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TESTING REACTIVE MODELS FOR SSTO IN INCAS SUPERSONIC WIND TUNNEL

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Abstract

A key point for different space missions, including satellite lunching and future space tourism, is the fuel consumption, which is linked to the propulsion system optimization. From the information related to actual aeronautical programs for supersonic jets and from published flight measurements of space launchers (Ariane5 and VEGA), it was concluded that currently used approach (CFD and wind tunnel testing) underestimates the base pressure and hence overestimates the vehicle drag. This is mainly due to the influence of the plume temperature on the complex flow field surrounding the base region, leading also to a large uncertainty in the heat loads and fluctuating loads on the nozzle. As a result from current investigations on the capabilities in Europe with respect to the active models simulations for space applications, INCAS has identified a real need for a facility able to provide this very specific capability for improved predictions. Traditionally INCAS supersonic wind tunnel, as many other wind tunnels, used cold plumes to simulate the jet-on conditions in tests, for flight ranging from transonic to supersonic conditions. This paper describes the work on the last development program aimed to enhance INCAS Supersonic Wind Tunnel testing capability by introducing hot plume testing capability under similitude conditions for space vehicles. This capability is based on a dedicated supply system for hydrogen peroxide, used as a monopropellant for the rocket engine system simulator, to be used complementary with the existing cold air supply system for jet simulations. Following this goal, we introduce a generic calibration model for base drag evaluation under similitude criteria. The built wind tunnel model is using a generic launcher configuration installed on a dedicated support, including a peroxide engine simulator able to simulate hot plume interactions in transonic and supersonic regimes and a secondary air flux. During testing it is possible to measure the global loads and pressure surface measurements using specific instrumentation of the model, contributing to the development of a set of scaling parameters and similitude factors for active rocket engines simulations in wind tunnels. The proposed approach goal is to improve the knowledge related to interaction between rocket exhaust plumes and the base region leading to an optimized launcher design. The basic work performed was taking into account the need for the new supply system to be qualified with respect to safety procedures needed for standard usage in wind tunnel tests at INCAS. Also, as a result from the test campaign, one engine testing rig was developed, able to measure the hydrogen peroxide engines parameters before they are installed on the wind tunnel model.

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Nomenclature

c – speed of sound
C – Crocco number
CFD – Computational Fluid Dynamics
C_{Pb} – Base pressure coefficient
HTP – High Test Peroxide
HP – High Peroxide
M – Mach
R – Reynolds number
T – temperature
V – Velocity
WT – Wind Tunnel
γ – Ratio of specific heats

1. Introduction

The purpose of this paper is to describe technical aspects of developing an active model that is used for testing in INCAS Trisonic wind tunnel. The work described here was done under ESA contract during CARESS project. This model is distinctive compared to other active models because it uses hydrogen peroxide as a fuel for the engine simulators.

Jet effects have been recognized to be responsible for a number of differences in drag, stability, and load results obtained in flight tests and common wind tunnel investigations. Because of the importance of these effects, jet simulation methods have been developed for wind tunnels, especially for rocket models.

Several methods was considered of producing hot jet that would be able to simulate the characteristics of engine exhausts. After taking into account the temperature reached by the jet gases and the space required to accommodate the system inside the model and its support, it was chosen to use liquid hydrogen peroxide as fuel.

This model is using two strain gauges balances to measure the axial forces, one of them assigned to measure the forces on the model base. For a body of revolution, the base drag may reach 30% of the total drag, and for a thin and streamlined body, the base drag is large compared to its small friction drag. For a missile, the base drag amounts to 1000 or 2000 lb if the total drag reaches several thousand lb. Therefore it is easy to see that the estimation of performance, trajectories, and propulsion requirements of missiles is impossible unless the base pressure is known [5].

2. The testing facility

The model development and its testing campaign was performed at INCAS Supersonic Wind Tunnel during the CARESS project. This is the most advanced facility existing on our experimental platform and is in operation since 1977. A important number of projects have been developed using the wind tunnel test results from the INCAS Trisonic Wind Tunnel, including transonic and supersonic aircraft (transport and military), missiles, rockets, etc.

This wind tunnel has 1.2m x 1.2m testing sections and is of the blowdown type. Its speed range is starting from low subsonic (M=0.1) and reaches a maximum supersonic Mach number of 3.5. This range includes transonic Mach numbers which are obtained through use of a perforated wall transonic test section. This transonic section is easily incorporated into the wind tunnel circuit when required.

