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► **To cite this version:**

Pierre Hellard, Thomas Gaillard, Dmitry Davidenko. Transitory injection simulation to study injector performance of an experimental Rotating Detonation Engine. IWDP & ICVDCW 2022, Aug 2022, Berlin, Germany. hal-03826979

HAL Id: hal-03826979

<https://hal.science/hal-03826979v1>

Submitted on 24 Oct 2022

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Transitory injection simulation to study injector performance of an experimental Rotating Detonation Engine

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Abstract

The injector of a Rotating Detonation Engine (RDE) is a key element providing stability and efficiency of its operation. On the one hand, it is widely accepted that experimental investigations of the injection and mixing processes in a RDE are difficult to perform. This is due to the short time period between consecutive detonation passages, the complex flow structure in the mixing zone and the severe conditions produced by the detonation in the combustion chamber. On the other hand, numerical simulation of the injection process represents a promising tool to investigate the unsteady effects produced by the rotating detonation on the injector operation. A modeling strategy has been previously proposed by ONERA to simulate the transitory injection in a RDE. This strategy is now applied to an experimental configuration, namely the H₂/Air RDE developed and tested at TU Berlin [1], to study the mixing of fresh reactants and to evaluate the fresh mixture quality. Instead of the whole injector, only one injection element is considered within a 3.6° sector with periodic boundary conditions. The simulated time period is between two consecutive passages of the detonation front over the injection element, evaluated from the available experimental results. The transitory injection simulations allow for quantification of the mixing efficiency in the combustion chamber and the deflagration losses that occur on the contact boundary between fresh and burnt gases. Transitory injection results are also compared to established injection results to highlight the effects of the burnt gases on mixing efficiency. This study shows that the expansion process of gases in the combustion chamber strongly influences the gas velocity in the mixing zone and therefore affects mixing efficiency. The studied injector seems to produce a moderately good mixing, and only a small fraction of burnt gases remains trapped in the base part of the chamber. The deflagration losses in the RDE are rather low, mainly because air is used as oxidizer, hence producing a relatively low combustion rate.

1 Introduction

RDEs are seen as a promising concept to improve the efficiency of conventional engines [2]. In its most studied version, the combustion chamber of an RDE is annular, and fresh gases are injected from its base end. One or multiple detonations propagate in the chamber along the circumferential direction, consuming the layer of fresh propellants injected during the time period between two consecutive passages of the detonation fronts over the same position.

Using detonation instead of constant-pressure combustion theoretically reduces the entropy creation during the combustion process, thus increasing the engine efficiency. Nevertheless, to the authors knowledge, no experimental studies have clearly demonstrated the efficiency increase in RDEs compared to traditional engines. Some studies have shown that RDEs are as efficient as conventional engines [3][4], but many loss factors reduce the potential energy output of RDEs, mainly deflagration losses [5], poor mixing [6][7] and discharge losses in the injector [5]. Therefore, the injector is a key element of an efficient RDE. Injection systems are more and more studied numerically [8][9] and experimentally [10][11][12]. When they aim at quantifying mixing, most studies use cold-flow experiments or simulations, but neither refilling process nor deflagration losses can be reproduced with these approaches. Also, the computational cost of a whole engine simulation is still prohibitive to perform a design optimization.

The present study aims at applying a numerical methodology to model the transitory injection in an experimental RDE. This method makes it possible to study mixing and deflagration losses occurring during one time period between two consecutive detonation passages.

2 Computational method

2.1 Numerical method

In the present study, compressible reactive Large Eddy Simulations (LES) are performed with the CEDRE [13] multiphysics software developed at ONERA. The CHARME solver is used to resolve the compressible Navier-Stokes equations. The finite-volume method on general unstructured meshes is utilized for spatial discretization. The MUSCL (Monotonic Upstream Scheme for Conservation Laws) interpolation scheme with the Van Leer slope limiter provide second-order accuracy on the convective fluxes. A central-difference second-order scheme is used to compute the viscous fluxes. A first-order Euler-implicit scheme is used for time-integration. The Smagorinsky model is chosen to account for the effect of subgrid turbulence scales.

2.2 Computational domain

The geometry studied hereafter is the annular chamber of the experimental RDE designed and operated at the Technische Universität of Berlin (TUB) [1]. The annulus inner and outer diameters are 74.8 mm and 90 mm respectively, resulting in a 7.6 mm radial gap, whereas the length of the chamber is 110 mm. Air is injected radially from the outer wall through a 1 mm slot and H_2 is injected through 100 evenly spaced 0.5 mm holes.

