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HISST 2025-319 - Hypersonic wind tunnels upgrades for Scramjet Experimental Studies

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Abstract

For the past three decades, MBDA France has developed and commissioned hypersonic blow down wind tunnels to carry on scramjet development. In order to increase its range of use, MBDA France has updated the test line 5, by adding cold air to the flow coming from the vitiator, and mixing them in a mixing chamber. This additional air supply can be shut down, depending on the flight conditions to simulate. With these device, the wind tunnel can still reach high temperature (up to 2100K) at limited air mass flow rate, or target higher air mass flow rate (up to 150kg/s) at an intermediate temperature. This major modification, added to the needs for the associated mock-ups and nozzles, required additional improvements in gas or fuel supplies.

In details, the modifications were aimed at increasing its field of application by simulating larger flight conditions toward lower Mach numbers and altitudes. In order to match those conditions, gaseous air and fuel supplies were added to the existing facility, and the wind tunnel previously developed for High Mach number flight simulation was modified to fit lower Mach numbers conditions. The hypersonic axisymmetric nozzle was adapted to fit the appropriate area ratio considering available mass flow rate resulting in a 1100mm diameter test section. Taking advantage of the short length of this new nozzle (4.5 meters) compared to the High Mach one, a mixing section about 4 meter long was inserted between this section and the vitiator. This device is able to provide an air mass flow rate up to 80 kg/s to dilute the hot flow provided by the H2/O2/Air vitiator that can reach a maximum total temperature of about 2100K and a maximum mass flow rate of about 70 kg/s. The mixing section is designed following the same concept as the vitiator. In particular, its uses a regenerative cooling enabling to reach long test durations and limiting heat losses which makes it more common to evaluate flow conditions and reduces vitiation rate. High temperature suitable screens was studied for turbulence management but are not used so far. Several runs, including flow characterization, shows satisfying working of the new facility.

Those modifications have shown excellent performances during the tests. Beyond the increase of range of use, the wind tunnel n°5 is now more versatile with this device, and more suitable to increase the tests rate with various configurations. They demonstrated the capability of the facility to simulate a large range of flight conditions that are necessary for Scramjet Development.

Keywords: Hypersonic aeropropulsive balance, Free Jet testing, Vitiator, Mixing chamber

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References

1- Development of a Free Jet test facility aiming at preliminary validating aeropropulsive balance prediction methodology for hypersonic airbreathing vehicles, HISST 2024

(F. Falempin , A. Duarte , M. Lechevallier , Q. Mouly , J. Lefieux , E. Choquet)

2- Calibration of the MBDA-Subdray Hypersonic Wind Tunnel n°5, HISST 2024

(A. Duarte Antonio , Q. Mouly, F. Falempin, G. Vilmart, C. Brossard , P. Nicolas)

3- Gas mixing in cylindrical chambers after radial jets injection

(A. Nirmolo, H. Woche*, E. Specht and R. Praetor, Progress in Computational Fluid Dynamics, Vol. 7, No. 8, 2007)

Nomenclature

M – Mach number
P – Pressure [Pa]
T – Temperature [K]

Subscripts
t – Stagnation (pressure, temperature…)
s – Static (pressure, temperature…)
dyn - dynamic

1. Contexte and objectives

The first wind tunnels at the Bourges Subdray facility were created at the end of the 1970s to support the development of the first ASMP missiles. Those lines have been regularly renovated and upgraded to meet the needs of new programs or evolving requirements. Today, they are used in ducted pipe and in semi-free jets configurations, which are necessary for the development of ramjet engines. In addition to the classical lines, a specific wind tunnel has been created to meet the development needs of dual-mode ramjets, with a free jet configuration : line 5.

It was commissioned in the 2020s with the purpose of performing tests in free jets, at high Mach numbers, with measurement of the aeropropulsive balance. The description of the Line and the first tests with mock-up and characterization system is detailed in documents 1- and 2-.

