

Impact of Turbulence on Wave Propagation in a $C_2H_4-O_2$ Rotating Detonation Engine

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1 Introduction

Over the last 30 years, there has been a renewed interest in the study of detonative propulsion methods. Recent years have seen a surge in interest, specifically for the rotating detonation engine (RDE), which operates by being continuously fed with a detonable fuel and oxidizer mixture, driving one or more detonations in a circular path defined by the engine's annular combustor geometry. Detonations in these geometries are described as either being co-rotating (all waves travelling at similar speeds and in the same direction) or counter-rotating/clapping (even number of waves travelling in opposite directions around the engine with periodic collision events between opposing fronts). Deviations from this classical, annular RDE configuration have been studied, including non-straight annular combustors [1], and hollow RDEs in which there is no inner wall to confine the detonations [2, 3]. The modern study of RDEs was pioneered by Bykovskii and Zhdan as early as 1980 [4–6] by the use of single-fill RDE combustors. Today the study of RDEs is focused on continuously rotating detonations with continuous injection, allowing for a deeper study into wavefront dynamics and instabilities. See, e.g. [7–10].

Despite the recent advancements, there still remains a need to apply knowledge about detonation structure and dynamics gained from fundamental studies (see, e.g. [11]) to the development of predictive RDE models. One topic of vital interest to RDE operation, and more generally to detonation-based propulsion devices, is the effect of turbulence on the propagation of detonation waves. While it is generally accepted that the turbulence generated by, and internal to, the detonation structure itself is necessary to the propagation of detonations in mixtures of interest for RDEs [12, 13], the effect of externally imposed turbulent motion on the propagation of a detonation wave is still mostly unknown. In recent experiments, Marjaba [14] used a classical detonation tube outfitted with a series of solenoid valves. The injection of the reactants was done rapidly (on the order of 100s of ms) to create an initially turbulent, reactive medium instead of the quiescent medium traditionally studied in fundamental detonation

studies. A detonation wave was directly initiated via a high energy spark discharge to study the propagation of an already established detonation through a turbulent medium. Marjaba found that at low initial reactant pressures (below 10 kPa) where the cell size is on the scale of the tube diameter, turbulence helped increase the detonation wave velocity above the baseline propagation velocity, closer to the theoretical Chapman-Jouguet velocity, thus helping to counteract wall friction losses. At higher initial pressures (above 20 kPa) where the cell size is significantly smaller than the tube diameter, the presence of turbulence caused the detonation wave speed to drop further from the baseline velocity in a quiescent medium, acting as a further loss to the detonation wave. The implication of the work is that when the largest turbulent scale is on the order of the cell size, detonation propagation is enhanced, whereas when the largest turbulent scale is much larger than the cell size, detonation propagation is hindered.

Most studies of turbulence in detonative propulsion were done in the context of deflagration-to-detonation transition (DDT) for pulse detonation engines (PDE). In the context of RDEs, Chambers et al. [15] studied the effect of injection turbulence on detonation initiation in a linear analog RDE. This study found that injection turbulence favours a deflagration to detonation transition (DDT), also enabling a higher wave velocity. Similar to our work, the geometry of the linear analog was modified using obstacles to promote a higher level of turbulence in the unreacted medium.

In this work, we study a straight annulus, un-nozzled, RDE fed by gaseous ethylene (injected radially from the inner chamber wall) and oxygen (fed axially). The impingement angle of the fuel injector holes with respect to the oxygen injector holes is modified to control the level of turbulence generated in the combustion chamber. The level of externally imposed turbulence is evaluated through numerical modelling. The dynamics of the propagating detonation(s) are observed and compared to determine the effect of externally imposed turbulence on the dynamics of detonation waves inside an RDE.

2 Experimental Setup and Engine Geometry

The test facility for this experiment consists of an unregulated blowdown flow system shown in Fig. 1. The injection system has an inner line diameter of 19.05 mm (nominal 3/4" diameter Swagelok tubing) and a reservoir volume of 27 L for each of the fuel and reactants, each rated for maximum initial pressures of 6.9 MPa (1000 psi). The mass flow rate is controlled independently for fuel and oxidizer by use of choked, metering orifices. This system is able to deliver total mass flow rates of up to 800 g/s at a stoichiometric ratio. In the current experiments, C₂H₄ and O₂ with initial reactant tank pressure of up to 5.5 MPa (800 psi) are used.