In this study, only a sector of the chamber is simulated, namely 1/100 of the whole circumference. This simplification allows the use of a fine mesh that permits to capture in detail the turbulent mixing and deflagration at a relatively low computational cost. A previous numerical study on a comparable geometry [14] has shown that the number of simulated injection elements has little impact on mixing.

A section of the computational mesh is shown in figure 1. The mesh is composed of 1.6 million tetrahedrons, with a minimum size of 100 μm in the mixing region, and the size is gradually increased towards the outlet. A prism layer is added on the walls of the slot to capture boundary layer effects. The mesh refinement is therefore comparable to previous RDE simulations performed by different laboratories [14][15].

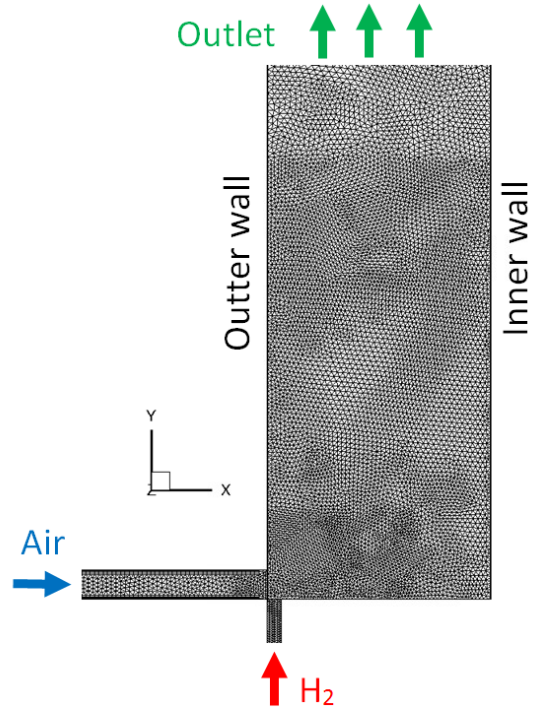


Figure 1: Sectional view of the computational domain corresponding to the TUB RDE

The conditions in the chamber are taken or evaluated from the experiment [16] as given in table 1. The selected chamber geometry has an outlet restriction of 50%, creating a sonic throat for the selected operating point. Mass flux and total temperature at the inlet of the Air slot and H_2 tube are imposed, whereas the outlet boundary condition is set as supersonic. Periodic boundary conditions are imposed over the radial planes. During the experiment, one detonation wave was obtained, propagating at 1550 m/s, approximately 80% of the theoretical Chapman-Jouguet speed (D_{CJ}) computed from the mean chamber pressure, global equivalence ratio and inlet propellants temperature. The speed of the detonation induces a $t_{end} = 170 \mu\text{s}$ time period of rotation. This time period is available for injection, in the present reinjection simulation.

Global equivalence ratio ER_{glob}	1
Mass flux at the chamber cross section ($\text{kg}/\text{m}^2/\text{s}$)	100
Mean static pressure in the chamber (bar)	2.1
Mean detonation speed D_{exp} (m/s)	1550

Table 1: Conditions of the selected operating point of the TUB RDE [16]

2.3 Initial condition

The reinjection simulation methodology described in [17] is used to model the burnt gases expansion in the chamber. In fact, due to the transient nature of the rotating detonation, pressure at the injection wall is strongly variable. According to [18], typical exponential decay of the pressure can be obtained at the bottom of the chamber during one period of the detonation propagation. This unsteadiness needs to be taken into account to correctly capture injection and mixing dynamics, especially the longitudinal stratification of fuel and oxidizer as obtained in previous numerical studies [19][20]. Therefore, a custom initial condition must be imposed in the chamber to model pressure

and temperature evolution produced after the passage of a detonation. The initial conditions in the injector channels are taken from established simulation with cold flow injection.

3 Results and discussion

3.1 Non-reactive simulation

Firstly, a non-reactive reinjection simulation is carried out to compare the reinjection dynamics with an established injection. To study mixing in the chamber, the Z_i variables (proposed in [17]) will be used below. Z_i are computed in every mesh cell and have a particular meaning: Z_{st} corresponds to the mixture volume fraction at stoichiometry (i.e. the volume fraction of propellants that can reach complete combustion), $Z_{H_2,ex}$ (respectively $Z_{O_2,ex}$) is the H_2 (respectively O_2) volume fraction in excess compared to stoichiometry, while Z_{bg} is the burnt gas volume fraction. Hence the sum of Z_i is equal to unity.

