Acta Astronautica 111 (2015) 334–344

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Numerical Optimisation in Non Reacting Conditions of the Injector Geometry for a Continuous Detonation Wave Rocket Engine

T. Gaillard *, D. Davidenko, F. Dupoirieux

ONERA, DEFA, Chemin de la Hunière, BP 80100, 91123 PALAISEAU CEDEX, France

A R T I C L E I N F O

Article history:
Received 7 November 2014
Received in revised form
4 February 2015
Accepted 6 February 2015
Available online 14 February 2015

Keywords:
Numerical simulation
Gaseous injection
Turbulent mixing
Rotating detonation

A B S T R A C T

The paper presents the methodology and the results of a numerical study, which is aimed at the investigation and optimisation of different means of fuel and oxidizer injection adapted to rocket engines operating in the rotating detonation mode. As the simulations are achieved at the local scale of a single injection element, only one periodic pattern of the whole geometry can be calculated so that the travelling detonation waves and the associated chemical reactions can not be taken into account. Here, separate injection of fuel and oxidizer is considered because premixed injection is handicapped by the risk of upstream propagation of the detonation wave. Different associations of geometrical periodicity and symmetry are investigated for the injection elements distributed over the injector head. To analyse the injection and mixing processes, a nonreacting 3D flow is simulated using the LES approach. Performance of the studied configurations is analysed using the results on instantaneous and mean flowfields as well as by comparing the mixing efficiency and the total pressure recovery evaluated for different configurations.

1. Introduction

The ability of detonation to increase the thermodynamic efficiency of an engine cycle, when it is used instead of deflagration [1,2], has been theoretically proved. This benefit is allowed by gas compression in detonation waves providing an additional pressure increase in the combustion chamber.

First theoretical performance estimations for a rocket engine operating in the Rotating Detonation mode (RD) are known from the report by Nicholls and Cullen [3] and the paper by Adamson and Olsson [4]. Since that time, a lot of experimental, computational and theoretical work has been performed by a group of Russian researchers at the Lavrentyev Institute of Hydrodynamics [5] to prove the feasibility of RD with various propellants. In a more recent study of Davidenko et al. [6] on a rocket engine fed with hydrogen and oxygen, it has been shown that the RD mode offers theoretical benefits over the conventional one.

This paper is devoted to a numerical investigation of different injection configurations, which can be applicable to rocket engines operating in the RD mode, also called Continuous Detonation Wave Rocket Engines (CDWRE). In a CDWRE, stable detonation waves are maintained in a layer of fresh mixture formed near the injector head. In the case we consider, the detonation waves propagate azimuthally in an annular combustor fed with two gaseous propellants, H_2 and O_2, in stoichiometric proportion. The period between two detonations is a small fraction of millisecond hence the injector must provide a very quick refilling of the combustor duct with fresh mixture. To preserve the theoretical benefit from the RD mode, two main requirements need to be

* Corresponding author. Tel.: +33180386067.
E-mail address: thomas.gaillard@onera.fr (T. Gaillard).

http://dx.doi.org/10.1016/j.actaastro.2015.02.006
0094-5765/

met: (i) high uniformity of the fresh mixture layer providing the highest possible compression by detonation and (ii) low losses of the injection total pressure to have finally some gain in the flow total pressure at the combustor exit.

The oxidizer and fuel can be injected either separately or premixed. From the theoretical point of view, a strong advantage of fully premixed injection is the possibility to obtain complete combustion and the highest possible compression from the detonation. With a perfect premix, the challenge is to properly fill the radial section of the chamber without excessive pressure loss and dilution of the fresh mixture by the hot combustion products.

Two risks must be considered: hot gas penetration enhanced by deflagration propagation when the back pressure in the chamber exceeds the feed pressure and secondly, detonation transmission through the injector holes. The second risk is the most important. To prevent it, it is necessary to reduce the diameter of the injection holes to a small value linked to the detonation cell size. This leads to very high losses of injection pressure and also to technological difficulties of injector manufacturing because of a large number of very small holes.

