Mid-Infrared Imaging of a Non-Premixed Rotating Detonation Engine

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1 Introduction

The detonations propagating through the annular channel of an optically accessible rotating detonation engine (RDE) are visualized using mid-infrared imaging. The RDE is operated on hydrogen-air mixtures for a range of air mass flow rates and equivalence ratios. Images of the radiation intensity from water vapor are acquired using a high-speed mid-infrared camera and a band-pass filter. The mid-infrared images are useful for observing detonation products that indicate the instantaneous size and shape of the detonation structures, position and angle of the oblique and reflected shock waves, and possible presence of deflagration between the fuel-fill zone and expansion region. The detonations increase in height as the air mass 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. Minimal radiation emission is observed directly in front of the detonation waves indicating that there is not significant mixing between the reactants and burned gases from the previous cycle. The measured mid-infrared images are similar to computed static pressure distributions reported in past work with qualitative agreement between measured and computed detonation wave heights and oblique shock angles. The mid-infrared images 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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2 Experimental Methods

A schematic of the 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 (1.78 mm) and corresponding air injection area (3.46 cm^2) is held constant in this work. Fuel is injected from a separate plenum through holes evenly spaced on a circle with a diameter (134 mm) located near the inner edge of the annular detonation channel. The diameter (0.89 mm) and number (120) of fuel injection holes results in a fuel injection area of 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. A quartz (GE124) tube (2.54 cm thick) is used as the outerbody to allow optical access of the annular detonation channel.

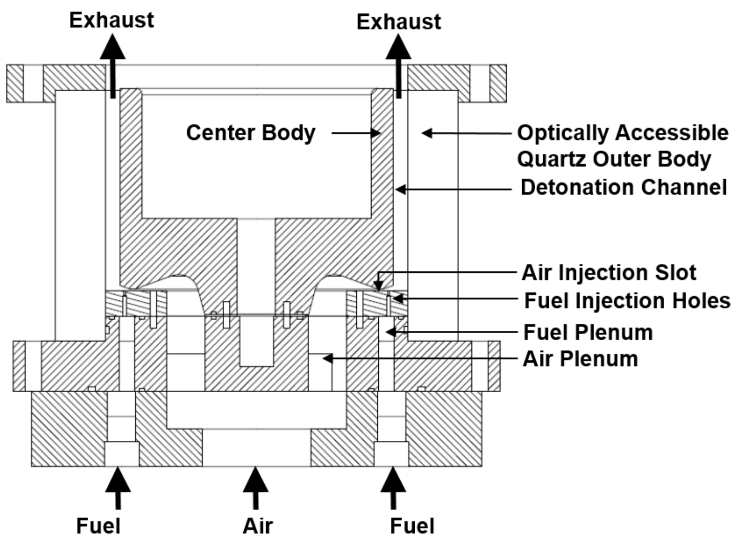

Figure 1. Schematic of the optically accessible rotating detonation engine.

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 – 1.30 if the hydrogen and air were premixed prior to injection. The operating conditions are summarized 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.

Images of the radiation intensity emitted from the detonation are acquired using a high speed mid-infrared camera with an indium antimonide (InSb) focal plane array (640 by 512 pixels). A band-pass filter (2.89 ± 0.033 μm) is positioned between the camera lens (25 mm, f/2.3) and focal plan array to measure the radiation emitted from water vapor (H_2O). The spatial resolution of the images is 0.59 mm/pixel at the center of the detonation channel. The exposure time and sampling frequency are 5 μs and 1.2 kHz, respectively.

Table 1: Operating conditions and geometric parameters for the rotating detonation engine. *Two detonation waves are propagating through the channel for these operating conditions.