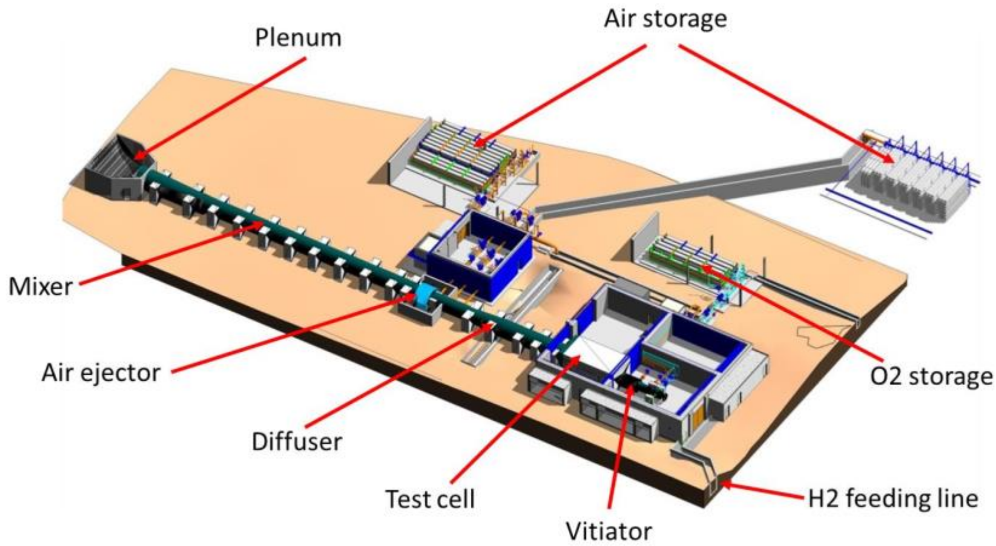

Figure 1 : General view of the free jet test facility at MBDA France ramjet test center

One of the main challenges in the development of dual-mode ramjets is the need to conduct wind tunnel tests over the entire operational domain. Therefore, to ensure the development of MBDA's new projects, upgrades to line 5 were necessary to perform tests with several combinations of Mach and Pdyn.

2. First configuration of Test Line 5

This configuration, the first to be designed, manufactured, and commissioned, was intended to simulate points at high altitude with high Mach numbers. A vitiator, burning Hydrogen/Air/oxygen, provides up to about 70 kg/s of hot gas to feed the supply nozzle with a maximum total temperature of about 2100K (higher total temperature is achievable but not used in operational conditions). The vitiator is equipped with co-axial three-flow injectors - Oxygen/Hydrogen/air – located in a front end and fed by dedicated plenums. The flame tube of the vitiator is cooled down by the injected air.

Fig 1 Vitiator

The supply nozzle has an exit diameter of 1.5m. It is constituted by several sections: an interchangeable water cooled throat giving the Mach number a first uncooled diverging part protected by zirconia oxide coating, a series of uncooled diverging parts outside the test-cell, a final section embedded in the test-cell with a removable upper part to allow integrating a mock-up partially immerged into the supplying nozzle to take benefit of the complete Mach rhombus (Fig 2).

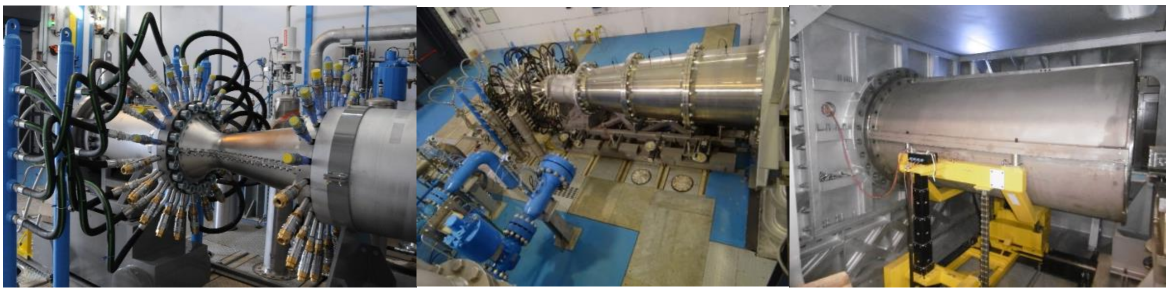

Fig 2 Supplying nozzle

The test-cell is 4 x 4 X 8 m^3. The test line can be accessed through lateral doors but the mock-up is integrated from the top after test-cell roof removal (Fig 3).

Fig 3 Test cell

The diffuser catch is 2 m in diameter. A long diffuser with a slightly converging section is driving the main flow to a circular ejector providing high mass flow rate of cold air to suck the main flow. Finally, a mixing section leads to a large plenum which redirects the flow vertically. The total length of the extracting system is about 80m (Fig 4).

