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Test of flow deflector demonstrators in LOX/Methane combustion gases

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Abstract

Ariane Group has been investigating the use of flow deflection using mobile deflectors inside the exhaust plume of a liquid rocket engine.
This technology offers layout flexibility when compared to fully gimballed engines and potential gain in cost at vehicle level. It can in particular benefit small low cost expendable launchers or vehicles with rocket engines confined inside a narrow fuselage-like structure such as spaceplanes or reusable fly-back booster. It can also be a competitor to classical actuators for upper stage thrust vectoring. However, the capability of the deflector material to sustain rocket engine exhaust gas temperature and the efficiency of such a thrust vectoring system remain limitations to be investigated.
By using in-house operational thermo-structural material, usually applied to aircraft engines hot gas section or LOX/LH2 liquid rocket engine nozzle extensions, Ariane Group manufactured simple deflector proof-of-concept models.
These demonstrators were tested during a thrust chamber test campaign, planned in the frame of Ariane Group LOX/Methane R&T program. The test consisted in positioning the flap demonstrator inside the thrust chamber exhaust plume. The objectives of this test were to characterize the thermo-structural material in LOX/Methane combustion gases as well as to measure aerodynamic loads on the flap itself.
This paper will focus on the preliminary results obtained through those demonstrator tests

Nomenclature

DLR	German Aerospace Centre
CFD	Computational fluid dynamics
I/F	Interface
LCH4	Liquefied Methane
LH2	Liquefied Hydrogen
LOX	Liquid Oxygen
LRE	Liquid Rocket Engine
MPa	Mega Pascal
PDM	Pathfinder Demonstration Model
TCA	Thrust Chamber Assembly

1. Introduction

Some vehicles, by their design, feature a constrained engine bay layout, which can make difficult the gimballing of a whole engine. These vehicles are typically winged vehicles with a narrow fuselage or small expandable launchers.
A more compact alternative to engine gimballing could be the use of mobile flow deflectors. The principle (see Figure 1) is to use an external surface that is inserted in the exhaust plume of the liquid rocket engine. By this deflection of the exhaust flow, a control of the thrust vectoring can be achieved.

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Mobile deflectors such as flaps or jet vanes were used in several applications:

- Jet fighters with high maneuverability capabilities such as the fighter demonstrator X-31 use flow deflectors applied to an aero-engine exhaust flow [1].
- The Intermediate eXperimental Vehicle (ESA reentry demonstrator) features body flaps performing deflection of hot air for achieving control during the vehicle reentry [2].
- Numerous applications of jet vanes inserted in the rocket engine exhaust flow can be found in the missiles domain, one of the most famous examples being the V2 missile used during World War II [3].

One of the issues to be tackled in the application of flow deflectors to LRE is the extremely high temperatures of the exhaust flow that few materials are capable of withstanding. C/SiC composite, a thermostructural material which is currently manufactured by Ariane Group, can be a good candidate. Indeed this material is applied to LOx/LH2 rocket engine extension nozzle for example on the Vinci Upper stage engine [4].

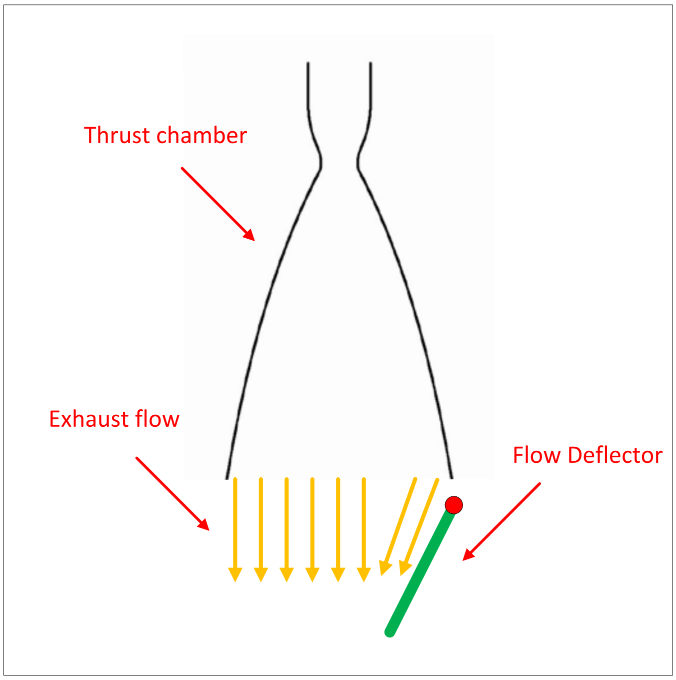

Figure 1 Flow deflection illustration

Flow deflection, with external flaps or jet vanes, is currently not applied to modern liquid rocket engines and launchers: most probably due to the performance penalty (drag) induced by such systems that could outweigh the need for compactness in the case of standard launchers. . In order to demonstrate the suitability of flow deflection Ariane Group initiated a proof of concept test. The main goal behind this demonstration is to assess the capability of a flow deflector, made of C/SiC, to withstand LRE exhaust gases. Since LOX/LCH4 is regarded by Ariane Group as a promising propellant combination, the opportunity arose for testing this proof of concept in a LOX/LCH4 thrust chamber exhaust plume. Moreover, while C/SiC is well characterized in LOX/LH2 LRE combustion gases, Ariane Group has no experience in the application of this material to a LOX/LCH4 LRE.
Using a simple design, a proof of concept of a flow deflector (or flap) is designed and manufactured. As part of a ride along test of a LOX/LCH4 thrust chamber test campaign performed by Ariane Group, this flap is inserted in LOX/LCH4 combustion gases.

