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CFD analysis of a hydrogen powered scramjet with multistage injection

O. Russo[1,a*], M. Marini[1,b], P. Roncioni[1], F. Cascone[1], S. Di Benedetto[1], M. Albano[2], G. Ranuzzi[2]

[1] Italian Aerospace Research Centre (CIRA), Via Maiorise snc, 81043 Capua, Italy

[2] Italian Space Agency (ASI), Via del Politecnico snc, 00133 Rome, Italy

[a]o.russo@cira.it, [b]m.marini@cira.it

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Abstract. The PhD topic focuses the attention on the internal flow path analysis of a hypersonic demonstrator equipped with a scramjet engine, which will fly in a 10-second experimental operation. The work is part of a project funded both by the national program PRORA, and ASI, by means of an agreement between CIRA and ASI on hypersonics. The combustion is non-premixed and the fuel chosen is hydrogen which is injected by multistage strategy in two different stages. Engine performance and parameters such as combustion efficiency are analyzed through nose-to-tail CFD analysis both in fuel-off and fuel-on conditions. An important result is the achievement of a high combustion efficiency by the conclusion of the engine cycle with stochiometric hypotheses and single step reaction. Future studies will examine the performance of the scramjet using more detailed chemical models and varying the injection strategy while also evaluating the effect of the air-fuel ratio. Finally, the numerical results will be possibly validated with experimental measurements.

Introduction

In recent years, several research projects supported by the European Commission have been launched with the aim of developing a high-speed aircraft that simultaneously combines aerothermodynamic, structural and propulsive aspects. CIRA, taking advantage of the strong involvement and experience in European projects such as HEXAFLY-INT [1] (flight test of a vehicle without propulsion for hypersonic flight), and previously in HEXAFLY [2], has set the challenge of designing a scaled hypersonic scramjet demonstrator for a future test flight, named the *Scramjet Hypersonic Experimental Vehicle* (SHEV). The project is co-funded by ASI.

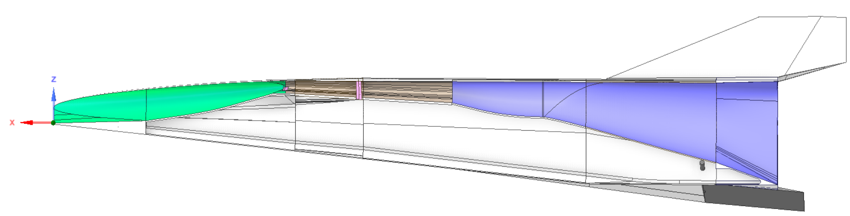

Fig. 1. Internal flow path of demonstrator. Inlet (green), combustion chamber (brown), nozzle (violet), combustor's struts (pink).

The scramjet engine is integrated into the demonstrator and is constituted by intake, combustion chamber and nozzle. The combustor is equipped with a two-stage multi-struts injector system, that is composed by two semi-struts, located at the beginning of combustor, and a full-strut located at the central zone of the same. The semi-struts distribute 65% of the hydrogen mass flow rate to the external regions; the central full-strut disperses the remaining quantity of fuel. As shown in Fig 2, the mission scenario involves an air-launched solution with an aircraft carrier releasing (Sep I) a launch system, consisting of a hypersonic demonstrator and its launch vehicle propelled by a solid booster, which brings the payload at specific speed and altitude. The booster accelerates the demonstrator to hypersonic speed through a controlled trajectory and releases it for a 10-second experimental operation (Sep II). CFD analysis employed the free stream conditions chosen for the experimental window (Mach 6÷8 and altitude 27÷32 km) to understand how the demonstrator behaves in these horizontal level flight conditions.

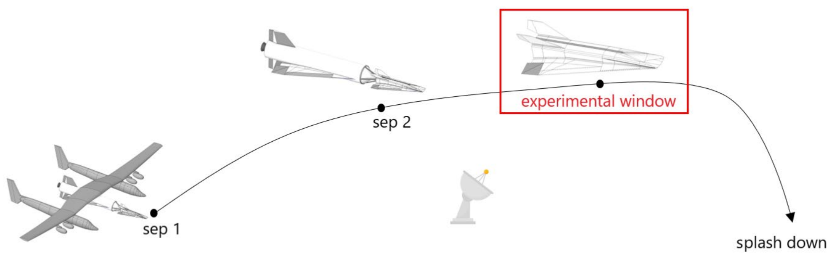

Fig. 2. Mission scenario

Numerical analysis and results

The performance evaluation of the scramjet engine was conducted by means of Computational Fluid Dynamics (CFD) analyses of the internal flow path. A simplified configuration was chosen focusing on half of the setup and employing an unstructured grid consisting of 1.9-million cells.

