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Combined Thermal and Mechanical Ground Test to Replicate Hypersonic Flight Design

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Abstract

Hypersonic flight exposes vehicles to harsh, combined environments, including aerodynamic heating, extreme mechanical loads, and vibrational stresses, all sustained over significant durations. To validate critical systems, ground-based tests must replicate these environments accurately. One of the main challenges is the simultaneous application and interaction of these diverse and demanding environments within a single, integrated test. For instance, thermo-structural resistance validation tests must impose both thermal and mechanical loads representative of hypersonic flight. Developing such ground tests involves several iterative design loops: identifying load cases through dedicated numerical simulations of the trajectory, defining a test program, designing a representative mock-up, and developing test facilities that can interface with the mock-up and coordinate to replicate hypersonic flight loads consistently. This study presents an overview of some combined tests employed by MBDA France to validate hypersonic vehicle concepts within its testing facilities. The first part of the paper describes some various combined tests conducted during the development phase, detailing their objectives and the main challenges encountered. The second part focuses on a specific combined test involving thermal loading and fuel tank draining. This section outlines the objective of such tests, provides a detailed description of the mock-up and its representativeness to the actual flight vehicle, explains the thermal loads, outlines the instrumentation and experimental setup, presents the post-test analysis method, and discusses the key challenges faced. This paper contributes to the understanding of integrated testing approaches for hypersonic vehicles, highlighting the importance of representative testing conditions and the complexities involved in validating these advanced systems.

Keywords: *high-speed environments, testing, thermal loading, fuel tank draining*

Nomenclature

CFD – Computational Fluid Dynamics
CAD – Computer Aided Design
EE&F – Environmental Engineering and Facilities
FE – Finite Elements
IR – InfraRed
Ps – Static Pressure
RCS – Radar Cross Section
TC – Thermocouple
Tw – Wall Temperature

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1. Introduction

Although flight testing remains the ultimate validation method for hypersonic technologies, ground testing plays an indispensable role in the development and validation process. Ground testing enables the detailed inspection of critical components and systems under controlled and repeatable conditions, providing valuable data that complements numerical simulations. Various aspects of hypersonic vehicle performance, including aerodynamic heating, structural integrity, and material behavior, can be thoroughly validated through ground tests. By connecting theoretical models with real-flight conditions, ground testing provides a strong and reliable way to develop hypersonic technologies.

The development of hypersonic technologies – whether for reusable vehicles, gliders or advanced propulsion systems – imposes extreme load cases on materials, structure and on board systems. At speed exceeding Mach 5, aerodynamic, thermal and mechanical interactions become highly coupled, generating severe and rapidly changing environments. In this context, combined testing –including thermomechanical loading, thermal fluxes, or tanks draining – is essential for assessing the real-world behavior of critical components under representative conditions.

Unlike isolated or unitary tests, combined tests aim to simultaneously reproduce the various loads experienced by hypersonic systems. This approach provides a deeper understanding of degradation mechanisms, thermal fatigue, stress relaxation and fluid-structure compatibility, while also offering valuable data for the validation of multiphysics numerical models. However, conducting such tests poses significant challenges in terms of experimental design, instrumentation and control of environmental parameters.

This article focuses on the importance and methodologies of combined ground testing, demonstrating how a comprehensive approach that integrates numerical simulations with meticulous ground experiments can effectively validate key systems and components before proceeding to flight testing.

Over the past few decades, France has conducted extensive system studies to evaluate the potential of high-speed air-breathing propulsion for both military and civilian hypersonic applications (Ref. [1] to [6]). To validate these technologies, several combined tests have been performed at MBDA's Environmental Engineering Facilities (EEF) in Bourges Subdray, France. The first section of this paper presents an overview of some of the various types of combined tests relevant to hypersonic applications that have been conducted in MBDA France's facilities, along with specific challenges encountered

The second section focuses in detail on a representative case study: the draining of a pressurized tank under thermal loads: experimental methodology developed to design a representative mock-up and to apply relevant thermal conditions, with the aim of accurately reproducing the coupled phenomena observed in hypersonic flight environments.

2. Case Studies of Combined Testing in Hypersonic Environments

This section presents various examples of testing that have been conducted by MBDA France in its facilities. It describes the scope of the test campaign, its objectives and the main technical challenges involved. While these examples provide valuable insights, they are not exhaustive: for instance, topics such as aeroelasticity or the extensive testing capabilities provided by wind tunnels are absent from this discussion here despite their significance in hypersonic applications.

Many of these tests involve significant thermal loading due to external aerodynamic flows and propulsive flows. Infrared (IR) heaters are a commonly employed technique for realistically replicating aerodynamic heating effects on structural test components of advanced supersonic and hypersonic applications (Ref. [7], [8]).

These heating systems are custom-designed to closely conform to the test specimens (Fig 1). Reflectors are used to concentrate the radiative flux on the model.

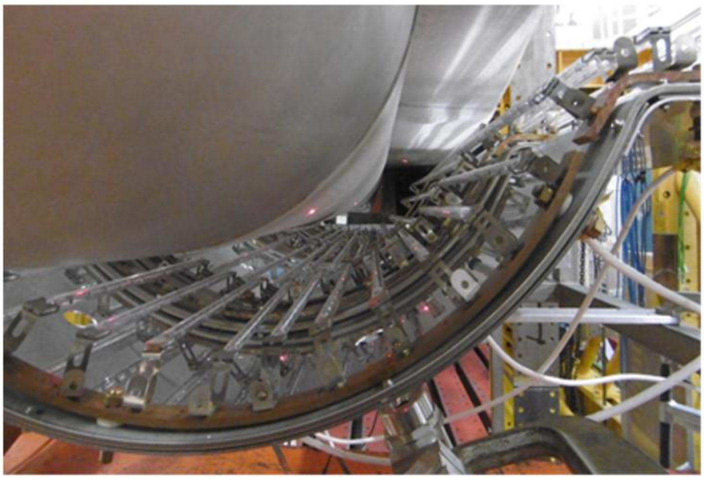

Fig 1. Visualization of IR heaters closely conform to fuselage

Multiple heating units can be independently controlled in a closed-loop system, each equipped with dedicated instrumentation, such as laser pyrometers or thermocouples, for precise thermal control (Fig 2).