Fig 4 Extracting system

3. Upgrade to reach higher flow rate at lower temperature

In addition to the configuration detailed above, modifications to the Test Line 5 have been designed, manufactured, and commissioned in order to expand the capabilities of the line. The main modifications include the addition of a mixing chamber with its air supply (maximum air flow rate of 80kg/s) and the installation of a new nozzle.

3.1. Mixing chamber

The main advantage of using a mixing chamber lies in its ability to expand the operational domain of the Test Line 5, in order to achieve higher flow rates at temperatures lower than the maximum total temperatures achievable in the vitiator-only configurations. This enables the extension of the operational domain to lower Mach numbers without changing the vitiator's geometry or operating mode. The device hence connects the high Mach domains and the domains of historical lines (low Mach, intermediate Mach), providing an especially relevant option for testing in the intermediate Mach ranges.

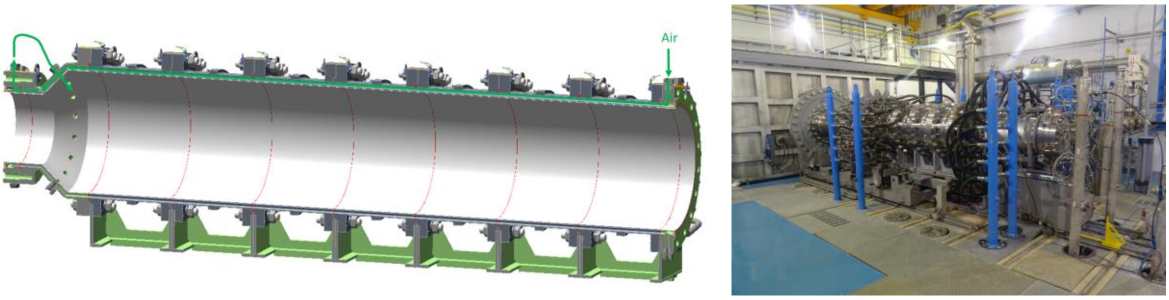

Figure 2 : General concept and picture of the mixing chamber configuration

It is made of two main sub-elements:

- The upstream divergent section, being the transition from the internal diameter of the vitiator to the internal diameter of the mixing chamber, while ensuring the injection of cold air
- The seven shrouds, mixing the cold air injected and the hot air from the vitiator

Like the vitiator or the former High Mach nozzle, the interface between the mixing chamber and its support mounts is made via several sliding pads, in order to avoid the stress due to the thermal expansion.

This device is cooled down from downstream to upstream (following the direction of the primary flow coming from the vitiator) by a secondary air flow, passing through all the components via 90 cooling channels. This secondary flow is then injected and mixed into the primary flow upstream of the device, in a conical section, which increases the total flow rate and reduces the total temperature of the flow.

This cooling principle, already used on the Test Line 5 vitiator, limits the thermal losses in steady state since the heat absorbed by the cooling circuit is injected into the overall flow (the zirconia layer also helps to limit thermal losses). This also reduces the viciation of the flow generated by the test section.

The geometry of the mixing chamber was initially designed using the formulations provided by reference 3-. The key points are the dimensionless penetration height (h/R) and the ratio of momentum fluxes between the hot air flow from the vitiator and the cold air flow injected into the mixing chamber.

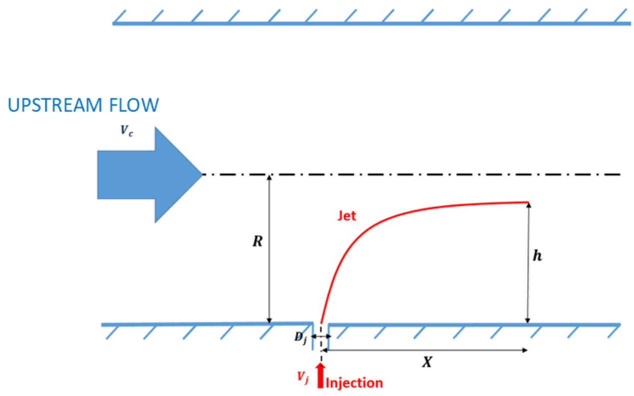

Figure 3 : Diagram of perpendicular injection into a flow within a cylindrical chamber

In a second step, the injections (position, number, angle, diameter, geometry), the internal diameter, and the length of the mixing chamber were optimized through CFD studies. Those calculations converged on the solution shown in the figure below.