For normal operation the control valve is manipulated to give a constant stagnation pressure and the stagnation temperature remains at approximately 20°C during a run. This latter is effected by causing the air to flow through a matrix of long steel tubes at the outlet of the air storage.

The compressor plant delivers 400 m3/min of filtered, dry air at maximum pressure of 20 bar and at about 20°C to the storage vessels. As a run is initiated, the air from the storage tanks flows into the settling chamber. This flow is regulated by the control valve to maintain the desired stagnation pressure in the settling chamber and the noise and turbulence levels are reduced to acceptably low values by baffles and screens.

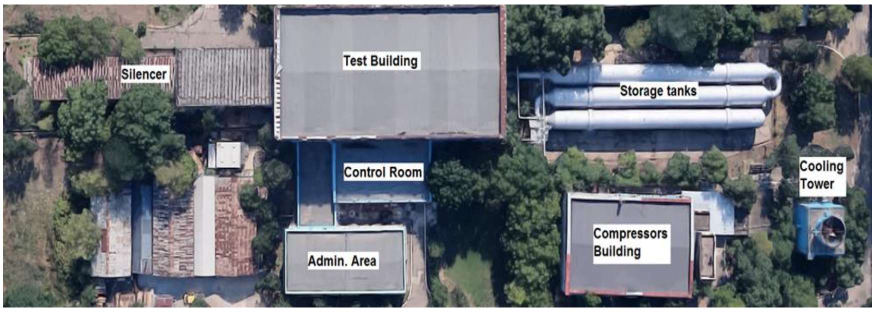

Fig. 1 - INCAS Trisonic Wind Tunnel

The air then accelerates in the nozzle to give the desired test section Mach number. After the air has passed through the test section, it is slowed down in the variable and fixed diffusers and finally discharged through an exhaust silencer to atmosphere. In the subsonic and transonic ranges the wind tunnel can be run at any desired Mach number. For the supersonic range, nozzle settings for nominal Mach numbers of 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3.5 are available.

3. New developed hardware

3.1. Model concept

During this active model development, two main model configurations were designed and tested. The model configurations are using some common parts and some specific components to each of them. The outer shape is based on a cone-cylindrical body attached to a side support.

One configuration is based on a larger single engine fed by hydrogen peroxide, that produce a hot jet, and it has an additional secondary air flux capability. In this way it is possible to simulate one single hot jet covered by a cold air flux. The second model configuration is based on four engines fed by hydrogen peroxide without secondary flux, in this way four hot jets are present at the model back side. The engine simulator utilizes a gas generator in which the HTP liquid enters the decomposition chamber through an inlet orifice. The catalyst bed is made up from several mesh wire screens of silver. High-test peroxide (HTP) is a highly concentrated (85 to 98 per cent) solution of hydrogen peroxide, with the remainder consisting predominantly of water. In contact with a catalyst, it decomposes into a high-temperature mixture of steam and oxygen, with no remaining liquid water.

These tests were not focused on the research and development of nozzles and for this reason only one type of nozzle was used for each engine.

A lateral support attached to the left side wall of the wind tunnel ensures model fastening. The main dimensions of the models are: 220 mm diameter and 1246 mm length, leading to a projected section/test section ratio of 0.057/1.44 (including the model support).

The model support was designed to be attached to the wall of the wind tunnel inside of experimental area and to maintain the fixed position of the model. It is a sub-assembly that makes possible the interface between the wind model and the test chamber. The problem of simulation at transonic speeds, however, was found to be more difficult because of the importance of support interference effects. The use of air or combustion systems based on air would require large feeding pipes that must be protected by thick supports and would lead to increased interference. In our case one model configuration is using the air only for secondary flux that do not require large amount of air and in this way it was possible to design a model support with relatively low interference. It was manufactured taking into account to allow crossing of the HTP and air supply systems paths into the wind tunnel model. Also the electrical and pneumatic connections to the transducers and to the acquisition subsystem are crossing the model support. The model support ensures that the front and rear flanges are positioned in the axial position of the model in order to allow front and rear strain gauges balances mounting.

As part of the testing facility system, the wind tunnel testing chamber allowed other sub-systems to be integrated for experimental campaign to be performed. The wind tunnel testing chamber required some adjustments in order to facilitate the integration of the model, the HTP supply and air system to provide interface for the model support. All these adjustments are reversible ensuring the wind tunnel operation in normal way.

