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Characterization of instabilities in a Rotating Detonation Combustor

Vijay Anand[*], *Andrew St. George*, *Robert Driscoll*, *Ephraim Gutmark*

Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, OH 45221, USA

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ABSTRACT

Rotating Detonation Combustor (RDC) operation is investigated under different air and fuel flow rates, and varied geometries to reveal four fundamentally different instabilities. Select test points are chosen to study these instabilities using qualitative and quantitative tools. First, for RDC operation at lean limits, or with subsonic air injection, or with large fuel injection orifices, the detonation wave inside the combustor undergoes aperiodic chaotic propagation around the combustor annulus characterized by incoherent pressure-time traces. The high incoherence in recorded pressure, along with the considerable variation in subsequent pressure peaks suggests numerous failure and re-initiation of the detonation wave. Second, almost all operating points at the variety of conditions tested exhibit some degree of low frequency sinusoidal oscillations characterized by periodic waxing and waning of subsequent detonation peak pressures. It occurs between 200 Hz and 500 Hz for the operating maps studied. Third, the phenomenon of mode switching in the RDC is also defined as instability since the sudden change in the number of detonation waves existing in the combustor is temporally unpredictable, and often unpredictable for a given geometry. It is found that RDC operation is more stable when there are multiple detonation waves inside the chamber. With a back-pressurizing convergent nozzle, at certain operating points, the RDC exhibits axisymmetric pulsed operation like the Pulsed Detonation Combustor (PDC). There is significant evidence to suggest that these longitudinal pulsed detonations (LPD) are manifested due to shock-reflection from the RDC exit followed by a subsequent shock-initiation of the fresh reactants. The frequency of this instability is around 3.8 kHz for the test case investigated.

Introduction

The use of detonation as the primary combustion mechanism in combustors and stand-alone engines is theoretically promulgated to enable higher combustion efficiency and work output when compared to traditional Brayton-cycle combustors [1]. Detonation is a supersonic combustion phenomenon characterized by the coupling of a shock wave with the reaction front behind it. The property of a detonation wave to produce pressure rise across the combustion front is the main motivation behind the research on combustors utilizing detonation instead of deflagration. Detonation combustors are further broadly classified into Pulsed Detonation

* *Corresponding author*. Tel.: +1 (513)556 3360.
E-mail address: ganeshvn@mail.uc.edu (V. Anand).

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Nomenclature

f	frequency, Hz
t	time, s
Ws	wave speed, m/s
Φ	equivalence ratio
ṁ	air flow rate, kg/s

Combustors (PDC) and Rotating Detonation Combustors (RDC). The operating frequency of the PDCs can extend up to 100 Hz [2], and is often limited by the cyclic ignition and valving requirements, since reactants filling, ignition and the subsequent purging are to be repeated every cycle. This produces very high mechanical complexity, which when added to the large dimensions of a PDC tube (due to the length required to enable DDT) [3] does not bode well for effortless integration with a gas-turbine engine. An RDC on the other hand, is characterized by its relatively smaller size with a much higher power density and the quasi-steady exit flow which is in contrast with the highly pulsating pressure profile attained at the PDC exit [4]. The RDC also necessitates continuous fuel and oxidizer injection that are combusted by an azimuthally propagating rotating detonation wave with the operating frequency at least an order of magnitude higher than that of the PDC. These attributes of the RDC have re-oriented research efforts from PDC to RDC. Over the last half-century, considerable research has been performed on various facets of the RDC. Different combustor designs have been tested [5]. The effect of combustor channel width has been investigated [5,6]. Subsonic air injection on the RDC performance has also been investigated [7,8]. The effect of fuel injection orifice area [8,9] and back-pressure [8,9] has also been investigated in detail. Hydrogen-air [5–9], acetylene-oxygen [5], hydrogen-ethylene-air blends [10], and heterogeneous mixtures like hydrogen-kerosene-air blends [11], liquid kerosene-oxygen [5,12] and hydrogen-coal-air [13] have also been tested. Several numerical studies [14–16] have studied the effects of the detonation wave on the injector orifices and determined that the detonation wave forces the injection to be locally unchoked. Different RDC operating modes, like single wave and dual wave propagation, have also been discussed both experimentally [5,8,17–19] and numerically [20–22]. However, the issue of various combustion instabilities in an RDC has not yet taken center stage.