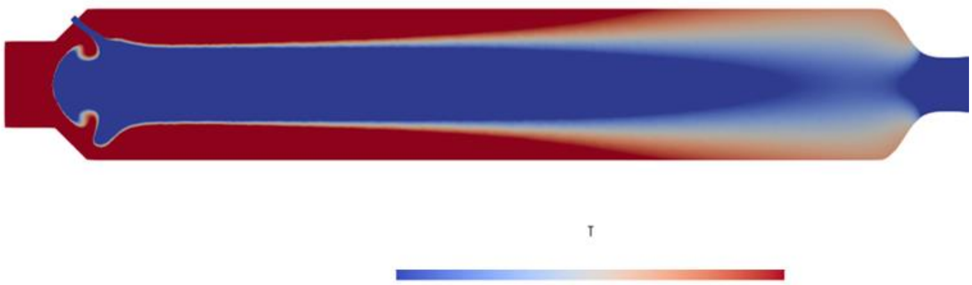

Figure 4 : Example of temperature field inside the mixing chamber

3.2. Modularity and possible configurations

In order to maintain high adaptability of the wind tunnel to quickly address new needs, the design of the mixing chamber has also been made to be modular :

- The shrouds are independent and can be removed or added to increase the dilution length if necessary

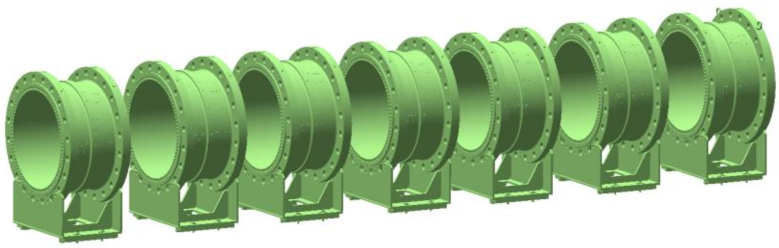

Figure 5 : Independent shrouds

- The air cooling system can be replaced, through minor adaptations, with a water cooling system, in order to keep the mixing chamber in place, even when additional air is not necessary

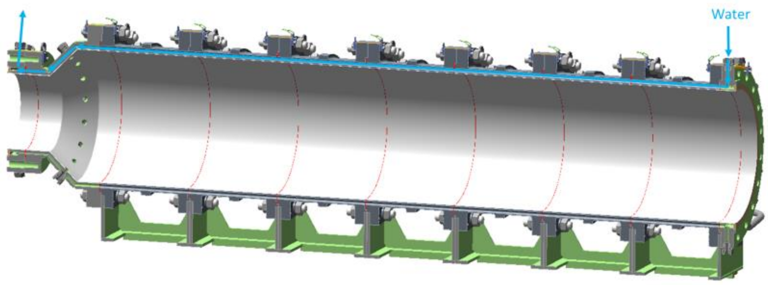

Figure 6 : Mixing chamber with water cooling configuration (without air injection)

- An anti-turbulence shroud has been designed to be added or installed instead of a classic shroud. If needed, depending on the mass flow ratio between the vitiator and the mixing chamber, this device is aimed at reducing the turbulence and improving the homogenization of the flow at the end of the mixing chamber.

  First, in order to design this device, an optimization of a combination of honeycomb and mesh had to be done. The best combinaison found for our needs is an assembly of :

  - Wide mesh
  - Honeycomb
  - Thin Mesh

  The thickness and materials were selected to withstand the pressure and temperature of the test line, while being easily supplied and manufactured.

- Eventually, the final configuration has been incorporated inside a shroud, with the same interfaces as the classic ones.

Figure 7 : Anti-turbulence Shroud

3.3. New Air supply

As said in chapter 3.1, a new air supply system was installed and commissioned, dedicated to the mixing chamber.
This air supply is similar to the burner air supply, with the same type of equipments.