Fig 2. Visualization of three independent IR lamp heaters

Several thermal considerations must be managed:

- unwanted thermal gradients between heated and non-heated areas must be avoided to prevent thermomechanical overstressing of the structures, which necessitates careful consideration of thermal expansion;
- desired thermal gradients, such as those over a wing, between the leading edge and the lifting surface, must be precisely controlled. The position, distance, and type of lamps can be adjusted to generate a heterogeneous flux when necessary.

Unlike wind tunnels, which have limited run durations and cannot accommodate large models, IR lamp heaters can achieve representative heating durations (both in terms of duration and heating dynamics) and can be scaled for large-sized models.

In the tests described in the following paragraphs, the chosen instrumentation - including its quantity, placement, precision, and method of data acquisition - is essential. It plays a critical role in managing and monitoring the tests, supports comprehensive post-test analysis, and ensures numerical models are accurately calibrated. Accurate and detailed data collection through instrumentation improves the reliability and utility of the test results, which is fundamental for refining simulations and ensuring they correspond with real-world observations.

2.1. Combined Thermal Load and Fuel Tank Draining

A representative test of liquid fuel tank draining under flight-relevant thermal conditions is a key component in the validation of hypersonic vehicle systems. In such configurations, the tank – filled with a liquid fuel – is subject to thermal loads representative of a hypersonic trajectory. These thermal fluxes are reproduced on ground – in MBDA EEF – using IR lamps (as detailed in the previous paragraph). This setup allows for controlled and repeatable heating of the tank's external surface simulating both aerodynamic and the propulsive heating. With this kind of setup, thermal loads closely replicate the heating dynamics of the flight trajectory.

In cases where the tank structure carries the mechanical loads, the test setup can be complemented with mechanical loading to reproduce representative thermo-mechanical coupling.

This type of tests enables several key objectives:

- the assessment of key thermal parameters such as tank wall temperature, fuel temperature and fuel stratification along the trajectory. Indeed, one of the primary challenges in hypersonic vehicle design is managing the thermal interface between the internal environment of the vehicle and the surrounding environment. Specifically, the fuel must be shielded from the external thermal environment to prevent boiling or potential explosion. This setup includes thermocouples that are strategically placed to ensure precise measurement of temperature distributions, enabling a comprehensive evaluation of heating dynamics. These tests help supporting the vehicle design through the validation of the thermal protection and fluid management systems;
- the evaluation of critical fluidic parameters, including pressure losses, massflow rate, and fuel pressure variation. The behavior of liquid fuels under dynamic temperature changes is crucial, as their physical properties (such as density and viscosity) directly influence these parameters;
- the calibration and validation of numerical simulations.

The main difficulty lies on combining fuel and IR lamps within the same test due to safety concerns, particularly the risk of ignition.

Further details on the design methodology of such tests are presented in the third paragraph.

2.2. Combined Thermal Load and Radar Signature Measurements

Stealth is a critical factor for hypersonic vehicles in the context of military applications. Specific materials, such as radar-absorbing materials, can be applied on the vehicle's external surfaces in order to reduce the radar signature. They directly influence aerodynamic behavior and are subjected to extreme aerodynamic heating. Therefore, they must not only maintain their structural integrity under sever thermal loads but also preserve their electromagnetic properties. In reality, the radar cross section (RCS) can vary significantly with the temperature.

To address this challenge, tests have been conducted in the MBDA EEF, simulating representative thermal loads while simultaneously measuring the radar signature, using IR lamps to reach hypersonic thermal load and using a specialized signature measurement system. Unlike material sample or panel testing, these tests involve a full-scale (1:1) representative mockup of the flight vehicle, such as a complete fuselage. This approach enables the direct measurement of the RCS of the vehicle.

The main objectives of such coupled testing are:

- to estimate the evolution of radar signature with temperature, by measuring the RCS of a full-scale mockup representative of the flight vehicle, equipped with stealth materials and coatings, under both representative thermal loads and ambient temperature This includes investigating how thermal expansion and material fatigue influence the vehicle's signature;
- to assess the thermal resistance of stealth materials by exposing them to temperature levels and gradients similar to those experienced during hypersonic flight;
- to analyze potential coupling between aerothermal effects and electromagnetic response, including deformation of the upper surface, material degradation or changes in surface roughness that can impact both RCS and aerodynamic performance;
- to support the design and validation of integrated stealth materials;
- to calibrate and validate the numerical simulations, ensuring that predictive models accurately reflect the complex interaction between thermal, aerodynamic, and electromagnetic factors.

The primary challenge in these tests is the need to rapidly remove the IR lamp heaters from the mockup (so that the IR lamps do not obstruct the signature-measurement area) while maintaining representative thermal conditions during the RCS measurement. This is crucial to prevent the convective cooling that might skew the results.

2.3. Combined Thermal Load, Mechanical Load and Pressure Load

This type of tests mainly concerns non-pressurized closed structures inside hypersonic vehicle. During hypersonic mission, if the internal volume of a closed structure (for example, inside the fuselage) is not specifically pressurized and if it is not perfectly sealed, its internal pressure is proportional to the external static pressure (Ps) which decreases with the altitude. As a result, the differential pressure between the internal and external pressures has an impact on the pressure loads acting on the structure. To accurately reproduce this condition on the ground – where the ambient pressure is approximately 1 bar at both inside and outside of the structure – it is necessary to actively control the internal pressure during the test. This enables a realistic simulation of the pressure differential encountered in flight.

In addition, while adapting the internal pressure to follow the flight profile, the model can be subjected simultaneously to representative thermal and mechanical environments. The thermal and mechanical loads are representative of those experienced during a hypersonic flight, including aerodynamic heating and inertial loads. All loads (mechanical, thermal, pressure) are applied along the trajectory. The objective is not to accumulate the maximal loads encountered over the entire trajectory but rather to apply at each moment the actual combined loads corresponding to that specific point in the flight profile.