2. Test article design description

This section aims at describing the test article and the logic taken for its design. The logic used for designing such a test article is described in Figure 2.

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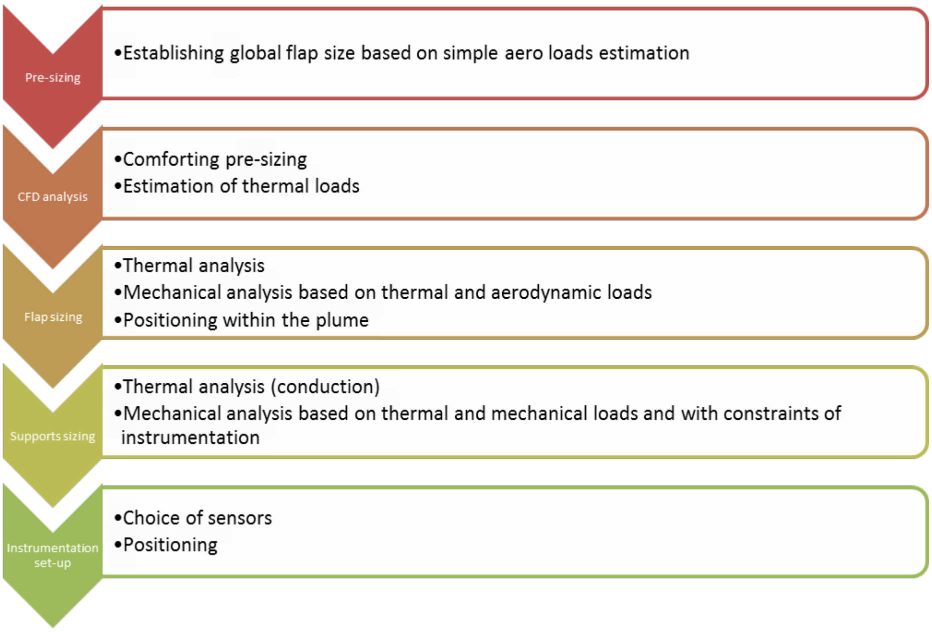

- Establishing global flap size based on simple aero loads estimation

- Comforting pre-sizing
- Estimation of thermal loads

- Thermal analysis
- Mechanical analysis based on thermal and aerodynamic loads
- Positioning within the plume

- Thermal analysis (conduction)
- Mechanical analysis based on thermal and mechanical loads and with constraints of instrumentation

- Choice of sensors
- Positioning

Figure 2. Test article design logic

The design of the flap was made in order to take into account the following constraints:

- Available blanks of material: due to time and budget constraints, no new material could be procured.
- Test bench installation: layout, operations constraints. Since the test is performed as ride-along no heavy test bench adaptation could be performed.
- Material characteristics.

The sizing parameters of the flap are shown hereunder:

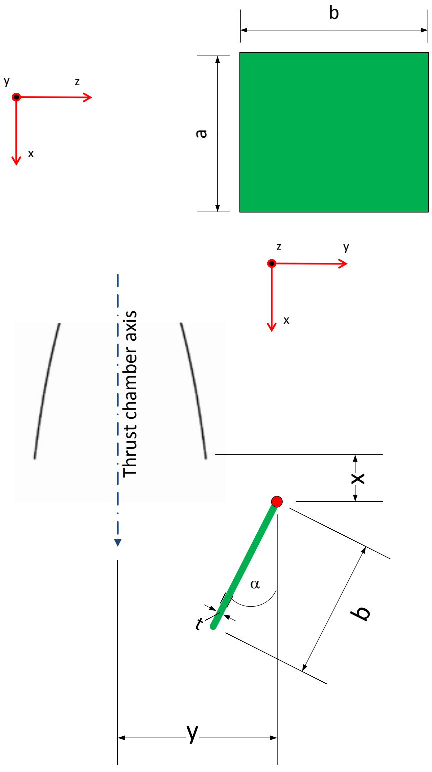

Figure 3: Flow deflector sizes and position

DOI: 10.13009/EUCASS2017-583

Parameter	Symbol	Value	Unit
chord	a	200	mm
span	b	250	mm
thickness	t	13	mm

Table 1 Flow deflector size

The flap was cut from an available blank plate; its area was chosen so as not to lead to excessive loads to be supported on the bench (typically less than 1t) while the thickness was selected as the best compromise for the flap to sustain both thermomechanical loads due to thermal gradient across its thickness, and aerodynamic loads. Supports were then designed for this application; a picture of the test article is displayed hereunder (see Figure 4). It is composed of:

