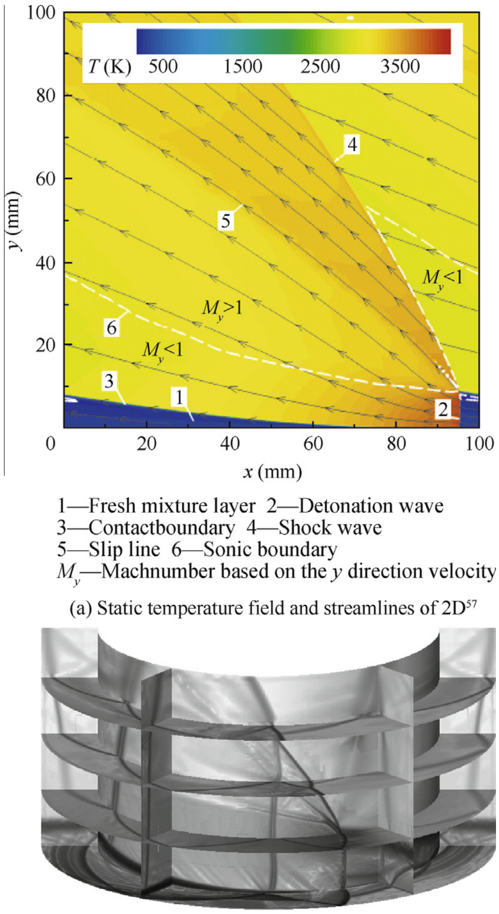
(c) Multi-head rotating detonation waves[48] (d) Hollow CRDE[49]

Fig. 22 Numerical results of CRDE at Peking University.

waves. They also investigated the effect of tail nozzle angle and length on the propulsive performance of CRDE, and gave the nozzle design parameters for optimal performance.[55]

Davidenko et al.[57] in France performed 2D CRDE simulations, as shown in Fig. 23(a). Combined with theoretical analysis, they showed that CRDE had a significant advantage over the conventional rocket engine in terms of cycle work and specific impulse. Moreover, they have also done 3D simulations and used the adaptive mesh refinement (AMR) method to increase the computation efficiency. They compared 3D results to that of 2D. The overall flow field in 2D and 3D simulations was similar to each other. However, the 3D flow had specific features due to the effects of the inner and outer cylindrical wall on detonation waves, as shown in Fig. 23(b).[58]

Based on 2D numerical results, Hayashi et al.[59] and Yamada et al.[60] in Japan discussed the threshold of detonation limit from three aspects: the computational area, the ignition energy and the injection parameters. The results showed that there were no stable detonation waves when the computational area was smaller than the lower limit. However, as for the upper limit, there was no such unstable phenomenon. They also pointed out that both upper and lower limits existed in the injection stagnation pressures. Beyond the two limits, no stable detonation waves formed, either. Tsuboi et al.[61] in



(a) Static temperature field and streamlines of 2D[57]

(b) 3D instantaneous fields of density gradient[58]

Fig. 23 Flow field of 2D CRDE by Davidenko et al.[57] and 3D CRDE by Eude et al.[58] in France.

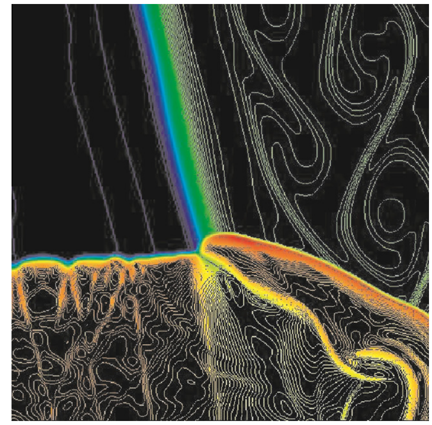


Fig. 24 Transvers waves at detonation front in numerical results by Uemura et al. in Japan.[62]

Japan, using detailed reaction model for hydrogen/oxygen, systematically analyzed the differences of the flow field structure and performance parameters between 2D and 3D CRDE simulations. Without the contraction tail nozzle, the specific impulse and thrust in 3D simulation are close to those in 2D simulation under the same conditions. With the contraction tail nozzle, the specific impulse and thrust in 3D simulation will be increased.

