Characterization of Detonation Wave Heat Release and Rotating Detonation Engine Mode Selection

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1 Abstract

The heat release process in a typical rotating detonation engine (RDE) relies on detonation waves propagating continuously around in an annular channel as the reactants are fed in a pulsating manner from the base of the annulus. The nature of the detonation wave propagation behavior should be affected not only by the heat release distribution that establishes the local Chapmann-Jouguet (CJ) condition following each lead shock wave front, but it should also be dependent on the RDE chamber geometry that determines the stability characteristics during steady-state operation. The objectives of this paper are to provide the physical insights and plausible explanations of the experimentally observed detonation wave speeds in RDE combustors and to demonstrate their importance in describing the mode selection process. In this paper, high-quality visualization images of various detonation waves propagating inside a channel geometry similar to an unwrapped RDE combustor flowfield are provided. The corresponding schlieren and chemiluminescence images are used to establish the structure of the detonation waves propagating through the model injector flowfield. Also, the average timing of the local pressure change and heat release fluctuations associated with the detonation waves is deduced from the high-frequency-response pressure transducer data, CH*/OH* radical chemiluminescence, and time-resolved general luminescence data. The results are used to characterize the fluctuating pressure and heat release fields in the wake of the detonation wave. Lastly, the reacting flowfield is modeled with a reduced-dimension approximate analysis to quantify the expected CJ detonation wave speed and demonstrate the mode selection process. Some of the data obtained in our linear rig experiments can be compared with the approximate analysis results.

2 Experimental Set-up

Our experimental setup consists of an array of transverse reactant jets placed inside a linear open channel, 7.6-mm wide, through which a detonation wave is propagated. The setup is designed to simulate a rotating detonation engine that is unwrapped in a linear direction without consideration for the curvature effect. We have employed two different test-section set-ups, one containing a series of 15 injectors each spaced

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6.4 mm apart, and the other a longer channel with 48 injectors with the same spacing. Each injector consists of a recessed tube, 2.5mm in diameter and 28.6 mm in depth, where the reactants are impinged at the base of the tube. The oxidizer is supplied through a 1.25-mm diameter orifice from the base of the injector tube, while the fuel is injected from the side of the tube through a 0.38-mm diameter orifice 3.2mm from the injector tube base. The fuel and oxidizer mix inside the recessed tube for the remaining 25.4-mm distance, before entering the channel as a partially premixed reactant jet. Figure 1 illustrates the experimental setup with the wave propagating from left to right. Figure 2 shows a typical set of detonation images obtained from this setup.

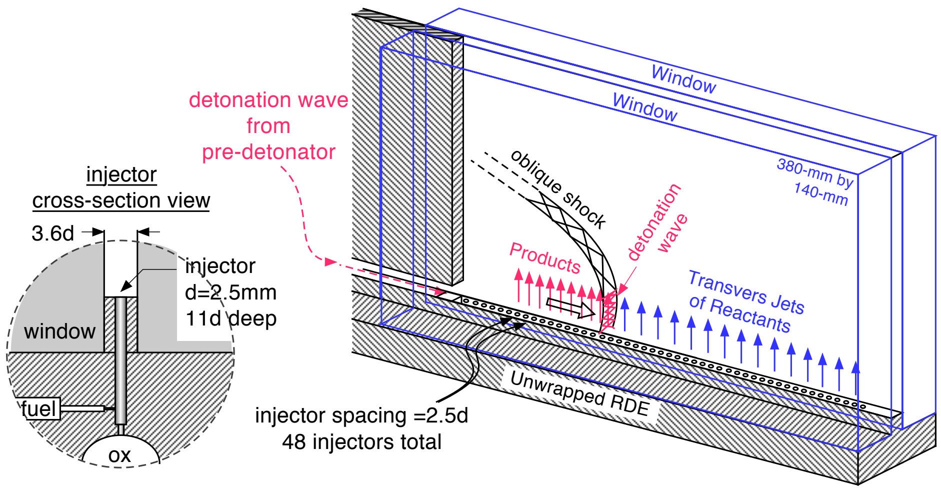

Figure 1. Unwrapped RDE combustor test setup (longer section)

