Numerical Optimization of a Partially Premixed Injector for a Rotating Detonation Rocket Combustor

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Rotating Detonation Combustors (RDCs) offer a promising alternative to conventional propulsion systems by exploiting pressure-gain combustion. However, experiments on a wide range of RDC configurations consistently report detonation speeds below theoretical predictions due to loss mechanisms and limiting factors, including the brief refill and mixing phase of the propellants. This study investigates a partially premixed injector concept, called ITEM, designed to improve the mixture quality of O_2-fuel gaseous mixtures while limiting flashback risk. An ITEM injection element consists of one axial fuel tube and two lateral O_2 tubes that join in a prechamber to initiate mixing. A series of five ITEM geometries is evaluated using LES cold-flow simulations, enabling comparison of mixing efficiency profiles and assessment of flashback risk. An iterative procedure is conducted to adjust two key geometric parameters: the prechamber axial length and the crossing point position of the axes of the O_2 lateral tubes. Some basic geometric guidelines were established to guarantee a suitable compromise between high mixing efficiency and low flashback probability. Experimental validation in a small-scale RDC with a 10 mm annular gap confirms that the optimal ITEM design achieves detonation speeds exceeding those reported in the literature for conventional fully separate injection. The work demonstrates that a carefully tuned partially premixed injector can reconcile efficient mixing with flashback mitigation, advancing the practical implementation of pressure-gain combustion in rocket propulsion.

Keywords: *Injection, Mixing Interactions, LES, Partial Premixing, Mixing Prechamber*

1. Introduction

Rotating Detonation Combustors (RDCs) are gaining attention as an alternative to traditional power-generation technologies because they harness pressure-gain combustion. Recent reviews [1,2] highlight the key aspects of RDC operation: injector geometry, combustor internal shape, system integration, and cooling. Experiments with RDCs consistently reveal a notable shortfall in detonation speed relative to the theory. This discrepancy results from several loss mechanisms [2], such as parasitic deflagration, and from limiting factors, including the inherently brief refill and mixing phase, which makes producing a high-quality fresh mixture between successive detonations difficult. Consequently, achieving a system-scale pressure gain remains challenging, since the fresh mixture quality, and the injector and RDC geometries, influence performance and operational stability.

Several injector concepts adapted to RDCs can be explored. Fully separate fuel-oxidizer injection employs diverse orifice (like triplet designs in [3]) and slot arrangements to try to achieve higher mixing efficiency, whereas premixed injection [4] must prevent flashback. Partially premixed injection [5] represents a compromise, offering better mixture quality than separate injection and retaining safety.

This paper presents a numerical study of a partially premixed injector to elucidate mixing interactions as a function of geometric parameters. It then briefly demonstrates the experimental benefits, including higher detonation speeds.

2. Numerical design of a partially premixed injector

2.1 Basic designs

In this study, injector design is carried out for a small-scale RDC tested at the GAP test facility of the Pprime Institute. The chamber has a length of 110 mm and an outer diameter of 80 mm. The annular gap can be either 10 mm or 5 mm. For this design, the mixtures of interest are CH_4/O_2 and H_2/O_2.

The injector design starts with the IMP concept [6], in which the reactants are brought into contact within a prechamber. Two lateral converging channels inject O_2 through openings with an offset of 2δ relative to the prechamber axis, while the fuel is injected axially. The swirl-driven mixing interactions created in the prechamber are maintained in the chamber. In order to use mixing principles of the IMP injector in the Pprime RDC, it needs to be adapted. In particular, the lateral channels are now tilted at 45° with respect to the prechamber axis.

Some geometric parameters of the design–below referred to as ITEM [7] (Fig. 1)–are identified for the mixing study: L_1, the prechamber length, d_{ox}, d_f and d_{inj}, the diameters of the O_2, fuel, and prechamber orifices respectively, L_2, the distance from the prechamber bottom to the intersection point A of the oxidizer tubes axes. The injector is composed of 72 injection elements with a total injection area of 20% of the chamber cross section, giving d_{inj} = 2 mm. Fuel and O_2 injection pressures are assumed to be the same. Also, assuming sonic stoichiometric injection, it comes $d_f = d_{ox} \approx 1.2$ mm (ITEM1 version).

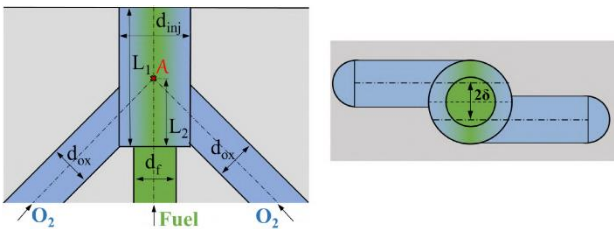

Fig. 1: Front ant top views of ITEM injection element.

2.2 ITEM element optimization

In the following, 5 ITEM versions (see Table 1) have been compared in Fig. 2 in terms of mixing efficiency η_{mix} (from [7]):

$$\eta_{\text{mix}}(y) = \frac{\iint_{S_y} u_y \rho Y_f / \max(ER_{\text{glob}}, ER_{\text{loc}})\, dS}{\iint_{S_y} u_y \rho Y_f / \min(ER_{\text{glob}}, ER_{\text{loc}})\, dS}$$

where u_y is the velocity component along the RDC axis y, ρ is the density, Y_f is the fuel mass fraction, and ER is the Equivalence Ratio, which can be global (equal to 1 here) or based on local composition. The risk of flashback has also been compared between the versions but is not detailed here.