Premixed injection is often considered in numerical simulations to simplify the computational approach. In different 2D and 3D studies, the injection is treated as uniformly distributed by using a specific model for the injection conditions (see for example [7–9]). In more complex 3D simulations, the flow is simulated in some portion of the injector but detonation transmission is artificially blocked within the injector [10–12].

Because of the difficulties inherent to premixed injection, separate injection of the oxidizer and fuel is commonly used in experiments on RD. In this case, detonation can not propagate back in the injector holes so that their diameter is not a priori strictly limited. However, the benefit of premixed injection is now lost. Thus, it is essential to ensure fast and efficient mixing between the propellants to get the expected potential of detonation. The experimental studies, known to us, provide little information concerning the injector design and real conditions in the layer of fresh mixture. In the experiment of Bykovskii et al. [13], stably propagating detonations were observed with a velocity deficit up to 20% of the theoretical value that may be due to imperfect mixing and pressure losses. For that reason, the numerical simulations presented in this paper are focused on separate injection.

The long-term objective of our work is to model operation of a complete CDWRE combustor by 3D flow simulations. To our best knowledge, there is no well-established design methodology for a CDWRE injector. Before dealing with a complete combustor, we have to achieve a first step consisting in optimization of the injector design in simplified ideal conditions being not perturbed by the travelling detonation waves. We consider a regular pattern of injection holes for both propellants. Fig. 1 shows an example of the injector layout with one ring of injection holes. Considering a regular and repetitive arrangement of injection holes along the azimuth and radius, the used methodology relies on the extraction of a single element from the whole injector configuration as schematically shown by the wireframe in Fig. 1.

The mixing of established propellant jets is simulated by Large Eddy Simulation (LES) in a 3D spatially periodic domain for different injection configurations. Among the considered configurations, the optimum one is identified by comparing their efficiencies in terms of H_2/O_2 mixing and total pressure recovery. These simulations do not perfectly match real conditions in a CDWRE combustor because they do not take into account the following main factors: first, the jet development phase after a detonation wave passage (we keep this subject for a future study) and second, the presence of combustion products, which can partially mix and react with the injected propellants. Regarding these factors, the simulation results are representative of the injection phase when the propellant jets are fully developed and of a part of the fresh mixture layer close to the injector head. Nevertheless, it will be shown that the differences in mixture quality obtained with the

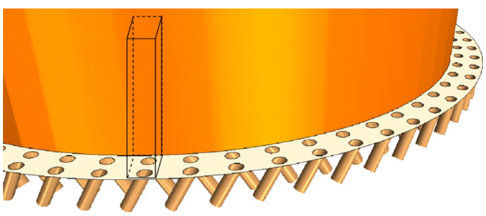

Fig. 1. Representation of one row of the hole pattern for separate injection. The wireframe outlines the domain extracted for the computational study of a single injection element.

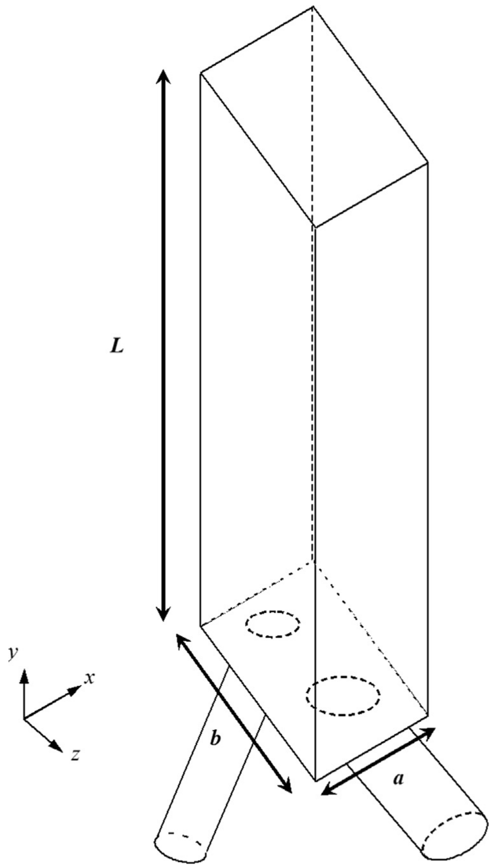

Fig. 2. Injection element and mixing domain.