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Investigation on the propagation process of rotating detonation wave

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ABSTRACT

Effects of mass flow rate and equivalence ratio on the wave speed performance and instantaneous pressure characteristics of rotating detonation wave are investigated using hydrogen and air mixtures. The interaction between air and fuel manifolds and combustion chamber is also identified. The results show that the rotating detonation waves are able to adapt themselves to the changes of equivalence ratio during the run, the rotating detonation waves decayed gradually and then quenched after the shutdown of reactants supply. The wave speed performance is closely related to the mass flow rate and the pressure ratio of the fuel to air manifolds at different equivalence ratios. The blockage ratio of the air manifold increases with the increasing of the wave speed due to high-pressure detonation products, while increasing of the equivalence ratios will reduce the blockage ratio of the hydrogen manifold. Higher equivalence ratio can enhance the stabilization of the rotating detonation wave and lower equivalence ratio will lead to the large fluctuations of the lap time and instantaneous pressure magnitude. The overpressure of rotating detonation wave is determined by the combination of mass flow rate and equivalence ratio, which increases with the increasing of mass flow rate in the equivalence ratio ranges that the rotating detonation wave propagates stably. The secondary spike in the instantaneous pressure and ionization signals indicates that a shocked mixing zone exists near the fuel injection holes and the reflection of shock in the mixing zone induces the reaction.

1. Introduction

A detonation wave is a supersonic combustion wave which consists of a leading shock and a following reaction zone. The reactants are adiabatically compressed and heated to generate sufficient active radical species, which lead to the rapid chain-branching reactions. The rapid chemical energy release in the reaction zone results in a further rise in temperature and a corresponding drop in pressure and density, which produces the forward thrust that supports the propagation of the leading shock [1]. The application of detonation in propulsion including rotating detonation engine [2] and pulsed detonation engine [2–7] is promising because of the higher thermal efficiency associated with the pressure gain combustion and minimum entropy creation [8,9]. RDE is a novel propulsion concept which utilizes one or multiple detonation waves propagating around the annular channel continuously to produce steady thrust. Compared to PDE, RDE has more compact design, continuous presence of a detonation after ignition [10], and the absence of energy loss during the deflagration to detonation transition [3]. Thus, it has received increased attention over the past few years.

Significant progress has been made in the research and development of RDEs [10], such as the effects of mass flow rate and equivalence ratio on the wave speed performance [10–17], the stability of RDW under the subcritical and supercritical injection of reactants [10,12,18,19], the feedback of high-pressure detonation products on the reactant manifolds [19–22]. Moreover, the ignition characteristics and the operation modes are investigated by integration of convergent nozzles [23,24], annular ejector [25], and afterburner [17]. Researches have revealed the basic characteristics of RDE. For instance, the wave speed increases with the increasing of mass flow rates and the equivalence ratios [12,17]. The basic operating modes of RDE are also identified – steady single wave [12], single wave and multiple waves alternation [26], steady multiple waves [12,17,27], and longitudinal pulsed detonation [18,19,28].

Experimental studies on the characteristics of RDEs rely on both the contact and contactless measurement, including the flush-mounted pressure transducers and ionization probes [26,29], Infinite Tube Pressure (ITP) measurement [24,25,30,31], moving photographic film [11,12,28], high speed imaging [29], planar laser induced fluorescence (PLIF) [32], OH* chemiluminescence [10] and absorption based spectroscopic techniques [33]. The application of the those state of art diagnostics techniques has supplied a better understanding of the flow

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Nomenclature

ER	equivalence ratio
RDW	rotating detonation wave
RDE	rotating detonation engine
PDE	pulsed detonation engine
ITP	Infinite Tube Pressure
BR	blockage ratio
p	static pressure
ρ	density
u	velocity
q	momentum flux ratio of hydrogen to air
$\dot{m}$	mass flow rate
P	stagnation pressure in the manifold
A	effective injection area
Γ	function of specific heat ratio, γ
a	sound speed
subscript	
1	state before ignition
2	midpoint during the hot-fire test
comb	combustor
plenum	hydrogen and air plenums

