Numerical Study of the TUB Pintle Injector for an H_2/Air RDC

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Rotating Detonation Engines (RDE) possess a higher theoretical thermodynamic efficiency than engines using deflagration combustion. Achieving real pressure gain with an experimental RDE remains unattainable according to the current literature because of the various loss factors depending on the chamber and injector design. In order to be optimized, RDE injectors need to be characterized in terms of performance. This study involves the Large Eddy Simulation (LES) of a new pintle H_2/Air injector design developed by TU Berlin (TUB). Featuring circular arrangements of fuel tubes for transverse injection in two coaxial air inlets, the injector provided good operation stability of an experimental Rotating Detonation Combustor (RDC). Mass flow rate and detonation wave speed from a single-wave experiment were used as simulation inputs. A cold-flow injection simulation of a chamber angular sector was performed, showing good mixing characteristics with a nearly-uniform composition reached at 20 mm from the injection plane. A 2D unwrapped chamber is simulated to reproduce the conditions behind the detonation wave. These conditions were used to model the injector response without having to resort to a full 3D chamber simulation. A non-reactive 3D reinjection is simulated, demonstrating the back-flow effect of the detonation and the ability of the injector to fill the first 22 mm of the chamber with fresh gases before the detonation passage. A second reactive reinjection simulation is carried out to model the deflagration in the fresh mixture, showing an equivalent fresh mixture total mass reached at 29 mm and a further decrease in mixing efficiency. In the total mass within the refill zone, burnt gases represent 21% in the non-reactive case and 47% in the reactive case respectively. This study provides a first estimation of the injector performance and can act as a baseline state for the simulation of a complete RDC with rotating detonation.

Keywords: *RDC, LES, Mixing Efficiency, Transitory Injection, Pintle Injector, Reactive Flow*

1. Introduction

The implementation of detonation in combustion systems is potentially able to provide a better thermodynamic efficiency when compared to the traditional deflagration, and also to make a compact chamber [1]. Pressure gain in an RDC has been accomplished in idealized computations [2]. However, it has yet to be demonstrated in practical experiments, as shown by measurements of Bach et al. [3], implying that the chamber design and especially the injector have to be optimized to achieve a real pressure gain. Reactive LES simulations are needed to accurately model effects like dilution and parasitic deflagration [4] that play a significant role in RDC performance.

The “reinjection” computational technique, implemented by Gaillard et al. [5] offers a simpler way to characterize mixture quality, including dilution and deflagration effects. This technique has already been applied to the previous TUB injector by Hellard et al. [6]. To model the injector performance, the studies [5-7] introduce the mixing efficiency, defined as the fraction of fresh fuel and oxidizer mixed in proportions corresponding to the target global equivalence ratio.

The research team at TUB created a double pintle injector using staggered rows of orifices for fuel injection in two coaxial air flows on both sides of the pintle injector as seen in Fig.1. This injection scheme, inspired by the classical pintle injector for rocket applications, uses an oblique fuel injection in an axial air flow slightly upstream from the chamber entrance. The present study aims at a preliminary performance evaluation of the new pintle-type injector design based on the mixing efficiency.

2. Computational approach

Cold-flow and transient reactive LES are performed using the operating conditions of the TUB experimental RDC and the pintle injector geometry.

The computational domain is a 6-degree periodic sector shown in Fig.1. It includes the inner and outer air plenums, the fuel plenum with two injection tubes, and the annular chamber with a 25% section restriction at the exit. The plenums are artificially extended in the axial direction to avoid interactions with the inlet boundary conditions.

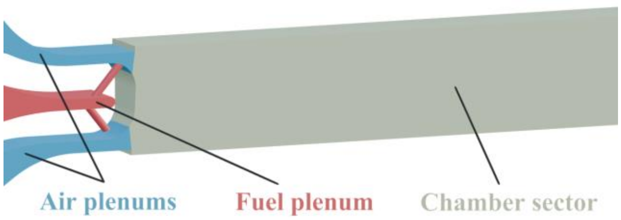

Fig. 1 3D periodic domain of the TUB RDC

The unstructured computational mesh is comprised of 2.1×10^6 cells with prism layers on the walls and tetrahedra filling the rest of the fluid volume. The CEDRE CFD software developed at ONERA, along with its CHARME solver for compressible reactive flows, is used to solve the Navier-Stokes equations.

The Smagorinsky model is chosen to account for the sub-grid turbulent scales. A simplified kinetic mechanism of 7 reversible reactions between 6 species is used for combustion modeling. Second-order accurate spatial schemes and implicit time integration are used for numerical solution.

A total air mass flow rate of 350 g/s is equally distributed between the two air plenums and a fuel mass flow rate of 9.98 g/s is injected to obtain a stoichiometric mixture. Both fluid flows have a total temperature of 300 K.