Uemura et al.[62] in Japan, using detailed reaction model, simulated the flow fields of a small size combustion chamber in a subtle way. Their numerical results showed that there were several transverse waves at the detonation front, as shown in Fig. 24. They found out that at the interaction point between the detonation front and the oblique shock wave, an unreacted gas pocket appeared and ignited periodically to generate transverse waves. The generated transverse waves propagated toward the inlet wall and then bounced back to the interaction point to maintain detonation propagation. Although fine detonation flow field structures were obtained, their research mainly focused on the micro-wave structures. The combustion chamber size is of the order of millimeter and quite different from the practical applications. Tsuboi et al.[63] from the same group, also using detailed reaction model, estimated the thrust performance on CRDE. They used both 2D and 3D numerical simulations to determine the effects of the CRDE parameters and the dimensional effects on the thrust performance under a low-pressure environment.

Kailasanath and Schwer, from U.S. Naval Research Laboratory, have performed numerical simulations of CRDE since 2011.[64–67] They have numerically obtained typical flow field of rotating detonation waves and have systematically investigated several different aspects of CRDE. These included the effects of the stagnation pressure, back pressure, combustion chamber size, different fuels, injection fill region and exhaust plenum on the flow field and performance of CRDE. In the previous simulations, the effects of the upstream mixture plenum on detonation waves are not concerned. To clarify the effects in detail, they made new attempts and created several more practical injection systems[68,69], as shown in Fig. 25. They have studied the effects of pressure feedback into the upstream mixture plenum. They also examined the effects of these different injector configurations on the stability of detonation waves and the performance of CRDE. These results provide technical support for the design of the chamber head in experiments.

In addition, Schwer and Kailasanath[70] also investigated exhaust effects on the flow field and performance of CRDE. The computational domain and the results are shown in Fig. 26 (1 atm = 101325 Pa). The results suggested that including an exhaust plenum had only a slight effect on the performance measurement and general flow field characteristics within the CRDE. Thus, the previous simulation of CRDE without an exhaust plenum is valid and reliable.

Lu et al.[71], from University of Texas at Arlington in USA, provided an assessment of the challenges of CRDE. They developed a cycle analysis model for an airbreathing CRDE and analyzed the effects of the flight Mach number on its propulsive performance.[72] Moreover, they made a performance comparison between airbreathing PDE and airbreathing CRDE and also a performance comparison between airbreathing CRDE and rocket-mode CRDE. In their simulations, an airbreathing CRDE, using hydrogen as fuel, reached a specific impulse of 3800 s. The specific impulse was 1500 s when propane was used as fuel.[73]

Stoddard and Gutmark[74], from University of Cincinnati in USA, performed 3D simulations of centerybodyless CRDE. Unlike Tang et al.[49], they used a Reynolds-Averaged Navier–Stokes (RANS) computational fluid dynamics (CFD)