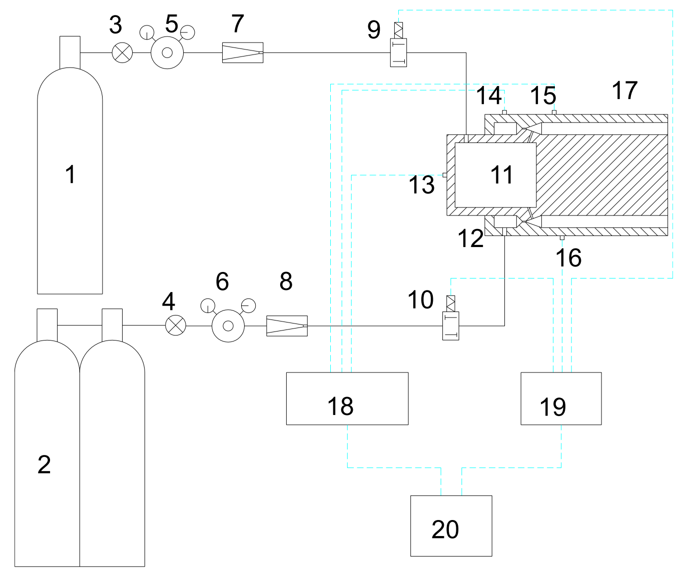

Fig. 1. Schematic of the RDE test facility: 1 tank with H_2, 2 tank with Air, 3–4 valves, 5–6 reducing valves, 7–8 sonic nozzles, 9–10 electromagnetic valves, 11 H_2 manifold, 12 Air manifold, 13–14 pressure transducers placed in manifolds, 15 chamber pressure transducer, 16 ignition device, 17 RDE chamber, 18 acquisition card, 19 control unit, 20 computer.

structure, identifying mixing characteristics and gas temperature transients [33]. The time-dependent pressure signals at different positions provide the propagation direction of RDW [26,29], the ionization signals give the information about the strength of the combustion front [18], the acetone PLIF images provide insightful information on the transient fuel injection process in RDE [32], the high speed images show the development of initial deflagration to rotating detonation wave as well as the propagation transients [29], the OH* chemiluminescence images allow observation of the instantaneous structure of RDWs [10].

However, due to the periodic heat release along the circumference, the flush-mounted transducers suffer from severe heat soaking which may cause damages. Most of the studies utilize ITP technique to judge the operation condition (unsteady, detonation, acoustically-coupled combustion [24]) in the chamber. The application of ITP loses the high fidelity of the pressure transients about RDWs. Moreover, detonation wave is considered as a leading shock followed by a reaction zone, the data acquired by flush-mounted pressure transducers and ionization probes gives much more transient information about the RDWs. Thus, to further investigate the effects of mass flow rate and equivalence ratio on the propagation characteristics of RDWs, and identify the interaction between the manifolds and chamber, the flush-mounted pressure transducers and ionization probes are utilized. The steady propagation and the quenching process of RDWs are analyzed. The influence factors of wave speed as well as the instantaneous pressure characteristics are also identified. Moreover, the effects of high-pressure detonation wave on the fuel and air injections are studied. The fuel utilized in this study is hydrogen (H_2), which is an ecological fuel being widely used in internal combustion engines [34,35], scramjet [36], and detonation engines [10,12,29,34,37].

2. Experimental setup and measurement techniques

Fig. 1 shows the schematic of the RDE test facility, which consists of a model RDE combustor, hydrogen and air delivery system, control system and data acquisition system. The inner and outer diameters of the detonation combustor are 70 mm and 80 mm, respectively, resulting in a channel width of 5 mm. A slit-orifice impinging mode is applied to achieve high-quality mixing of hydrogen and air, shown in Fig. 2(a). The air is injected into chamber through the Laval-nozzle like slit, while the fuel is injected through 90 uniformly distributed orifices along the inner body of RDE. The hydrogen and air mass flow rates are metered upstream of the respective manifolds using two sonic nozzles. The global equivalence ratios in all the tests are based on those two values. The detonation in the combustor is initiated using a vertically instrumented initiator about 8 mm downstream of the injection plane. Hydrogen and oxygen are injected into the initiator (12 mm diameter, 600 mm long) separately, and the mixture is ignited by a spark when the static pressure in hydrogen and air manifolds reached steady state. The initiator and the combustor were separated by a thin plastic membrane, which was destroyed during each test, to minimize the interaction between combustor and initiator before ignition.

The instantaneous pressure and ionization signals in the detonation channel, time-averaged static pressures in the manifolds are applied to evaluate the transient characteristics of rotating detonation wave and the operation mode in the combustor. The instrumentation is shown in Fig. 2, the PCB 113B24 piezoelectric transducers are flush-mounted at the outer body to acquire the time-dependent pressures in the combustor. The resonant frequency of this kind of PCB is larger than 500 kHz and the rise time is less than 1 μs. Average static pressures in the hydrogen and fuel manifolds are measured by the diffused silicon pressure transmitters with the sensitivity of 0.5%FS.Besides, an absolute piezoresistive transducer KELLER PAA-21 PY is used to measure the average pressure in chamber before ignition. Table 1 shows the instrumentation along the axial as well as circumferential direction. NI X series multifunction DAQ with data acquisition card (USB-6366) based on NI-STC3 synchronization technology is used to capture the pressure and ionization signals. All instrumentation is sampled at an acquisition rate of 500 kHz and the operation time of RDE is set to 0.2s throughout this work.

The mass flow rates of propellants are regulated by the pressure upstream of the sonic nozzles. The ambient temperature is 25±5 °C during the tests. The uncertainty in the determination of mass flow rates is analyzed through linearized systematic error. Thus, for the air and hydrogen mass flow rates of 106.9 g/s and 4.8 g/s, the uncertainties are ±1.67 g/s and ±0.11 g/s, respectively, which in turn results in an error of ±0.045 in equivalence ratio. Note that the mass flow rate is normalized by the cross-section area of the combustor.