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Characterization of initiator dynamics in a rotating detonation combustor

A. St. George *, S. Randall, V. Anand, R. Driscoll, E. Gutmark

Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH, United States

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ABSTRACT

The performance of a tangentially-injecting initiator tube of a rotating detonation combustor (RDC) is assessed for a range of initiator conditions. Two initiator fuels are evaluated for a range of RDC channel pressures, and channel widths to determine the effect on the blast wave generated by the initiator tube. Blast wave trajectories exhibit asymmetric bias in the initiator injection (forward) direction. The energy content is estimated by fitting the blast wave trajectory to a theoretical model for blast propagation. Maximum energy deposition is achieved for a rich H_2–O_2 initiator mixture ($\phi > 2$), which provides twice the energy deposition of the highest performing C_2H_4–O_2 mixture. The highest recorded initiator energy deposition is an order of magnitude smaller than the critical value to directly initiate detonation in a stoichiometric H_2–air mixture, precluding direct initiation for this configuration. RDC initiation behavior is assessed for a near-stoichiometric H_2–air mixture using the highest-performing initiator tube setting, and verifies the absence of direct initiation. A complex, transitory period follows the subcritical initiation event and culminates in stable detonation rotation within several milliseconds.

1. Introduction

Pressure gain combustion (PGC) has the potential to boost overall cycle efficiency and reduce fuel consumption by up to 9% when integrated into existing engine cycles [1]. The implementation of a constant volume combustion process allows for pressure gain, across the combustor, which can be used to augment cycle power output or reduce engine size. Detonation is a supersonic mode of pressure gain combustion consisting of a shock wave coupled to a reaction zone. Detonative PGC may boost cycle efficiency by up to 15% [2]. As a result, there has been a widespread experimental and computational effort to study the integration of detonating PGC into existing systems and harness this potential performance benefit.

The rotating detonation combustor (RDC) has emerged as the leading PGC candidate for near-term adoption into existing systems due to its high specific power output, thrust-to-weight ratio, and volumetric efficiency [3]. An RDC is generally comprised of an annular channel, supporting a detonation wave, which continuously rotates tangentially through the channel at supersonic velocities. The channel is continuously fed with fresh reactants, which are consumed with each successive pass of the rotating detonation wave, and products are ejected axially downstream [4]. The RDC concept is particularly advantageous over other PGC concepts in that it is mechanically simple, extremely compact in size, and exhibits reduced exhaust unsteadiness [5]. Despite these advantages, significant technical challenges impede widespread adoption [3,6], including heat loading, stability, reactant mixing, and detonation initiation.

Direct initiation of a detonation in fuel–air mixtures requires an immense amount of energy deposition (on the order of 100 kJ) [7]. Tangentially-injecting "pre-detonator" initiator tubes are commonly used for initiation in RDCs [8–12]. A detonation is established in the initiator tube using a highly detonable fuel–oxygen mixture, and propagates into the RDC annulus. For successful transmission of the detonation wave into the annulus, the detonation must simultaneously adapt to diffraction into a larger volume and changing mixture composition [14]. Considering the diffraction process, critical initiator tube diameters for successful transmission into an unconfined space are on the order of 10 mm for fuel–oxygen mixtures and 250–1000 mm for fuel–air mixtures [15]. For diffraction into a confined volume, such as a thin channel, reflection of the emerging detonation with the confining walls is the main mechanism of initiation [16]. Considering detonation behavior at an abrupt change in mixture composition, the initial fuel–oxygen detonation transmits a strong blast wave (i.e. leading shock followed by an expansion) into the target mixture as it reaches the interface [17]. For a sufficiently strong blast wave and high target mixture reactivity, an exothermic reaction couples with the leading shock and stabilizes to a detonation.

* Corresponding author.
E-mail address: Andrew.StGeorge@gmail.com (A. St. George).

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For many practical fuel–air mixtures, energy deposition from initiator tubes may not attain the critical value for direct initiation (i.e. subcritical energy). A delay is observed between ignition process and the onset of rotation within the RDC for hydrogen–air [10,11], hydrogen–vitiated air [12], and methane–oxygen [13] mixtures. Frolov et al. [10] report that the duration of the starting transient depends on combustor geometry, the initiating detonation, and the reactivity of the mixture. Miller et al. [18] developed a linear, "unwrapped" RDC apparatus to visualize the initiation process for H_2–air mixtures with a gaseous H_2–O_2 initiator tube. The leading shock decouples significantly from the combustion front, indicating subcritical initiation. The resulting deflagration combustion front must undergo a deflagration-to-detonation transition (DDT) process to reestablish the detonation.

Detonation initiation by a strong blast wave requires the blast strength (i.e. leading shock Mach number) to remain above a threshold value for a minimum duration of time [19]. Heat release behind the shock is not immediate due to the finite induction time of the reactants. In a successful initiation scenario, the decay of the initiating blast wave is halted by the rapid onset of heat release, and the reaction front couples with the leading shock. If the blast energy is below the critical value, the heat release is not sufficiently rapid and the reaction front decouples from the leading shock. The strong blast wave then decays monotonically to a sound wave ($M_s \to 1$) as the leading shock progressively separates from the reaction front.

