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Numerical simulation of a Rotating Detonation with a realistic injector designed for separate supply of gaseous hydrogen and oxygen

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A B S T R A C T

This paper presents numerical results for a Rotating Detonation (RD) propagating in a layer of combustible mixture, created by injection of gaseous hydrogen and oxygen. 3D Large Eddy Simulations (LES) of a reacting flow have been performed in a domain of planar geometry in order to eliminate possible effects of the chamber curvature. First, the results for a 2D case with uniformly distributed premixed injection are presented to characterize the RD propagation under the most idealized conditions. Then a 3D concept is introduced for the injector composed of a series of injection elements. The RD propagation is simulated under the conditions of premixed and separate injection of the propellants at globally stoichiometric proportions. The case of separate propellant injection is the most realistic one. The computational results, represented by instantaneous and averaged flowfields, are analyzed to characterize the flowfield and the conditions of RD propagation. This analysis allows identifying the effects due to two major factors: the injection through discrete holes with respect to the distributed one and the separate propellant feeding with respect to the premixed one. Macroscopic quantities, such as the RD propagation speed, mean chamber pressure, average parameters of the mixture, and mixing efficiency are evaluated and compared in order to characterize the studied effects.

1. Introduction

The interest in the Rotating Detonation (RD) to enhance rocket propulsion efficiency was already noticeable in the 1960s [1–3]. During the last two decades, one could observe an important rise of research activities in the experimental, theoretical, and computational fields to study the feasibility and expected gain of Rotating Detonation Engine (RDE) concepts. The issues that must be tackled to bring these concepts to reality are summarized in different papers such as [4–6]. A large amount of experimental work has been carried out with the objective to identify these issues and propose technological solutions. RDE operation with gaseous and liquid propellants has been tested as reported in Refs. [7–11]. Experimental studies have been conducted since several decades in Russia and later in Poland and France [12,13]. More recently, researchers from the United States and China started actively participating in experimental testing of RDE.

Semi-analytical and simple 0D models have been developed to evaluate the theoretical performance of RDE [14,15]. Even if parametric studies are more complex with 2D/3D models, numerical simulations are now commonly used, as in Refs. [15–22], because they can depart from too simplifying assumptions and give a deep insight into the flow physics. However, the injection of a homogeneous fuel-oxidizer mixture was considered in most of the simulations.

Injection of a homogeneous fuel-oxidizer mixture is possible and desirable to ensure the most favorable conditions for the RD propagation. But it can also be troublesome: a deflagration initiated by the contact of fresh and hot gases, when the injection is blocked after the RD passage, may propagate upstream in the injector. Another risk is the detonation transmission through the injection holes. To avoid these two risks, one should respect some limitations related to the hole diameter.

Far from the propagation limit, detonation has a multi-head shock front with moving shock intersections. Trajectories of these intersections in a plane along the propagation direction form a cellular pattern with diamond-shaped cells. The detonability of a fuel-oxidizer mixture under particular conditions is characterized by the mean cell width λ. For detonation propagation in a tube, there exists a critical diameter d_{crit}, below which the propagation is not possible. The critical diameter can be evaluated according to Fay's theory [23] and Virot [24] as $d_{crit} = \lambda / \pi$. As

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an idealized case of RD propagation, consider a stoichiometric mixture of hydrogen and oxygen at $p = 0.1$ MPa and $T = 300$ K for which $\lambda \approx 1.4$ mm according to the measurements of Manzhalei et al. [25]. At a realistic injection pressure of 1 MPa, λ decreases to about 0.15 mm [25] and the corresponding critical diameter for the injection holes is $d_{crit} \approx 48$ μm. Respecting such a limitation would lead to important technological issues as well as tremendous pressure losses.

The only way to prevent combustion from propagating inside the injector is to feed the oxidizer and fuel separately as in the practice of RD experiments. However, the necessity to mix the fresh propellants inside the combustion chamber results in less favorable conditions for the RD propagation. For example, a propagation speed deficit amounting up to 20% with respect to the ideal Chapman-Jouguet (CJ) detonation under premixed conditions was found in the experiment described in Ref. [8].

An evolution from an idealistic to more realistic approach in simulation of propellant injection can be observed during the last decade. For example, in early 2D simulations, Zhdan [16] and Davidenko et al. [26] considered uniformly distributed injection. Then, to account for the section variation from the injector to the chamber, slotted injection was used by Eude et al. [27]. Five different slotted injection configurations were simulated and compared by Liu et al. [28]. Schwer et al. [29] analyzed the pressure feedback in the injector due to the RD propagation over a series of holes. However, in the aforementioned simulations, the injected propellants were perfectly mixed. The work of Frolov et al. [30] is the first one demonstrating a 3D simulation of a RD with a real geometry and separate injection of gaseous propellants. In Ref. [31], separate injection of H_2 and air is considered but only a cold flow simulation is presented in combination with the "Induction-time Parameter Model" for the H_2-air detonation. Separate injection is also considered in Ref. [32] but the simulation is non-reactive and the computational domain is reduced to a sector of an RDE annulus. Recently, Cocks et al. [33] have also performed RD simulations with separate injection of H_2 and air in a 3D configuration studied at the Air Force Research Laboratory.