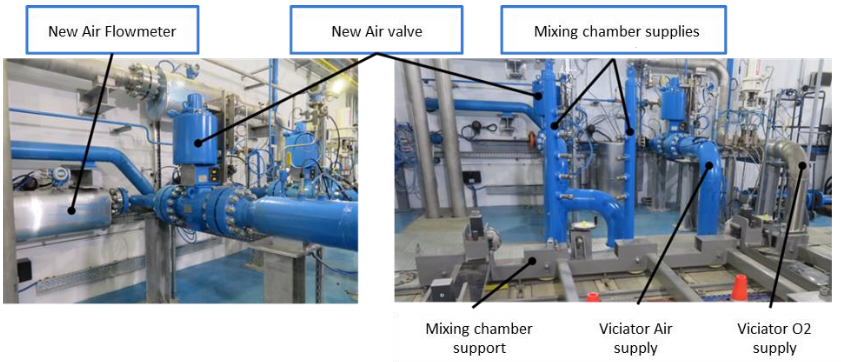

Figure 8 : New air supply for the mixing chamber

3.4. New supplying nozzle

In addition to the mixing chamber and new air supply, and to meet the need for expanding the operational domain to the lowest Mach numbers, a new nozzle has also been designed, manufactured, and commissioned. This nozzle takes into account the accumulated experience from previous nozzles to improve the quality of the generated flow, while maintaining the same concept (divergent in two parts to integrate the mock up)

This new supplying nozzle has an exit diameter of 1,100 mm, with an uncooled throat due to the lower stagnation temperatures than before (but is nevertheless protected by a zirconia oxide coating).

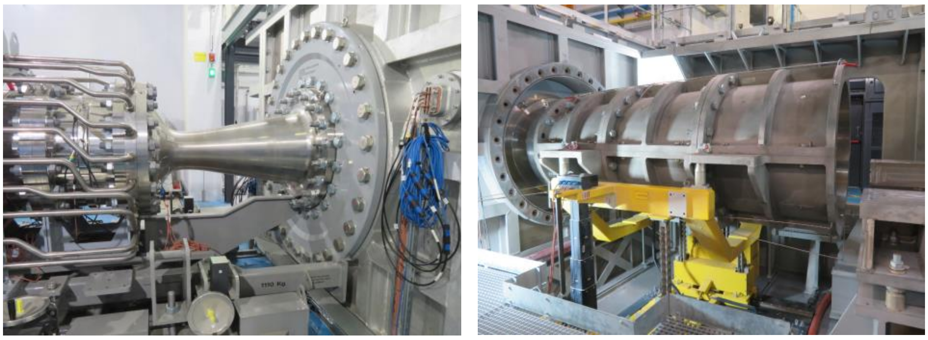

Figure 9 : Supplying Nozzle

4. Mock up fuel supply upgrades

Along with the increased capabilities of the test lines, the mock up supply systems have also been upgraded to increase both their total capacity and their modularity with higher numbers of lines.

4.1. Liquid fuel supply

The new Liquid fuel supply system, after its upgrade, can meet the requirements across the entire studied domain. Several independent lines ensure the regulation of different flow rates for the various model injections.

It is composed of six volumetric pumps, each with a different range of use, and several injection valves to optimize response time, particularly during the initial phases of mock up starting or changes in trajectory.

Figure 10 : Part of the new liquid fuel supply

4.2. Gas Supply

On the same principle, the new CH4-H2 supply system, after its upgrade, meets the requirement for the new flow rate needs. This system replaces the old one, expanding its capabilities and modularity. In addition, the historical storage was extended to maintain the same test durations as before, with higher flow rates.

Figure 11 : New CH4-H2 storage

5. Tests / Commissioning

The commissioning of the new Test Line 5 configuration was carried out with several stages:

5.1. Commissioning of the air regulation valve for the mixing chamber, and the mixing chamber itself

This first step, similar to the previous commissioning of the vitiator regulation valves, was to determine the valve law, which is the relationship between the opening and the requested mass flow rate. This step helps as well to check the sealing of the flowpath, the instrumentation, and the proper functioning of the control system in this configuration.

5.2. Commissioning of the test line with vitiator ignition without mock up.

This step demonstrated the proper ignition of the vitiator despite different downstream conditions, compared to the configuration without the mixing chamber. In order to maximize the probability of ignition, and with the experience gained with the previous tests, the mixing chamber flow rate at the ignition point was chosen to have a counter pressure close to the previous configuration.