3.2. Fuel Supply System for Engines

The fuel supply is a system, composed of several devices, which is interfaced with the model to provide HTP to the engines thus enabling their operation. It was designed to provide the fuel for both model configurations (with one engine or with four engines) when is integrated in the wind tunnel facility but it can also be used for off-site testing. The fuel supply system has sufficient flexibility to ensure the supply of hydrogen peroxide at the parameters required for proper operation of the engines whether it is interfaced with the single-engine or four-engine configuration.

Fig. 2 - Engine supply system

The fuel was stored on a special stainless-steel tank to avoid unwanted reactions that could change its properties but also for safety reasons. Also the models were feed using stainless steel pipes through the WT wall and model support. Pressurized nitrogen was used to create pressure inside the hydrogen peroxide tank to order to feed the engines simulators from the model.

The fuel supply system contains a pressure regulator to control the pressure inside the hydrogen peroxide tank ensuring the safety operation but also two pressure manometers, one to check the nitrogen pressure and one to check hydrogen peroxide pressure. One electric valve actuator is included in the supply system chain in order to control the start and stop of the hydrogen peroxide flow from distance. This was connected to the wind tunnel control system to turn on the engines during the tests.

The feeding lines go from the stainless-steel tank, where the hydrogen peroxide is, to the model crossing the wind tunnel wall and the model pylon.

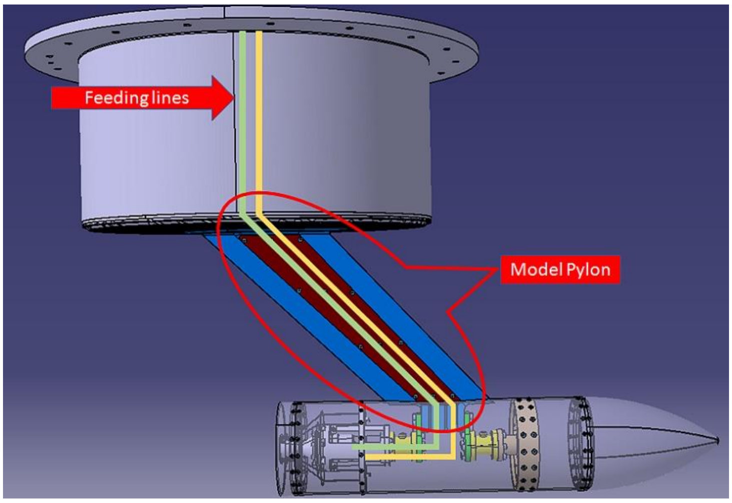

Fig. 3 - WT setup using model pylon

For the tests high concentration hydrogen peroxide (80% - 90%) was used. It was obtained by distillation of lower concentration hydrogen peroxide (35%).

3.3. Air system supply for the secondary flow

The air supply system ensures the secondary air flow operation for one engine model configuration. The model's air supply system was integrated inside the main hall of the wind tunnel, as close as possible to the test section to minimize losses. It is based on a buffer tank of eight cubic meters (1.6 meters in diameter and 3.4 meters in length) which can be fed by the main wind tunnel compressor or an auxiliary one. It is designed to work at 12 bar and to be able to supply the necessary air for 19 seconds with a maximum flow rate of three kilograms per second.

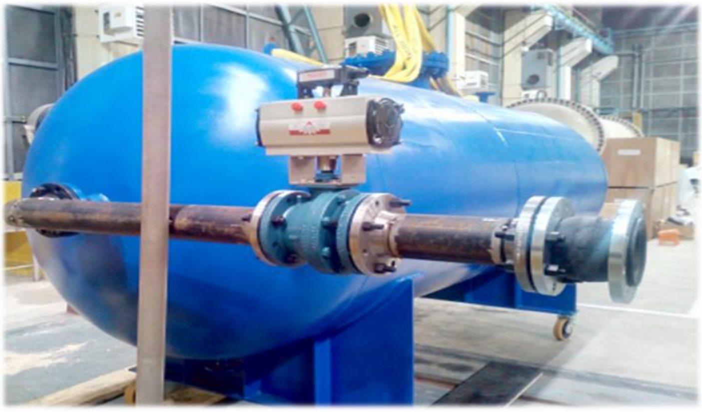

Fig. 4 - Secondary flow tank

An electro-pneumatic valve is mounted on the outlet pipe of the tank that starts the air flow when the signal is transmitted from the main control computer to ensure the required conditions during the test. The air supply pipe follows the path from the air tank into the test chamber, crossing the model support.