Figure 2 shows the $Z_{H_2,ex}$ field at $t = 5, 10$ and $15 \mu s$. Blocking and backflow of burnt gases in the fuel tube can be clearly seen at $5 \mu s$. The same phases happen for the *Air* slot (not shown here). At $10 \mu s$, the chamber pressure falls below the H_2 injection pressure, allowing the injection of H_2 . On the other hand, the *Air* slot is still blocked. This phenomenon creates an axial stratification and a fuel rich mixture close to the outer wall of the engine at $t = 15 \mu s$.

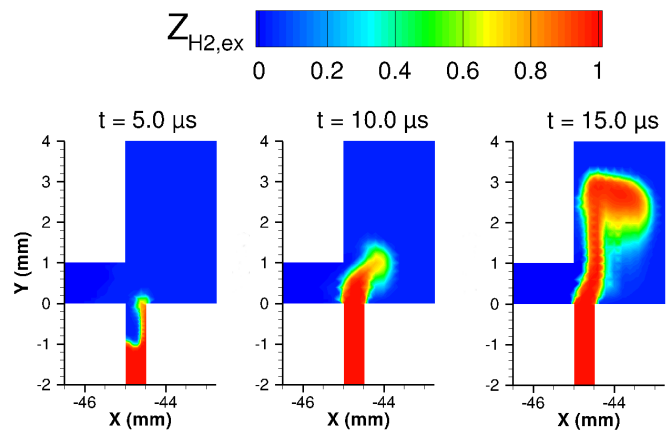


Figure 2: Instantaneous fields of $Z_{H_2,ex}$ at $t = 5, 10$ and $15 \mu s$ in the mid plane of the injection element

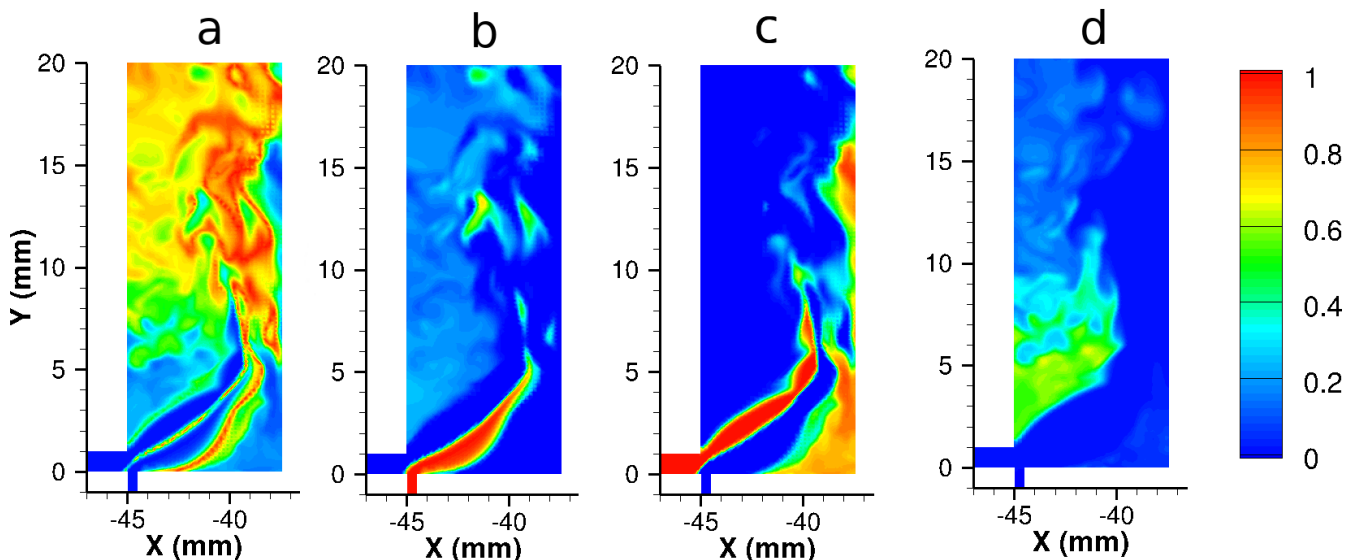


Figure 3: Instantaneous fields in the mid plane of the non-reactive flow at $t = 170 \mu s$: a) Z_{st} , b) $Z_{H_2,ex}$, c) $Z_{O_2,ex}$, d) Z_{bg}

At the final state (see figure 3), that corresponds to the mixture the detonation will consume, a good mixing is obtained above $y = 5$ mm and slightly closer to the inner wall of the engine (see

figure 3a). The rich zone created close to the outer wall at the beginning of the simulation can still be observed (see figure 3b). It is located in a recirculation zone, in which a part of the burnt gases from the previous detonation are stuck (see figure 3d). Meanwhile, a lean mixture is formed in the recirculation zone located at the bottom of the chamber, and along the inner wall (see figure 3c).

