



Numerical Analysis of the Initial Flow-Field Characteristics of a Disk-Shaped RDE Using a Non-Premixed Ethylene/Oxygen Mixture

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Abstract

This study presents a numerical analysis of the initial flow-field characteristics of a Disk-shaped Rotating Detonation Rocket Engine (DiskRDE) using a non-premixed ethylene/oxygen mixture. The primary objective is to explore the flow dynamics and combustion characteristics within a compact and efficient propulsion system suitable for upper-stage rockets. Numerical simulations were conducted using a density-based, compressible turbulent reactive solver. The results reveal the progression of the detonation process through five distinct stages, from ignition to limit cycle detonative mode. Instantaneous and spatiotemporal contours of pressure, temperature, pressure gradient, and mixture fraction provide detailed insights into the detonation wave's behavior, including the complex interactions of primary and secondary wavefronts, as well as the formation of rarefaction and transverse waves. The study highlights the role of combustion dynamics in stabilizing the detonation process, offering valuable information for optimizing the performance of DiskRDEs. The validation of the numerical results against experimental data demonstrates the reliability of the computational framework, confirming its potential for future design improvements.

Keywords: *Disk-type Rotating Detonation Rocket Engine (DiskRDE), Numerical simulations, Combustion dynamics, Detonation wave, Ethylene/oxygen mixture*

Nomenclature

p – stagnation pressure
 T – stagnation temperature
 Δz – grid spacing along z-axis.
 ms – milli-seconds
 μs – milli-seconds

h – channel width
 t – computational time-step

1. Introduction

The development of the Disk-type Rotating Detonation Rocket Engine (DiskRDE) is an essential part of advancing space propulsion technology, particularly for the upper stages of small-scale sounding rockets like the SLVST system. The DiskRDE design is driven by the need for compact and efficient propulsion systems capable of meeting stringent size and weight constraints for the SLVST rocket. As small-scale rockets become more prominent in space research and development, DiskRDEs offer a promising solution due to their potential for high thrust-to-weight ratios and improved fuel efficiency compared to traditional propulsion methods [1]. These engines, designed to operate at altitudes between 1.4 km and 2.58 km, offer significant benefits, including reduced length and weight while maintaining a robust performance level [2]. The importance of studying DiskRDE lies in its ability to overcome several limitations in conventional rocket engines, including inefficient combustion processes and large size requirement [3]. By adopting a disk-type configuration, these engines offer improved operational efficiency and reduced complexity, addressing concerns like the high manufacturing costs

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and limited scalability of traditional systems. Moreover, understanding the flow dynamics within these systems is crucial for optimizing their performance and ensuring stable detonation, particularly under varying operational conditions [4]. Ultimately, by improving the design and performance of the DiskRDE, this research supports broader goals in space transportation, advancing technologies that are crucial for future space missions and infrastructure development.

2. Numerical Methodology

The numerical simulations were performed using an in-house, density-based, compressible turbulent reactive solver based on the finite volume method (FVM) with a structured grid topology. The turbulence was modeled using the Improved Delayed Detached Eddy Simulation (IDDES), a hybrid LES/RANS approach that captures both large-scale turbulence structures and near-wall effects. Chemical kinetics were represented using a quasi-global mechanism consisting of nine species and ten reactions, specifically involving C_2H_4 , H_2 , CO , CO_2 , O , O_2 , H_2O , OH , and H . The combustion process was modeled without an explicit combustion model, relying on direct chemical kinetics. Spatial discretization was achieved using a fifth-order MUSCL scheme, while fluxes were computed using a modified Roe scheme. Temporal advancement was handled through an implicit second-order Lower-Upper Symmetric Gauss-Seidel (LU-SGS) scheme with a four-stage Newton-Raphson sub-time iteration to ensure stability and accuracy. A CFL number of 0.5 was employed for time stepping. Parallel computing was implemented using the Message Passing Interface (MPI) with 254 computational blocks. The total computational cost for the simulations amounted to 192.6 wall-clock hours. A more comprehensive description of the solver and numerical methodology can be found in previous works [5, 6], which provide additional details on the computational framework and solution techniques.