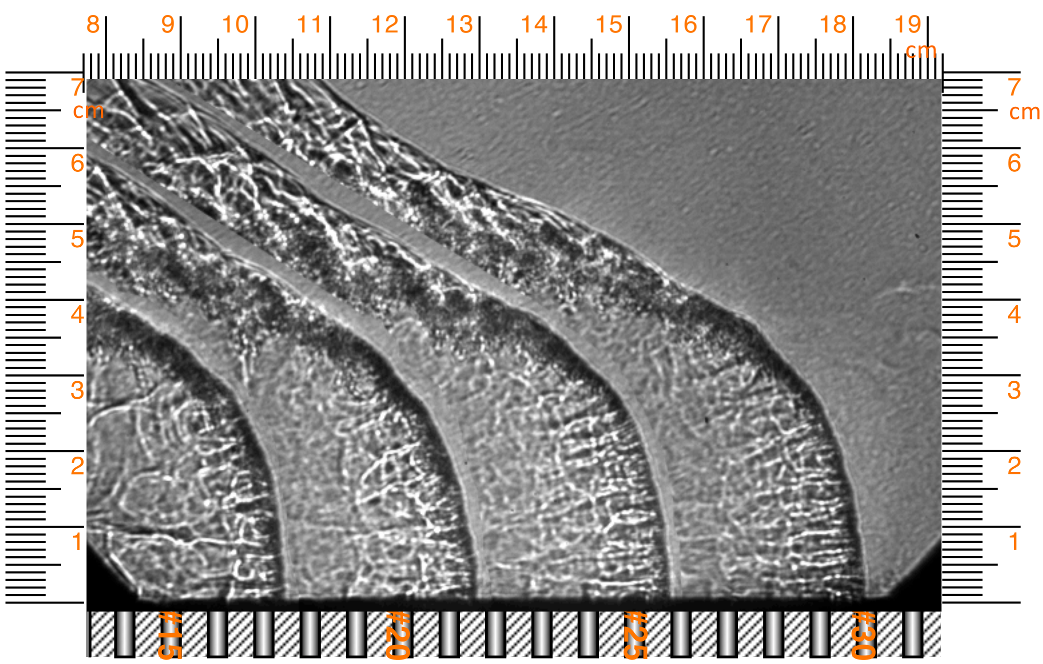

Figure 2. Sequence of a detonation wave propagating into CH_4-O_2 reactants in the unwrapped RDE setup

3 RDE Detonation Wave Speed

In one-dimensional approximation, a detonation wave can be modeled as a normal shock wave followed by a zone of exothermic reaction that sustains the shock wave speed (ZND). A typical steady-state analysis in a wave-referenced frame assumes that the incoming reactants approaching the wave initially at a supersonic speed get shocked down to a subsonic speed. Subsequently, the elevated-temperature flow reacts exothermically and causes thermal choking via Rayleigh heating. The induction time is not important in the one-dimensional analysis, as the thermal choking depends only on the total amount of heat release. The solution forces the products to reach the sonic speed in the wave-referenced frame, and this yields the same detonation speed as the CJ theory. (CJ) It is well known that the CJ detonation wave can be analytically obtained using Rankine-Hugoniot solution for various amounts of heat release for various compositions of reactants and products.

In an RDE configuration, however, the affected volume of the products is only partially confined by the channel geometry, allowing the flow expansion toward the downstream direction as well as the potential flow reversal into the injector plane. As a result, only the amount of heat release that is closely coupled to the lead shock wave front may play a role in driving the actual detonation wave speed. Figure 3 shows both a schlieren image and a luminescence image, associated with a typical detonation wave propagating in our linear channel set-up. It can be clearly observed that the zone of luminescence is stretched broadly into the product region following the detonation and the associated oblique shock wave. This indicates that some of the heat release may indeed be distributed over the expanding flow region, and not all heat release may be directly coupled to the lead shock wave front. Then, only the specific portion of the total heat release, which is close-coupled to the lead shock wave front and is locally choking the shocked flow, is expected to contribute in establishing the detonation wave speed.