Such tests have been conducted in MBDA EEF – with a mockup representative of full scale fuselage – using hydraulic actuators for the localized mechanical loads, IR lamp heaters for thermal loads and a vacuum pump to control the internal pressure.

This type of tests enables:

- the assessment of key thermal parameters such as structures' wall temperature and internal temperature environment along the trajectory. Indeed, one of the primary challenges in hypersonic vehicle design is managing the thermal interface between the internal environment of the vehicle and the surrounding environment;

- evaluating the thermo-mechanical behavior of the structures, supporting the vehicle design through the validation of the thermal protection and identifying available design margins;
- the calibration and validation of numerical simulations.

One of the main difficulties lies in the precise synchronization and control of all three loading types to accurately replicate the time-dependent flight conditions. In addition, the structure deformation induced by the combined loads must be carefully monitored while the model is exposed to significant thermal fluxes from the IR lamps (in order to ensure reliable interpretation of the results and proper validation of numerical models). Moreover, it is necessary to deal with the electrical interaction and the physical interaction between the cylinders for mechanical load and the position of the heaters to avoid interference and heating of the actuators.

Fig 3. Visualization of interaction between IR lamps heaters and mechanical loads

2.4. Combined Functional and Mechanical Testing of Fuel Pump under Vibration Loads

In hypersonic vehicles, fuels pumps –with moving parts– must operate reliably and with high accuracy under extreme dynamic conditions. Indeed, the vibrational loads form propulsion systems and vehicle dynamics introduce additional mechanical stresses on this actuator. Moreover, the hydraulic circuits downstream introduce mechanical loads on the fuel pump that impact its performance. Understanding the pump’s behavior under such combined conditions is essential for ensuring overall propulsion system performance during hypersonic flight.

Some tests were made inside at MBDA EEF and involve operating a pump supplied with fuel while imposing mechanical loads through flow restriction at the outlet. These restrictions replicate the hydraulic resistance of the downstream circuit encountered in the vehicle. Simultaneously, the pump and its supporting structure are subjected to vibrational excitation representative of in-flight mechanical environments. The test bench is equipped with instrumentation to measure pressure, flow rate and vibrations.

The main objectives of this test is to:

- evaluate the pump’s functional performance and durability under realistic operating condition, including flow constraints and mechanical vibrations;
- estimate the pump operation limits, to detect possible failure modes and to improve the design robustness in a representative environment.

Key challenge of this testing approach includes the safe handling of liquid fuel in a complex test environment and preventing leaks to avoid damaging the vibration shakers. Furthermore, the amount of instrumentation required for this type of tests can be quite difficult to implement.

Similar tests can be conducted by incorporating a thermal load at the pump level by heating the fuel. This allows for varying its characteristics (viscosity and density) and evaluating the pump's performance at different fuel temperatures.

2.5. Combined Thermal and Mechanical Loads on Moving Parts

Hypersonic vehicles often incorporate mobile mechanical components such as control surfaces or air inlets. These components are subjected to severe and evolving mechanical and thermal environments, depending on the trajectory. Mechanical and thermal loads do not necessarily peak simultaneously, and the position of the mobile elements can vary at different points along the trajectory. MBDA France conducts thermomechanical tests on mobile components using IR lamp heaters to simulate thermal loading and hydraulic actuators to apply mechanical loading.

The objectives of these tests are:

- to validate the thermomechanical durability of the mobile component and assess the temperatures reached by the various constituent materials;
- to verify the correct kinematics of the mobile assembly under combined thermal and mechanical loads representative of hypersonic flight;
- to evaluate design margins;
- to validate and refine numerical simulation models.

A key challenge is managing the synchronization of thermal and mechanical loads throughout varying phases of heating and cooling on the trajectory. The vehicle will experience both heating and cooling phases, leading to thermal expansions of various components and this can generate friction on the moving pieces. While IR lamp heaters effectively simulate heating phases by replicating the dynamic conditions of a flight, replicating the cooling phases reliably is more demanding. Due to the thermal inertia of the heating systems, achieving equivalent cooling rates to those experienced in flight is particularly challenging. Therefore, maintaining accurate thermal conditions and realistic operational motion speeds during rapid cooling phases can be challenging. For scaled-down mockups or designs with simple geometries, active cooling of the material is feasible (Ref. [9]). However, for more complex case, careful consideration and sophisticated strategies are necessary to ensure the speed of the moving part operates under varying operational conditions representative of the trajectory.

2.6. Wind tunnel tests

Any discussion of critical testing required for the development of a hypersonic concept would be incomplete without considering wind tunnel testing. Indeed, wind tunnel tests play an essential role in the aerothermal characterization of hypersonic vehicles, particularly during early design and validation phases.

However, because wind tunnels have limited size, because each test run has limited duration and because it is typically conducted at a single Mach number or within a narrow Mach number range, accurately replicating the dynamic evolution of flow and thermal conditions throughout a full-scale mockup over an entire trajectory is challenging. Indeed, wind tunnel tests often focus on characterizing either the propulsive performance (using a representative model of the internal flow path) or the aerodynamic and aero-propulsive properties (Ref. [10]) (using models that represent the external shape of the vehicle) at specific flight point.

Despite these limitations, wind tunnel tests allow evaluating specific materials and components such as leading edges which are exposed to high stagnation temperature. In addition, wind tunnel tests can be used to replicate the engine combustion environment. For example, within the ATLLAS-II program, a test campaign on ceramic injectors and on CMC panels has been conducted in MBDA France's dual-mode ramjet facility METHYLE that allowed for testing at operational relevant conditions of an equivalent ramjet/scramjet flight at Mach 6 (Ref. [1], Ref. [11], Fig 4).