3. Computational Domain

The computational domain is designed to simulate the reactive flow dynamics within a disk-shaped RDE using ethylene (C_2H_4) as fuel and oxygen (O_2) as the oxidizer. The injection system features discrete injectors modeled as slits, ensuring an equal mass flow rate for both reactants. Ethylene is injected from the bottom, while oxygen enters from the top, forming a 45-degree inclined impingement zone that promotes efficient mixing. The ignition process is supported by Zel'dovich-Neumann-Döring (ZND) calculations, conducted using the shock and detonation toolbox [7], to establish the detonation wave structure. The computational domain consists of a channel with a radius of 5 cm and a chamber height of 0.55 cm, leading to an exhaust with a supersonic choked nozzle throat of 4.05 cm. To stabilize the detonation structure, the high-pressure and high-temperature regions in the post-shock area are appropriately filtered. Boundary conditions are imposed as follows: the inflow is defined by a specified mass flow rate, the outflow follows characteristic supersonic exit conditions, and the sidewalls are modeled as slip conditions. A detailed schematic of the computational domain, illustrating the injector arrangement and flow pathways, is provided in Figure 1 a).

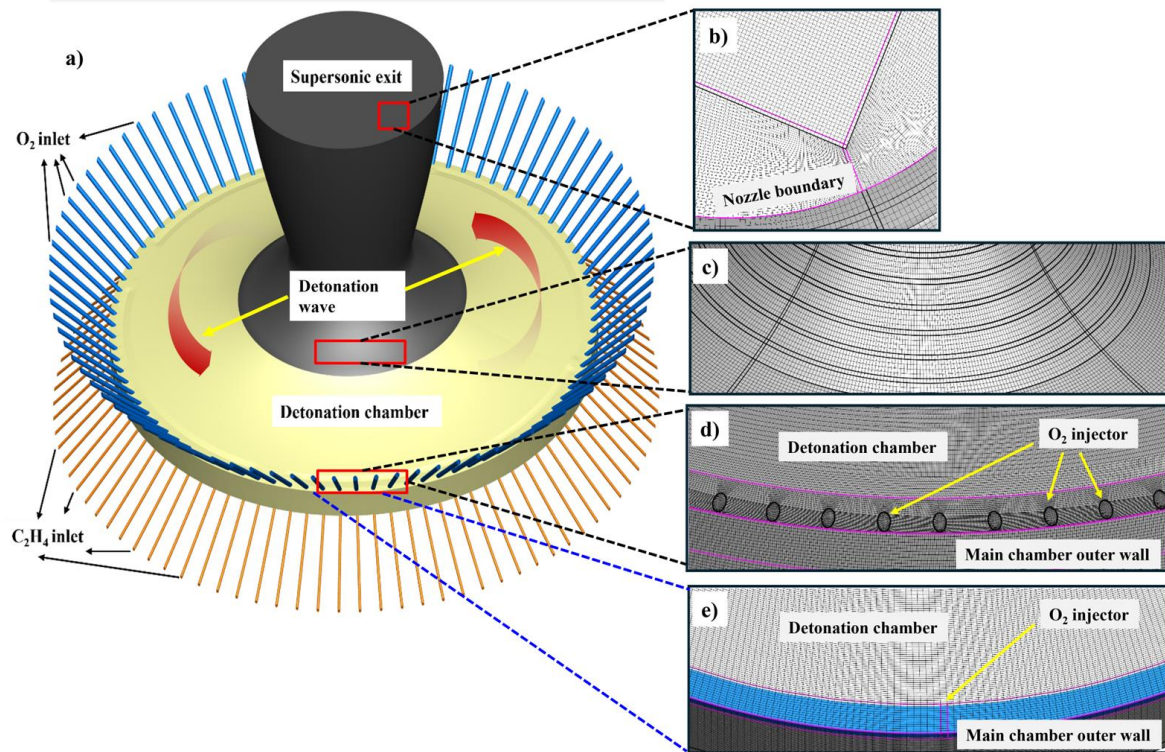


Fig 1. Computational domain showing the Disk-shaped RDE

4. Results and Discussions

4.1. Grid resolution study and validation

A grid resolution study was conducted to ensure numerical accuracy and grid independence. The baseline coarse grid was determined using Choi et al. criterion [5], requiring at least five grid points within the heat release zone of a steady ZND wave. The reference ZND structure, computed using CalTech's ZND solver [7] was used, which is based on an equivalent ratio of 1.37, an inflow temperature of ~ 500 K, and a pressure of ~ 5.0 bar. Successive refinements by a factor of ~ 2.0 improved detonation wave speed accuracy from 6.09% (coarse) to 1.45% (fine). The medium grid, ensuring computational efficiency and accuracy, was selected for further simulations. Table 1 below summarizes the details of the grid independence study.