Mixing efficiency from the reinjection and established flow simulations can be compared. Mixing efficiency is defined by equation (1). It corresponds to the mass fraction of fresh gases which are in proportions that respect the global equivalence ratio of the chosen operating point (ER_{glob}) whereas ER is the local equivalence ratio.

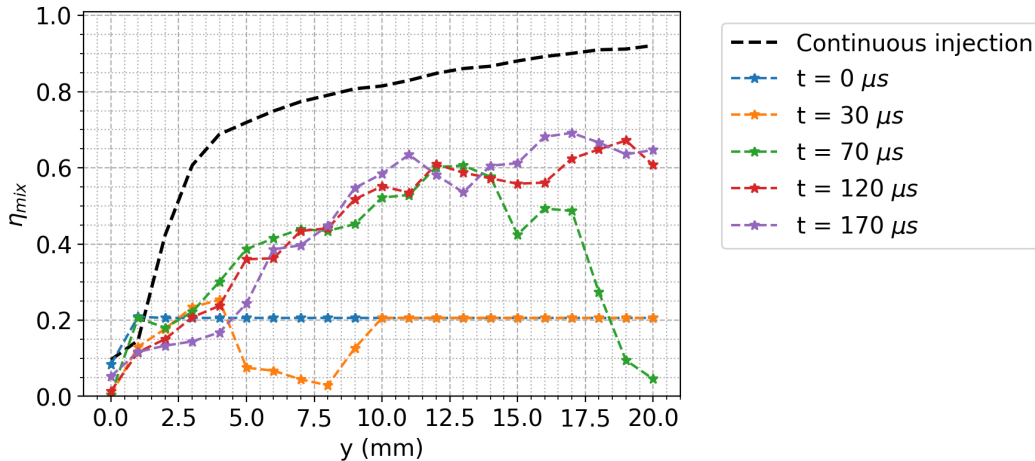


Figure 4: Mixing efficiency versus axial position in the computational domain. In black: time-averaged continuous injection; in color: mixing efficiency for various time instants

$$\eta_{mix}(y, t) = \frac{\iint_{S_y} \frac{\rho Y_{H_2}}{\max(ER, ER_{glob})} dx dz}{\iint_{S_y} \frac{\rho Y_{H_2}}{\min(ER, ER_{glob})} dx dz} \quad (1)$$

Instantaneous profiles of mixing efficiency at different times from the reinjection simulation and the time-averaged mixing efficiency of the established injection are compared in figure 4. Mixing efficiency increases with time and gets to a maximum at $t = 120 \mu s$. At the same time, the fresh mixture layer reaches $y = 20$ mm (the maximum axial distance shown in figure 4). The mixing efficiency of the reinjection simulation is far below the mixing efficiency of the established simulation. In fact, the established injection simulation was performed with the mean outlet chamber pressure from table 1. On the contrary, the chamber pressure is not constant in the reinjection simulation, and it falls below the mean outlet pressure after approximately $50 \mu s$. This lower pressure increases the flow velocity in the chamber, thus the reactants mix further away from the bottom of the chamber (above 20 mm) compared to the continuous injection.

3.2 Reactive simulation

The reinjection simulation presented in this section is performed with chemical reactions. The kinetic mechanism for the present H_2 /Air mixture was proposed in [21] and contains 7 chemical species and 7 reactions. It has been tested for H_2/O_2 detonation and H_2 /Air deflagration, demonstrating good results compared to more complex detailed mechanisms.

The reactive simulation presents few differences compared to the non-reactive one. Only an increase of Z_{bg} in the recirculation zone located just above the slot can be seen, which is due to the

combustion of fresh gases. The reactive simulation makes it possible to compute the deflagration losses in the engine. Multiple strategies can be used to determine the mass of fresh gases consumed by deflagration. Here, it was decided to use the mass balance of fresh gases between the inlet and outlet of the combustion chamber. The CEDRE software allows to save the instantaneous mass flow rates at the inlet and outlet boundaries (\dot{m}_{in} and \dot{m}_{out}) and the mass integral in the computational domain (m_{cmb}). Hence for each reactant, the rate of consumption by deflagration (\dot{m}_{def}) can be computed for each timestep with equation (2).

$$m_{cmb}(t + \Delta t) = m_{cmb}(t) + \int_t^{t+\Delta t} (\dot{m}_{in} - \dot{m}_{out} - \dot{m}_{def}) dt \quad (2)$$

The amount of fresh propellants in the chamber, divided by the total mass injected during the simulation is shown in figure 5. It is computed as the difference between the mass injected in the chamber and the mass consumed by deflagration.