At certain conditions the pressure-time trace breaks down into complete incoherence [23–26], and may indicate sporadic failure and subsequent re-ignition of the detonation wave [10] inside the combustor annulus. Periodic “bursting”, where the detonation is initiated and extinguished alternatively, probably by a low speed deflagration flame or flame-holding inside the combustor, has also been recorded by prior studies [10,11]. Low frequency oscillations characterized by cyclic waxing and waning of subsequent detonation waves is observed in prior studies [23,27,28]. Previous studies have observed diverse propagation pattern for the rotating detonation wave. Single wave mode and multiple wave mode [5,6,8,17–19], contra-rotating waves mode [29,30] and colliding waves mode [29] are the operating modes that have been discovered to date in an RDC. While the modes themselves may be relatively stable after onset, their manifestation inside the RDC annulus is highly spontaneous and unpredictable [17–19]. This “mode switching” behavior of an RDC is yet to be understood. Additionally, at certain conditions, the RDC exhibits pulsed detonations instead of the preferred continuously rotating detonation wave inside the annulus [5–7,9,10,29].

While the above-mentioned instabilities are unique in their manifestation and behavior from each other, they have been amalgamated under the broad canopy of “instabilities”, hitherto. Thus, the primary aim of the current study is to qualitatively and quantitatively segregate all the different types of instabilities in an RDC. Results from RDC hot-fire tests using hydrogen-air mixtures are used to characterize the instabilities seen in an RDC to date. Commentary is provided along with each instability type to relate to studies that have previously observed them.

Experimental methodology

The current paper utilizes data collected from RDC testing using H_2-air mixtures for varied flow rates, equivalence ratios, geometry and back-pressures. The RDC facility (Fig. 1) is part of the Gas Dynamics and Propulsion Laboratory at the University of Cincinnati (UC). The highly modular RDC (based on [31]) can be easily re-arranged to have different fuel injection schemes, nominally choked/completely subsonic air injection, and back-pressure by utilizing a convergent nozzle [8]. A schematic of the RDC geometry is given in Fig. 2. Increasing the thickness of the oxidizer spacer increases the pressure ratio across the air injection, and vice versa. The fuel plate can be similarly changed to attain different fuel injection schemes, while the combustor annulus width can be altered by varying the diameter of the center body. Fuel is injected axially into the combustor annulus through the fuel plate having an annular arrangement of orifices, and the air is injected radially inward as shown in Fig. 3. The dimensions of the RDC are given in Table 1. Detonation is initiated in the combustor annulus through DDT attained by introducing an overdriven detonation wave from the pre-detonator, which is

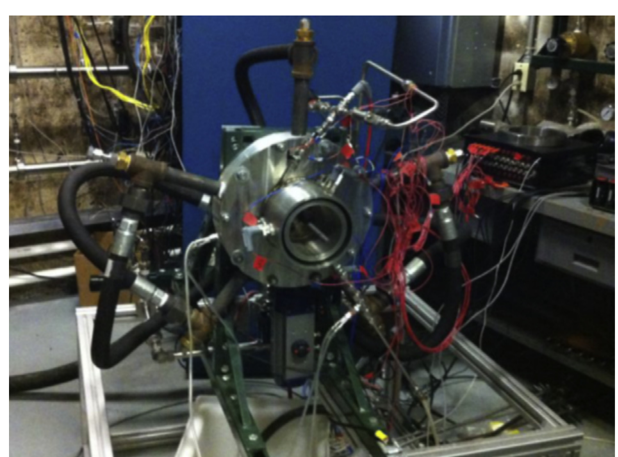

Fig. 1 – UC RDC facility.

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