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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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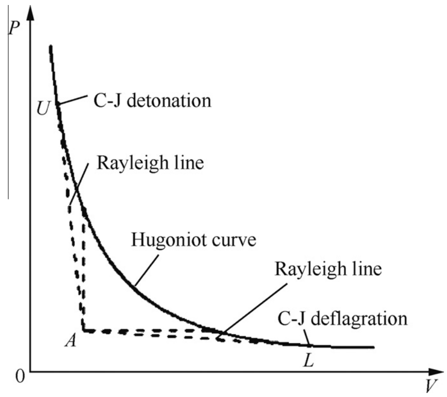

Fig. 1 Rayleigh lines and Hugoniot curve in *P*–*V* diagram.

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 preheat 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

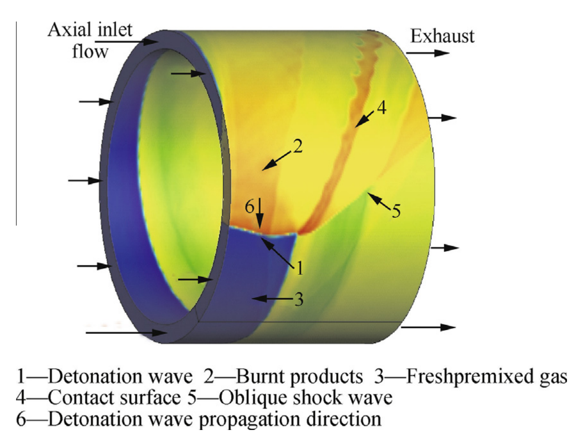

Fig. 2 CRDE propagation schematic structure.