Numerical Investigation of Three-dimensional (3D) Rotating Detonation Engine with Premixed Hydrogen/Air

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1 Introduction

The Rotating Detonation Engine (RDE) is a cutting-edge concept for creating thrust by series of controlled explosions in a continuous power generation cycle. With combustion velocities of thousands of meters per second, RDEs are highly efficient and powerful. Since the initial study on its application to propulsion systems [1], there were many numerical/experimental research were undertaken. The extensive recent survey can be found in [2 and 3]. While previous research has focused primarily on two-dimensional (2D) RDEs, there is still a lack of understanding about the complex flow-field and detonation structure of 3D RDEs. The focus of this study is to numerically study the 3D RDE and understand the fundamental unsteadiness of the flow-field during detonation propagation and provide some insights for the demonstration of a realistic design for practical applications.

2 Numerical Methodology

2.1 Governing Equations

Unsteady, compressible Navier-Stokes equations are solved in a fully coupled solver. Equation (1) & (2) gives the necessary governing equations.

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+\frac{\partial G_v}{\partial z}+w \tag{1}$$

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$$Q=\begin{bmatrix}\rho_i\\ \rho u\\ \rho v\\ \rho w\\ e\\ \rho k\\ \rho\omega\end{bmatrix} E=\begin{bmatrix}\rho_i u\\ \rho u^2+p\\ \rho vu\\ \rho wu\\ (e+p)u\\ \rho uk\\ \rho u\omega\end{bmatrix} F=\begin{bmatrix}\rho_i v\\ \rho vu\\ \rho v^2+p\\ \rho wv\\ (e+p)v\\ \rho vk\\ \rho v\omega\end{bmatrix} G=\begin{bmatrix}\rho_i w\\ \rho wu\\ \rho wv\\ \rho w^2+p\\ (e+p)w\\ \rho wk\\ \rho w\omega\end{bmatrix} E_v=\begin{bmatrix}-\rho_i u_i^d\\ \tau_{xx}\\ \tau_{xy}\\ \tau_{xz}\\ \beta_x\\ \mu_k\,\partial k/\partial x\\ \mu_\omega\,\partial\omega/\partial x\end{bmatrix} F_v=\begin{bmatrix}-\rho_i v_i^d\\ \tau_{yx}\\ \tau_{yy}\\ \tau_{yz}\\ \beta_y\\ \mu_k\,\partial k/\partial y\\ \mu_\omega\,\partial\omega/\partial y\end{bmatrix} G_v=\begin{bmatrix}-\rho_i w_i^d\\ \tau_{zx}\\ \tau_{zy}\\ \tau_{zz}\\ \beta_z\\ \mu_k\,\partial k/\partial z\\ \mu_\omega\,\partial\omega/\partial z\end{bmatrix} \mathrm{w}=\begin{bmatrix}w_i\\ 0\\ 0\\ 0\\ 0\\ s_k\\ s_\omega\end{bmatrix} \quad (2)$$

2.2 Computational Domain

RDE geometry has been created with a structured grid with a grid spacing ($\Delta x=\Delta y=\Delta z$) of 0.02. Fig. 1(a) shows a schematic of the grid and Fig. (1)b shows the instantaneous temperature plot. The spatial discretization and temporal discretization were treated by 3rd-order WENO and 2nd-order implicit method respectively. The convective fluxes were discretized using AUSMDV (Advection Upwind Splitting Method flux Difference and Vector splitting biased) flux-splitting scheme. For the chemistry model, the UCSD H_2/air reaction mechanism with 8 species and 21 reaction steps was chosen. A detailed description of the numerical scheme and the solver approach can be found elsewhere [4 and 5].