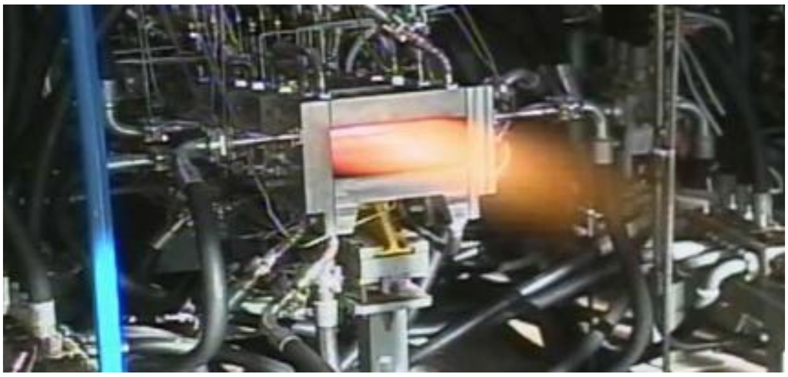

Fig 4. MBDA's dual-mode ramjet facility METHYLE

3. Implementation of a Combined Thermal Load and Fuel Tank Draining Test

3.1. Test Presentation

This test aims to drain a pressurized fuel tank while heating the tank's external walls with thermal fluxes representative of a hypersonic trajectory.

The main objectives are:

- to validate the fuel draining behavior:
  - ability to pressurize the tank;
  - ability to deliver the desired fuel flow rates;
  - evaluate the remaining fuel quantity (un-drainable fuel) in the tank at the end of the trajectory.
- to validate the thermal management of the tank:
  - evaluate the fuel temperature within the tank;
  - evaluate the temperature of the tank walls and internal components.
- to validate the thermo-mechanical integrity of pressurized equipment (tank, bladder, piping);
- to calibrate thermal and fluid numerical models.

The test setup consists of two tanks; each subjected to different thermal loading conditions simulated using IR lamp heaters:

- Tank#01 is heated on its upper face and lower face ;
- Tank#02 is heated on its upper face and central face.

The fuel is drained according to a flight drainage profile, under nitrogen pressure and bladder deformation.

The following figure (Fig 5) illustrates the test mock-up.

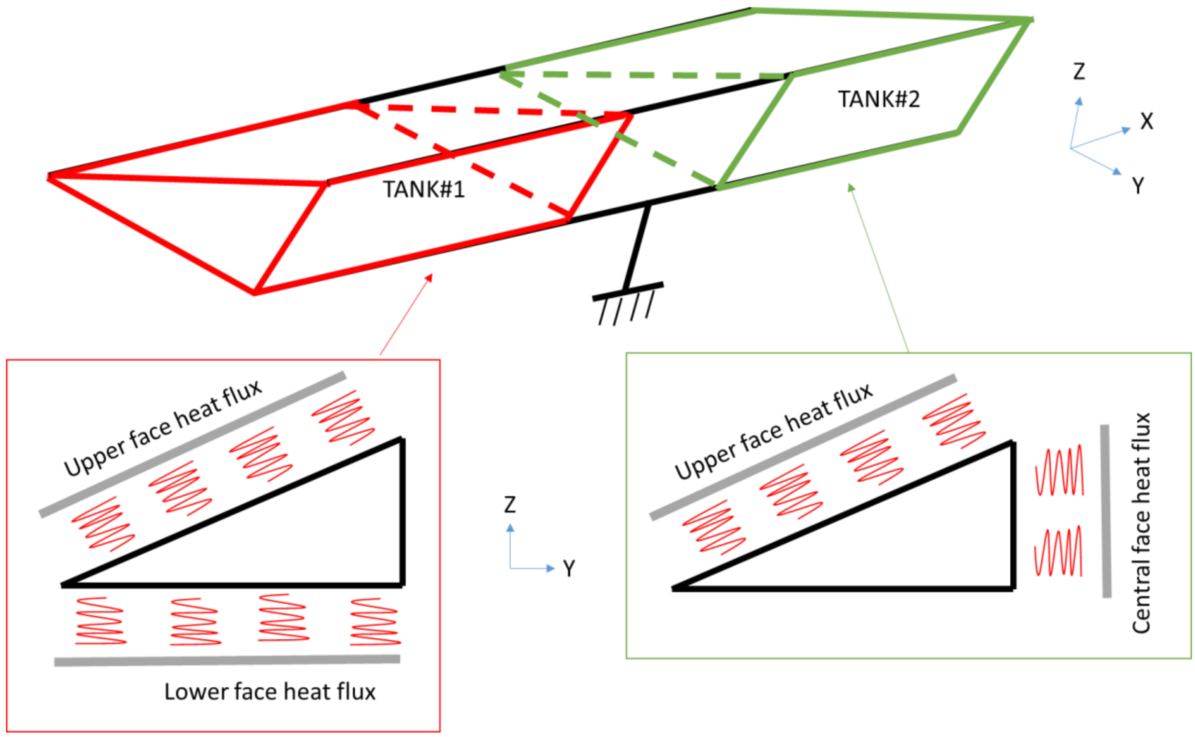

Fig 5. Visualization of the test mockup and heat fluxes

3.2. Mockup details

The following figure (Fig 6) illustrates the architecture of the mock-up.

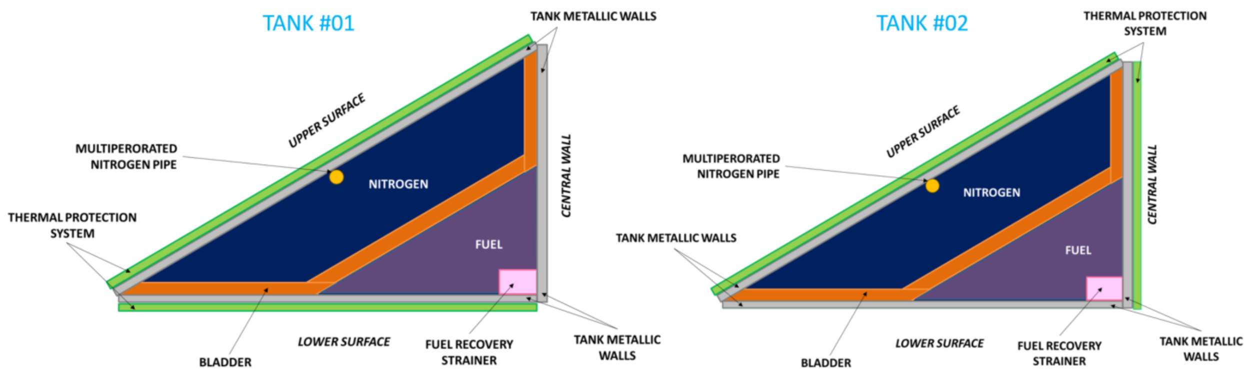

Fig 6. Mock-up Architecture (cross sectional view)