The engine is bolted to an 8-inch flange which is itself attached to an 8-inch exhaust assembly that channels the engine's exhaust outside the facility. Attached to the exhaust conduit is a viewing section allowing for direct optical access to the RDE annulus. The wave speeds, number, and dynamics are recorded by use of a Photron NOVA S12 high-speed camera running at 288 000 fps. The engine is initiated using a custom-built automotive spark initiator capable of delivering up to \approx 100 mJ of energy.

The tested engine geometry is a straight annulus, nozzle-free RDE with a combustion chamber outer diameter of 69.9 mm (2.75 in) and an annulus thickness of 5.5 mm. Oxygen enters the engine oxidizer plenum through radial ports around the circumference of the RDE, while fuel is injected axially through the back of the engine and into a cavity inside the plug that constitutes the inner wall of the combustor. This inner cavity constitutes the fuel plenum. The reactants are injected into the combustion annulus in a jet-in-crossflow configuration. Oxidizer is fed axially through 96 holes centered with respect to the annulus height. Fuel is injected radially through 39 injector holes in the plug. All injector holes have a diameter of 1/16". In the baseline configuration, the impingement angle is $\alpha = 90^\circ$.

Two modified injector designs are considered, designed for the same flow rates as the 90° injector. One injector leads to increased turbulence by increasing the impingement angle to $\alpha = 135^\circ$ (towards the

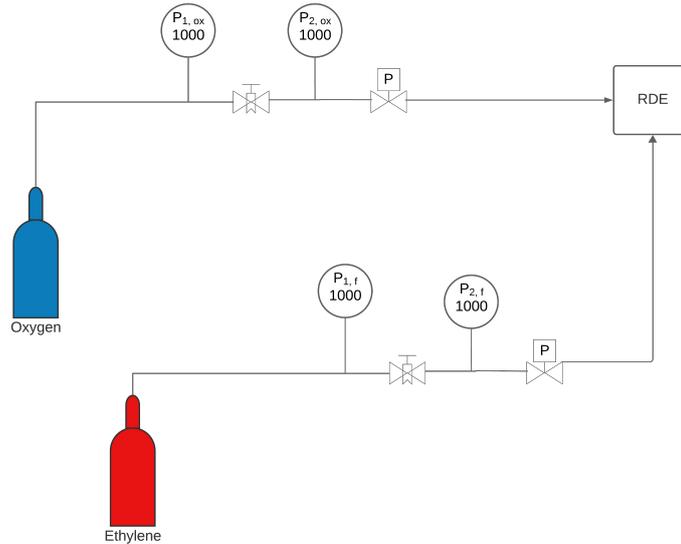


Figure 1: Simplified plumbing & instrumentation diagram (P&ID) of the RDE flow system.

oxidizer injectors, Fig. 2 left), while the other injector reduces the amount of turbulence by decreasing the impingement angle to $\alpha = 45^\circ$ (away from the oxidizer injectors, Fig. 2 center). All other injection parameters, including the injection area, are held constant.

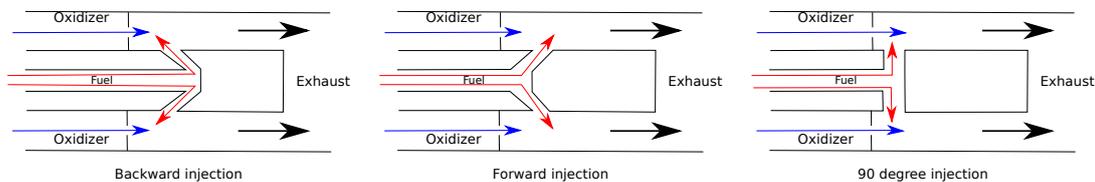
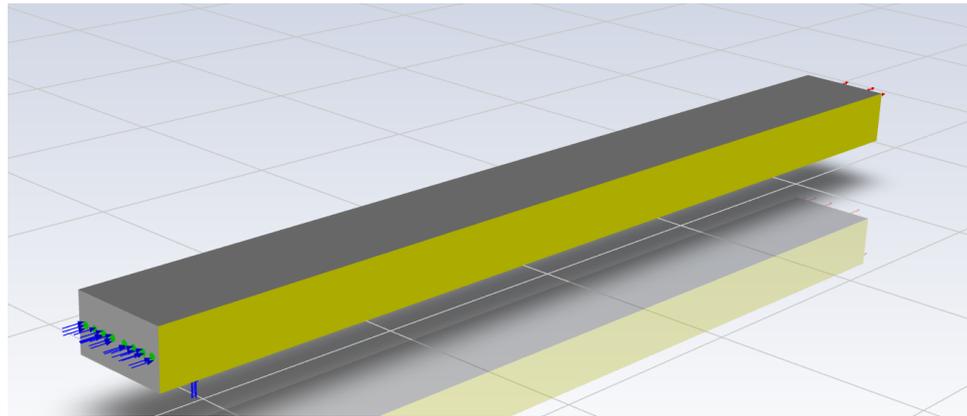