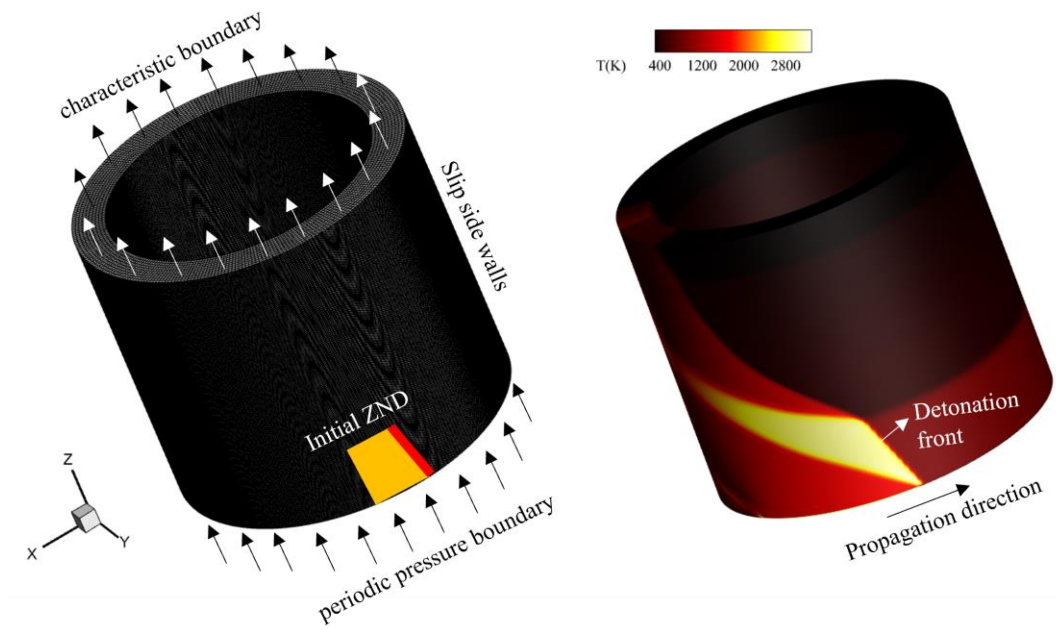

Figure 1: (a) Grid system of a cylindrical channel; (b) instantaneous temperature contour

Periodic pressure boundary for inflow and characteristic boundary for outflow [6], whereas sidewalls are modeled as slip conditions. A grid refinement study has been carried out and selected an appropriate resolution. One-dimensional (1D) steady Zeldovich–von Neumann–Döring (ZND) structure solution was employed as the initiation of detonation wave.

4 Results

The primary focus is the examination of unsteady flow characteristics and azimuthal detonation structures after reaching a quasi-steady state. The results presented in Figure 2 depict the exit Mach recorded by a random probe at the exit. Following an initial fluctuation, stability is attained at 0.35 ms, and all subsequent results are discussed based on data collected after this timestep.

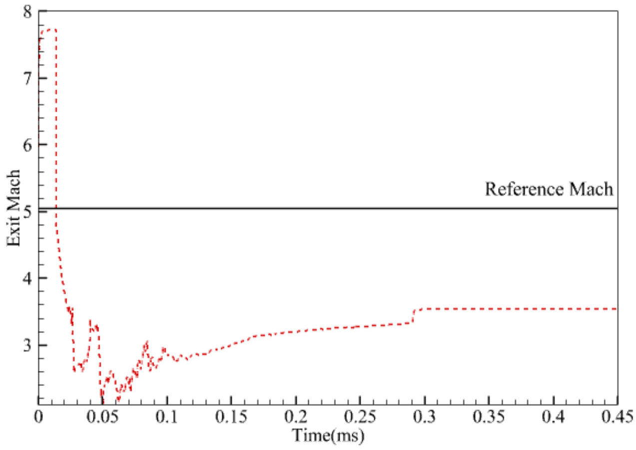

Figure 2 Exit Mach recorded for the whole simulation

4.1 Unsteady flow features

Figure 3 displays the 2D unwrapped domain centered on the radial axis. The axial and azimuthal velocity demonstrate the dynamic inflow conditions, where there is no inflow at the detonation wave, subsonic inflow behind the wave, and supersonic inflow in front of the wave. Multiple triple points can be observed behind the wave front, with the strongest ones being closest to the front and weakening as they move away from the channel. The density contours reveal the cell structure, and high density behind the detonation wave indicates a concentration of matter in that region. Mass fraction profiles illustrate the concentrations of H_2, O_2, and OH along the azimuthal direction. The high concentration of OH observed behind the detonation wave and secondary wave suggests an efficient combustion process with active chemical reactions.