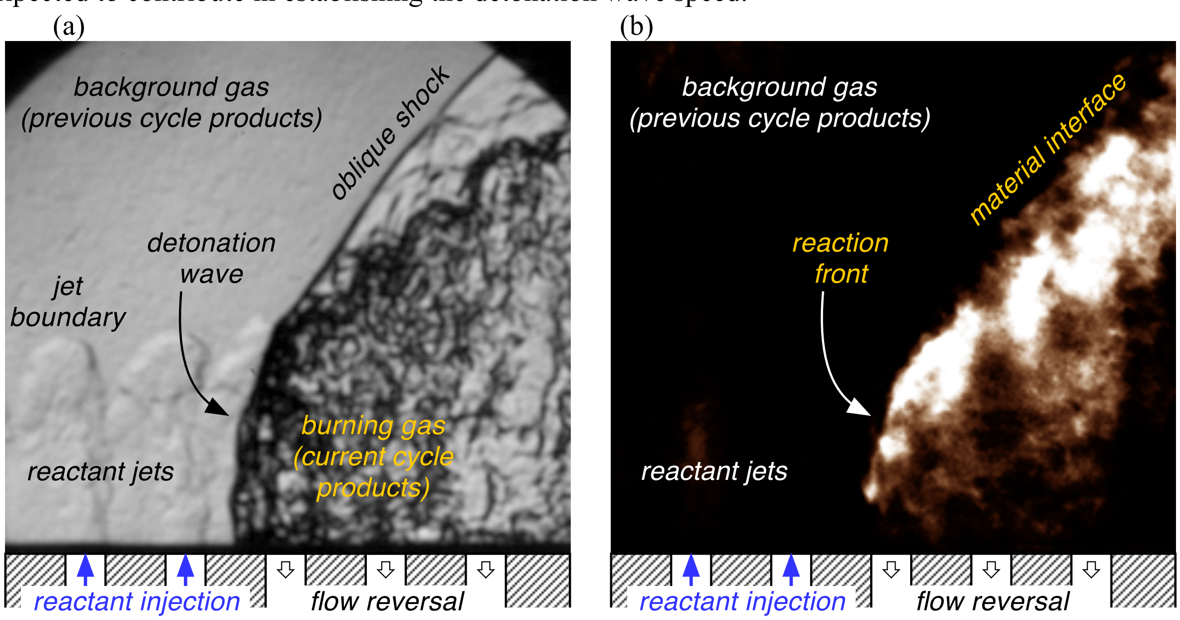

Figure 3. Flow structure depicted in a wave stationary frame of reference (i.e., flow from left to right) (a) schlieren image showing density gradients, and (b) luminescence image showing the reaction zone

Considering only that amount of heat release closely-coupled to the shock wave before the flow expansion will affect the driving of the wave speed, we need to separate the contribution of total heat release into the detonation reaction part which is closely coupled and the deflagration part post the initial expansion of the flow. A simple model to assess the variation in CJ detonation wave speed due to partial detonation reaction is illustrated in Fig. 4, and the corresponding pseudo-code for Cantera implementation is shown in Fig. 5.