The prototype comprises two sealed metallic containers that incorporate flexible bladders, enabling the draining of fuel under nitrogen pressure. The surfaces thermally exposed to a representative heat flux are covered with a thermal protection system to limit the temperature of the fuel (on the upper side of both tanks, the lower side of Tank#01, and the central wall of Tank#02).

The nitrogen supply system, designed to pressurize the tanks is located between the two tanks. The nitrogen supply is symmetrically distributed to the two tanks and it is then diffused through multi-perforated supply tubes within the tanks.

For ground testing, the filling process must be simple and efficient, as it will involve multiple fill and drain operations. Additionally, the prototype should include a special draining system designed for use during testing if needed. At the bottom of each tank, there is a fuel recovery strainer (perforated sheet) designed to collect the fuel from each tank. Under the influence of nitrogen, the bladder forces the fuel towards the strainer and is fully deployed over it. The strainers are interconnected.

For this type of test, specific modifications are required to enable ground testing of the mock-up. This modification depends on the degree of representative needed: early in the development or pre-development phase, when a specific technology is being demonstrated, the mock-up is designed to the specific needs of the demonstration. For instance, in our case, the tanks have a constant cross-section to simplify their fabrication, the piping is adapted to easily fill and drain the tanks or the strainers can be interconnected or not in order to assess the impact of the draining sequence on the tank's behavior. When development progresses to qualification testing, the mock-up is as representative as possible of the actual flight vehicle: for example, same pipes (diameter, length) in order to get the right pressure drops and response times, same fuel tank volume, same fuel pump etc. However, regardless of the level of testing, some adaptations are still necessary. For example, in this case, a support structure (mast) is required to keep the mock-up in place on the ground and some handle are added in order to facilitate the handling of the tank.

All these specific modifications are taken into account during the implementation and post-test analysis. Indeed, it is necessary to verify that they will not affect what we intend to assess through these tests, or if they do, they need to be considered in the post-test analysis (e.g., thermal wells induced by these specific modifications, response times, pressure drops, etc.).

Additionally, since the mockup does not perfectly represent the actual vehicle, thermal Finite Element (FE) analyses must be conducted on the mockup's CAD model to validate its mechanical integrity, including all its specific features. These mechanical simulations are performed at temperature, following the thermal loading cases determinate for the mockup (see next paragraph).

3.3. Thermal Load Definition

The initial step involves analyzing the existing reference trajectories of the studied concept to define dimensioning load cases: thermal and flow rate. Thermal load case depends on maximum Mach number and maximum trajectory duration. Flow rate load case depends on maximum dynamic pressure. Notably, the various maximum load cases are not necessarily achieved on the same reference trajectory. For instance, the maximum fuel flow rate across all trajectories is not attained on the trajectory that reaches the maximum Mach number. When constrained by the number of tests (e.g., deterioration of testing equipment with each heating cycle), it is possible to create an artificial trajectory dedicated to the test, which consolidates all the maximum load cases into a single sequence. However, care must be taken to ensure that this artificial trajectory does not become over dimensioning, thus potentially leading to inaccurate or unrealistic test results.

Once the trajectory is selected, a classical approach is employed (Ref. [12]). This involves performing aerothermal computational fluid dynamics (CFD) simulations on the flight vehicle to determine the 3D thermal fluxes at the vehicle's walls, which serve as boundary conditions for subsequent thermal analyses. Due to computational resource constraints, only a few critical points along the trajectory are analyzed using CFD, specifically those points that drive the most demanding (dimensioning) conditions.

Using the heat fluxes coming from the CFD computations, some FE computations are made on the flight vehicle CAD model in order to compute the fluxes [kW/m²] for each walls along the trajectory. Thus, this allows to determine the thermal boundary conditions on the mock-up. Subsequent calculations are performed on the CAD model of the mock-up model using these flight conditions to give an initial estimation of the IR lamp radiation temperatures.

Due to differences in the thermal response between the mock-up and the flight vehicle model, iterative adjustments are made to refine the applied radiation temperatures. This process ensured that the mock-up temperatures aligned with the expected in-flight thermal conditions. Some comparisons are made between tanks walls temperature computed on the flight vehicle and temperatures computed on the mock-up. The same is made for all the interesting part such as fuel temperature and bladder temperature.

Overall, the heating of the system through radiative fluxes applied to the upper surfaces results in internal temperature levels that are consistent, maximum differences are found to be less than 10 K (Table 1).

Table 1. Tank walls temperature

	TANK#01 Upper	TANK#01 Lower	TANK#01 Central	TANK#02 Upper	TANK#02 Lower	TANK#02 Central
Tw [K] *Flight model*	474	445	431	458	402	420
Tw [K] *Mock-up model*	465	445	430	462	400	415

3.4. Instrumentation

Instrumentation plays a crucial role in the implementation and post-processing of this type of test.

Specific instrumentation is employed to control the IR lamp heaters in a closed-loop system, which includes a pilot thermocouple for temperature regulation and a safety thermocouple to ensure temperature safety in case of pilot thermocouple failure.

Since one of the primary objectives of the tests is to identify the thermal behavior of the mockup, it must be extensively instrumented with temperature measurements. Therefore, the mockup's walls (external and internal) are equipped with a total of 30 thermocouples. For instance, thermocouples are strategically placed to evaluate fuel stratification, as shown by the 5 thermocouples positioned along a generatrix in the following figure (Fig 7). Thermocouples are also placed in areas of interest, such as thermal bridges.