In the absence of heat release, as in the case of a blast wave propagating into an inert mixture, the blast strength at a given radius is a function of the total energy contained within the blast wave [20]. Theoretical similarity solutions for blast wave propagation assume that the density, velocity, and pressure profiles behind the leading shock are of the same shape as the blast propagates outward. When scaled appropriately by a similarity variable, these profiles can be normalized and collapsed, yielding an approximate solution for the blast propagation. The historical approximate solution developed by Taylor is valid for very strong blast waves ($M_s \gg 1$), but breaks down at intermediate blast wave strengths ($M_s < 3$). The quasi-similarity approach of Oshima [21] improves upon this approach, extending the accuracy of the solution to weak blast waves at larger shock wave radii ($M_s \sim 1$). The total blast energy can be estimated by collapsing the experimentally observed trajectory onto the theoretical curve [22].

A series of experiments are conducted to characterize the strength and directivity of the initiator blast wave as it propagates into the RDC channel. To properly isolate the blast strength, the blast wave must propagate in an inert medium, and the RDC channel is supplied only with air. Two initiator mixture types, H_2–O_2 and C_2H_4–O_2, are explored for a range of equivalence ratios from near-stoichiometric to rich. The blast wave trajectory and strength is collapsed to a theoretical model to estimate the blast energy deposition from the initiator tube into the RDC annulus. The optimal mixture equivalence ratio is selected for each fuel, and the RDC channel width and pressure are varied to assess the effects on initiator performance. Estimates of energy deposition are used to evaluate the feasibility of achieving direct initiation with tangentially-injecting initiators for typical RDC fuel–air mixtures. The study concludes with experimental characterization of RDC initiation behavior for a stoichiometric H_2–air mixture for optimized initiator tube settings.

2. Experimental approach

The present study is conducted in the University of Cincinnati Detonation Engine Test Facility, part of the UC Gas Dynamics and Propulsion Laboratory. The air-breathing RDC used in this study is configured for radially-inward air injection and axial fuel injection. The modular design can accommodate adjustments to the channel width and exit area with the installation of various center body hardware and converging nozzle spacer components (Table 1). Instrumentation ports are located on the outer wall of the combustion annulus as described in the schematic (Fig. 1). For additional information, a more thorough description of this facility and baseline components, instrumentation, and capabilities is provided in [23].

The initiator tube used in this study enters the RDC tangentially at a height of approximately 21.5 mm from the fuel injection plate, located at the base of the combustor. Approximately 50 mm prior to entering the RDC channel, the initiator tube inner diameter contracts from a smooth section (d_i = 4.8 mm) down to a threaded section (d_i = 3.2 mm). Many of the RDC components were originally developed by the Air Force Research Laboratory, and are identical to the design employed by Shank et al. [24]. The present study preserves the original initiator tube geometry in the entry region, including the reduced inner diameter and threaded section (meant to approximate a Shchelkin spiral [32]).

Fuel and oxidizer for the initiator are supplied through a pair of Parker solenoid valves and impinge in a mixing junction, as seen in Fig. 2. Flow rates for the initiator fuel and oxidizer supply are calculated from supply pressures upstream of the solenoid valves using flow coefficients determined from choked flow valve calibration. A nitrogen purge valve is located upstream of the mixing junction on the fuel supply line to expunge any residual gases after the conclusion of each test to improve repeatability. Ignition within the initiator tube is provided by an automotive spark plug, powered by an aftermarket ignition system. A pair of ionization probes is installed within the tube to verify the existence of combustion, measure the detonation wave speed, and estimate the arrival time of the initiating blast in the RDC channel.

The test procedure begins by establishing a constant, steady air flow rate through the RDC channel. Gaseous oxygen and gaseous fuel are injected into the initiator tube for 20 ms to completely fill the tube with reactants. At the completion of the fill phase, the solenoid valves are shut, terminating the flow of fuel and oxygen. Simultaneously, the spark ignition is triggered, and combustion begins within the initiator tube. A detonation propagates through the tube and is recorded with the ionization probes before entering the RDC channel. The initiator blast propagates through the RDC and attenuates, and the test concludes. Approximately 1 s after the conclusion of the test, nitrogen is administered through the purge supply valve for 0.5 s, clearing out the exhaust gases from the initiator tube.

To properly capture the blast wave trajectory and peak pressure, an array of twelve PCB pressure transducers (model 113B24) are flush mounted within the outer wall of the RDC channel. The baseline RDC instrumentation layouts employed in this study consist of five azimuthal stations in four axial rows, clustered around the initiator tube entry region. The axial spacing between instrumentation rows is approximately 25 mm, while the azimuthal spacing is 30° (Fig. 3). The station closest to the initiator entry plane is designated

Table 1
Design parameters for the RDC and initiator tube.

RDC			Initiator tube		
Channel length	140	mm	Length	210	mm
Outer diameter	154	mm	Outer diameter	6.4	mm
Inner diameter	146, 142, 139	mm	Inner diameter	4.8	mm
Channel width	3.8, 5.7, 7.6	mm	Entrance diameter	3.2	mm
Air injection area	4.90	cm^2	Volume	3.7	cm^3
Channel area	35.0	cm^2			
Exit area	8.48, 11.8, 35.0	cm^2			