Combustion and Flame 176 (2017) 12–22

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

# Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine

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ARTICLE INFO

*Article history:*
Received 30 December 2015
Revised 13 February 2016
Accepted 17 September 2016
Available online 10 November 2016

*Keywords:*
Rotating detonation engine
Chemiluminescence imaging

ABSTRACT

The detonations propagating through the annular channel of an optically accessible rotating detonation engine (RDE) operating on hydrogen–air are visualized using $OH^*$ chemiluminescence imaging. The images are useful for observing the instantaneous size and shape of the detonation structure, oblique shock wave, and possible presence of deflagration between the fuel-fill zone and expansion region containing detonation products. The detonation increases in height as the air flow rate is increased for low flow rates, experiences subtle changes for intermediate flow rates, and transitions from one to two waves for higher flow rates. The two detonation waves typically propagate in the same azimuthal direction. Counter-rotating waves resulting in detonation–detonation interactions are observed for some configurations with a reduced number of fuel injection jets. Time-dependent static pressure measurements show that acoustic interactions between the detonation channel and air plenum are important for low air flow rates and large air injection areas. The $OH^*$ chemiluminescence images, pressure, and wave speed measurements provide benchmark data that are useful for evaluating RDE models and simulations, improving fundamental understanding of the detonation structure in RDEs, and identifying critical design parameters that influence RDE operation and performance.

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## 1. Introduction

Rotating detonation engines (RDEs) have received increased attention over the past few years because of the potential for (1) high thermodynamic efficiencies associated with pressure gain combustion, (2) the continuous presence of a detonation after ignition thus avoiding the need for multiple ignition and deflagration-to-detonation transitions, and (3) compact aerospace engines. Significant progress has been made in the research and development of RDEs over the past few years [1–3]. Experimental and computational studies have evaluated the effects of fuel and oxidizer compositions [4–6], stagnation and back pressures [7–10], injection geometries [11–13], detonation channel geometries [14–17], channel curvature [18–20], and exhaust nozzles [21–23] on the flow field and on the overall operation and performance of RDEs. Experimental studies have focused on acquiring time-dependent and time-averaged static pressures [5,24], thrust [24], and broadband images [4,25]. Temperature and water vapor mole fraction measurements recently have been acquired in a converging-diverging nozzle positioned downstream of an RDE using tunable diode laser absorption spectroscopy [23]. The computational studies typically have solved the Euler equations in two- or three-dimensions with reactions modeled using detailed chemistry [26,27], an induction parameter [7,28], a single-step reaction [29], or a simple finite rate constant [9,22,24]. Thermodynamic models based on Zeldovich–von Neumann–Döring detonation theory also have been used to analyze the flow field and corresponding performance of RDEs [30–34].

The detailed flow field and structure of detonations propagating through the annular channel of RDEs have been studied in several experimental [4,25,35] and computational [6–10,22,28] investigations. A brief description of the flow field inside the annular detonation channel is provided here [8,28]. The fuel and air are injected near the bottom of an annular channel, and the detonation propagates in the azimuthal direction near the inlet. The products expand in the azimuthal direction behind the detonation and in the axial direction towards the channel exit. An oblique shock is

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http://dx.doi.org/10.1016/j.combustflame.2016.09.020
0010-2180/Published by Elsevier Inc. on behalf of The Combustion Institute.

established near the downstream region of the detonation. A slip line occurs between the products detonated during the current and previous cycle. The high-pressure region immediately behind the detonation prevents inflow of the reactants and can lead to back flow into the fuel and air plenums. Fresh reactants flow into the bottom of the annular channel behind the detonation front. Deflagration may occur between fresh reactants and products from the previous detonation cycle.

Rotating detonation engines operating on hydrogen–air [24,25,35] or oxygen [14,15] with a range of fuels have received the most attention. Modeling and simulation efforts have shown that RDEs operating on hydrocarbons are feasible, and the flow field is similar to the one observed for RDEs operating on hydrogen [6]. Two-dimensional simulations have been used to show that the detonation wave height is determined primarily by the stagnation pressure while overall performance is affected predominately by the ratio of the stagnation pressure to back pressure [8]. For high pressure ratios, the flow expands to supersonic conditions behind the detonation, isolates the detonation channel, and limits the effect of back pressure on the flow field [8]. For low pressure ratios, the flow is influenced by a series of secondary shock waves that slow it down and produce significant losses [8]. The flow field characteristics have been shown to scale with the mean diameter of the detonation channel which has minimal effect on performance [16].

Significant opportunities exist for improving the fundamental understanding and the operation and performance of RDEs. More specifically, further attention is needed to quantify the effects of partial premixing, lateral relief, channel curvature, and turbulence on the behavior of detonations in an RDE environment. The effects of partially premixed fuel and air, resulting in non-homogenous or stratified mixtures, on detonations propagating through linear channels have been explored in several studies [36–40]. The effects of lateral relief, which results in partially confined detonations in the lateral direction relative to the detonation propagation direction, have received minimal attention. Turbulence–detonation interactions and their quantifiable relative importance also represent a potentially important topic.