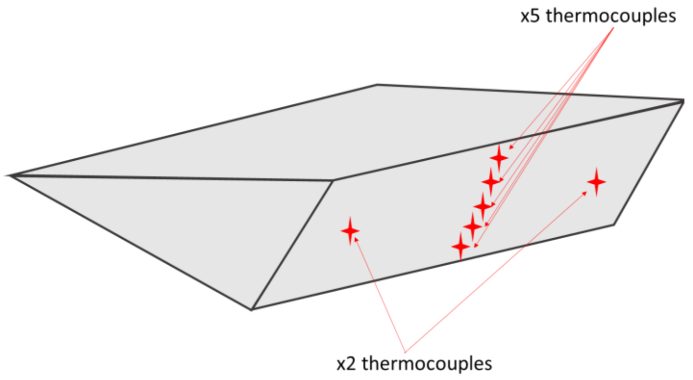

Fig 7. Example of Thermocouple Placement on the Central Wall of Tank#02

It was not possible to install thermocouples on the bladders that deform inside the tank. The chosen solution involves sticking thermal-sensitive patches that change color when a specific temperature limit is reached. Three patches were placed on each bladder.

Temperature sensors are also present in the hydraulic and pneumatic circuits. Four thermocouples measure the fuel temperature: one in each tank near the strainers, one at the outlet of the common header for both tanks, and one at the outlet of the cooler, just before the flow meter (see next paragraph). Three thermocouples measure the nitrogen temperature: one in each tank and one at the common nitrogen inlet to the tanks.

A Coriolis flow meter is used to measure the fuel flow rate at the outlet of the tanks. The flow meter's reference range is chosen to be consistent with the expected flow rate range.

Pressure sensors are used to evaluate the pressure levels within the tank and the piping. Six pressure sensors measure the fuel pressure: one in each tank near the strainers, one at the outlet of the common header for both tanks, one at the outlet of the cooler (just before the flow meter, see next paragraph), one downstream of the pump, and one at the fill valve level (for safety aspects). Three pressure sensors measure the nitrogen pressure: one in each tank and one at the common nitrogen inlet to the tanks.

A surveillance camera is employed during the tests.

3.5. Experimental Setup

The experimental setup is composed of three main components:

<u>a. The fluid circuit (nitrogen and fuel)</u>

The fluid circuit (Fig 8) includes interfaces for tank filling and integrates nitrogen supply circuits as well as fuel drain circuits. The nitrogen supply circuits include nitrogen bottles which are connected to a pressure regulator to control the nitrogen pressure entering the tanks. The fuel drain circuits include a fuel pump to drain the tanks at the desired flow rate, a flow meter to evaluate the fuel flow rate during the test. The circuit also includes a cooler located just downstream of the mockup (and upstream of the flow meter and pump), which cools the fuel before it passes through the flow meter and pump to prevent any equipment damage. Additionally, essential safety elements such as safety valves or expansion tank to manage fuel expansion are included. The fluid circuit also incorporates all necessary instrumentation for post-test data analysis as described previously.

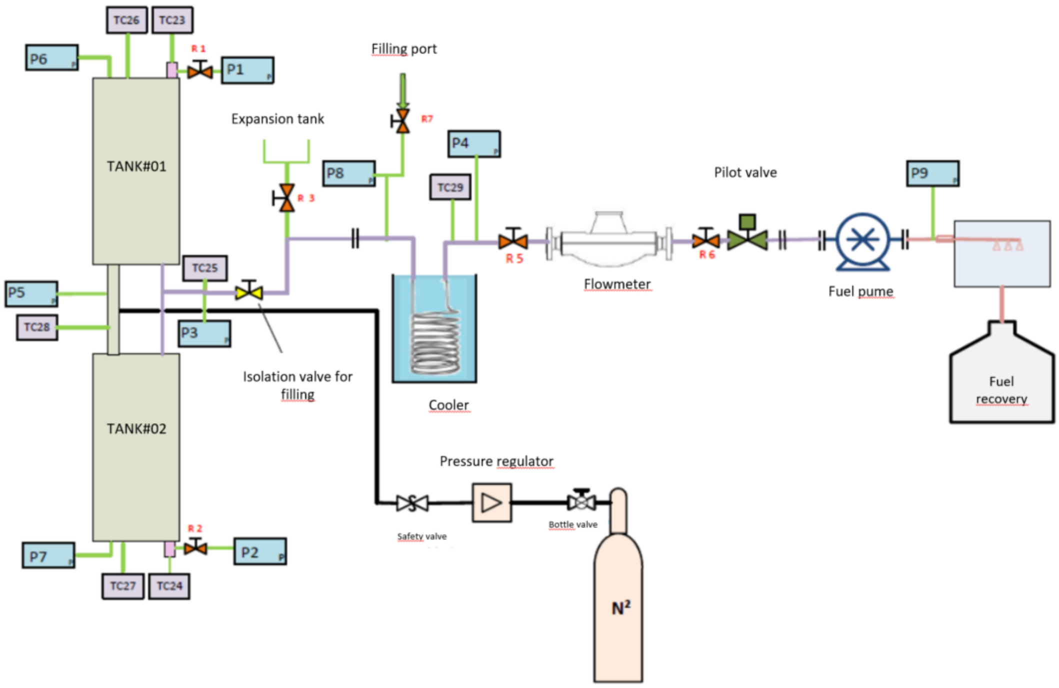

Fig 8. Fluid Circuit Synoptic

b. IR lamp heaters

Temperature control of the tanks is achieved using four IR lamp heaters. These heaters are especially designed to meet the required thermal flux levels, as determined from the previously described thermal FE computations and in order to fit the shape of the mockup properly.

c. Control of the experimental setup and data acquisition

The experimental setup is managed by the EEF facilities control center. A sequencer coordinates the various control components (valves, pump, and heaters). The pump is controlled in an open-loop configuration. Dedicated pump tests are conducted before the final test to adjust the pump control in order to match the specified setpoints. The four heaters are controlled independently in a closed-loop configuration using dedicated instrumentation (see previous paragraph).