Cases	Size (Million cells)	Cells included in the HRZ*	Average Von-Neumann peak pressure (Mpa)	Time-averaged chamber pressure (Mpa)	Detonation speed (m/s)
Coarse	4.77	7.21	1.76	0.57	1740 (#6.09%)
Medium	9.61	14.42	2.36	0.66	1819 (#1.83%)
Fine	19.23	28.84	2.39	0.69	1826 (#1.45%)

*Heat release zone length (HRZ) = 4.711×10^{-5} cm

#Relative error comparing with experimental detonation speed which is 1853 m/s

Tab 1. Summary of the grid study

To ensure the reliability of the numerical framework, simulation results were validated against experimental data [8]. The wave stabilized approximately 1.2 ms after the simulation start, with a total simulation runtime of 5 ms. Key validation metrics included pressure history, detonation wave speed,

and time-averaged chamber pressure. Figure-2 illustrates the pressure-time profile at the chamber center, comparing experimental and simulated pressure traces. A black line denotes the experimentally recorded detonation wave propagation pressure at 5 mm from the circumferential wall, while the orange dashed line represents the time-averaged simulated pressure. Discrepancies arise due to sensor limitations—WIKA S-20 static pressure sensors (response time 1–3 ms, ~ 1 kHz) fail to resolve high-frequency combustion-induced oscillations in the experiments, whereas simulations capture the full amplitude of the detonation pressure spike. Given that the detonation wave rotates at ~ 13 kHz, achieving precise pointwise agreement is inherently challenging. Nevertheless, the solver accurately replicates the overall chamber detonation behaviour. Comparisons averaged over 17 cycles indicate low relative errors: 1.83% in detonation speed and 4.15% in rotational frequency, demonstrating the solver's capability in capturing detonative combustion dynamics.

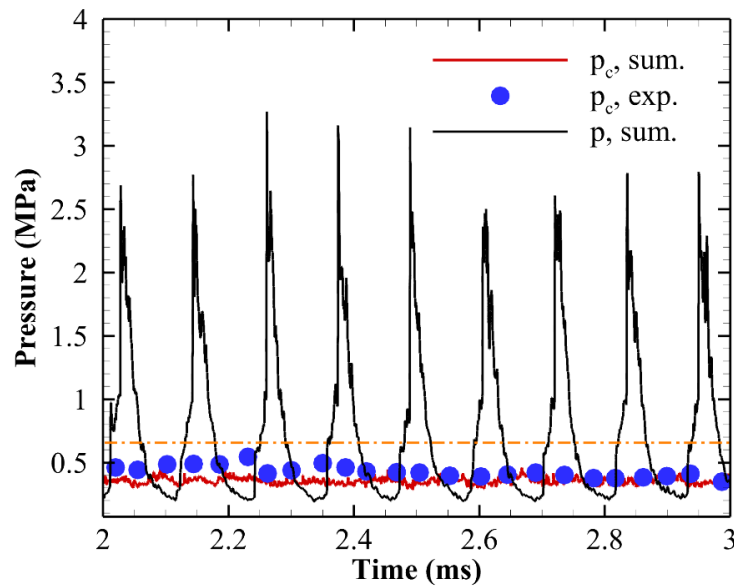


Fig 2. Comparison of the center chamber pressure (p_c) history obtained from the experiment (symbol), the simulation (red solid line), along with the simulated detonation wave propagation pressure (black line) measured 5 mm downstream from the chamber's circumferential wall and the time-averaged chamber pressure value of the simulation (orange dashed line).

4.2. Simulation Sequence

Two principal strategies are widely utilized for simulating the startup and sustained operation of numerical RDREs. The first method closely replicates experimental procedures: the combustion chamber is initialized at atmospheric pressure (1bar) and ambient temperature (298.15K) at $t=0$ s. Upon commencement, non-premixed fuel and oxidizer are introduced through their respective injectors, progressively filling the chamber until a quasi-steady, stoichiometric environment is achieved. At this stage, the simulation is temporarily halted, and a one-dimensional (1D) detonation front—computed via the classical Zel'dovich–Neumann–Döring (ZND) steady-state solution is manually imposed as an ignition source. This ZND-based front, representing a steep pressure and temperature discontinuity in line with Chapman–Jouguet (CJ) conditions, triggers the onset of the rotating detonation phase once the simulation resumes. This method aligns with established protocols for wave initiation in rotating detonation combustor (RDC) studies, with ZND profiles generated using the Shock and Detonation Toolbox.