From an operation and performance perspective, one of the most important issues involves identifying fuel and air injection schemes that optimize mixing, minimize acoustic interactions between the air plenum and channel, and reduce pressure losses across the air inlet so that the pressure gain associated with detonations can be realized. Reducing the pressure losses across the inlet typically results in large oscillations in the air and fuel plenums upstream of the detonation channel [6]. Another opportunity involves developing injection schemes that allow RDEs to operate on liquid hydrocarbon fuels and air.

The capability to observe the detonation process in the channel is critical to supporting progress in the areas previously discussed. The research and development of RDEs can be supported by the application of existing diagnostics techniques such as OH* chemiluminescence imaging [35]. This capability is utilized in this work to contribute instantaneous images of OH* chemiluminescence emitted from detonations propagating through the annular channel of an optically accessible rotating detonation engine.

Motivated by these considerations, the primary objectives of this work include the following. First, we acquire, analyze, and interpret instantaneous OH* chemiluminescence images of the detonation propagating in the annular channel of an optically accessible RDE for a range of operating conditions. The imaging results improve understanding of the effects of air mass flow rate, equivalence ratio, air injection area, and fuel injection jets on the detonation structure. Second, we measure the time-dependent and time-averaged static pressure in the detonation channel, air plenum, and fuel plenum. The pressure measurements provide quantitative insights into detonation waves speeds, acoustic interactions between the detonation channel and air plenum, and pressure gain combustion. The results collectively provide benchmark OH* chemiluminescence images, static pressure, and wave speed data useful for evaluating models and simulations, improving fundamental understanding, and enhancing operation and performance of RDEs. The application of well-established diagnostic techniques such as OH* chemiluminescence imaging to emerging propulsion devices such as RDEs is defining a new research direction and represents one of the novel contributions of this work.

## 2. Experimental methods

### 2.1. Optically accessible rotating detonation engine

Schematics of the optically and non-optically accessible RDE are shown in Fig. 1. Air is injected from a plenum through a circumferential slot (123 mm diameter) into an annular detonation channel. The height of the air slot (0.89, 1.78, or 3.56 mm) is varied to change the air injection area (3.46, 6.92, or 13.83 cm$^2$). Fuel is injected from a separate plenum through holes evenly spaced on a circle with a circumference (134 mm) located near the inner edge of the annular detonation channel. The diameter (0.71 or 0.89 mm) and number (120 or 80) of the fuel injection holes is varied to change the fuel injection area (0.48 or 0.75 cm$^2$). The inner and outer diameters of the annular detonation channel are 138.7 mm and 153.9 mm, respectively, resulting in a channel width of 7.6 mm. The height of the annular detonation channel is 101.6 mm. A quartz (GE124) tube (2.54 cm thick) is used as the outerbody to allow optical access of the annular detonation channel.

A visible photograph of the optically accessible RDE during operation is shown in Fig. 2. The RDE is operated by injecting hydrogen and air from separate plenums. The fuel and air mass flow rates were metered upstream of the respective plenums using two sonic nozzles. The air mass flow rate is varied in the range 0.15–0.86 kg/s. The hydrogen and air mass flow rates would result in equivalence ratios ranging from 0.70 to 1.30 if the hydrogen and air were premixed prior to injection. The operating conditions and geometric configurations are reported in Table 1.

The RDE operation sequence involves establishing the air and fuel flow followed by initiating the detonation. The detonation in the annular channel is initiated using a small tube. Hydrogen and oxygen flow into the small tube (6.35 mm diameter, 63.5 mm long), and the mixture is spark ignited. The deflagration-to-detonation transition occurs in the small tube. The detonation enters and initiates the detonation in the annular channel of the RDE. The pressure in the fuel and air plenums initially increases due to the backpressure associated with the detonation in the channel. Data are reported after steady state conditions have been achieved in the plenums. For the purposes of this work, steady state conditions are defined to occur when the detonation limit-cycle has been reached and the phase-averaged static pressure in the detonation channel remains independent of time.

### 2.2. Imaging of OH* chemiluminescence

Images of OH* chemiluminescence are acquired using a high-speed camera (Photron SA-5 CMOS) and UV intensifier (LaVision IRO). The images are acquired using a 45 mm lens ($f$/1.8) and band-pass filter ($320 \pm 20$ nm). The spatial resolution of the images is approximately 0.31 mm/pixel. The images are collected with an intensifier gate time of 300 ns at a sample frequency of 20 kHz. Images are recorded for 0.5 s resulting in 10,000 images for each operating condition. The spatial and temporal resolutions are sufficient to minimize blurring effects (less than three pixels) associated with imaging the high-speed detonation wave. The