The test sequence is similar to what was done before with the High Mach number configuration :

- Air is injected in the vitiator and the mixing chamber, in order to prevent depressurization in the supply hoses when the extracting system starts, and to create the target pressure in the vitiator before ignition
- The extracting system starts, to empty the test cell
- After a few seconds, Oxygen is injected in the vitiator with a mass flow rate corresponding to the ignition point
- Hydrogen flow is started and, during its ramp-up, the vitiator is ignited thanks to a H2/Air torch.
- Once the viciator ignition is confirmed, all mass flows are ramping-up to their nominal values (vitiator + mixing chamber).
- At the end of the test sequence, the vitiator is turn off, and a minimum mass flow rate or air (vitiator and mixing chamber) is kept a few seconds to cool down the test line.

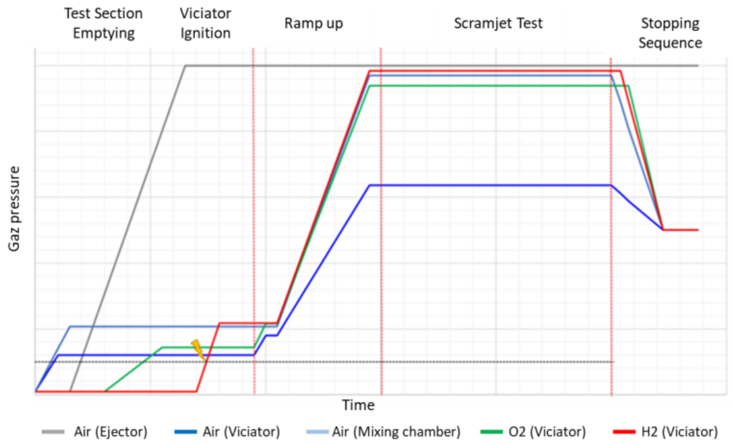

Figure 12 : Test Sequence

Conducting these commissioning tests validated the proper functioning of the new test line, and its thermomechanical integrity.

5.3. Commissioning of the test line with a LEA mock up to represent a real obstruction

Once all previous steps were successfully completed, a test with a LEA mock up has been conducted. This mock up is based on the LEA vehicule (See reference 1-), without the scramjet inside. It was used to represent a similar obstruction compared to a real mock up equipped with a scramjet.

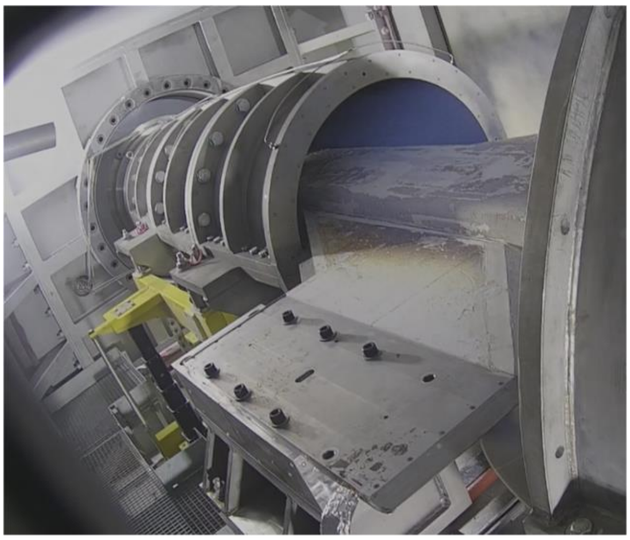

Figure 13 : LEA mock up during test

This test demonstrated a nominal behavior of the test line, even with the mock up obstruction.

5.4. Comparison with CFD studies

The results obtained during the tests with the LEA mock-up have been compared to the CFD studies.

The several tests and CFD calculations carried out with the previous configuration helped to determine the best methodology to simulate the test cell flow field topology (nozzle – test cell – diffuser).

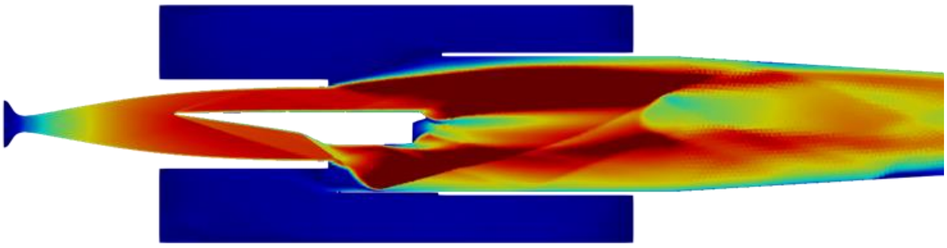

Figure 14 : LEA Mock up in the test cell - Mach field

In particular, the static pressure measured at three different positions in the nozzle has been compared to the values determined with CFD studies

- First plan is at the mock up nose
- Second plan is after the mock up nose
- Third plan is the exit nozzle plan.