Alternatively, in the second strategy, the chamber is initially filled with a stoichiometric, premixed fuel–oxidizer mixture. Immediately at $t>0$ s, a ZND-profile detonation is introduced at a predetermined ignition site along the azimuthal wall, directly initiating detonation propagation and circumventing the initial filling phase. While the first strategy provides greater fidelity to experimental startup conditions, the second is preferred in the present work due to its substantial savings in computational resources. Accordingly, all simulation results discussed in this paper are obtained using the prefilled, instantaneous

ZND ignition protocol. Fig. 3 (a–c) present the simulation results for the discrete injector case, showing the instantaneous 3D temperature contour during steady-state detonation, with two stable detonation fronts rotating counterclockwise. Fig. 3 (b) provides an axial–radial temperature slice, highlighting the structure of the detonation wave. Fig. 3 (c) displays the axial–radial distribution of mixture fraction (f_{mix}), illustrating the persistence of fresh reactants and the zones of active combustion.

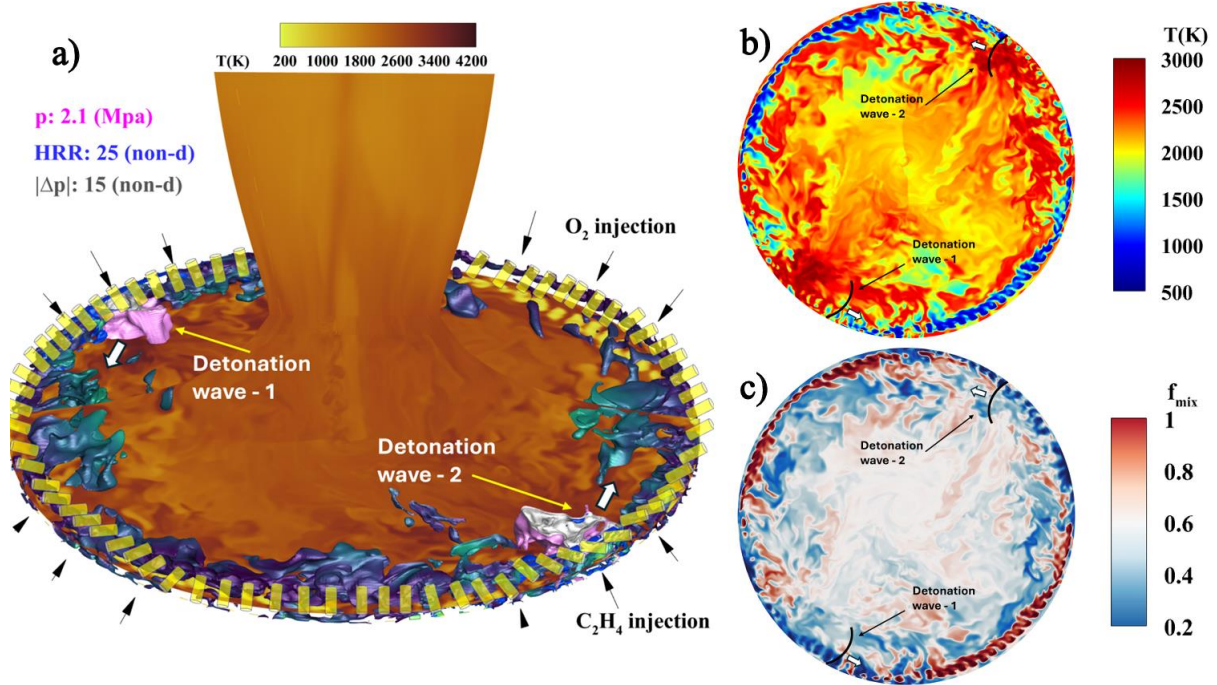


Fig 3. Instantaneous flow-field features for discrete injector configuration during steady dual-wave operation: (a) 3D temperature contour with overlaid iso-contours of pressure (pink), non-dimensional heat release rate (blue), and pressure gradient (gray) for the discrete case; (b) axial–radial temperature slice highlighting the structure of rotating detonation fronts (discrete); (c) axial–radial (f_{mix}) distribution showing fresh reactant persistence and combustion zones (discrete)