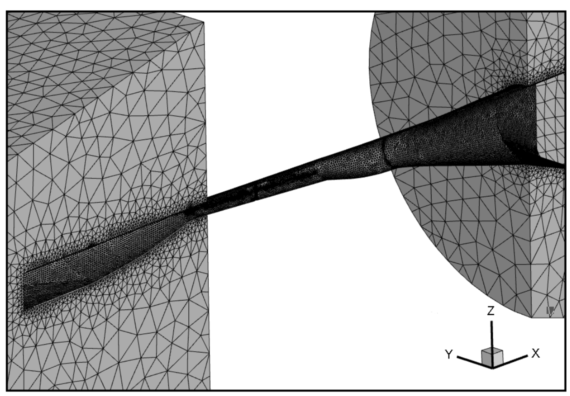

Fig. 3. Computational grid for simulation

Preliminary numerical analyses were performed with inviscid flow and in fuel-off conditions to assess the air MFR (mass flow rate) under various conditions chosen for the experimental window. The single-step chemical scheme (eq. 1) with a stoichiometric air-fuel ratio, $\phi=1$, was assumed to model air-hydrogen combustion. This approach made it possible to determine the total hydrogen MFR, that is partitioned and injected into the combustor with a multi-stage injection strategy.

$$2H_2 + O_2 + \frac{79}{21}N_2 \rightarrow 2H_2O + \frac{79}{21}N_2 \quad (1)$$

Further analyses have been performed to evaluate the effects of viscosity on internal propulsive flow path performance of SHEV with k–ω SST model. The quantities shown in the following figure represent the average values, integrated over different sections for some axial locations of the SHEV.

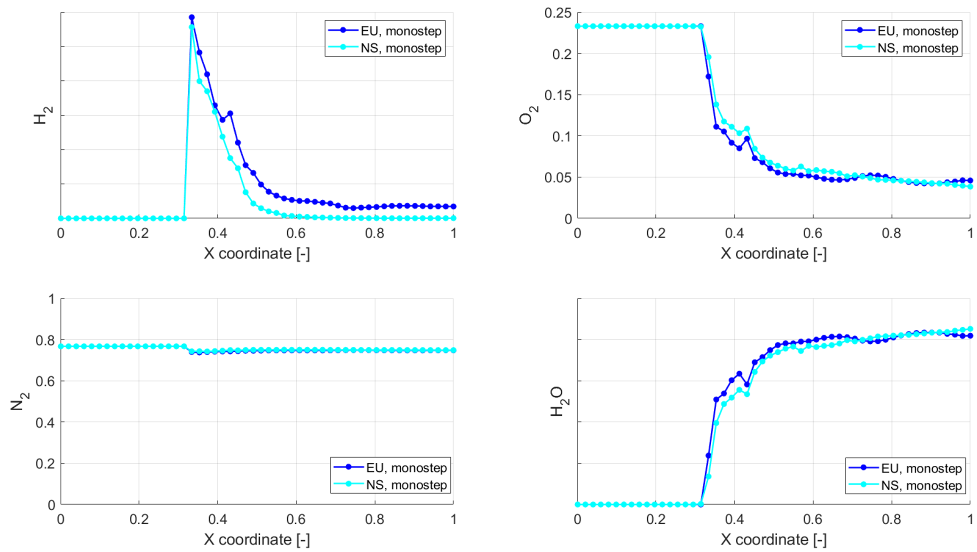

Fig. 4. Comparison of averaged mass fractions profiles for different species along the SHEV internal flowpath at the same altitude. Viscous (NS) and inviscid (EU) effect.

Another comparison between inviscid and viscous effects has been done in order to study the effects on thermodynamic and kinetic dimensionless parameters.