- Flap:
    - The flap is made of a simple C/SiC plate.
- Studs:
    - The studs are made from already available blanks. They are screwed in the flap itself. During the manufacturing process, flaps and studs are assembled before the final SiC densification.
- Steel clamps:
    - The steel clamps ensure the coupling between the C/SiC parts and the metallic supports.
- Rods:
    - The rods are the metallic supports; they are instrumented with full strain gauge bridges. The choice of aluminum was made in order to have enough deformation of the rods during test for measurement of the loads.
- Steel bracket:
    - The steel bracket is the interface part to the test bench structure.
- Thermal protection:
    - Thermal protection was used in order to shield the supports of the flap from any exhaust plume recirculation.

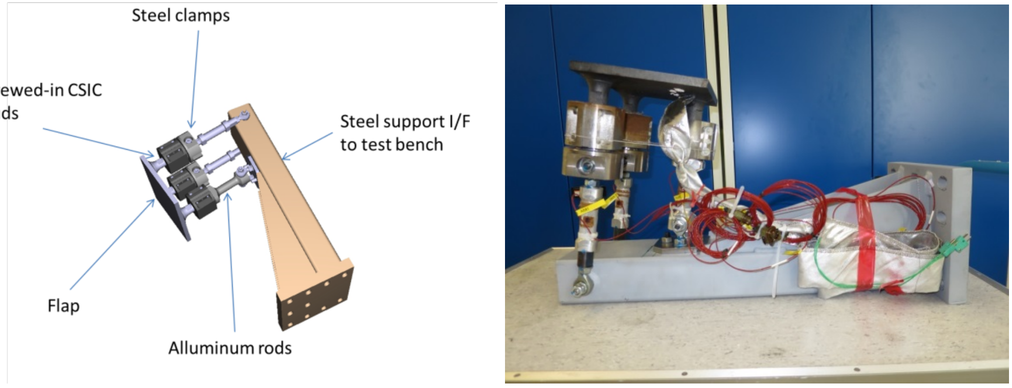

Figure 4. Test article description

No capability of variation in flap angle of attack was built-in, originally the flap would only have to withstand one test. Note that, due to the budget and time constraints, no cooling was implemented on the supports. The flap would be positioned at the outskirt of the exhaust plume, thus shielding the supports from the hot gases. CFD (computational fluid dynamics) simulations were performed in order to assess the risk of hot gas recirculation at the back of the plate.

The instrumentation includes:

- A thermal camera which would comfort the temperature experienced by the test article. The thermal camera is positioned so as to have a view on the flap surface impacted by the exhaust flow.
- Thermocouples installed at the back of the plate to correlate their readings to the thermal camera measurements through a simulation tool.

DOI: 10.13009/EUCASS2017-583

Figure 5. Thermocouples installed on the flap

- Strain gauges installed on the supporting rods for estimation of the loads on the flow deflector. They are self-compensating full strain-gauge bridges. The aim of these sensors is to evaluate the flap tensor which is essentially the normal force and tangential forces as well as the moment along the chord axis on the flow deflector.

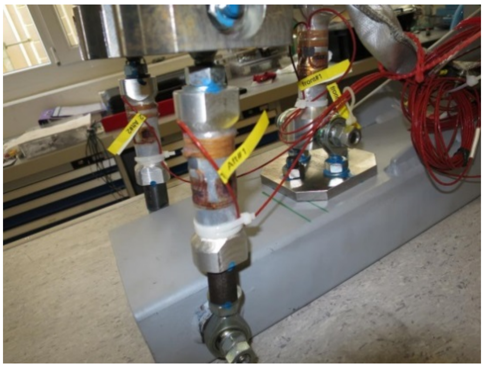

Figure 6. Strain-gauge bridges

3. Test

3.1 Test configuration

The test of this flow deflector took place during a LOX/LCH4 combustion chamber test campaign performed by DLR and Ariane Group between December 2015 and November 2016 [5]. This test campaign was performed on the high pressure test bench P3.2, operated by DLR in Lampholdshausen, Germany. It consisted in testing a full-scale thrust chamber assembly (TCA) demonstrator called Pathfinder Demonstration Model (PDM) (see Figure 7). The main operating parameters of this thrust chamber are displayed in the table hereafter:

