High-Speed Schlieren Imaging of Rotating Detonation Engine Fuel Injection During Operation

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1 Introduction

Rotating detonation engines (RDEs) offer high power output with no moving parts and a shorter combustor compared to air-breathing deflagration-based engines, making them ideal for volume-limited applications. They operate by axially injecting reactants and combusting them with an azimuthally rotating detonation wave. Diagnostics such as planar light-induced fluorescence (PLIF) [1], laser absorption spectroscopy (LAS) [2], chemiluminescence [3], and schlieren [4,5] have all been used to study various aspects of RDEs, but so far, none have been able to directly record shockwave progression in the annulus of the RDE. This study uses a novel shadowgraph setup to directly observe shockwave progression and fuel-oxidizer mixing directly downstream of the fuel injection point in a partially optically accessible RDE.

2 Methods

Hardware

The RDE in this study has an annulus with an outer diameter of 17.15 cm and inner diameter of 13.87 cm. The centerbody was 11.43 cm long, and the area ratio of the air injector to annulus was 0.2. The fuel injector plate used 120 equally spaced 0.89 mm holes in a jet-in-crossflow setup to radially inject gaseous fuel into an axial air flow directly upstream of the combustion chamber. Figure 1. shows a cross section of the RDE.

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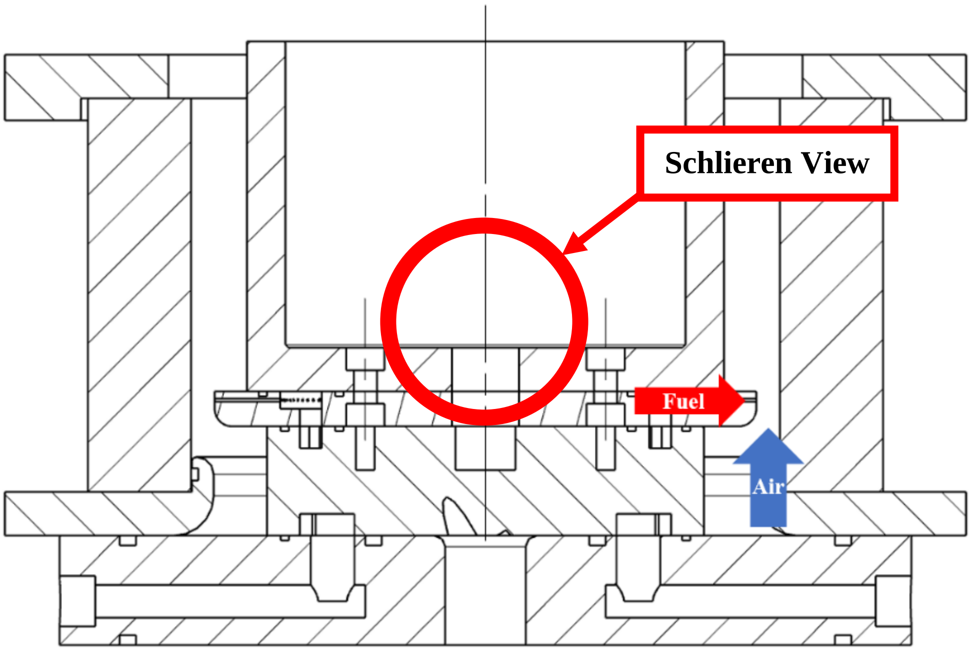

Figure 1. RDE Cross Section

The RDE operated on hydrogen-air mixtures with mass flows ranging between 0.227 kg/s to 0.907 kg/s and equivalence ratios between 0.60 and 1.20. Slots on the outerbody and centerbody held 5.08 cm by 10.16 cm sapphire windows that allowed direct optical access into the annulus.

Optics

The optics setup is shown in figure 2. A CAVILUX Smart UHS laser sends ~640 cm light through a linear polarizer (LP). The polarized light is directed by a polarized beamsplitter (PBS) through an achromatic doublet (AD, THORLABS ACT508-500-A-ML) followed by a quarter wave plate (QWP). This turns the linearly polarized light into circular polarization. It is reflected by the mirror (M) and is the opposite handed circular polarization upon reflection. If it were left-handed circular polarized on incidence, it would be right-handed circular polarized upon reflection. From there, it goes back through the quarter wave plate which turns it back to linearly polarized, but now the opposite of what it was from the laser, i.e. if it were originally vertically polarized, it is now horizontally polarized. It goes back through the achromatic doublet and passes through the polarized beamsplitter now that it is the opposite polarization as what was emitted from the laser. An iris at the doublets focal point cuts any refracted light, and the unrefracted light is recorded by the camera. The camera is a Phantom TMX that recorded at 100 kHz with 1 µs exposure. The laser was synchronized to turn on during the integration time of the camera, and it stayed on for 20 ns each integration period. Figure 3. shows how the optical setup is arranged.