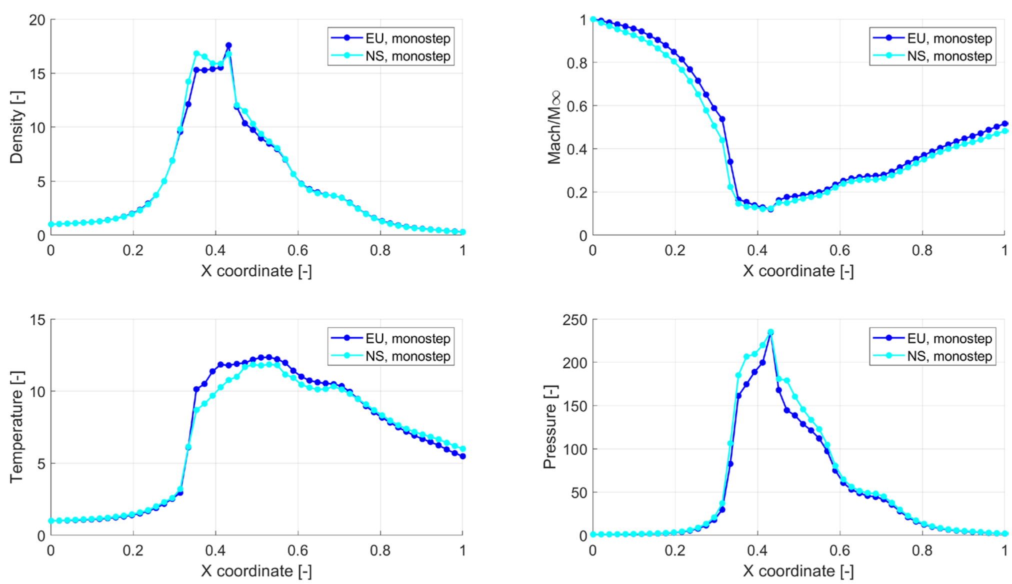

Fig. 5. Comparison of thermodynamic and kinetic averaged parameters profiles for different species along the SHEV internal flowpath at the same altitude. Viscous (NS) and inviscid (EU) effect.

An important parameter that measures the amount of fuel burned compared to that injected at different locations of the SHEV is the combustion efficiency, η_c, defined as:

$$\eta_c = \frac{m_{H_2\,injected} - m_{H_2}}{m_{H_2\,injected}} = \frac{m_{H_2\,burned}}{m_{H_2\,injected}} \tag{2}$$

As shown in Fig 6, viscosity impacts significantly the engine performance in NS simulations. That seems related to the more properly modelled mixing of the air-fuel mixture that gives an improvement of the combustion efficiency. The air-hydrogen combustion is almost completed in the nozzle, where combustion efficiency reaches a plateau due to frozen condition of the species.

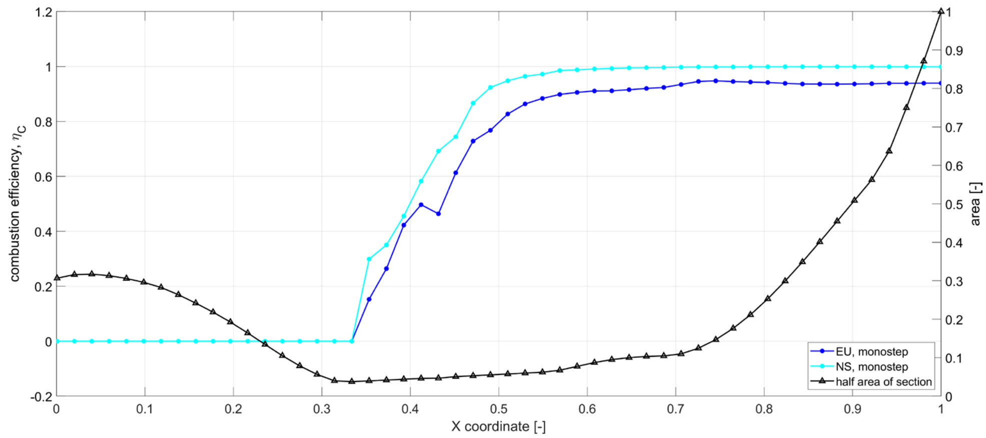

Fig. 6. Comparison of combustion efficiency along internal flow path of SHEV. Viscous (NS) and inviscid (EU) effect.

The project represents a significant research endeavor in the field of scramjet engines, providing a detailed insight into the performance and challenges associated with this advanced propulsion technology in the context of hypersonic flight.

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