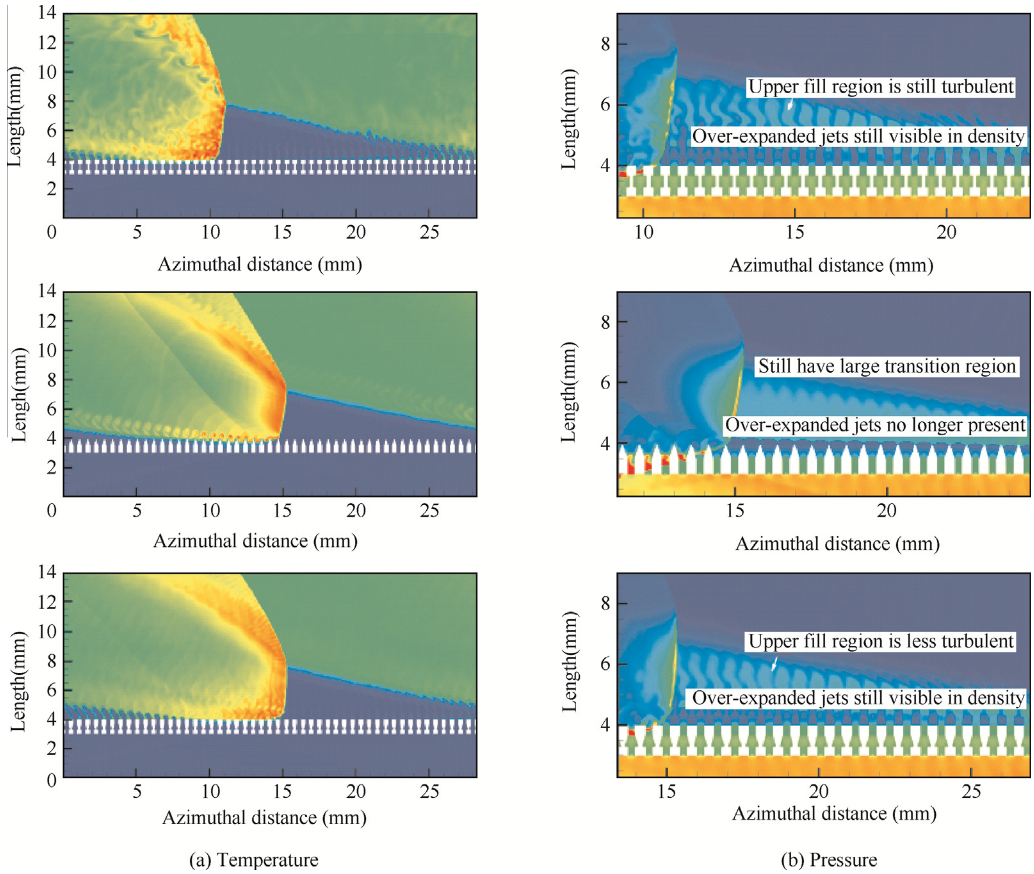


Fig. 25 Numerical results of CRDE with different injectors by U.S. Naval Research Laboratory.[68]

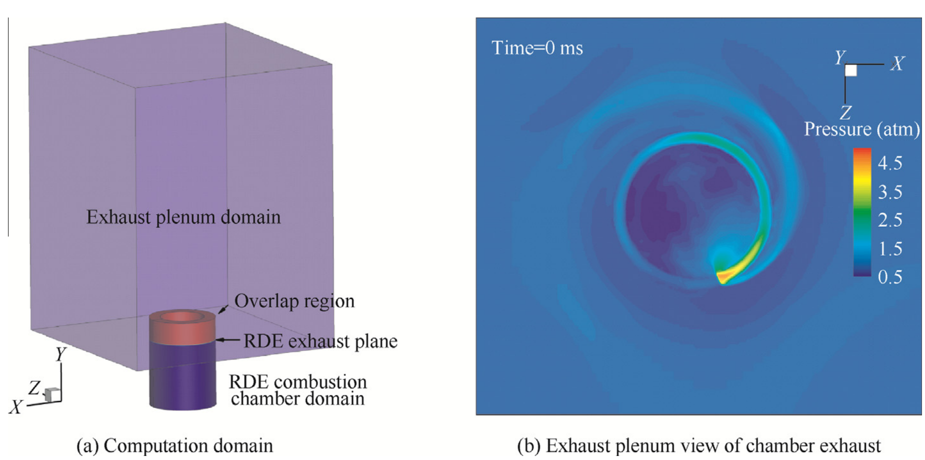


Fig. 26 Numerical results of CRDE with an exhaust plenum by U.S. Naval Research Laboratory.[70]

program Fluent by ANSYS and a Spalart–Allmaras turbulence model to better simulate mixing of hydrogen and air. The feasibility of CRDE without inner wall under non-premixed injection was validated, and the effect of various alterations was studied, including hydrogen injection hole size alteration, longitudinal walls, and an ejector.

Folusiak et al.[75] and Swiderski et al.[76], from space technologies center institute of aviation in Poland, performed numerical studies on CRDE, using unstructured grid. The computational model is quite similar to experimental devices in their lab, as shown in Fig. 27 (DW-large scale structure of the detonation wave, IP-injection plane location, SW-shock wave propagating downstream). Due to the simple shock-capturing scheme and large grid size, they did not obtain fine flow field structures. However, their numerical results provided a quantitative reference for experimental researches.