Air Mass Flow Rate (kg/s)	Equiv-alence Ratio	Fuel Mass Flow Rate (g/s)	Air Injection Slot (mm)	Fuel Injection Holes (mm – number)
0.16	0.99	4.6	1.78	0.89 – 120
0.30	1.05	9.1	1.78	0.89 – 120
0.61	1.01	17.9	1.78	0.89 – 120
0.84	1.05	25.6	1.78	0.89 – 120
0.30	0.87	7.6	1.78	0.89 – 120
0.30	1.29	11.2	1.78	0.89 – 120

3 Results and Discussion

Figures 2 and 3 show instantaneous images of the H_2O radiation emissions in the optically accessible RDE for varying air mass flow rates and equivalence ratios. Figure 2 shows instantaneous images of the H_2O radiation emissions in the optically accessible RDE for four air mass flow rates (0.16, 0.30, 0.61, 0.84 kg/s). The equivalence ratio (1.0 ± 0.05), air injection slot (1.78 mm), and fuel injection scheme (120 holes with 0.89 mm diameter) are held constant for the images in Fig. 2. The instantaneous detonation structure is stochastic with significant variation in the size, shape, and intensity of the H_2O radiation emissions from cycle to cycle. The height of the detonation, as identified by regions of high H_2O radiation emission, initially increases as the air mass flow rate is increased from low (0.16 kg/s) to intermediate (0.30 kg/s) values. Negligible increase in the detonation height is apparent as the air flow rate is further increased (to 0.61 kg/s). The detonation transitions from one-wave to two-wave operation as the air flow rate is further increased (to 0.84 kg/s) resulting in a reduction in the fuel fill height and corresponding detonation height.

The three-dimensional detonation structures are characterized by a leading shock wave composed of transverse waves originating from triple shock interactions. In homogeneous fuel/air mixtures, the triple shock waves intersect and form a structured cellular pattern. In non-homogeneous fuel/air mixtures, the locally varying fuel concentrations cause locally varying velocities of the triple shock waves which intersect and form a distorted cellular pattern. [1, 2] The distorted cellular pattern appears as localized regions of low and high intensity along the detonation front in the mid-infrared images. Most of the images show negligible signal directly in front of the detonation waves. This observation indicates that there is not significant mixing between the reactants and burned gases from the previous cycle ahead of the detonation wave.

Figure 3 shows instantaneous images of the H_2O radiation emissions for three equivalence ratios (0.87, 1.05, and 1.29). The air mass flow rate (0.30 kg/s), air injection slot (0.89 mm), and fuel injection scheme (120 holes with 0.89 mm diameter) are held constant for the images in Fig. 3. The mid-infrared images for the fuel lean condition show a more wrinkled and distorted detonation wave. The images for the stoichiometric and fuel rich conditions are qualitatively similar. The measured mid-infrared images are qualitative similar to computed static pressure distributions reported in past work.[3] The measured and computed detonation wave heights and oblique shock angles are quantitatively in agreement.