Considering the small number of publications concerning the RD simulation with separate injection of fuel and oxidizer, the injection and mixing processes as well as their interaction with the RD need better understanding. That is why this topic is mainly addressed in the present contribution.

The authors proposed in Ref. [34] a realistic manufacturable configuration for separate injection of gaseous hydrogen and oxygen, which was optimized using non-reactive unsteady 3D simulations. As an extension of that previous work, simulations of a RD propagating over a row of optimized injection elements from Ref. [34] will be presented in the following sections.

In section 2, the context of the study linked to the operation of a RDE is presented. In section 3, the computational approach is explained. Section 4 presents 2D reference results on the RD propagation with uniformly distributed premixed injection. Section 5 reminds the characteristics of the optimized injection configuration used in the 3D computations of a RD. Section 6 is dedicated to the numerical methodology of the 3D LES simulations. The main features of the reactive flow are presented in section 7 for an established RD propagation. The results for the premixed and separate injection regimes are compared considering the obtained flowfields and several macroscopic parameters characterizing the operation conditions. The conclusion section summarizes the obtained numerical results and suggests improvements of the modeling methodology for the injector optimization. Appendix A presents simulations results for freely propagating detonation and deflagration used to validate the modeling approach. Appendix B describes the procedures used to post-process the 3D simulation results.

2. RDE operation principle

Among possible configurations of RDE combustion chambers, the one with an annular cylindrical combustion chamber is considered in the present study. Its operation principle is schematically shown in Fig. 1. The fuel and oxidizer (1) are fed through holes in the injection wall (2). After detonation initiation at the engine start, one or several RD fronts (3) propagate in the layer of combustible mixture (4) created by the propellant injection. The height of the RD front, h, and the spatial period, l, between successive fronts are proportional and depend on the propellants and injection conditions. At a stable operation regime, the RD waves propagate continuously in the same azimuthal direction thus having rotational motion about the chamber axis. The RD waves induce oblique shocks (5) in the burnt gases. Combustion products generated by the RD waves expand in the chamber and discharge through the open end (6) of the duct.

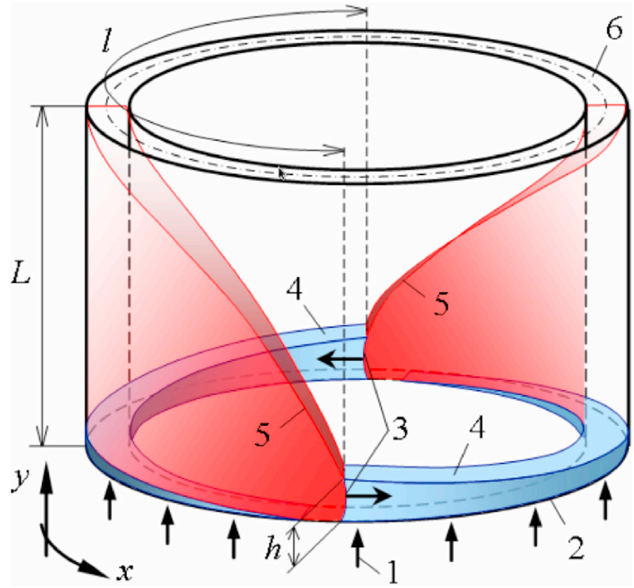

Fig. 1. Principle of the RDE operation: 1 - propellant injection; 2 - injection wall; 3 - RD fronts; 4 - fresh mixture layer; 5 - oblique shocks; 6 - outlet section; h - height of RD front; l - spatial period between successive RD fronts; L - chamber length.

3. Computational approach for RD simulation

Although the present paper is devoted to simulation and analysis of RD propagation under realistic injection conditions, the chamber is considered in a simple way with no relation to a particular geometry of the duct. The main reason for this is the intention to study the effects due to the injection without coupling them with the other ones, such as the effects due to the curvature of the annular passage and the viscous interaction on the cylindrical walls. It was shown by Eude et al. [35] that the 3D flowfield in an annular chamber becomes close to the 2D flowfield if the mean radius of the annulus is sufficiently large with respect to the duct width (radial distance between the cylindrical walls), hence there will be no critical change in injector operation if used in a real chamber.

Only one row of injection elements is considered assuming that mixing interactions with the adjacent rows are modeled using periodic conditions on the lateral boundaries as explained in section 5. This assumption is not applicable to a near wall row. This implies that the perturbations have a periodic behavior, which may not be true in reality because the RD is not always at the same position across the rows. Another reason for duct geometry simplification is to limit the computational cost of 3D simulations. Thus simulations could be run with different conditions for comparative analysis and during sufficiently long physical time to obtain well established flowfields.

Multiple RD can propagate in the annular chamber of a RDE if its diameter is sufficient. When the propagation regime is stable, the number of waves, the distance between them, their velocity and their height are