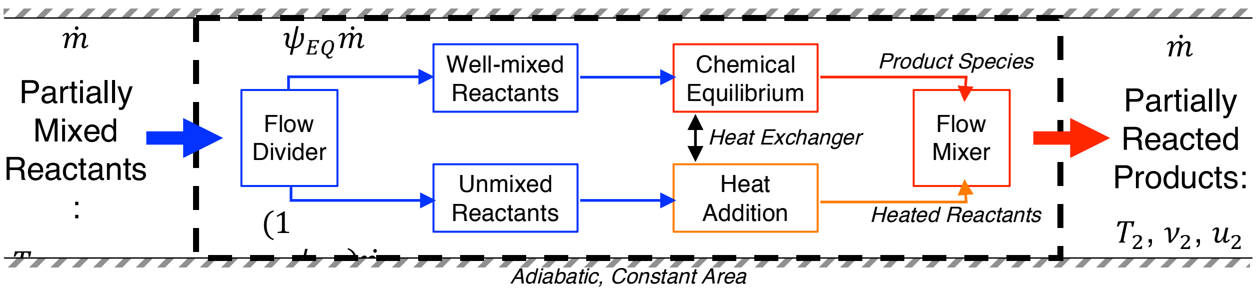

Figure 4. Partial mixture detonation model

The extent of mixing is quantified with the partial fraction parameter ψ_{EQ}, which represents the mass fraction that detonates before the flow expansion thus contributing to the driving of the detonation wave front. This rapidly reacted mass fraction is assumed to be in thermodynamic equilibrium with the yet unreacted flow at the unique final state given by T_2 and v_2, yielding a species composition $\bar{Y}_{EQ}$. The remaining fraction of unmixed reactants can be brought to the same temperature and specific volume for wave speed calculation; although the remaining fraction may be allowed to react after the flow started expanding resulting in deflagration front that does not contribute to initial thermal choking.

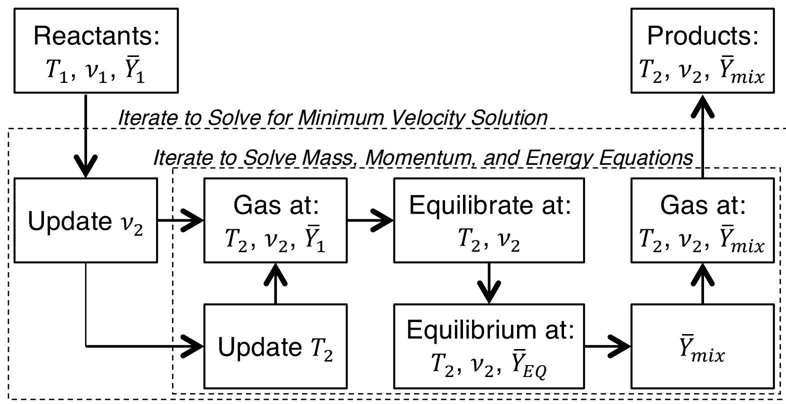

Figure 5. Pseudo-code for Cantera-based iterative partial mixture detonation model.

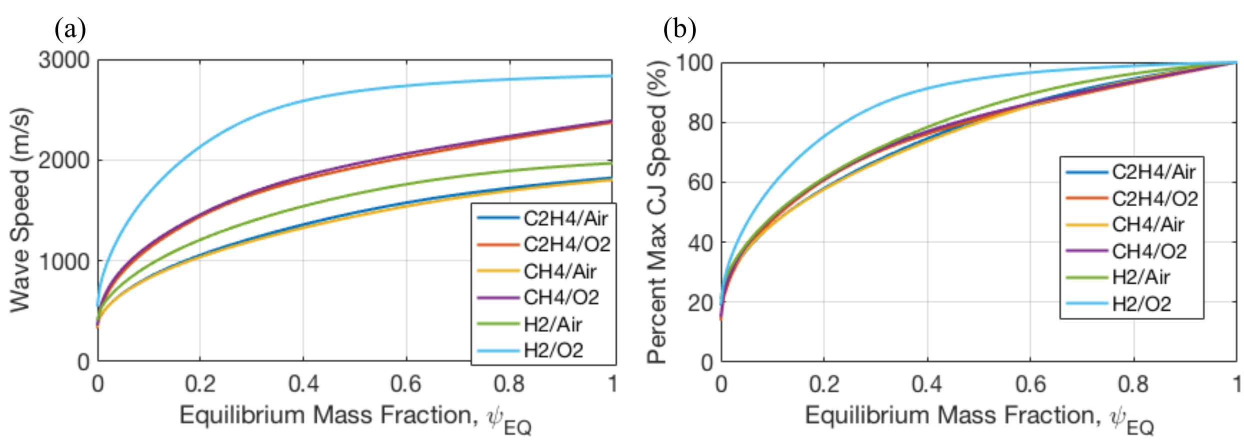

Figure 6. CJ detonation wave speed in RDE setup associated with partial fraction detonation model

