proceedings

Abstract

Thermal simulations and experimental tests to support the development of a small reusable spacecraft †

Diana Martins[1], Joseph El Rassi[1], Amandine Denis[1], Simone Del Monte[1], Bernd Helber[1], Giovanni Medici[2], Jaime Gutierrez[2], Francesco Barato[3], Lorenzo Gerolin[4], Paulius Kirstukas[5] and Valentina Raimondi[6]*

[1] Von Karman Institute for Fluid Dynamics (VKI), 1640 Sint-Genesius-Rode, Belgium; diana.martins@vki.ac.be ; joseph.elrassi@vki.ac.be ; amandine.denis@vki.ac.be ; simone.del.monte@vki.ac.be ; bernd.helber@vki.ac.be
[2] Deimos Engineering and Systems SLU, 13500 Puertollano, Spain; mailto:mgimedici@indra.es, jgbriceno@indra.es
[3] Department of Industrial Engineering, University of Padua, 35131 Padua, Italy; francesco.barato@unipd.it
[4] Technology for Propulsion and Innovation SpA (T4I), 35043 Monselice PD, Italy; l.gerolin@t4innovation.com
[5] Kongsberg Nanoavionics (KNA), 10224 Vilnius, Lithuania; paulius.kirstukas@nanoavionics.com
[6] "Nello Carrara" Applied Physics Institute - National Research Council of Italy (CNR-IFAC), 50019 Sesto Fiorentino FI, Italy; v.raimondi@ifac.cnr.it
* Correspondence: v.raimondi@ifac.cnr.it; Tel.: +390555229379
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Abstract: The rapid development of space economy is posing big challenges, a major one being space debris mitigation. Under this respect, the Horizon Europe EARS project aims to introduce the disruptive concept of reusability in the SmallSat market, taking a step towards a more sustainable exploitation of space. EARS main objective has been to outline the concept of operations (CONOPS) of a small reusable satellite and the maturation of the relevant key enabling technologies needed to guarantee a safe re-entry to the satellite and its payload. In this paper, we present the preliminary design of the EARS spacecraft, its CONOPS and mission engineering with an overview of the simulations conducted to assess the aerodynamic load during spacecraft re-entry and the Plasmatron tests executed for the selection and characterization of the materials suitable for the construction of an inflatable thermal protection system to guarantee a safe atmospheric re-entry.

Keywords: satellite, reusability, atmospheric re-entry, aerothermodynamic load, Plasmatron test.

1. Introduction

The space economy is growing at a swift pace, offering unprecedented opportunities but also posing significant challenges, primarily in space debris mitigation but also in resources availability. The Horizon Europe EARS (European Advanced Reusable Satellite) project [1] aims to introduce the disruptive concept of reusability in the SmallSat market, taking a step towards a more sustainable exploitation of space. The main objective has been to outline the concept of operations (CONOPS) and the preliminary design of a small reusable satellite, together with the maturation of the relevant key enabling technologies, namely: greener propulsion for steering capabilities; precise Guidance, Navigation, and Control (GNC) for re-entry, and an inflatable heatshield to protect the spacecraft – and the payload – during the atmospheric re-entry.

In this paper, we present an overview of the simulations conducted to assess the aerodynamic load during the re-entry of the EARS spacecraft and the Plasmatron tests executed for the selection and characterization of the materials suitable for the construction of an inflatable thermal protection system.

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2. The EARS spacecraft

The EARS spacecraft is a low-cost, flexible satellite designed to support microgravity manufacturing and small scientific experiments in space at affordable costs [1]. The EARS spacecraft is conceived to be easily produced in large numbers - thanks to its communalities with commercial satellites - and to be reused after minimal refurbishment, also thanks to lessons learnt after each flight. Its specifications include a total wet mass of 150 kg (max.) with a payload mass of 20 kg (max.), with a total length of around 1.1 m. The EARS orbit will be an equatorial, Low Earth Orbit with nominal altitude of 300 km. Mission duration is expected to ensure at least 6 months of payload operation. Further details on the EARS spacecraft design and mission engineering can be found in [2,3].

Figure 1 shows the CONOPS of the EARS spacecraft: at the end of the mission the spacecraft is deorbited and its rear part pointed in the direction of flight in order to decrease the velocity. A flip maneuver is then performed, and the heatshield is inflated to protect the spacecraft within its wake. Passive re-entry in the atmosphere occurs along a ballistic trajectory, followed by a deceleration phase implemented by means of a parafoil. Finally, a helicopter recovers the spacecraft and its payload through a Mid-Air Retrieval (MAR) maneuver.

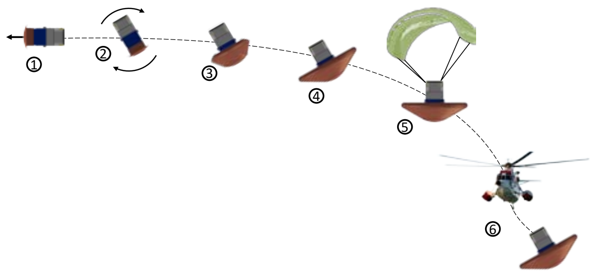


Figure 1. EARS spacecraft Concept of Operations (CONOPS).