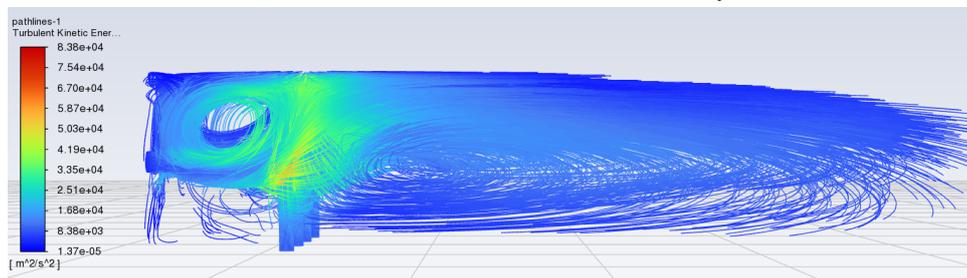
Figure 2: Different fuel injector schemes showing axial changes in orientation. Left: Backward-facing fuel injection, showing the fuel injector pointing upstream toward the oxidizer injector. Centre: Forward-facing fuel injector, showing the fuel injector pointing toward the engine’s exhaust. Right: Straight port/90° injector

3 Numerical Evaluation of Turbulence Intensity

To assess how each injector design influences the level of turbulence in the combustion chamber, non-reactive numerical simulations are performed using ANSYS Fluent to establish the non-reactive flow patterns, and the average Turbulent Kinetic Energy is used to quantify the level of turbulence generated by the injection, as well as an evaluation of turbulent mixing. The simulation model is an unwrapped and reduced version of the RDE annulus, 5.5 mm in height, 10 mm wide by 140 mm long. The resulting computation domain, shown in Fig. 3a, equates to a section of the RDE annulus containing eight oxygen injector holes and four fuel injector holes. Being a reduced model, the side walls of the domain are defined as periodic boundaries. The mesh is composed of 2.26M polyhedral cells, and simulations are run using the $\kappa - \omega$ SST model. As shown in Fig. 3b for the case of the $\alpha = 90^\circ$ impingement angle, two recirculation zones are created: one near the axial injector face, upstream of the radial injector plane, and another elongated recirculation zone, downstream of the radial injector plane and extending towards the combustion chamber exhaust. As expected, turbulence is mainly generated near the radial injector



(a) CFD domain used in the turbulence study.



(b) Pathlines coloured by turbulent kinetic energy.

Figure 3: Comparison of CFD domain and turbulent kinetic energy pathlines.

exit. Preliminary results and analysis indicate that for $\alpha = 135^\circ$, the upstream recirculation zone is absent, while the downstream recirculation zone is strengthened. The turbulence intensity is increased. In the $\alpha = 45^\circ$ case, the upstream recirculation zone is stretched, the downstream recirculation zone is atrophied, and the turbulence intensity is decreased.

4 Experimental Results

In the baseline experiments, $\alpha = 90^\circ$, a long deflagration to detonation transition (DDT) time of 29.7 ms was measured followed by a stable counter-rotating mode. This indicates that the RDE initiated in a counter-rotating mode through turbulent interactions fed by the fuel-oxidizer injector configuration. The wave speed in this clapping mode is measured at about 1200 m/s or about $0.5 U_{CJ}$. This high velocity decrement is consistent with typical clapping modes considering the mode's inherent periodicity of collision-extinction-reignition events. The modified injection schemes shown in Fig. 2 will be tested and compared. In Fig. 5, we notice that the backward-biased injection exhibits single wave modes at all mass flow rates tested, while the perpendicular injector shows 2 wave modes at all tested flow rates.