All instrumentation data are acquired by a dedicated time-synchronized recording system.

3.6. Testing procedures

Preliminary tests are conducted to ensure the availability for the final experiment:

- fuel circuit characterization tests validate the feasibility of the required flow rate by the entire fuel circuit;
- nitrogen leak tests verify the integrity of the tanks by pressurizing them with nitrogen;
- IR heaters control validation tests are performed without fuel and with reduced thermal loading to validate heaters control and avoid any equipment damage.

Following these preliminary tests, the final experiment can be conducted.

Although the tests are not performed in a controlled environment, ambient conditions are recorded at the start of each test, including atmospheric pressure, ambient temperature, and relative humidity.

The mockup is weighed before filling, after filling, and after draining. Ambient temperature is systematically recorded to facilitate the calculation of residual quantities at the end of draining, accounting for fuel expansion

3.7. Tests Analysis and Experimental Challenges

Given the high volume of measurements and the number of tests conducted, a systematic post-processing approach is required. Each sensor's data must be carefully examined to identify any abnormal behaviors, such as sudden changes in slope, initial bias, or noise. Each of these issues must be analyzed. Although extensive precautions are taken before the test, anomalies are often identified during post-processing, necessitating adjustments during the test campaign. Below are some examples of analysis performed and corrections made during this test.

The graph below (Fig 9) shows the required temperatures of the IR lamp heaters and the temperatures measured by the thermocouples controlling these heaters. A significant electrical noise is observed, caused by a challenging electrical environment resulting from the operation of the variable frequency drive of the fuel pump and maybe to the power controllers supplying the heaters. To mitigate this issue, a network with equipotential bonding of grounds connected to Earth will be employed in the next test.

Additionally, there is a notable difference between the required and the measured temperatures for one of the four heaters (pink curves). The cause has been identified: the heaters power controllers, configured as 'unlimited' during the preliminary tests, were actually in 'limited' mode (i.e., power-limited) during the test. This configuration change was the result of a reset made before the test. This issue will be addressed in the next test.

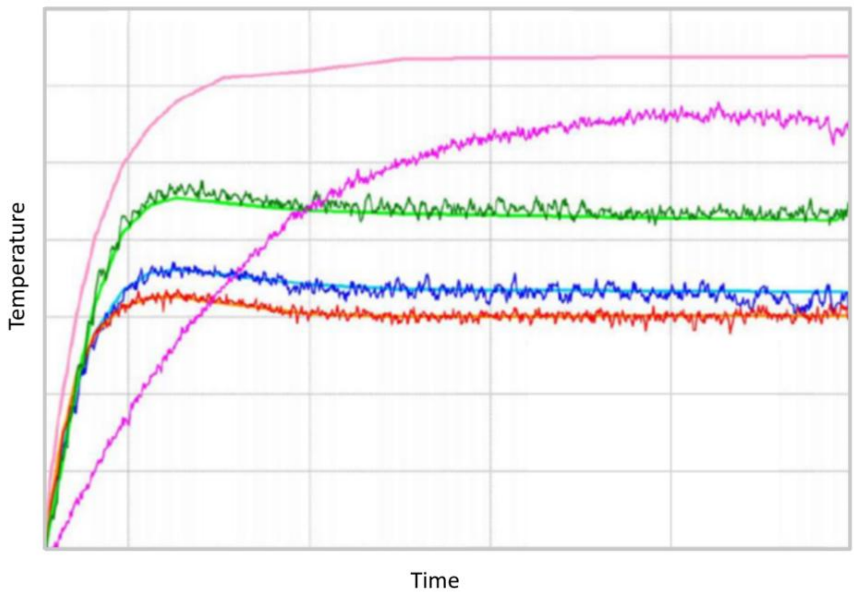

Fig 9. IR Lamp Heaters temperatures (measured and desired)

The following graph (Fig 10) illustrates the evolution of the nitrogen pressure measured at the common inlet of the tanks and in each tanks. A significant pressure drop is observed at the beginning of the trajectory, which is attributed to excessively high pressure losses in the upstream circuit. Modifications will be made to the nitrogen circuit to reduce these pressure losses in the next test.

Additionally, pressure measurements shows an offset in the y-axis. The identified cause is a variation in the electrical reference of the sensors due to the operation of the variable frequency drive of the fuel pump. This electrical interference depends on the frequency generated, and thus, on the rotational speed of the fuel pump. For the next test, an equipotential bonding network will be implemented among all grounded components (motor, pump, piping, heaters, etc.) to reduce these interferences and the associated measurement offsets. This should mitigate the problem, leading to more accurate and reliable pressure readings.

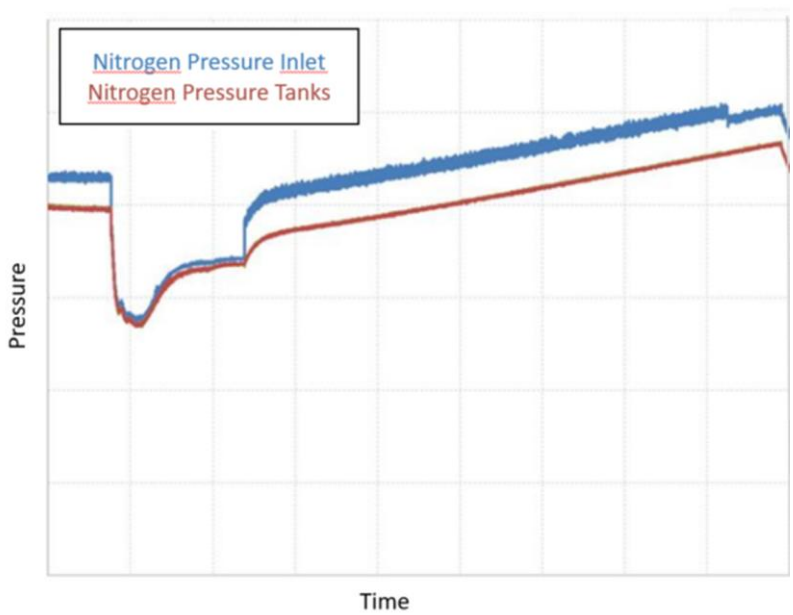

Fig 10. Measured Nitrogen Pressures

The graph below (Fig 11) compares the fuel flow rate measured by the flow meter at the tanks outlet to the required flow rate. It is observed that the maximum flow rates are not achieved, despite the flow rate required having been perfectly met during the preliminary tests of the standalone fuel circuit. When disassembling the pump, degradation of the internal membranes was noted. These membranes will be replaced in the next test.