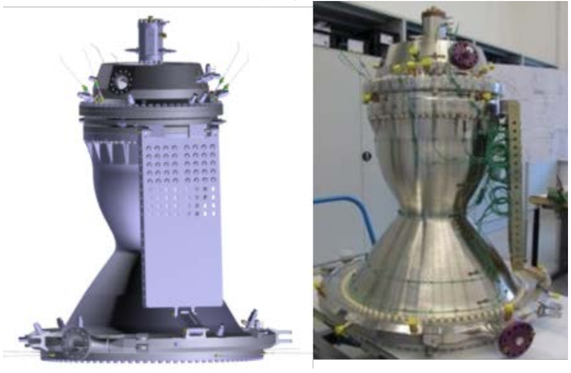

Figure 7. TCA PDM layout

DOI: 10.13009/EUCASS2017-583

	PDM TCA
Propellant combination	LOX/LCH4
Chamber Pressure [MPa]	4.7
Mixture Ratio O/F	3.4

Table 2. TCA PDM operating parameters

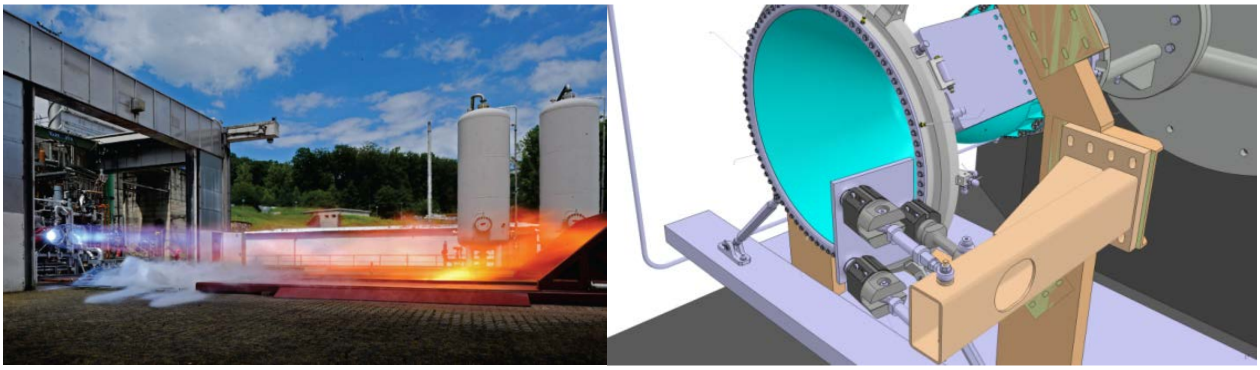

Figure 8. Picture of TCA Hot firing test (left) and Flow deflector test configuration (right)

The flow deflector test article is connected to a steel frame around the thrust chamber. The flow deflector is positioned with regard to the thrust chamber axis and exit plane so as to be able to get a view of the impacted surface with the thermal camera during test.

3.2 Test predictions

During the design of the flap, in order to set-up the final test configuration and to have a basis for comparison with the test results, several simulations were performed.

CFD simulations of the test set-up were first produced using an Ariane Group in-house CFD tool, designed for high Mach numbers applications [6]. The CFD simulations were useful in getting estimations of the aerodynamic loads and thermal fluxes on the flap. They also helped to assess the exhaust flow field geometry with an inserted flow deflector; it was used in the risk analysis for this test. Extracts from the CFD simulations are shown hereunder (see Figure 9). One can note that the supports of the flap are not simulated. The flap is positioned in such a way that the impact of the supports on the flow field would be limited. The range of hot gas temperature in the flap surroundings is up to 2600K with thermal fluxes (assuming a wall temperature of 290K) going up to 20 MW/m^2.

The estimated aerodynamic loads are displayed in Table 3.