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Table 1 Dimensions of the ITEM versions

Version	1	2	3	4	5
L_1 [mm]	2	5	3	3.8	4.5
L_2 [mm]	0.6	2	2	1.8	1.5
d_{ox} [mm]	1.2	1.15	1.15	1.15	1.15

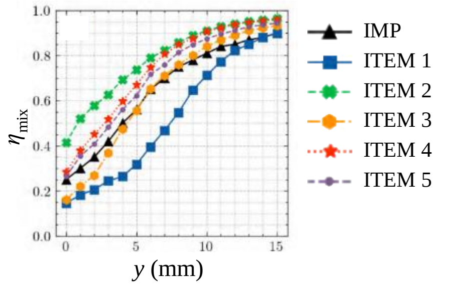

Fig. 2: Time-averaged η_{mix} along the distance from the injection plane for various simulated injection geometries.

LES simulations in a chamber sector with one injection element are performed according to the cold-flow methodology introduced in [8]. The prescribed total mass flow rate is 170 g/s, with a total temperature of 300 K and a 1.6 bar average pressure.

For ITEM1, Fig. 2 indicates that η_{mix} is lower than for IMP. Additional results in Fig. 3 show that the O_2 jets do not penetrate the fuel jet core, creating a poorly mixed zone in the chamber. Furthermore, the injection total pressure of the fuel is slightly higher than for O_2, which leads to stratification of the reactants. Hence, ITEM2 is designed with a lower O_2 injection section, giving a higher O_2 momentum. L_1 and L_2 are also increased to facilitate jet interaction. As a consequence, Fig. 2 indicates a higher η_{mix} for ITEM2 than for IMP, particularly due to its long prechamber that allows significant premixing. Consequently, this case presents a risk of detonation propagation back into the prechamber. Thus, L_1 is reduced by 2 mm for ITEM3.

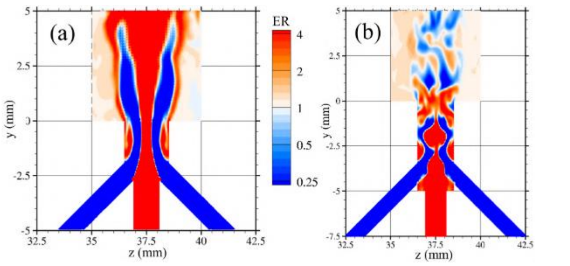

Fig. 3: Instantaneous *ER* field in the mid plane of the injection elements ITEM1 (a) and ITEM2 (b)

For ITEM3, however, Fig. 2 shows that reducing L_1 significantly decreases η_{mix}. In ITEM3, the prechamber is too short to create mixing interactions after the first impact of the O_2 jets on the prechamber walls, contrary to ITEM2. A deeper analysis of the results suggests that point *A* must be positioned at least 2 mm before the prechamber exit, i.e., $L_1 - L_2 \geq 2$. Thus, L_1 and $L_1 - L_2$ were increased for ITEM4.

For ITEM4, Fig. 2 thus shows a significant increase in η_{mix}. However, the entry of the O_2 jets creates a recirculation zone at the bottom of the prechamber. A partial premix already forms in this zone, which raises the risk of flame stabilization in the prechamber in the event of a flashback: L_2 should be reduced to limit the recirculation zone.

ITEM5 optimal design compensates for the reduction of L_2 by increasing L_1. Figure 2 shows that η_{mix} is higher throughout the chamber than with IMP. ITEM5 (hereafter referred to as ITEM) therefore appears to be a good compromise between mixture quality and flashback risk.

3. Experimental validation of ITEM performance

The goal of the experimental validation is to prove that the selected ITEM mixing configuration provides good conditions for detonation rotation in the RDC. Figure 3 compares detonation speeds in CH_4/O_2 mixtures for ITEM, a triplet injector in [7], and other literature data (in black) as a function of the RDC mass flux. The comparison demonstrates that the detonation speeds obtained with ITEM and a large annular gap of 10 mm are higher than the other results.

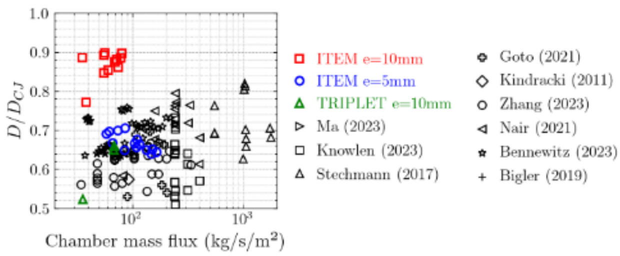

Fig. 4: Detonation speed ratio from experiments with annular RDCs fed with CH_4/O_2.

4. Conclusion

The numerical design of a partially premixed injector (ITEM), aimed at enhancing mixing in a RDC for rocket propulsion, is presented. Parametric LES studies demonstrated that some ITEM variants significantly increase the mixing efficiency compared with the reference IMP injector. However, there exists a risk of flashback with these variants, which required adjusting the prechamber length and impact location of the lateral O_2 jets. The optimal ITEM5 design combines a sufficiently long prechamber with a reduced recirculation zone at the prechamber bottom, providing a compromise between mixture quality and reduced flashback risk. Experimental validation confirmed that ITEM5 can help attain detonation speeds exceeding those with fully separate injection.

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