Simulation of rotating detonation in a hollow H_2-O_2 combustor under fuel-rich conditions

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Stable propagation of detonation waves and high wave velocity are of primary importance for practical use of rotating detonation combustors (RDC). These characteristics may depend on the choice of RDC configuration. According to known experimental studies, hollow or center-body-less RDCs provide stable detonation propagation in an extended range of conditions in terms of mass flow rate and equivalence ratio, as well as a high wave speed close to the theoretical Chapman-Jouguet (CJ) value, compared to annular RDCs with the same outer diameter and length. Experimental tests performed at DLR in the scope of a common project with ONERA, demonstrated efficient operation of a hollow RDC fed with gaseous H_2 and O_2 under very fuel-rich conditions. The experimental RDC is equipped with an injector with partial propellant premixing designed at ONERA. The present study relies on a large-eddy simulation (LES) of that experimental case to provide a detailed insight in the complex flowfield and to characterize the fresh mixture consumed by the rotating detonation. Simulation of a single-wave mode requires considering the entire RDC. The computational domain includes the injector with the propellant plenums and a damp volume at the chamber outlet. A 6-species and 7-reaction kinetic mechanism is used to correctly predict the reactive gas composition. The simulation resulted in a wave speed higher than the CJ value. With a phase-averaged flowfield, a complex shape of the fresh mixture layer is visualized. Without center-body, the flow has a high radial velocity toward the mixture layer, resulting in its spreading on the chamber side wall. Average parameters of the fresh mixture consumed by detonation are evaluated. The injector with partial premixing provides a high level of mixing efficiency in the fresh gas layer ahead of the detonation front.

Keywords: *rotating detonation, hollow combustor, fuel-rich, hydrogen-oxygen, large-eddy simulation*

1. Introduction

For practical implementation of rotating detonation combustors (RDC), it is important to realize their theoretical capacity to provide a pressure gain, which directly depends on the fresh mixture compression and hence on the detonation speed. Another important requirement is stable operation in a range of mass flow rate and equivalence ratio (ER). Fresh mixture quality, provided by the injector, is an evident factor defining the RDC performance. A less evident one is the chamber geometry. In this regard, a hollow RDC represents a specific case considered in the present study.

Some interesting results on hollow RDCs are known from the literature. Using H_2 and air, Anand et al. [1] obtained a wave speed close to the CJ value and stable operation under fuel-rich conditions. Wu et al. [2] found that their RDC, fed with H_2 and O_2, operated stably at a higher ER than an annular RDC. Hellard [3] tested two injector types with CH_4 and O_2 and obtained better propagation characteristics for a hollow RDC compared to an annular one. Bard et al. [4] got stable operation and a high wave velocity using very rich H_2-O_2 with ER up to 3.

The purpose of the present computational study is to provide a detailed insight in the experimental case of [4].

2. Simulated case

2.1 Computational domain and mesh

A quarter of the full computational domain is shown in Fig. 1. It consists of two coaxial annular plenums for H_2 and O_2 feeding through the planar faces pointed by arrows. Each plenum is connected by feeding tubes to 72 cylindrical prechambers. The feeding tubes have equal inclinations of 45° with respect to the prechamber axis and diameters of 1 and 1.5 mm for H_2 and O_2 respectively. The prechambers have a length of 5 mm and a diameter of 2.2 mm. They serve for partial premixing of the injected propellants before their injection into the chamber. Each prechamber and a pair of its feeding tubes represent an injection element.

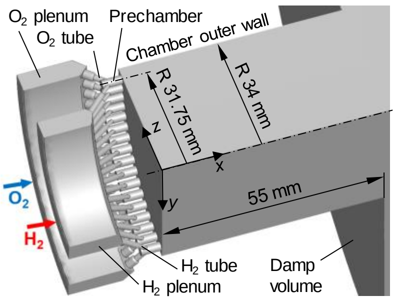

Fig. 1 Quarter of the computational domain.

The combustion chamber has a length of 55 mm and a radius of 34 mm. The centers of injector orifices are situated at a radius of 31.75 mm. The chamber opens in a large damp volume to evacuate burnt gases and absorb waves emanating from the chamber.

The computational mesh is composed of prism layers along the walls and tetrahedra in the core flow. The finest mesh with cells of 80 µm is inside the prechambers and within the mixing zone in the chamber. The total number of cells is around 62×10^6.

2.2 Boundary conditions

Propellant mass fluxes together with a total temperature of 293 K are imposed at the inlet boundaries. The mass flow rates of H_2 and O_2 are respectively 17.1 and 40.3 g/s. No-slip

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conditions are imposed on the walls of the feeding tubes, prechamber, and combustion chamber. All the walls are adiabatic excepting the chamber walls, which are at a constant temperature of 400 K. Atmospheric pressure and non-reflecting boundary conditions are set on the outflow boundaries of the damp volume.

2.3 Numerical method and models

A large-eddy simulation (LES) of the reactive flow is performed with the CEDRE CDF code of ONERA. Fluxes are approximated by 2nd-order accurate numerical schemes. An implicit method is used for time integration.