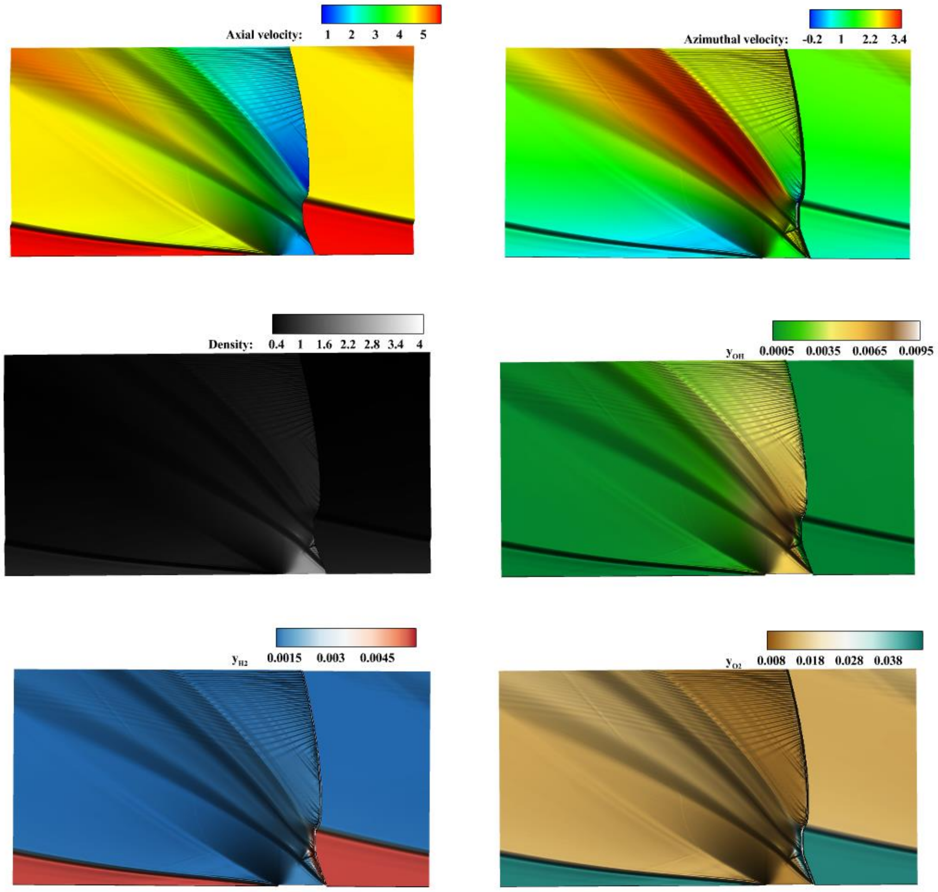

Figure 3: 2D unwrapped flow-field of (a) axial, (b) azimuthal velocities, (c) density, and mass fractions of (d) OH, (e) H_2, (f) O_2.

4.2 Azimuthal detonation structure:

Fig. 4 presents the instantaneous azimuthal profiles of various flow-field quantities extracted along a line in the detonation wave and Fig. 5 shows the instantaneous profiles at different heights.