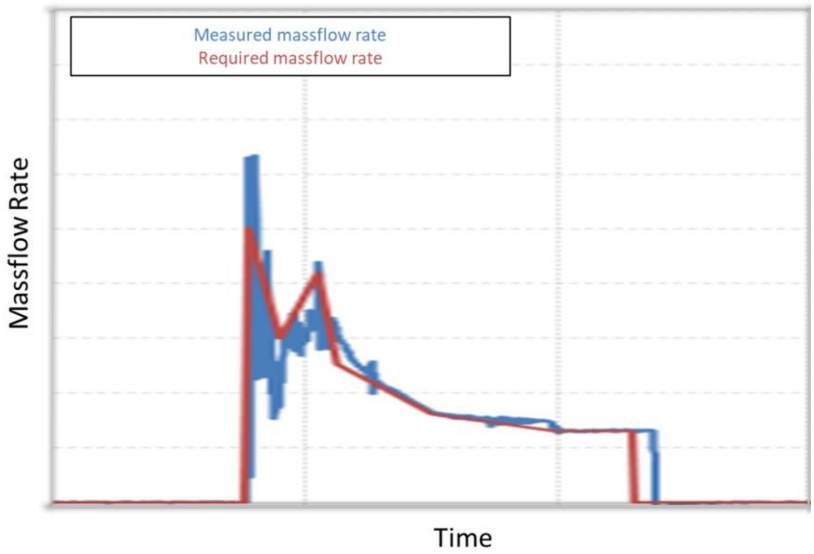

Fig 11. Required and Measured Fuel Massflow Rates

The figure below (Fig 12) compares the fuel temperature levels measured in the tank to those estimated through thermal EF calculations. It is observed that the trends are similar, although the temperature levels are not perfectly matched. This difference occurs because the calculations assume an average fuel temperature within the tanks. This approximation does not allow for the precise determination of temperature levels in specific zones of the tank. If further refinement is needed for the test analysis, the EF model used for numerical simulations can be improved.

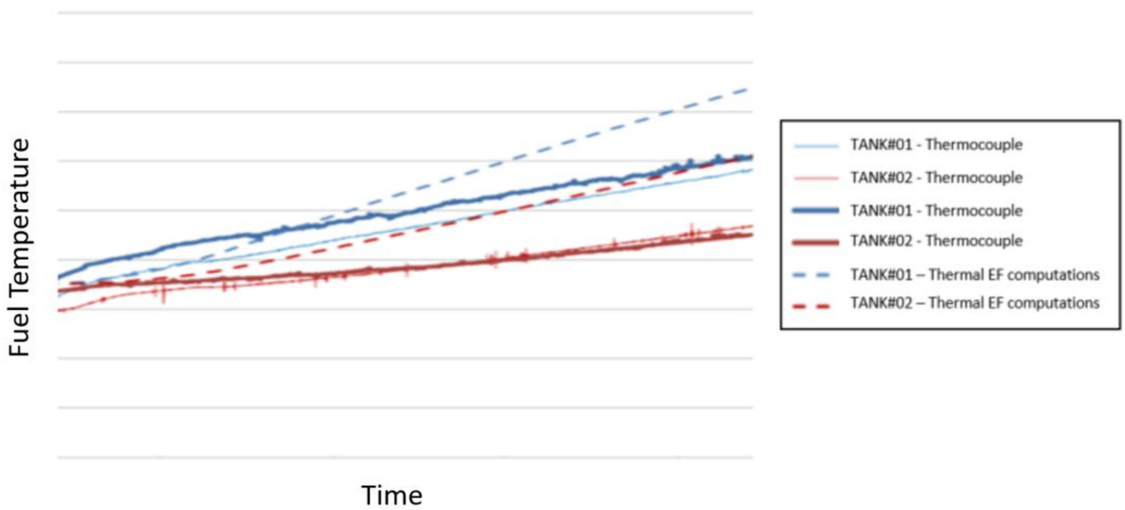

Fig 12. Computed and Measured Fuel Temperatures

Finally, by identifying each difference between the EF simulations of the mockup and the test results, it is possible to calibrate the EF thermal model for flight. Depending on the impact of this update, flight trajectories can be revised based on the new opportunities or constraints revealed by this validation. For example:

- Constraint: The fluid simulation underestimates pressure losses. In a fixed architecture, this may result in the inability to achieve the maximum flow rate during the trajectory, thus imposing a new constraint on trajectory generation.
- Opportunity: Temperatures are overestimated in the EF calculations. Consequently, thermal management can be re-evaluated to reduce, for example, the thickness of materials, leading to an overall mass reduction in the vehicle. This mass savings can improve the vehicle's performance during trajectory recalculations.

In addition to data analysis, post-processing includes a physical inspection of the mockup. This expertise material examination is crucial for identifying any physical anomalies or degradation that may not be apparent from sensor data alone. By combining these findings with the analytical results, a comprehensive understanding of the mockup's performance can be achieved, ensuring that all aspects are considered for subsequent improvements. This multi-faceted analysis allows to extract correlations between the collected data and physical observations.

4. Conclusion

While flight testing remains the ultimate validation method for hypersonic technologies, ground testing is shown to be an irreplaceable tool for the development process, providing substantial insights and reliable validation of key systems and components. The methodologies outlined in this article demonstrate that a comprehensive approach, integrating numerical simulations with meticulous combined ground experiments, enhances our understanding of complex, coupled environments faced by hypersonic systems.

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