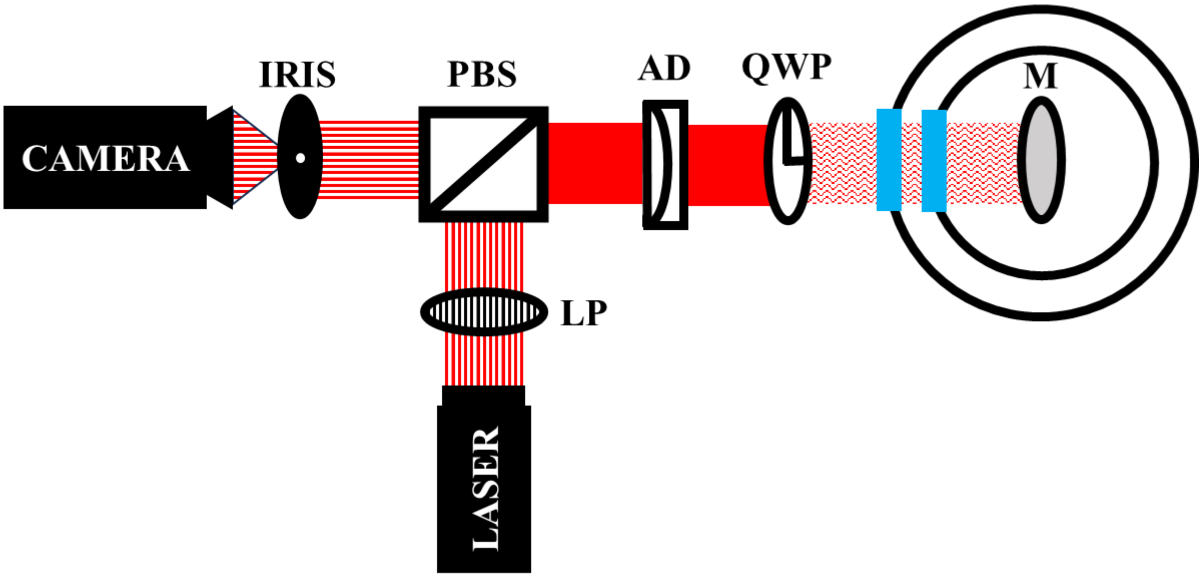

Figure 2. Optical Setup

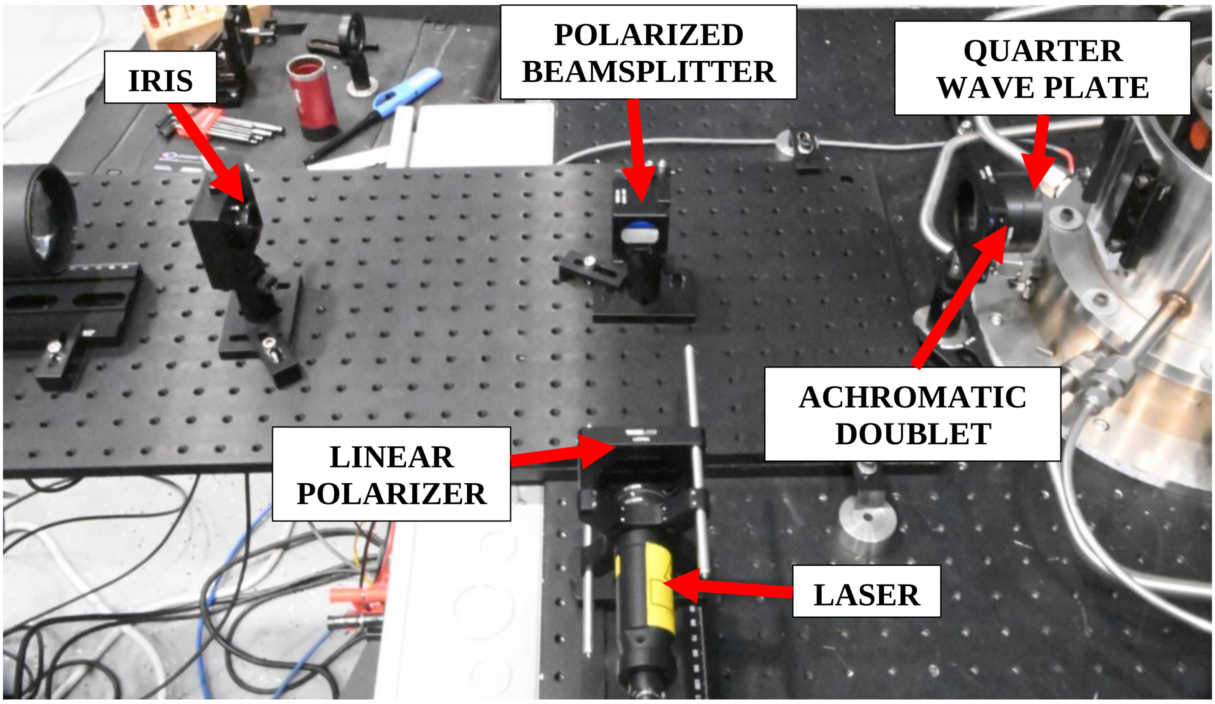

Figure 3. Photograph of Setup

3 Preliminary Results

The study started by examining the detonation initiation sequence. Air with no fuel was flowed through the RDE, and the initiator created a small detonation that propagated into the annulus. If both air and fuel were present, then the detonation would continue propagating into the annulus where it would undergo a sequence of deflagration, axial acoustics, azimuthal acoustics, and finally rotating detonations if the correct conditions were present. Figure 4. Shows the progression of the initial shockwave across the optically accessible section.

