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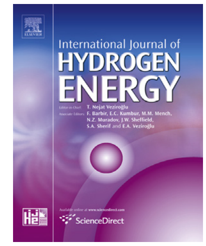

Theoretical investigation of air vitiation effects on hydrogen fuelled scramjet performance

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ABSTRACT

The renewed interest in the next generation hypersonic vehicles for commercial and military applications requires combined efforts between multidisciplinary teams involved in computational and experimental work. A common feature of experimental tests, at least for studies on air breathing propulsion systems, is the relatively short test time, limited by the test flow conditions high dynamic pressure and total enthalpy, i.e. 10 MPa at Mach 8 flight conditions. In general, it can be stated that test times decrease as the flow Mach number increases, with changes of several orders of magnitude: a few tens of microseconds for shock tube based tunnels (Mach numbers above 10–15) to tens of seconds or even minutes for the high supersonic range (Mach 4–7.5). In many cases the test flow chemical composition differs from the standard air composition because of pollutants production by the different techniques adopted to increase the flow stagnation enthalpy (combustion products, ionized species, dust, ...). The real flow conditions are thus not perfectly duplicated, but only partially simulated in terms of a few main parameters, such as velocity, pressure, and temperature. Few studies have been performed until now, therefore a deep investigation of the air vitiation effects on combustion is mandatory to extrapolate ground to flight correlations. Numerical simulations accounting for the effects of vitiation are also scarce and a characterization of the chemical and turbulence models is still lacking. In this context, CFD simulations of the LAPCAT II MR2 combustor configuration have been performed to provide useful information in terms of efficiency at various vitiation percentages. Theoretical laws and remedies have been proposed for the ground to flight data extrapolation.

Introduction

Understanding the effects of vitiation on Hydrogen/air [1,27,28] combustion performance is critical for the correlation of ground to flight test data. Effects of air vitiation due to the presence of H_2O, OH and NO on flame temperature and ignition delay have been investigated by several authors [2–17]. An exhaustive review has also been written by Pellet et al. [18,19]. The critical issue of air vitiation arises from the requirement for testing high M vehicles in flight, to duplicate, in wind tunnels, three non-dimensional groups such as Mach, Reynolds and Damköhler [20]:

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- Mach number: $M \sim U/\sqrt{\gamma RT}$
- Reynolds number: $Re \sim \rho UL/\mu \sim pL(U/T^{3/2})$
- Damköhler number: $Da \sim L/U/\tau_c$

where τ_c is the hydrogen/air ignition delay time. Due to the hydrogen/air third–body reactions [21], the ignition delay time depends exponentially on temperature and inversely on pressure, i.e. $\tau_c \sim exp\ (\theta/T)/p$ and consequently, $Da \sim pL/[U \cdot exp\ (\theta/T)$ (with θ being the auto-ignition temperature).

Therefore, in order to replace M, Re, Da, attention must be posed on the selection of the following five parameters: static pressure p, static temperature T, velocity U, the characteristic length of the model L, and the gas composition. In fact, to obtain high M flows during ground tests, the obvious way is to increase air pressure and then let it expand, converting enthalpy into kinetic energy. If the high pressure air is at room temperature (a common occurrence in so-called blow-down facilities) the expansion will ensure high Mach, but the temperature will drop with pressure, and will be much lower than that of the air entering the engine in flight. Thus the air at high pressure must be preheated before being expanded to reproduce the flight M. In this way, velocity, temperature, pressure and geometry flight conditions are replaced, however, uncertainties due to the different gas composition are introduced. Typical percentage of steam (in molar fraction) are estimated in 5–30%\cite{Pellet}. The main issue in wind tunnels operations is therefore the prediction, the estimation and, if possible, the control of vitiation [18] on scramjet (SCRJ) test performance. What follows is a theoretical analysis of these effects by means of 2D Reynolds Averaged Numerical Simulations of the LAPCAT II MR2 combustor configuration, developed within the LAPCAT II European project, performed for different vitiated air compositions.

Numerical simulations of the impact of air vitiation on the MR2.4 combustor

LAPCAT II MR2.4 scramjet

The LAPCAT II European project has the ambitious goal to investigate the feasibility of a hypersonic commercial passenger vehicle able (see Fig. 1) to achieve the anti-podal range Brussels-Sydney (~18000 km) in about 2 h at Mach 8 [22,23]. The 3D LAPCAT II MR2.4 scramjet combustor geometry is shown in Fig. 2 [24]. The injector system of the LAPCAT II MR2.4 flight concept is a V-shaped array of full-strut fuel injectors; every strut is equipped with two rows of injection holes. For this preliminary study, a simplified 2D geometry of the LAPCAT II MR2.4 combustor has been simulated. The 2D combustor chamber consists of a rectangular shape (see Fig. 3) that extends along the axis x by $x_{inlet} = 29.445\ m$ to $x_{outlet} = 38.729\ m$ for a total length of 9.284 m and along the y axis for a total width of 2.09 m. Only 11.5 of the 23 injectors have been simulated: these 11.5 injectors, spaced from each other, along y, of about 15 cm, are placed along a virtual line inclined by about 40° downwards. Combustor inlet conditions for all cases are reported in Table 1. The flow is assumed uniform at entrance.

Fig. 1 – LAPCAT conceptual vehicle.

Numerical simulations of the impact of air vitiation on the MR2.4 combustor

Reynols Averaged Numerical simulations have been performed by means of the commercial code Fluent13 (Ansys Inc. 2011). This domain is discretized with approximately 71,400 cells. The speed of the incoming flow, parallel to the x axis is $V_{air} = 2500\ m/s$. The RANS simulations have been performed assuming a density-based implicit formulation. The subgrid scale model is the k-ε [25], 2nd order for the turbulent kinetic energy k and the turbulent dissipation rate ε and a 3rd order for all other variables. The turbulent Prandtl number has been assumed equal to 0.85 and the turbulent Schmidt number 0.7. The Jachimowski chemical scheme with 19 species and 32 reactions [6] has been implemented. The Turbulence/chemistry coupling is the Eddy Dissipation Concept (EDC) model [26].

Comparison between dry and vitiated air with H_2O

The composition of air at the combustor inlet for the different cases analysed is shown in Table 2.

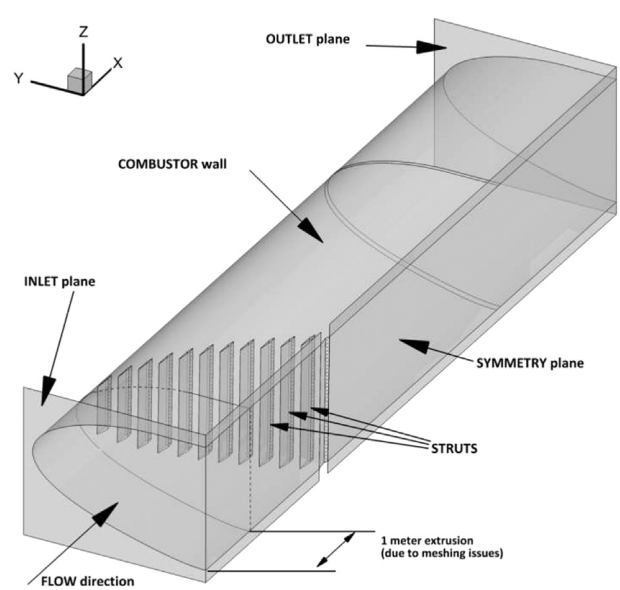

Fig. 2 – 3D MR2.4 combustor configuration.