Aerodynamic Loads	
Fx/Drag (DaN)	115
Fy/Lift(DaN)	582

Table 3. Aerodynamic loads on flap

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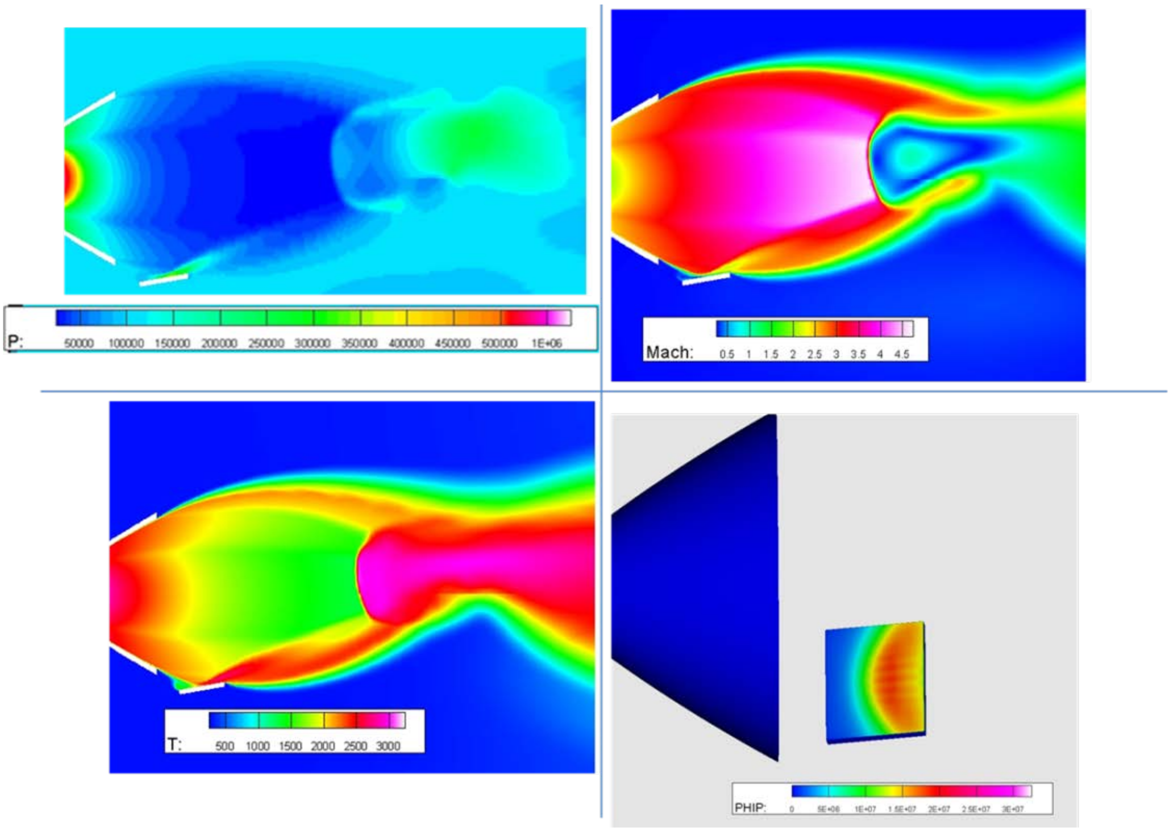

Figure 9. CFD simulations with static pressure (Pa), Mach (-), static temperature (K), and thermal fluxes (W/m^2)

Thermal 2D analysis across the chord of the flaps was performed in the design phase in order to build inputs for the thermomechanical analysis. The selected section for this analysis is located in the middle of the flap's span; this location features the maximum heat fluxes. The predictions show that the exposed surface of the flap quickly reaches temperatures close to 2100K, a temperature that is close to the material limits in the case of a LOx/LH2 combustion application.

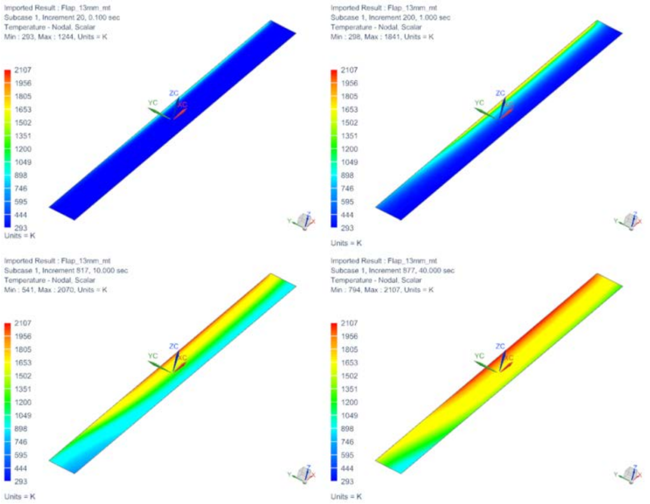

Figure 10. 2D thermal predictions for exposition duration of 0.1s, 1s, 10s and 40s

DOI: 10.13009/EUCASS2017-583

3.3 Test plan:

While the TCA PDM test campaign ran for about 10 months, the flow deflectors testing occurred as a ride-along test during the first 3 weeks of September 2016 where 3 TCA PDM tests were performed. At this point of the campaign, Multi-ignition tests were performed. It means that during one multi-ignition test, 2 ignitions, separated by an off-time, also called coast phase, could be performed. The aim of the coast phase would be to reach acceptable thermal conditions for a second ignition.

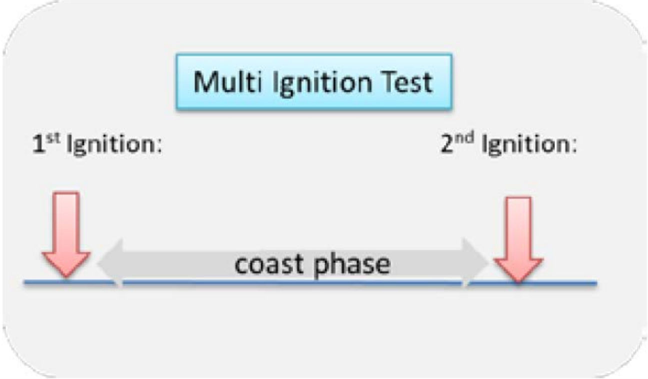

Figure 11. Coast phase between 2 ignitions

The Figure 12 shows a typical profile of the chamber pressure during the flow deflector tests. The TCA PDM is ignited at a so called “low power mode” during which the chamber pressure is a roughly 20% of its reference value, this low power lasts for a few seconds before the chamber pressure ramps up to reference value then to the different load points specified in the test plan of the campaign. Note that with this test configuration and during low power mode, the flap would not be impacted by the thrust chamber exhaust flow. Indeed at this chamber pressure, the exhaust flow separates within the divergent part of the thrust chamber and features a much narrower diameter in its cross-section.