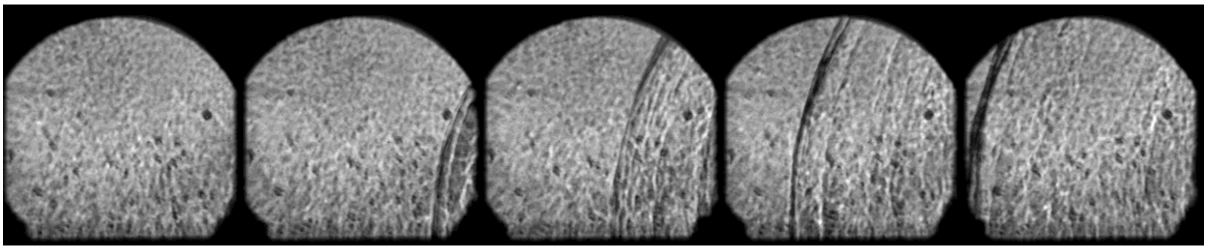

Figure 4. Shock from initiation (Δt = 20 μs)

When the RDE was fired, the turbulence of the air and fuel mixing hid the detonation wave at lower mass flows and equivalence ratios because the wave would tend to ride closer to the inner diameter, making it more difficult to spot the detonation in those conditions. Higher equivalence ratios and mass flows allowed direct observation of the propagating wave though since it rode close to the outer diameter. Figure 6. shows a detonation wave at $\varphi = 0.99$ and $\dot{m} = 0.922$ kg/s. The shockwave is located within the boxes. Frames C and D show product-reactant mixing post reaction.