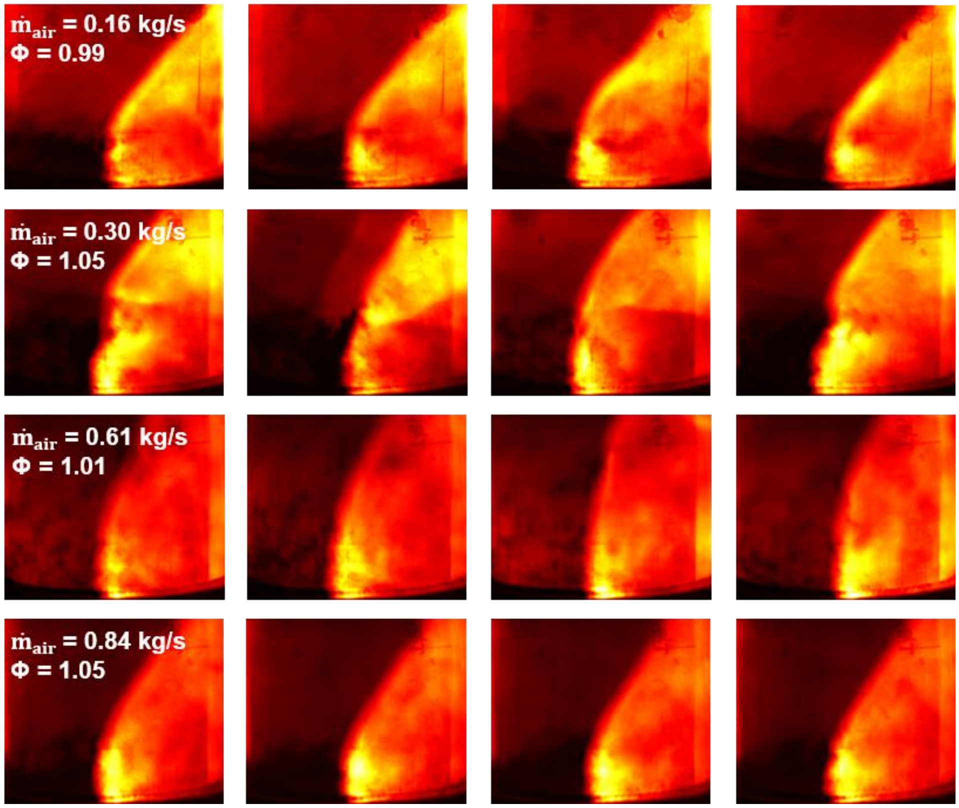

Figure 2. Instantaneous images of the H_2O mid-infrared radiation (2.89 ± 0.033 μm) in the optically accessible rotating detonation engine for four air mass flow rates.

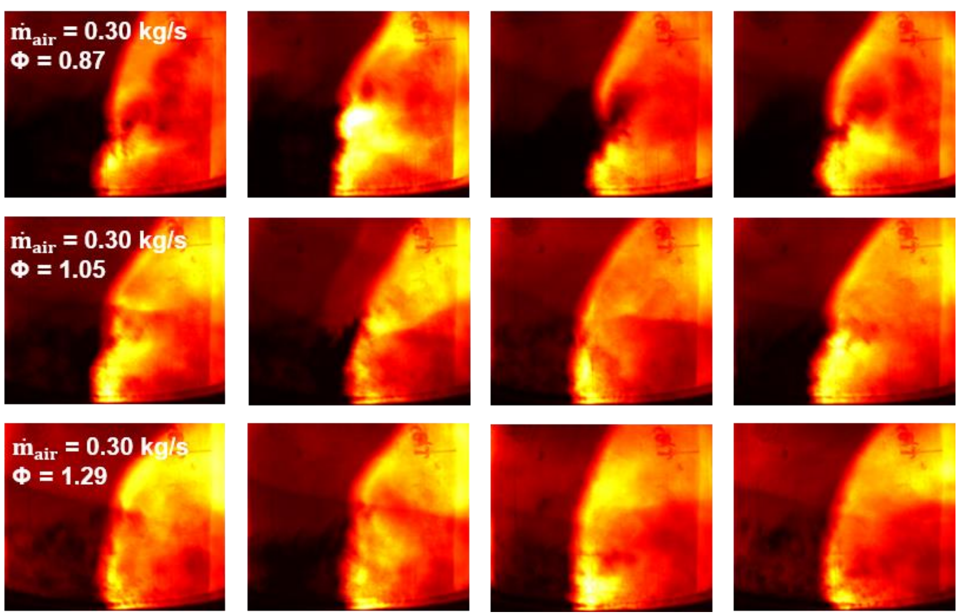

Figure 3. Instantaneous images of the H_2O mid-infrared radiation (2.89 ± 0.033 μm) in the optically accessible rotating detonation engine for three equivalence ratios.

4 Conclusions

A representative optically accessible rotating detonation engine operating on hydrogen-air is studied using high-speed mid-infrared imaging of the radiation emitted from water vapor. The primary conclusions from this work include the following.

(1) The instantaneous detonation structure is stochastic with significant variation in the size, shape, and intensity of the H_2O radiation emissions from cycle to cycle. The height of the detonation, as observed by H_2O radiation emissions, increases as the air mass flow rate is increased for relatively low flow rates. Subtle changes are observed in the detonation size and shape for intermediate air flow rates. The RDE transitions from one-wave to two-wave operation as the air flow rate is further increased to relatively high values resulting in a reduction in the fuel fill height and corresponding detonation height.

(2) Most of the mid-infrared images show negligible signal directly in front of the detonation waves indicating that there is not significant mixing between the reactants and burned gases from the previous cycle.

(3) The measured mid-infrared images are qualitative similar to computed static pressure distributions reported in past work.[3] The measured and computed detonation wave heights and oblique shock angles are quantitatively in agreement.

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