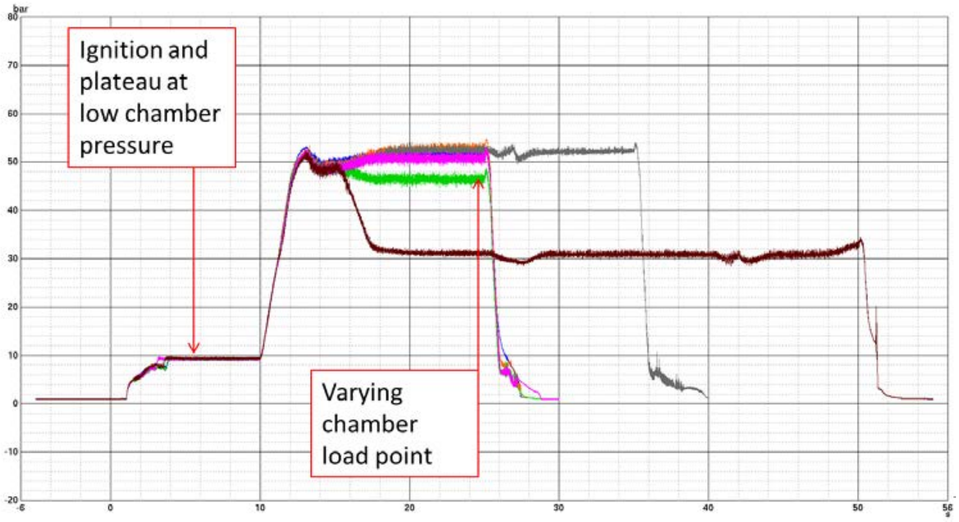

Figure 12 TCA PDM pressure profile

After each test (consisting of two hot firings) a visual inspection is performed. The aim of this visual inspection is to assess from experience the capability of the flap to perform an additional test. During inspection damage such as cracks or erosion of the material are closely looked at.

4. Preliminary results

This section aims at presenting the immediate results obtained after a reading through the test data. Ariane Group foresees a deeper analysis of these results, with the use of simulation tools correlated with test data.
6 hot firings (3 tests) were performed with the flow deflectors test article, against one originally foreseen.

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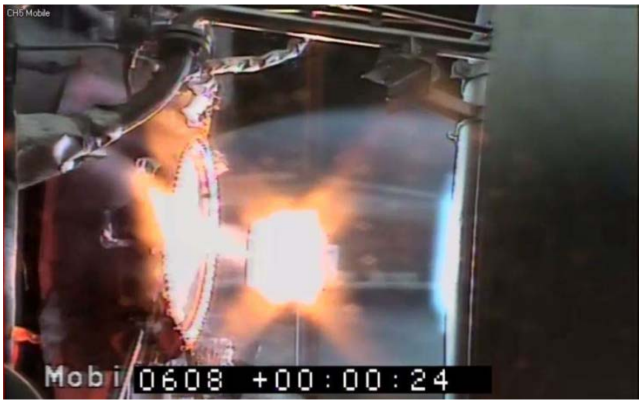

Figure 13. Flow deflector testing

3.4 Visual inspection

The flow deflector test article cleared 3 inspections after test, and could have been used for at least another test. Pictures taken before the first test and after each test (in between 2 hot runs) are displayed hereunder (see Figure 14). After the first 4 hot runs a white compound appears on the surface of the flap where the heat fluxes were the highest. This is silicon dioxide (or silica) which is a product of the reaction, occurring at extreme temperatures, between silicon (contained in the silicon carbide of the composite material) and water. Cracks were also observed. They were potentially caused by thermomechanical stresses at the interface between the C/SiC and the layer of silica, which have different coefficients of thermal expansion. The cracks were deemed unlikely to propagate based on experience from past tests on this composite material.