The standard Smagorinsky model is used to treat the turbulence on the sub-grid scale. A simplified kinetic mechanism of 7 reactions between 6 species models the H_2-O_2 combustion. Standard thermodynamic polynomials and tabulated transport properties are used for the chemical species.

3. Results

Combustor operation in a single-wave mode is simulated until the total mass flow rate is stabilized and the detonation propagation is established with a velocity of 3914 m/s, referred to the wall radius of 34 mm, against the CJ speed of 3722 m/s. Then, 73 instantaneous flow states are collected during a full rotation period. The Phase-Locked Ensemble Averaging (PLEA) method [5] is used for post-processing. First, the collected flowfields are mapped onto an orthogonal structured grid in cylindrical coordinates. Second, the detonation wave position is detected with respect to the closest injection element. Third, the flowfields are rotated to set that element at the same position. Phase-averaged flow parameters are weighted by mass.

Figure 2 shows the pressure field on the combustor bottom wall and the fresh mixture layer surface, which corresponds to 20% mass fraction of burnt gas. The detonation propagates in the clock-wise direction. Its location is marked by the highest pressure on the bottom wall and by the abrupt end of the mixture layer. The pressure field near the bottom wall features an overall variation from the high-pressure zone past the detonation to subatmospheric pressure on the opposite side. The wrinkled inner surface of the mixture layer is due to the closely situated jets. During growth, the layer forms a mushroom-like head, then it is vertically stretched near the detonation front.

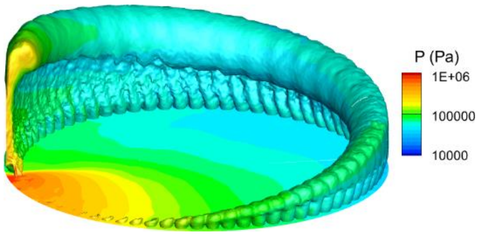

Fig. 2 Phase-averaged field of pressure on the bottom wall and the surface of the fresh mixture layer.

The structure of the fresh mixture layer ahead of the detonation front is illustrated by the phase-averaged fields of temperature, burnt-gas mass fraction, and mixing efficiency, shown in Fig. 3. The velocity vectors indicate a strong radial flow towards the fresh mixture layer with a velocity magnitude of the order of 1 km/s. This flow results in spreading the most concentrated fresh mixture along the side wall. In the contact zone with hot products, the temperature ranges from 600 to 1200 K due to dilution with burnt gases from 20% to 50% by mass. The injector with partial premixing provides good mixing efficiency in the chamber up to 80%. The presence of burnt gases reduces the mixing efficiency in the contact zone.

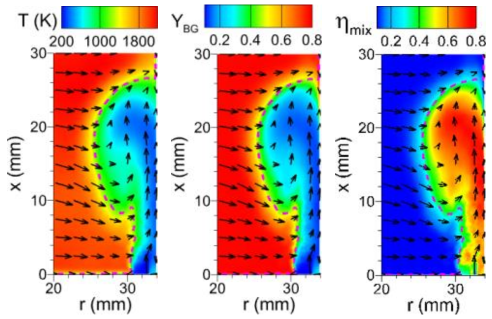

Fig. 3 Phase-averaged fields of temperature, T, burnt gas mass fraction, Y_{BG}, and mixing efficiency, η_{mix} with velocity vectors and 1230 K isotherm (dashed contour) in a radial cut of the fresh mixture layer ahead of the detonation front.

The 1230 K isotherm in Fig. 3 delimits the area within an azimuthal sector over one injection element, which contains the mass injected through this element during a detonation rotation period. It can be considered as a control volume containing the fresh mixture burnt by detonation. Average quantities in this control volume are: a temperature of 597 K, a burnt gas mass fraction of 19%, and a mixing efficiency of 60%.

4. Conclusion

An LES of a hollow RDC under very fuel-rich conditions has been performed, resulting a detonation wave velocity higher than the CJ value. This is due to the high mixing efficiency provided by the injector with partial propellant premixing, but also due to the flow conditions ahead of the detonation front, specific to the hollow RDC, and front inclination to the side wall. The obtained result corroborates with the known experimental results, which demonstrate apparent wave velocities closely below [1, 4] or higher [3] than the CJ speed.

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References

[1] V. Anand et al. Hollow rotating detonation combustor. *54th AIAA Aerospace Sciences Meeting*, San Diego, CA, 2016.

[2] Y. Wu et al. Wave mode observation of hydrogen/oxygen driven rotating detonations in the hollow and annular rotating detonation rocket engine. *Phys. Fluids*, 36: 115105, 2024.

[3] P. Hellard. Étude numérique et expérimentale d'une chambre de combustion à détonation rotative à injection partiellement prémélangée. *PhD thesis*, ISAE-ENSMA, 2024.

[4] E. Bard, et al. Investigation on the influence of operation and injection conditions on the wave dynamics of GH_2/GO_2 rotating detonation combustors. *35th ISTS*, Tokushima, Japan, 2025.

[5] P. Nassini. High-fidelity numerical investigations of a hydrogen rotating detonation combustor. *PhD thesis*, University of Florence, 2022.