4.3. Results and Discussions

4.3.1. Spatio-temporal Profiles

In this section, the combustion dynamics of detonative combustion development are analyzed through a spatiotemporal contour of pressure as a function of angular position (θ) and time, as depicted in Fig. 4. The analysis reveals five distinct stages in the detonation process. Stage I (0–200 μ s) is characterized by the initiation of high-pressure ZND ignition, where the combustion zone is established. In Stage II (200–500 μ s), ignition-induced fluctuations lead to a significant rise in pressure within the combustion chamber. Stage III (500–750 μ s) sees these high pressures causing a blockage of the inflow for a brief period, interrupting the continuous fuel supply. During Stage IV (750–1200 μ s), the system experiences transverse to detonative tangential mode instability, which contributes to further fluctuations in pressure. Finally, Stage V (1200–2500 μ s) represents the limit cycle detonative mode, where the

combustion process stabilizes into a sustained detonation, completing the cycle of detonative combustion.

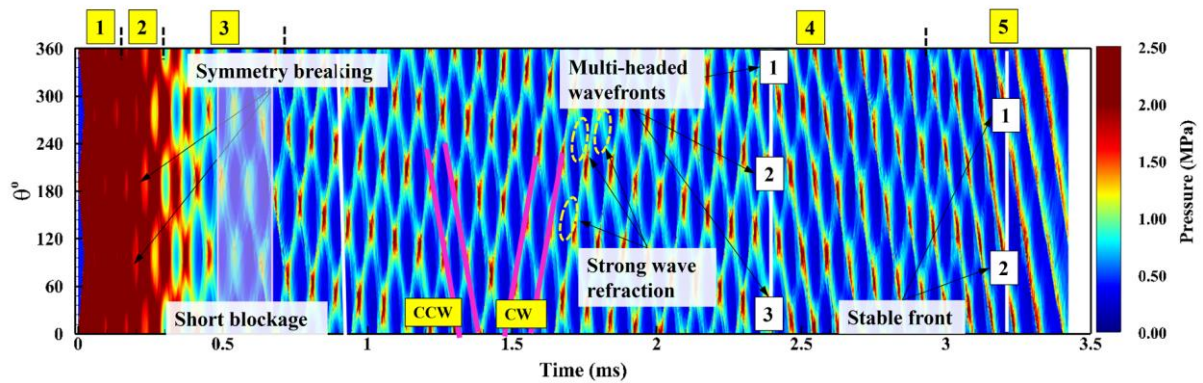


Fig 4. Temporal plot of pressure as a function of angular position (θ) at a location 5 mm downstream from the chamber's circumferential wall, illustrating the spatiotemporal structure of rotating detonation waves.

4.3.2. Instantaneous Pressure Contours

The evolution of the detonation structure in disk RDREs is fundamentally dictated by injector geometry. The instantaneous axial-radial pressure contours, as shown in Fig. 5 for the discrete injector, provide deep insight into how each configuration mediates wave propagation, and stability across key fundamental regimes. Fig. 5 reveals that discrete injectors generate sharply defined, localized high-pressure zones immediately following ZND-type ignition. The pressure fronts are highly localized, reflecting rapid mixing and efficient energy release. In the discrete configuration, intersecting radial pressure waves rapidly coalesce into organized rotating structures. The transition is marked by clear angular rotation and fast establishment of a stable propagation pathway. The pressure contours highlight strong, bi-directional radial propagation, with symmetry breaking occurring through the rapid organization of initial pressure fronts. The efficiency of transition from a chaotic to a periodic detonation regime is a key differentiator. In Fig. 5, discrete injectors promote a swift decline in random high-pressure zones, with boundary-confined waves rapidly evolving into periodic structures. Transitional flow is marked by short-lived turbulence, but the dominant trend is towards self-organization and pressure regularity. Multi-wave behaviour is clear but transitions smoothly toward the dominance of

one or two main fronts, with minimal turbulent pockets. The final regimes illustrate the ultimate efficiency and stability achievable by each injector type.