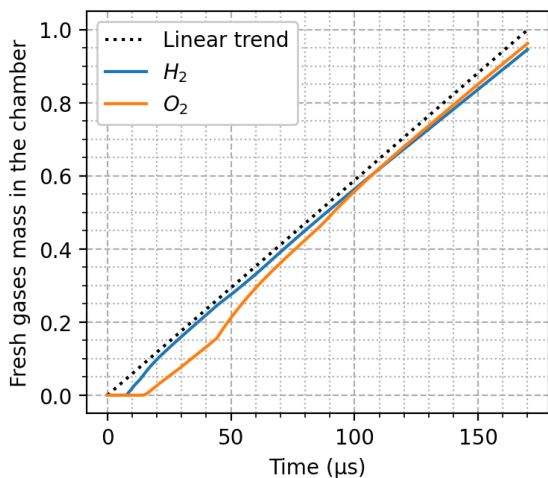


Figure 5: Amount of fresh gases in the chamber divided by the total mass injected during the simulation for H_2 (blue) and O_2 (orange)

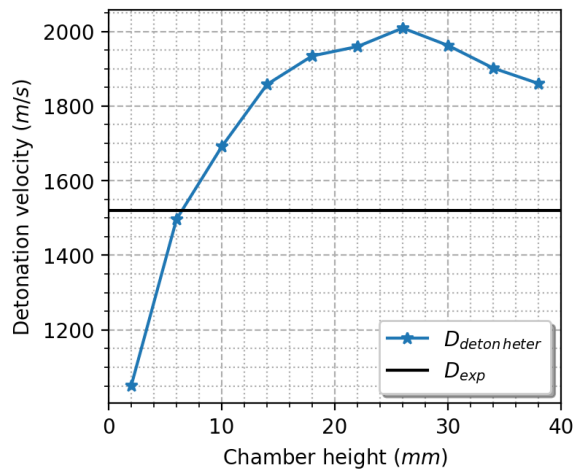


Figure 6: Detonation speed evaluated with the inhouse *DetonHeter* code compared to the mean experimental value

The time delay between the start of H_2 and Air reinjections is visible. The deflagration losses are of the same order of magnitude for the two reactants: only 5% are consumed by deflagration. Therefore, the consumption of fresh gases is small under the conditions of the present study.

3.3 Detonation propagation

The final flowfield from the reactive simulation is used as input for the inhouse *DetonHeter* code, which can account for mixture heterogeneities to evaluate the detonation propagation speed. The computational domain is divided into 10 slices of 4 mm in height, and the computation is performed with the heterogeneous state of each slice. The detonation propagation speed obtained is displayed in figure 6. The experimental value is shown for comparison.

The computed detonation speed presents a bell shape as seen in figure 6. In fact, in the bottom of the chamber, fresh gases are not well mixed, inducing an important speed deficit. As shown before, mixing improves along the chamber axis, thus increasing the detonation speed, which reaches a maximum around 26 mm above the injection wall. The following decrease is caused by the growth of burnt gas mass fraction, that remains on the top of the fresh mixture layer.

The experimental detonation propagation speed lies within the range obtained with the *DetonHeter* code. Nevertheless, the experimental speed is about 400 m/s slower than the maximum

numerical detonation velocity. In the present modeling approach, state parameters of the reactive mixture are related to the equivalence ratio of fresh mixture and the mass fraction of burnt gases. As well, the model uses simplified assumptions of uniform pressure and flow speed past the detonation. Such a model may be too simple to accurately predict the detonation propagation velocity, especially when the mixing is as heterogeneous as in the present simulation.

4 Conclusion

In the present numerical study, a custom initial condition was used to model the transient behavior in an experimental RDE. It was shown that the effect of the burnt gas expansion has a major impact on the mixing process: it can create an axially stratified mixture, leading to a global reduction in mixing efficiency because of the non-synchronized propellant admission during the pressure drop on the injector. Thus, mixing in the reinjection simulation may be significantly different as compared to the established injection. For the TUB RDE, few differences in mixing are obtained between the reactive and non-reactive cases. Moreover, deflagration losses, computed from the reactive simulation, show that little amount of fresh gases is burnt by deflagration in the TUB RDE. Finally, the detonation speed computed from the mixture state in the simulation was found above the experimental velocity.

5 Acknowledgement

The comparison between numerical and experimental results of the RDE was possible thanks to the experimental data shared by TU Berlin. Special thanks to Prof. Myles Bohon who quickly accepted this sharing, and Dr. Eric Bach who provided the data.

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