Mixing-limited detonation wave speeds were calculated for a number of stoichiometric reactant mixtures and are shown in Fig. 6. Figure 6a shows the value of these CJ speeds, while Fig. 6b normalizes the CJ speed with the expected CJ speed for a well-mixed and fully reacted mixture. For all reactant mixtures the CJ speed approached the bulk sound speed of the reactants as the equilibrium mass fraction approached zero, and approached the well-mixed CJ speed for the mixture as the equilibrium mass fraction approached unity. In all cases the trend between CJ speed and equilibrium mass fraction, and by extension the amount of heat release to the flow, agrees well with the classic Rankine-Hugoniot calculation. Also, the behavior of C_2H_6 and C_3H_8 closely matched that of CH_4 and C_2H_4, although only two hydrocarbon fuels are displayed in Fig. 6 for clarity.

4 RDE Mode Selection from Rayleigh Criterion

Dynamic pressure along the detonation wave path was recorded using a set of wall-mounted PCB pressure transducers. For these tests, one of the quartz windows was replaced with a metal window that allowed flush mounting of the pressure transducers. Figure 7 shows one set of such records obtained from one of the test runs involving hydrogen-oxygen reactants. Two of the pressure transducers were mounted on the pre-detonator section (Fig. 7a), while the other four pressure transducers represent the measurements from the channel. The change in pressure amplitude in Fig. 7b suggests that the shock wave strength initially weakened entering the channel, possibly due to the decoupling of the reaction zone following the detonation wave diffraction at the connection point. Figure 7c shows that the pressure amplitude recovers further downstream, suggesting re-initiation of the detonation front.

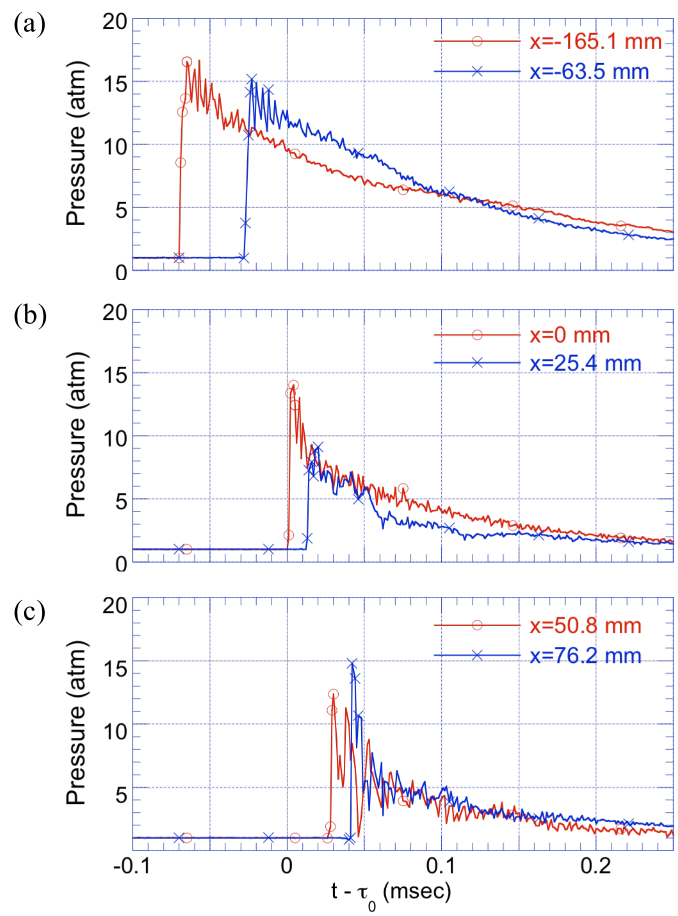

Figure 7. Typical pressure-time traces obtained with PCB pressure transducers mounted at respective locations

Assuming a certain relation between the local heat release rate and the chemiluminescence data, the measured pressure and luminescence data following the detonation wave may be used to check for the Rayleigh criterion and establish the stability characteristics inside the RDE combustor for various modes of continuous RDE operation. In particular, this approach can be used to compute the Rayleigh index from the experimentally obtained pressure and chemiluminescence data.