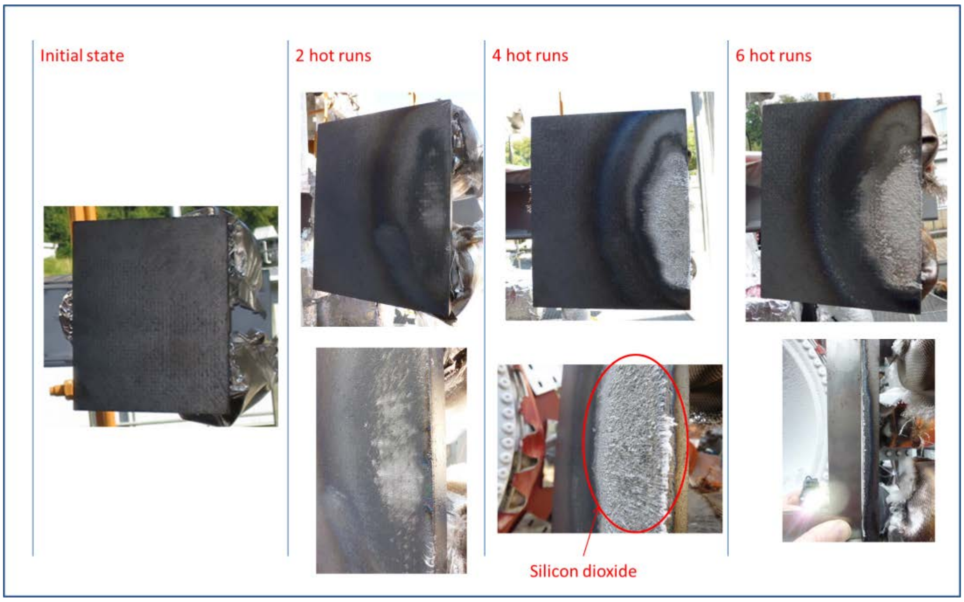

Figure 14.Test article pictures during visual inspection

3.5 Temperature recording

As mentioned previously temperature recordings are of two kinds: a thermal camera is installed so as to measure temperatures at the impacted surface of the flap, thermocouples are installed at the back of the flap for latter correlations using simulation tools.

The thermal camera successfully recorded the 3 tests. A first comparison between the camera readings and the CFD simulations shows a good matching (Figure 15). It is to be noted that the temperatures seen in the flap surroundings are well above limits in material temperatures.

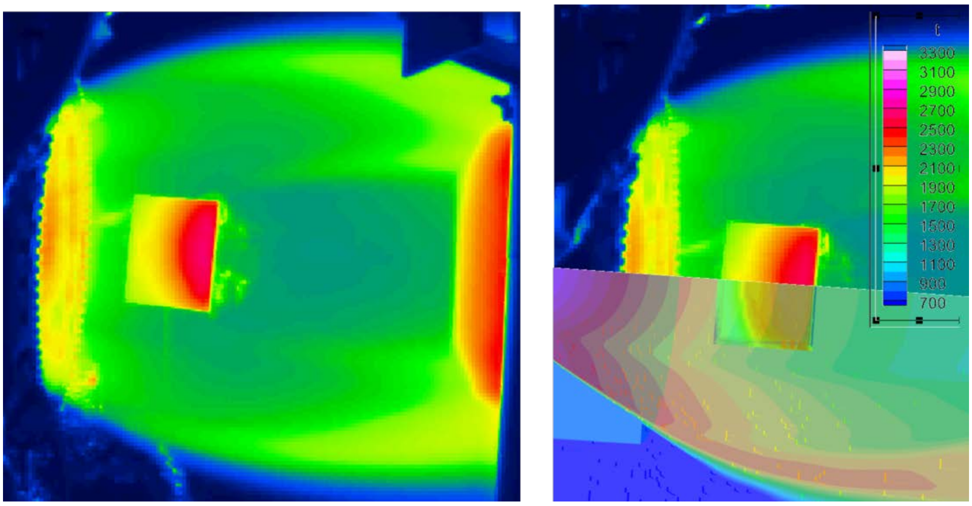

Figure 15. Thermal camera readings

Temperatures at the back of the flap were also successfully recorded; note that the 2 thermocouples are located at different depths in the flap, which explains the measurement discrepancy between the two readings. Temperature measurements are now to be correlated with the results of the simulations. Note that, as expected, no significant increase in temperature occurs during the low power mode phase, when the exhaust plume does not expand sufficiently to impact the flap. The temperature increase during this phase is due to radiative heat fluxes.