To initialize the 3D transient simulation, a rotating detonation simulation in a 2D unwrapped RDC of TUB is performed. To match the experimental single-wave operation with 79% of the Chapman-Jouguet (CJ) speed, H_2 is diluted with a non-combustible species H_2*, which is gradually converted into H_2 by an artificial reaction modeling the mixing process. For instance, an initial fuel dilution by 65% damps the heat release,

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lowers the detonation speed down to 85% of the CJ value, and decreases the pressure wave magnitude.

Flow parameter profiles right behind the 2D detonation wave are imposed as an initial condition downstream from the injector in the 3D transient simulations taking into account the refill time and the detonation effect on the fresh mixture recovery. The section restriction at the chamber exit is truncated by setting non-reflecting outflow conditions with a backpressure inherited from the 2D case.

3. Results

Figure 2 presents the fields of H_2 mass fraction relative to its stoichiometric mass fraction in the H_2/Air mixture in three different 3D cases. In the first cold-flow case, the design demonstrates good mixing capabilities with an almost homogenous stoichiometric mixture obtained at $x \approx 20$ mm. The reinjection non-reactive case is shown in the middle. The pressure wave generates a back-flow, delaying the injection. The fresh gases fill an area within $x \leq 22$ mm after a delay of 160 µs, corresponding to the experimental wave period. Finally, the influence of deflagration in the fresh mixture appears in the third case where H_2 is consumed in the middle of the chamber. The mixture spreads up to $x \approx 32$ mm due to the deflagration products pushing gases outwards of the reaction zone.

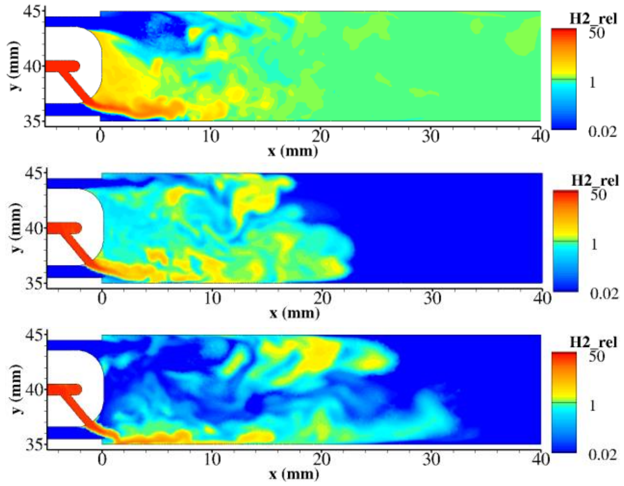

Fig. 2 Relative H_2 fields for the cold-flow simulation (top), non-reactive reinjection at 160 µs (middle), and reactive reinjection at 160 µs (bottom)

To evaluate the mixing efficiency, the mass-weighted reactant fractions are averaged in time for the cold-flow simulation. The following equation expresses the mass-weighted mixing efficiency in a cross section as a ratio between the mass of reactants in stoichiometric proportions and the mass of gas mixture:

$$\eta_{mix}(x) = \frac{\iint_{S_x} \rho \min(Y_{H_2}/Y_{H_2}^{st}, Y_{O_2}/Y_{O_2}^{st})\, dS}{\iint_{S_x} \rho\, dS}$$

The mixing efficiency curves in Fig.3 confirm the observations made previously. The instantaneous profile from the first reinjection case show a similar trend as the cold-flow case up to $x = 10$ mm, then deviates due to the bunt gas dilution. The deflagration results in an overall reduction in mixing efficiency for the reactive simulation.

Burnt gases proportions in the refill zone are computed for both cases. An equivalent total mass is contained within the first 22 mm of the chamber for the non-reactive case and 29 mm for the reactive case. Burnt gases represent 21% and 47% of this total mass respectively.

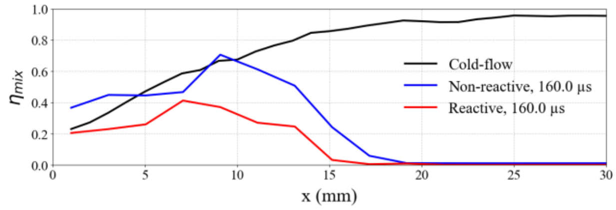

Fig. 3 Mixing efficiency evolution along the chamber length for the cold-flow and reinjection simulations

4. Conclusion

Operation of a new pintle-type injector of the TUB RDC was characterized numerically in terms of mixing efficiency. Cold-flow and reactive LES under experimental operating conditions were achieved. Effects of the transient refill process have been illustrated with and without deflagration.

Further work will be done to validate these results using a finer mesh and a more accurate kinetic mechanism, and finally, by performing rotating detonation simulation in a full RDC. The present work is a demonstration of the reinjection method that can be applied to various RDC injector designs and provide a baseline for a full RDC 3D simulation.

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