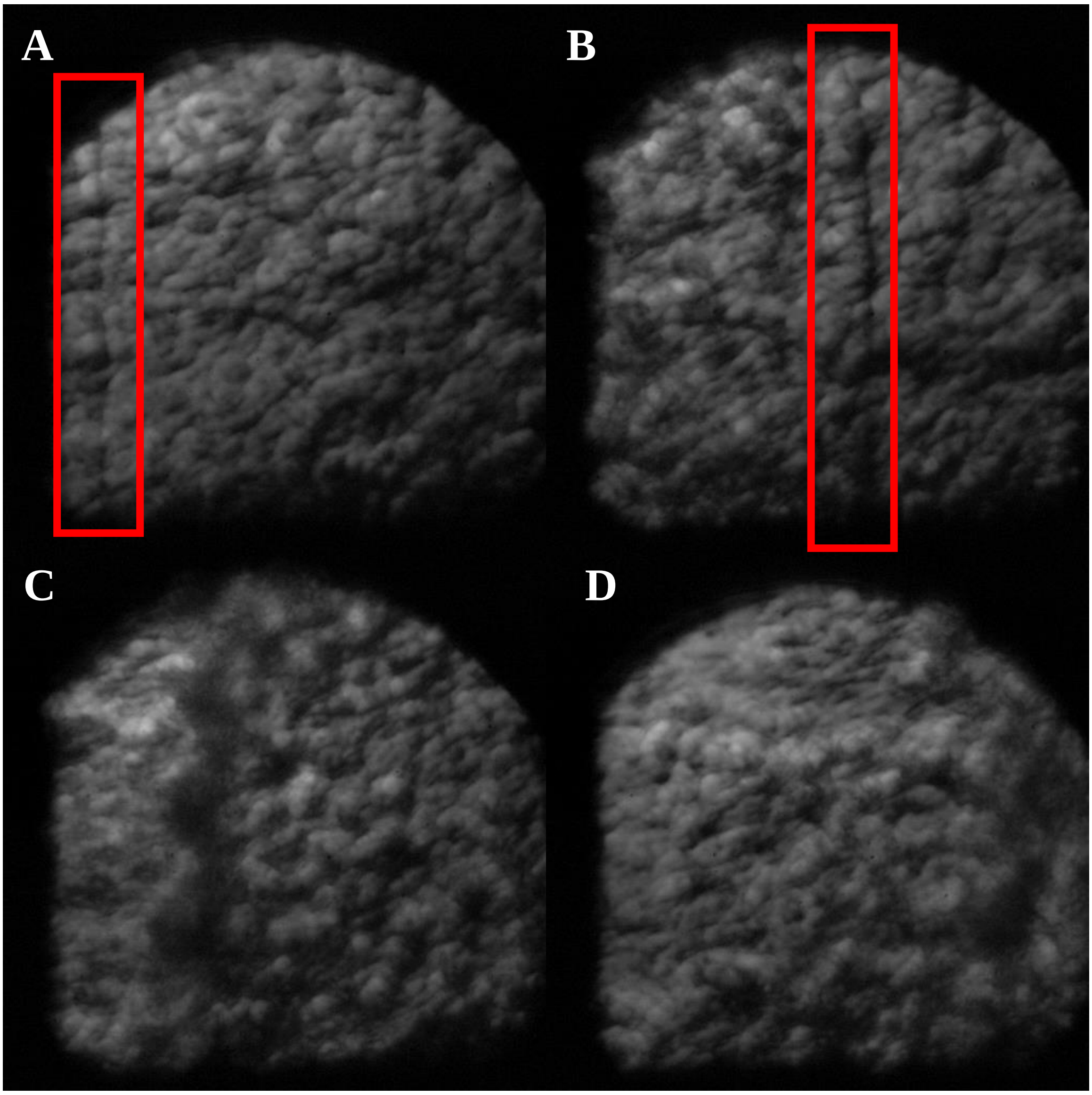

Figure 5. Detonation wave propagation from left to right (Δt = 10 μs)

In addition to the detonation waves, this method can directly observe axial acoustics as they propagate. Figure 6. shows an axial acoustic.