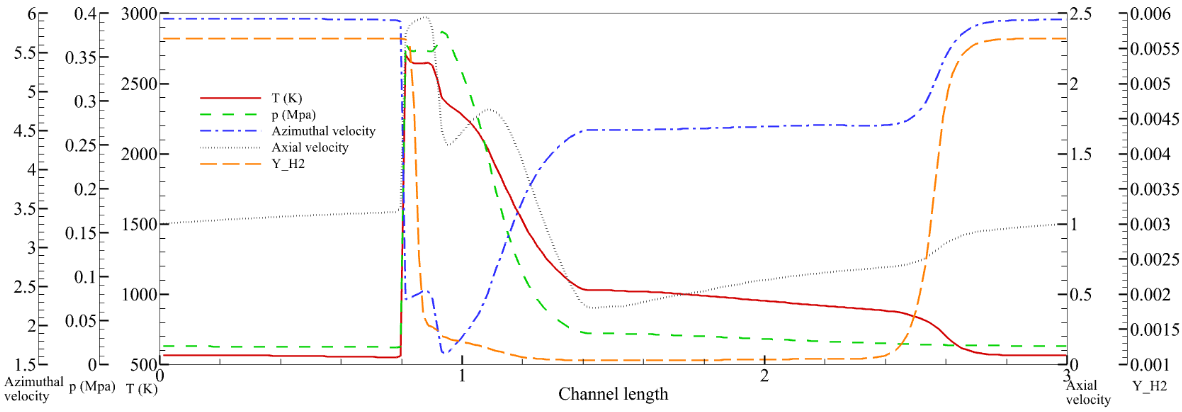

Figure 4: Instantaneous azimuthal profiles of various flow-field quantities.