2. Aerothermodynamic load simulations

An essential step in EARS design and mission engineering has been the selection of the most suitable heatshield configuration (deployable or inflatable) and its aerothermodynamic assessment in order to determine the expected levels of heat flux and wall temperature on the heatshield for different Angle-of-Attack (AoA) attitudes.

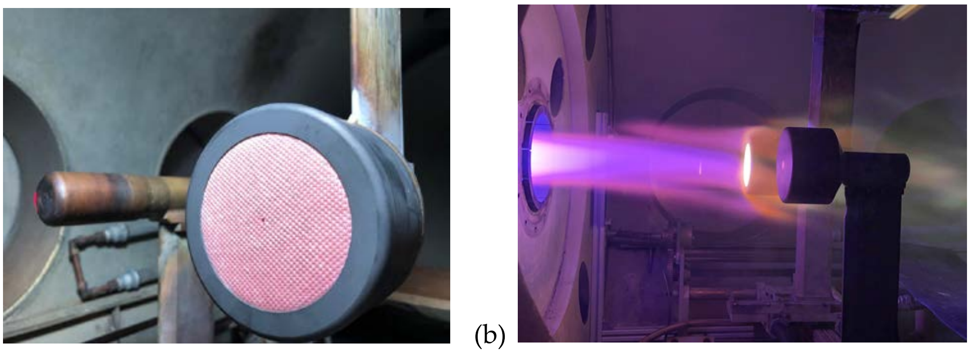
A Flexible Thermal Protection System (FTPS) stack-up design was identified as the best solution for the heatshield, followed by its preliminary sizing and the definition of its geometric, inertial, and aerothermal parameters. The heat shield is made of two parts: (1) the rigid nose made of traditional Ceramic Matrix Composite and placed at the top of the spacecraft; and (2) the FTPS, a multilayer structure made of three different layers: outer layer, insulator layer and gas barrier. The FTPS is accommodated in the relevant housing beneath the rigid nose, ready to be inflated during the re-entry phase (Figure 1). Further details on the FTPS design can be found in [4].

An aerothermodynamic assessment of the FTPS was carried out taking advantage of AoA spectrum identified through Flying Qualities Analyses [5,6]. The aerothermodynamic analysis provided the expected levels of heat flux, up to 440 kW/m^2 at a spacecraft height of 68 km with AoA of 8°. As far as wall temperature on the heatshield is concerned, under radiative equilibrium flux assumptions and at 0° and ±8° AoA attitudes, the simulations showed that some limited areas of the heatshield may reach temperatures above the maximum operative temperature of the heatshield's outer surface material, strongly depending on the material's emissivity which was tentatively set to 0.37 on the basis of literature data [7]. The latter delivers full **compliance** with the material's operational temperatures under the hypothesis of an emissivity of 0.55. A thorough evaluation of the material's emissivity is thus crucial to determine the temperature at the heatshield surface, although its measurement poses several challenges due also to the material texture.

3. Materials testing at Plasmatron

Based on the preliminary design of the heatshield, the materials for the construction of the Flexible Thermal Protection System (FTPS) were selected and procured. Further details on the materials selected for the heatshield construction can be found in [3].

Representative FTPS material stack-up samples were fabricated to be used as test samples and instrumented with type-K thermocouples to better understand the material performance during the tests. Different types of test samples were prepared: Figure2a shows a test sample made of the FTPS outer layer material (Refrex® 1420) before undergoing the test. The samples were tested in the Plasmatron facility by simulating the expected re-entry conditions for the EARS spacecraft in a high-enthalpy plasma flow. The tests on the FTPS materials were conducted both in stagnation (subsonic) and in flat-plate (supersonic) configuration. Different conditions of heat flux, pressure, power, AoA and test duration were applied to a wide set of test samples, including multilayer structure samples with laced seams. Figure 2b shows the stagnation point test on the selected FTPS outer material (Refrex® 1420) running in the Plasmatron (Heat flux: 270 kW/m^2, Pressure: 15 hPa, Power: 155 kW, Duration: 153 s).



(a) (b)

Figure 2. Plasmatron tests on Flexible Thermal Protection System (FTPS) materials: (a) Test sample (Refrex® 1420) before test; (b) Stagnation test running on the material inside the Plasmatron.

4. Conclusions

An inflatable FTPS has been proposed as the best tradeoff to enable safe atmospheric re-entry to the EARS spacecraft, a small reusable satellite to support commercial and scientific activities.

FTPS aerothermodynamic load simulations were performed to assess its performance during the atmospheric re-entry and to determine the expected levels of heat flux and wall temperature on the heatshield for different Angle-of-Attack (AoA) attitudes. The results showed an overall compliance of the heat fluxes and surface temperatures with the specifications of the selected FTPS materials under the hypothesis of medium material emissivity values. Low emissivity values, however, may bring about higher temperatures than the nominal operational temperature of the material in a limited number of spots of the FTPS surface. In this respect, additional effort will be needed to obtain a thorough measurement of the material emissivity.

FTPS material tests at Plasmatron demonstrated their capability of surviving the aggressive thermal, chemical and mechanical re-entry environment expected for the EARS spacecraft. Some limitations, however, could arise with respect to their reusability after atmospheric re-entry and would require further investigation on the surface temperature, emissivity, catalytic effects, and gas-surface interaction and/or mitigation through heatshield design refinement to make FTPS also reusable.

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