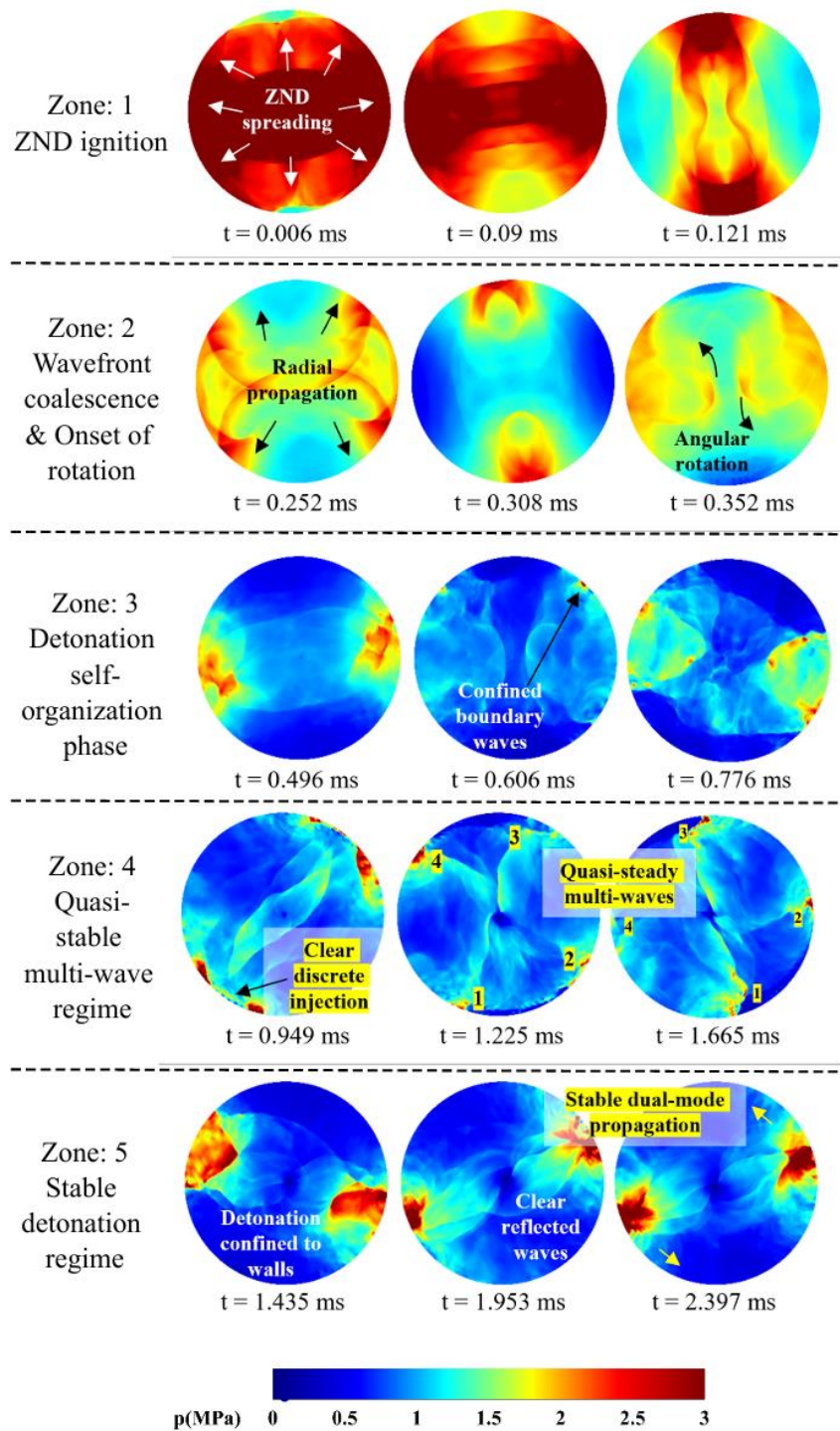


Fig 5. Axial-radial slices of the instantaneous pressure contours for the discrete injector configuration, illustrating the evolution of detonation structure in a disk-RDRE across distinct combustion regimes.