Frolov et al.[77] in Russia performed 3D simulations of CRDE with separated supply of hydrogen and air. The physical model of CRDE and the main operation parameters were the same as those of the experimental setups at Lavrentyev

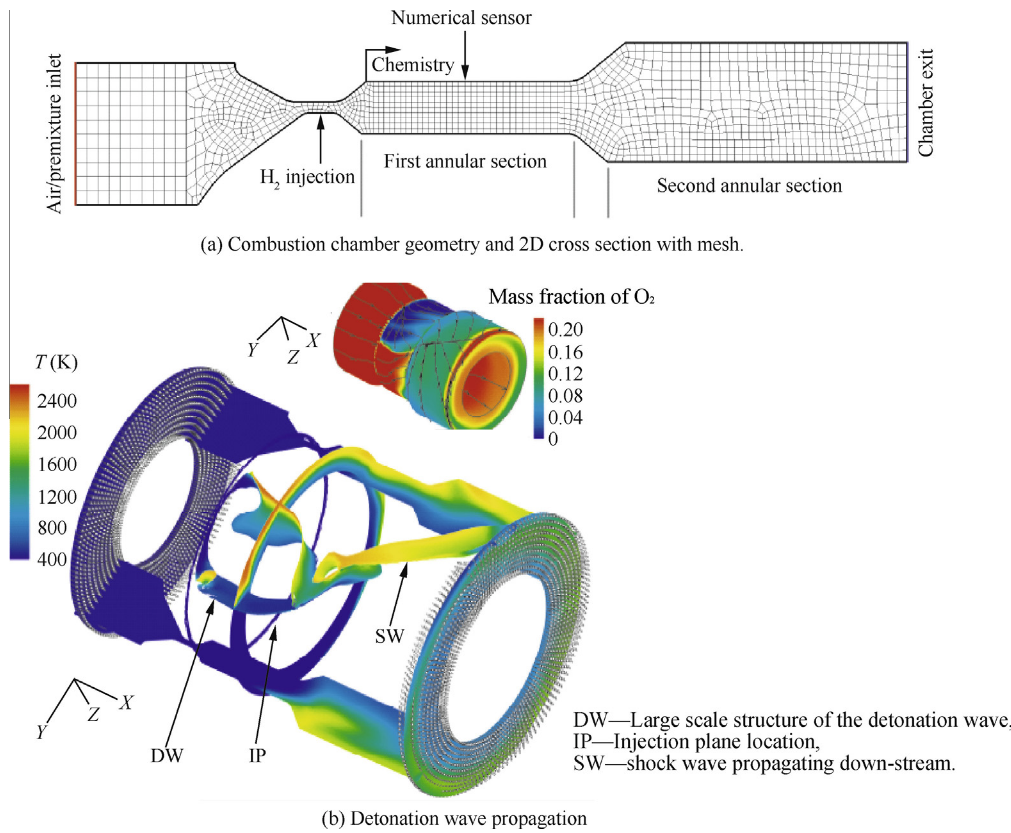


Fig. 27 Computational model and flow field of CRDE in numerical work by Folusiak et al.[75] and Swiderski et al.[76] in Poland.