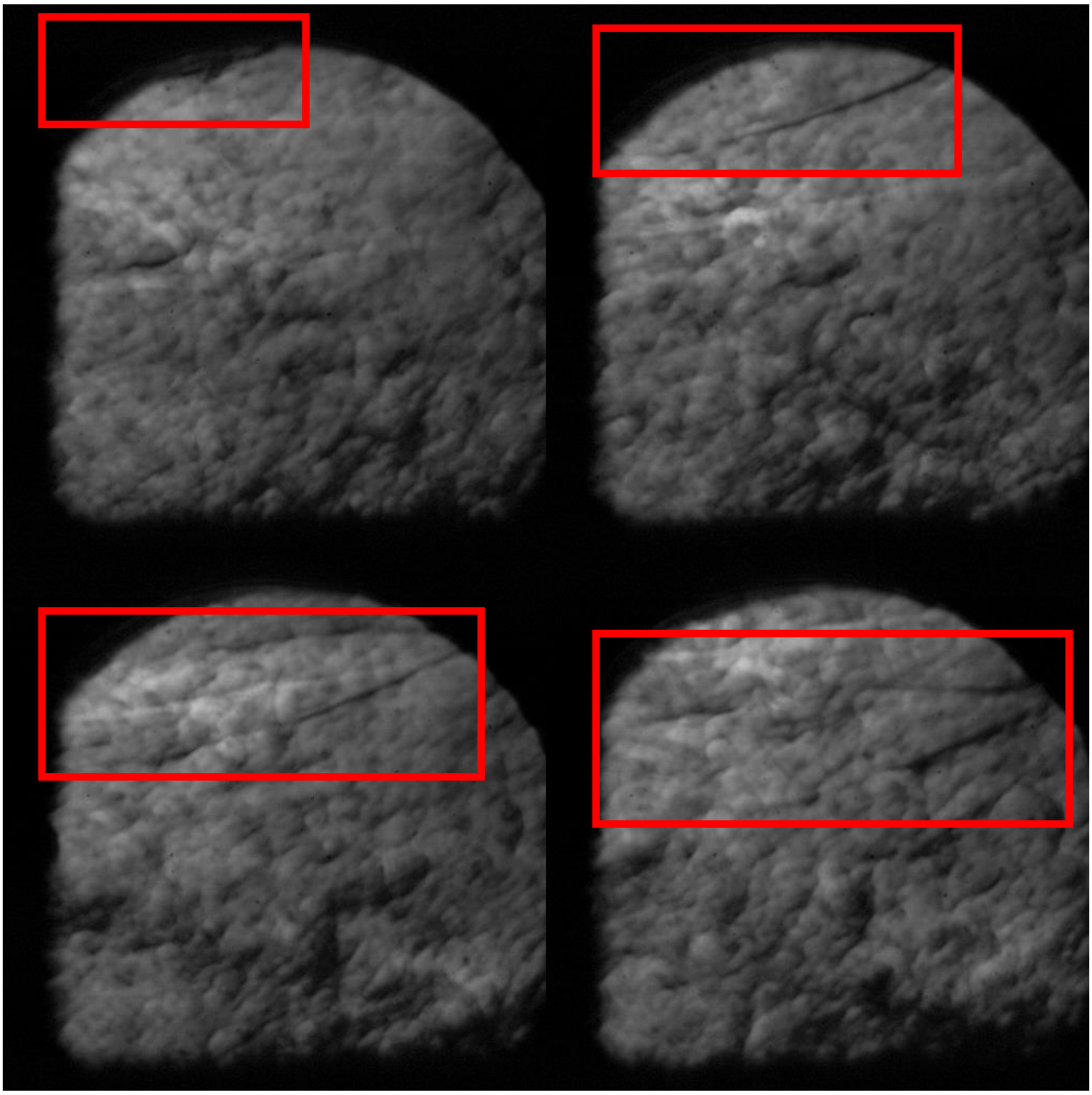

Figure 6. Axial Acoustic Propagation (Δt = 10 μs)

4 Conclusion

This study investigates mixing dynamics, refill rate, and shock propagation using a novel schlieren setup to image RDE operation immediately downstream of fuel and air injection. Preliminary findings demonstrate that both axial and azimuthal shocks are visible, and further image processing will potentially show finer details of propagation and fuel injection.

References

[1] R. B. Wang *et al.*, “500-KHz OH PLIF and OH* chemiluminescence imaging of deflagration and rotating detonation in Ch4-o2 and H2-Air Mixtures,” *Proceedings of the Combustion Institute*, vol. 40, no. 1–4, p. 105770, 2024. doi:10.1016/j.proci.2024.105770

[2] G. C. Mathews, M. Blaisdell, A. I. Lemcherfi, C. D. Slabaugh, and C. S. Goldenstein, “High-bandwidth laser-absorption measurements of temperature, pressure, CO, and H2O in the annulus of a rotating detonation rocket engine,” *AIAA Scitech 2021 Forum*, Jan. 2021. doi:10.2514/6.2021-0418

[3] M. Stocke, B. Sell, K. Cho, J. Hoke, and R. Fievisohn, “High-Repetition Rate Chemiluminescence Imaging in an Axially Injected Air Rotating Detonation Engine,” *International Workshop on Detonation for Propulsion*, Jun. 2024.

[4] R. T. Fievisohn, J. Hoke, F. Schauer, and K. Y. Cho, “Experimental study of a linear RDE section coupled to an operating RDE,” *AIAA Scitech 2019 Forum*, Jan. 2019. doi:10.2514/6.2019-1251

[5] A. Gupta, D. Langner, R. Miller, S. Sawaya, and A. K. Agrawal, “Imaging exhaust flow of radial RDE using Rainbow Schlieren deflectometry,” *AIAA SCITECH 2023 Forum*, Jan. 2023. doi:10.2514/6.2023-2391

