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Coexistence of detonation with deflagration in rotating detonation engines

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ABSTRACT

Rotating detonation engines of high thermal efficiency and specific impulse have been studied a lot. However, rotating detonation waves lead to uneven flow field, local high temperature and high pressure, tending to damage the combustor. An experimental way to keep both rotating detonation waves and deflagration in the combustor and to combine the advantages of rotating detonation engines and deflagration engines, is introduced here. Pressure sensors measure the pressure of rotating detonation waves and gas mass flow controllers control the mass flow rates of reactants. A standard speed camera captures the events of rotating detonation and deflagration. It is discovered that the rotating detonation is much more intense than deflagration. Both upstream rotating detonation waves and downstream deflagration respectively dependent on the trunk stream and the tributary can coexist in the combustor. The predetonator is the boundary between the detonation region and deflagration region in the combustor. The coexistence of detonation and deflagration weakens the combustion instability caused by rotating detonation, which may be helpful for rotating detonation to be applied.

Introduction

A detonation wave of pressure-gain combustion is a shock wave followed by a reaction zone according to the ZND theory [1–3]. Detonation engines have higher thermal efficiency than deflagration engines (conventional engines, such as rocket engines and air-breathing engines) because detonation has a lower entropy production than deflagration. At present pulse detonation engines (PDEs) [4] and rotating detonation engines (RDEs) are being studied widely. The PDE cycle is inherently unsteady compared to the deflagration cycle and not suitable for integration in a gas turbine engine. However, if a detonation wave rotates along the circumference of the annular combustor channel and the flow is continuous, continuous detonation will be obtained and the propulsion performance will be improved. That is the RDE, requiring only one initiation during one run and then detonation waves will keep rotating in the combustion chamber. There may be a few rotating detonation waves (RDWs) moving in the combustor. Fig. 1 shows the operating principle of an RDE. The RDE combustor is usually annular and the cross section may be circular [5] or convex polygonal [6]. A detonation wave is formed in the predetonator linked with the combustor tangentially and injected into the combustor to detonate reactants. Thus, an RDW is formed. The RDW with a contact

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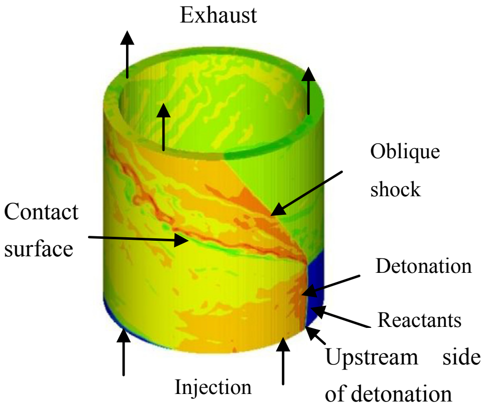

Fig. 1 – Operating principle of an RDE.

surface and an oblique shock wave is rotating perpendicularly to the flow. The contact surface is the discontinuity between fresh detonation products and old products from the last RDW cycle. The oblique shock wave in the product region is caused by the RDW and always spreads out of the combustor. The RDW pressure is so high that backflow occurs in a small part of the inlet, but the backflow region is narrow and the reactants still flow into the combustor through other parts of the inlet. The propagating RDW leads to an uneven and unsteady flow field. The pressure and tangential velocity behind the RDW are much higher than those in other parts of the flow field. However, the flow field becomes even gradually due to expansion when it comes to the RDE outlet. The specific impulse 117 s of ethylene–oxygen mixture for an RDE without nozzles was achieved and it could be increased to 139 s when a conical-shape tail was added to the combustor [7]. Preliminary tests of an RDE without any nozzle were carried out to evaluate the propulsion performance and a specific impulse 341.7 s for hydrogen–oxygen mixture was obtained [8]. Due to the detonation cycle, RDEs may have 20%–25% higher thermal efficiency than deflagration engines [9].

Sometimes a few RDWs were observed in the experiments and the number of RDWs was increased with the increased mass flow rates [10–12]. The height of RDW front was reduced with the increasing wave number as there was a positive correlation between the height and the cycle of a single RDW. When there were two counter-rotating detonation waves, they would collide with each other and cause detonation failure. This case was always transient [13]. Counter-rotating detonation waves were related to the insufficient mixing of fuels and oxidants [14]. Thus, multiple co-rotating detonation waves could be a steady state. Especially, the specific impulse would not change when the RDE entered the transition region from one RDW to two RDWs. Since the RDW was non-premixed combustion in the experiments, the wave front was concave with respect to the fuel fill region in front of the detonation whereas the wave front of numerical premixed RDW was almost flat. More than 430 tests of multiple configurations of RDEs were carried out by Pratt & Whitney Rocketdyne, including multiple propellants, multiple injectors, multiple nozzles, with and without transient plasma augmentation [15]. Preliminary evaluations showed that wide variety of behavior at identical flow conditions was heavily dependent on engine configurations. A survey of detonation engines was conducted by Wolanski and one conclusion was that the RDE coupled to an aerospike nozzle had a great advantage [16]. However, RDE has some disadvantages over conventional deflagration engines, such as high temperature and pressure near RDW, high combustion instability, uneven and unsteady flow field and so on. That will increase the mechanical and thermal loads, causing the engines to be damaged. The disadvantages make the combustor difficult to be coupled with the nozzle. Low frequency detonation instabilities, intermediate frequency detonation instabilities and high frequency detonation instabilities were discovered, according to the fluctuations of pressure traces for RDWs [17,18]. Interactions between the propellant feed system and the unsteady heat release from the RDW resulted in low frequency detonation instabilities (hundreds of Hz). Intermediate frequency detonation instabilities (around 1000 Hz) were caused by interactions between unsteady heat release and the combustor boundaries. High frequency detonation instabilities were caused by RDW movements and the frequency was equal to the RDW frequency. RDW instabilities manifested in such a way that subsequent detonation pressures waxed and waned in magnitude throughout the test length [19,20]. Detonation instabilities limited the application of RDEs. In particular, there was a region where fresh premixture was in close proximity to burned gases, and might burn before hit by the detonation wave [21]. This region could support a deflagration wave propagating from the products to the reactants, but the short time spans that existed between RDWs meant only a small fraction of the mixture would be deflagrated. This deflagration region was inherent with the RDW.

In this study deflagration parts are increased to weaken detonation instabilities in an RDE since deflagration is almost isobaric. Two pressure sensors and a standard speed camera are employed to capture the detonation and deflagration events. Gas mass flow controllers are employed to control the mass flow rates of reactants. It is discovered that both upstream RDW and downstream deflagration respectively dependent on the trunk stream and the tributary can coexist in the RDE when there is the trunk stream and the tributary into the combustor after ignition. The existences of the RDW or deflagration are steerable by controlling the flow of the trunk stream and the tributary, as may be a kind of potential technology to be developed for RDEs. This kind of hybrid engine will take advantage of both detonation and deflagration.

Experimental facility and methodology

The experimental system shown in Fig. 2 is mainly comprised of a gas supply system, a cooling system, a data acquisition system, an ignition system, a combustor and an exhaust system. The trunk stream is the flow of reactants directly into the combustor and the tributary is the flow into the combustor through the predetonator. The gas supply system, supplying hydrogen and oxygen to the combustor and the predetonator, includes gas sources, reduction valves, check valves, solenoid valves, single-chip computers, mass flow controllers and

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