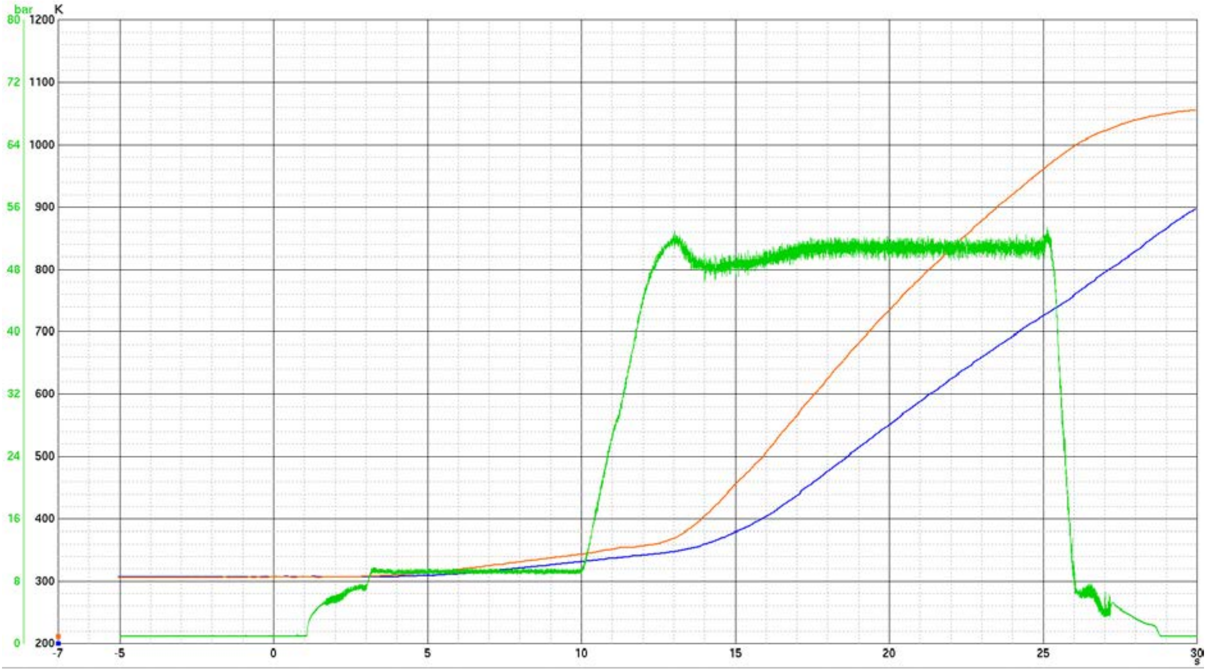

Figure 16. Chamber pressure and Temperature readings at the back of the flap during a hot run.

3.6 Loads

Strain gauges readings were successfully recorded during the last 2 tests as strain gauges were not installed for the first test, due to a procurement issue. The restitution of the tensor of loads on the flap was performed.
Note the discrepancy between predictions (see Table 3) and measurements. This discrepancy is considered as an anomaly and analyses to determine its cause are ongoing. Several causes could explain this discrepancy: measurement issue (gauge malfunction), prediction issue (for example the supports were not modelled in the simulations), simulations would also need to be re-run in order to take into account the exact thrust chamber load point and the flap position during test.

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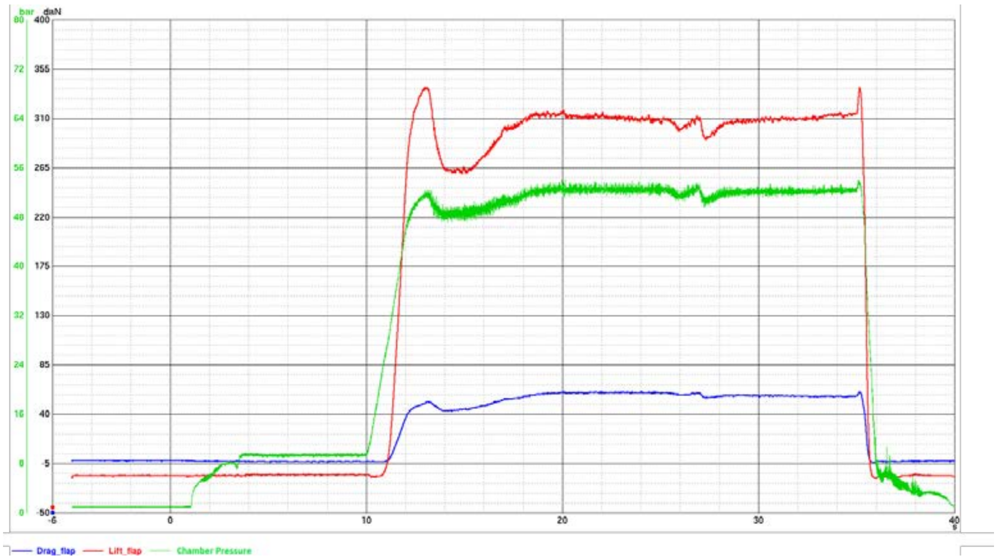

Figure 17. Restitution of loads on the flap

5. Discussions and conclusions

Ariane Group performed tests of a proof of concept of flow deflectors, envisaged as a way of providing thrust vectoring control to launch vehicles.

The primary objective of this test was to assess the capability of a flow deflector made of C/SiC to withstand the deflection of a LRE exhaust plume. The flow deflector could be tested and was submitted to exhaust gases of a LOX/LCH4 combustion chamber, it sustained several thermal cycles. Although a deeper investigation of the material will be performed, these tests comfort the use of such a material for LRE exhaust flow deflection.

In addition, recordings and data were gathered. They will be used in a deeper analysis including simulation tools. Ariane Group will build upon the results of such a demonstration to consolidate the studies of such flow deflector systems.

6. Acknowledgements

The reported test preparation and flow deflector testing mentioned in this paper have been realized at the P3.2 test facility operated by DLR. The authors would like to thank DLR for their support and cooperation and especially the test team for its engagement during all the tests.

Last but not least the effort of all Ariane Group colleagues involved in the field of design, manufacturing and test campaign preparation, is acknowledged.

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