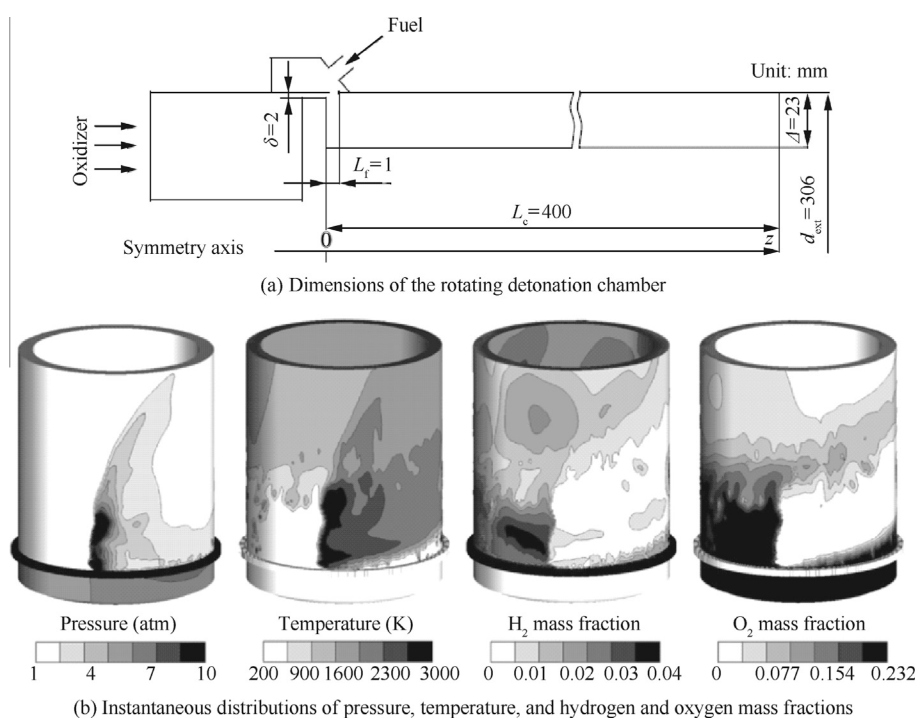


Fig. 28 Physical model and flow field of CRDE in numerical work by Frolov et al.[77] in Russia.

Institute of Hydrodynamics (LIH), as shown in Fig. 28(a). The numerical results successfully showed the non-premixed burning process of detonation waves, as shown in Fig. 28(b). The obtained flow field coincided with experimental observation by Bykovskii et al.[13] However, in contrast to these experiments, in which two or three detonation waves traveling in the combustion chamber were observed, the calculations under the same conditions predicted stable operation mode with only one detonation wave. These discrepancies between the calculation results and experimental data require further studies. Sustainable and efficient mixing of fuel and oxidant has been an important prerequisite for the stable detonation propagation. The numerical results by Frolov et al.[77] provided quantitative data to examine the mixing process and the mixing degree of fuel and oxidant.

Pan et al.[78] at Nanjing University of Science and Technology in China also performed numerical simulations on continuously rotating detonation waves and obtained the overall flow field.

4. Challenges of CRDE

Although significant progresses of CRDE have been achieved in recent years, there are still many issues that need further exploration.

(1) Injecting and mixing mechanism of fuels and oxidants

Sufficient mixing is required for all combustion processes, especially for CRDE. In practice, the mixing must happen rapidly and in a short distance to sustain detonation waves. These requirements are exacerbated by the high mass flow rates of CRDE, the rapid propagating velocity of detonation waves, and the high-pressure detonation products. Therefore, it needs to further clarify the intake way, the mixing mode and the blending process of fuel and oxidant. At present, most numerical simulations are based on the ideal injection model in which combustible mixtures are stoichiometric premixed. In the future, simulations of CRDE should be carried out under non-premixed and different equivalence ratio conditions.

(2) Characteristic and performance of rotating detonation waves with different fuels and oxidants

Currently, gaseous hydrogen is usually used as fuel in simulations. However, the gaseous mixtures are unrealistic in practical applications. It is necessary to research the appropriate equivalence ratio range of different fuels and oxidants in depth, within which rotating detonation wave can be formed. Numerical simulations can be helpful to determine quantitatively the propulsive performance of CRDE with different fuels and oxidants.

5. Conclusions

In recent years, stable continuous detonation waves of long duration have been successfully achieved using a variety of fuels in combustion chamber of different structures under various injection modes for experimental research. Preliminary thrust and specific impulse of CRDE have been measured. Usually, pressure transducers are used to record the pressure signal and compensation technique and high-speed camera are used to capture the flow field inside the combustion chamber of CRDE. In numerical simulations, detailed flow field structures are obtained. And the effects of injection conditions, intake models and chamber geometries on the flow field structure and propulsion performance of CRDE have been thoroughly studied. These numerical results are in good agreement with the experimental data. Combined with theoretical analysis, thermodynamic cycle of continuous detonation has been numerically researched. Network and thermal efficiency of CRDE have been quantitatively calculated. The superiority of CRDE's performance has been verified. Currently, the engineering application of CRDE has also been gradually carried out. Reliable prototype of CRDE is expected to be built in the near future.

Although rich experience related to CRDE has been gained and the many characteristics of CRDE have been mastered, there are still more questions than answers at present. This requires international collaboration among worldwide scholars. CRDE is expected to bring good prospects for military applications and the relevant agencies should pay attention and offer support to its development.

Acknowledgements

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