The Figure 15 shows this comparison of static pressure (blue = calculations, other colors = measurements), along the nozzle wall.

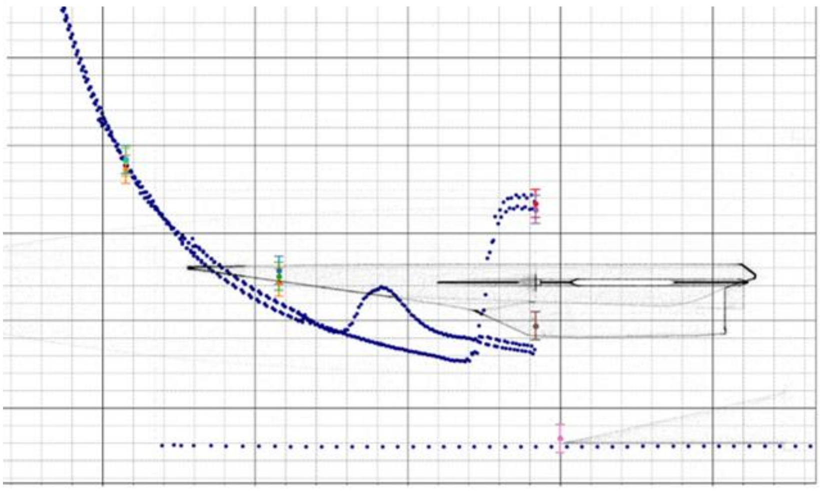

Figure 15 : Static pressure (measurements vs calculations)

Overall, it shows a good match between calculations and measurements, especially at the first plan, as well as the test cell pressure.

These results confirm that the numerical simulation model implemented during the High Mach Number analyses is showing a good accuracy even on lower Mach Number, with a mock inside the test line.

5.5. First characterization of the test line using pitot probes, tunable diode laser absorption spectroscopy (TDLAS), and laser

Eventually, a partial test line characterization test was conducted using some of the instruments already deployed during the previous tests. Specifically, pitot probes and TDLAS systems were implemented.

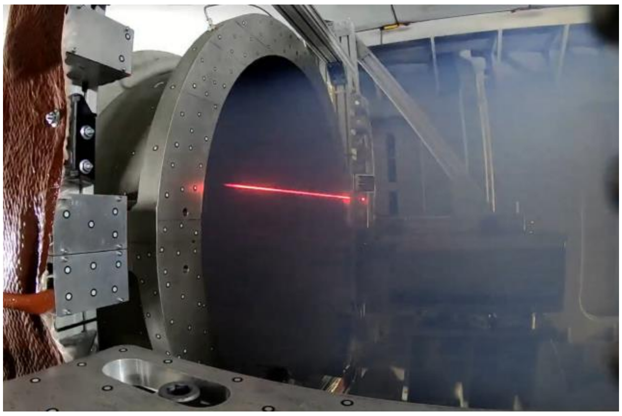

Figure 16 : Laser showing condensation during test

First CFD studies, conducted by MBDA France and ONERA, had shown the presence of condensation in the flow, which can have non-negligible effects on the flow (pressure, velocity, for example), and therefore on its representativeness.

During the tests, the flow characterization confirmed the presence of condensation, with the same order of magnitude as the calculations, helping the understanding and estimation of this phenomenon.

6. Conclusion

With the commissioning of these major upgrade of test Line 5, MBDA France continues to expand the capabilities of its wind tunnels dedicated to dual mode ramjet testing. Thus, with an increasingly versatile line, the goal is to achieve higher testing rates by minimizing configuration-change times, while offering a wider range of Mach numbers and higher flow rates than before.

The understanding of the physical phenomena involved, the thermostructural integrity of the test lines, and the characterization of the flows remain at the center of the wind tunnel upgrade studies. All tests conducted help to continually progress in these areas by accumulating experience, which is mandatory for future developments.

This also demonstrates another advantage of these test line evolutions. More correlations between CFD calculations and experimental results can be made, which is fundamental for the development of future scramjets.