5 Conclusion

Three different radial injection schemes are tested: one normal injection, and two axially-biased schemes, one impinging and one "co-flowing". These variations produce different turbulence characteristics. Wave speed, and initiation and propagation dynamics are observed in each test. The injection schemes are compared to fundamental detonation experiments studying the effect of turbulence on detonations,

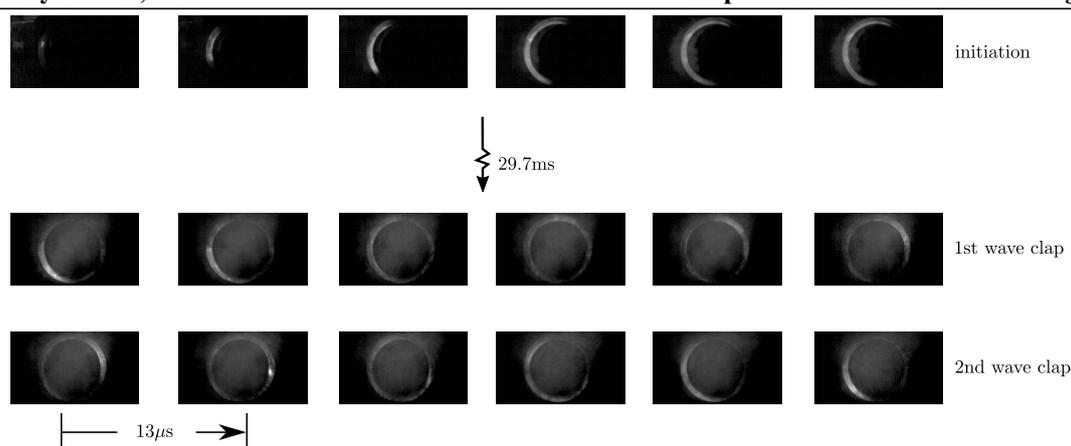


Figure 4: Sequence of frames showing the initiation of a deflagration inside the RDE annulus (line 1) at a mass flow rate of 76 g/s, followed by a long deflagration to detonation transition (DDT) (29.7 ms), indicating detonation initiation through turbulent interactions. A single-cycle clapping mode is shown (lines 2 and 3). The time between each frame is 13 μ s. Frame 1 of line 1 corresponds to the moment of initiation when the shock wave from the initiator transitions to the annular combustion chamber. A steady wave mode is observed after a 29.7 ms delay, corresponding to the first frame of line 2.

conducted by Marjaba [14]. The impact of turbulence on RDE combustor dynamics and the feasibility of achieving a particular RDE operating mode through geometric control of imposed turbulence will therefore be assessed.

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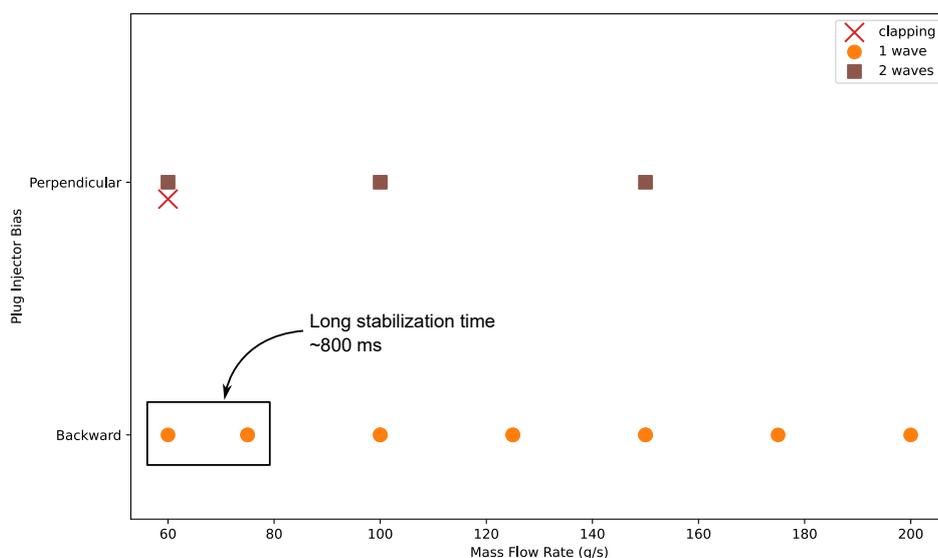


Figure 5: Initial results showing the wave mode that appears for two separate plug injectors (perpendicular and backward-biased)

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