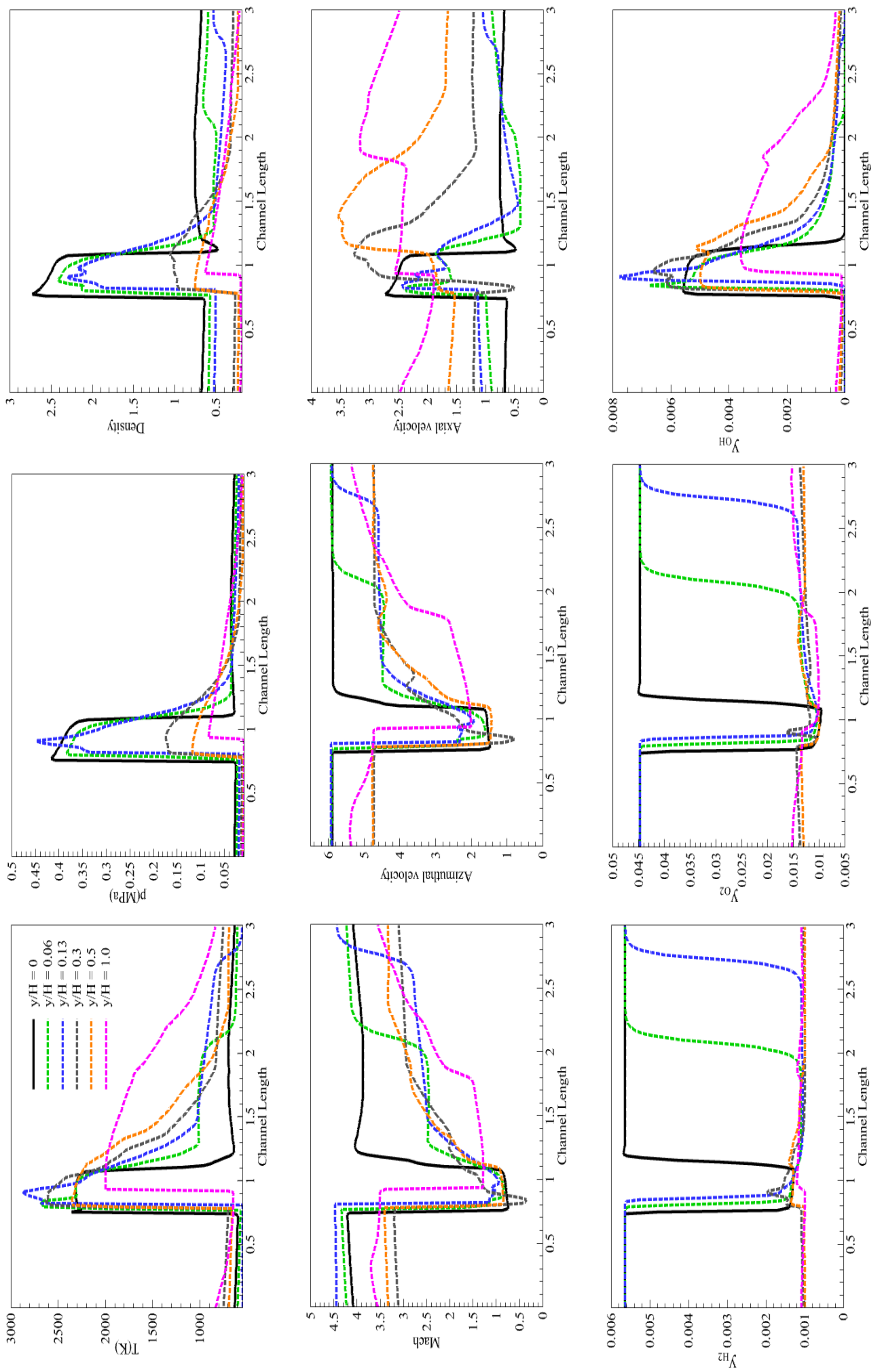

Figure 5: Instantaneous azimuthal profiles of (a) temperature, (b) pressure, (c) density, (d) Mach, (e) Azimuthal, (f) Axial velocity, and mass fractions of (g) H_2, (h) O_2, (i) OH at different heights. The height is normalized by the total height of the combustor.

The flow-field quantities are examined to understand the detonation structure in the azimuthal direction at different heights. Totally six probes (*z/H* = 0, 0.06, 0.13, 0.3, 0.5 and 1.0) are kept along the channel height to study various phenomenon such as detonation-front height, temperature, and mass fractions. Results shows that the pressure profiles displayed a strong spike at around *z/H* ≈ 0.13, indicating a detonation front that extended up to two-third of the channel height. The temperatures at the shock front were found to be close to the CJ condition (T_{CJ} = 2870 K). The temperature dropped from approximately 2400 K to 300 K for *z/H*=0. However, at higher heights, the temperature remained higher for a longer azimuthal distance. H_2/O_2 concentration was found to be highest at the injected plane, but it decreased almost to zero by *z/H* ≈ 0.3. Along the detonation-front, the H_2/O_2 was consumed and as a result, it decreased to zero in the post-detonation regions at all heights.

5 Conclusion

The purpose of this study was to gain an understanding of the detonation structure in a 3D RDE. By examining the flow-field quantities, the dynamics of the detonation and its correlation to different operating conditions and design parameters were investigated. The findings revealed that the temperature at the detonation front reached approximately 2800 K, almost equal to CJ condition. The temperature was found to be higher for a longer distance at higher heights. The H2/O2 concentration decreased to zero in the post-detonation regions at all heights as it was consumed along the detonation front.

References

[1] Nicholls JA, and Cullen RE. (1958). The Feasibility of a Rotating Detonation Wave Rocket Motor. Report No. RPL-TDR-64-113, The University of Michigan

[2] Xie Q, Ji Z, Wen H, Ren Z, Wolanski P, and Wang B. (2020) Review on the Rotating Detonation Engine and It's Typical Problems. Transactions on Aerospace Research. 4. 107-163

[3] Wolański P. (2021) Research on detonative propulsion in Poland. Institute of Aviation Scientific Publication No. 60. Institute of Aviation

[4] Choi JY, Kim DW, Jeung IS, Ma F, and Yang V. (2007) Cell-like structure of unstable oblique detonation wave from high-resolution numerical simulation. Proceedings of the Combustion Institute, 31(2). 2473-2480

[5] Jeong SM, and Choi JY. (2020) Combined diagnostic analysis of dynamic combustion characteristics in a scramjet engine. Energies. 13(15). 4029

[6] Niyasdeen M, Oh S, Kim KS, and Choi JY. (2015) Quasi-steady state simulation of rotating detonation engine. International Journal of Aeronautical and Space Sciences. 16(4), 548-559