4.3.3. Combustion Characteristics

Fig. 6 illustrates the scatter plots of f_{mix} , OH mass fraction (y_{OH}), and key variables such as temperature, heat release rate (HRR), and normalized density (ρ/ρ_0), revealing distinct combustion characteristics in the discrete injector configurations in the disk-RDRE. Both configurations show primary combustion near the stoichiometric regime ($f_{mix} \approx 0.21-0.22$). Discrete configuration (Fig. 6a) is characterized by a sharper, denser OH ridge and steeper gradients. The yellow-to-red plume centered near the peak indicates robust and spatially localized combustion, reflecting efficient energy release and rapid radical generation. Regions of strong post-flame decay and quenching, reflecting localized, jet-driven mixing and more intense but spatially confined reaction regions. The discrete injector (Fig. 6c) produces high reaction rates and significant OH radical concentrations in both stoichiometric and fuel-rich pockets, a consequence of strong jet-driven localized mixing and enhanced oxidizer entrainment. This results in broader, more intermittent reaction zones and greater spatial variability. The broad density spread in Fig.6e) shows substantial local stratification and the persistence of unburned or partially burned pockets in discrete cases.

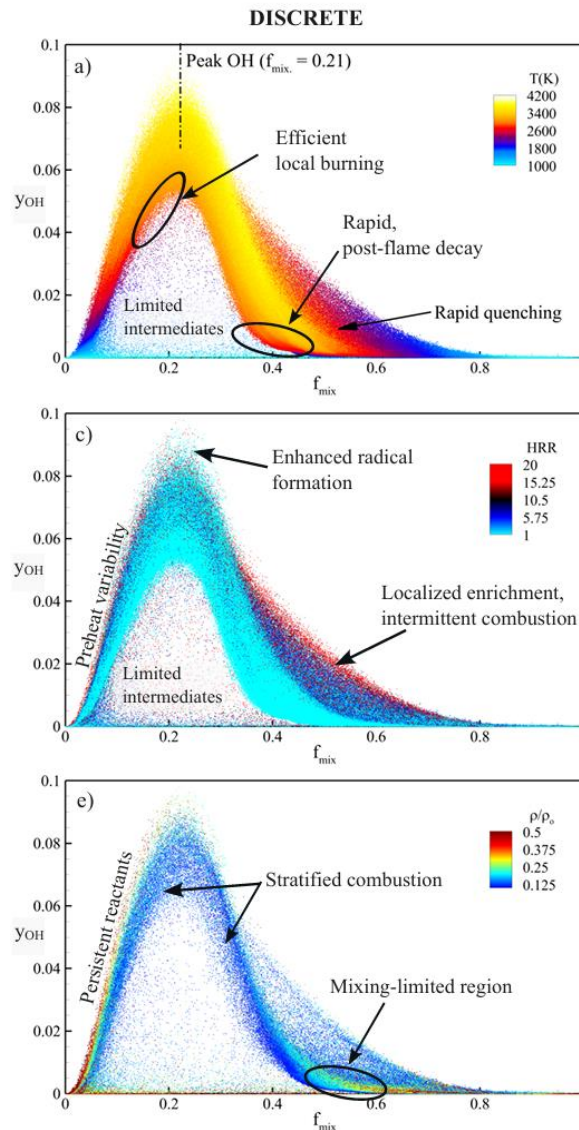


Fig 6. Scatter plots showing key variables comparing (a, c, e) discrete injector configurations in the disk-RDRE. Panels (a, b) show temperature, (c, d) shows HRR, and (e, f) shows ρ/ρ_0 .

5. Conclusion

This study conducted a detailed numerical investigation of the initial flow-field evolution in a Disk-shaped Rotating Detonation Rocket Engine (DiskRDE) employing a non-premixed ethylene/oxygen mixture. The simulations captured the complete progression of the detonation process, delineating five characteristic stages from ignition through the establishment of a stable limit cycle. The spatiotemporal analysis of pressure, temperature, pressure gradient, and mixture fraction fields provided comprehensive insights into the dynamics of detonation wave propagation, including the interaction between primary and secondary wavefronts, as well as the emergence of rarefaction and transverse waves. These findings underline the critical role of combustion-driven instabilities and wave interactions in sustaining detonation stability within compact propulsion systems. Furthermore, the close agreement between numerical predictions and experimental data confirms the robustness of the computational framework and reinforces its applicability for future optimization and design of DiskRDE configurations, particularly in the context of high-efficiency upper-stage rocket propulsion.

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