3.4. Instrumentation

To monitor and measure the operating parameters of the model, it was instrumented with different type of sensors like pressure sensors, temperature sensors and strain gauges balances.

For pressure measurements on the model surface pressure taps were installed and connected to the sensors. Also two sensors were mounted directly on the model's base, near the engines region. Pressure taps and temperature probes were installed on the engines, on the nozzles and on the settling chambers, to monitor their parameters. Since the configurations are different, using one or four engines, and in addition one of them has a secondary air flux, the number of installed sensors was distinct. For the configuration with one engine, pressure taps were fitted to the secondary airflow nozzle. In this way, 15 pressure sensors were used for the four-engine configuration and 31 for the one-engine configuration.

To check the temperature values on the engines, seven sensors were used for both configurations. They were installed on the settling chambers and engine nozzles. Since we expected temperatures over 500 degrees Celsius on that areas, their wires are protected by coatings resistant to high temperatures.

To measure the aerodynamic forces two balances were mounted on the model support and they were located in the same positions for all the tests as shown in the picture. Their purpose is to measure the axial forces from the model fuselage and engines. The fuselage of the wind tunnel model is attached to the front-mounted balance (B1), measuring its corresponding contribution. The engines and the model base plate are attached to the rear balance (B2) measuring the resulting forces. The two balances are measuring in opposite directions and the parts attached to the front balance are not touching the parts from the back balance to avoid interactions.

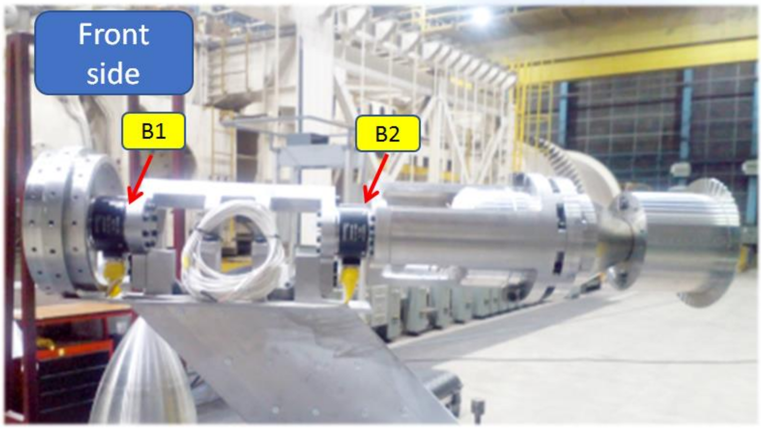

Fig. 5 - Balances locations (single engine configuration)

4. The tests performed

After the model installation inside the wind tunnel, tests were performed at different conditions with active model in both configurations positioned at zero degrees incidence for the entire campaign.

The model was tested at the following Mach numbers 0.5, 0.6, 0.8, 0.9, 0.95, 1.05, 1.10, 1.2, 1.6, 1.8, 2.0, 2.5, 3.0 and 3.25. The tests were performed in both, solid walls and perforated walls test sections according to the Mach number.

For each Mach number the engines were set to different regimes by varying the hydrogen peroxide feed flow, including some cases where the engine power was turned off for reference. The pressure inside the engine supply tank was set to 20, 30, 35 and 40 bar. Also, for the single engine configuration, the secondary airflow was set on and off to observe its effect.

Fig. 6 - Model mounted perforated and solid walls test section

Since the Trisonic WT is a blowdown type, mainly, in order to perform one test, a considerable air quantity is pumped to the tanks (with a capacity of 2000 mc) until they reach the necessary pressure. In parallel the active model and the rest of the systems were set, including the Fuel Supply System for Engines and Air system supply for the secondary flow when needed.

When all the conditions were met, the test begun and the air flow started inside the test chamber. The engines were started by supplying them with HTP and the secondary air flow was turned on when required, taking into account the model configuration. After each test was necessary to refill the wind tunnel tanks, the hydrogen peroxide tank and the tank for the secondary air flow supply system.

Several types of data were recorded with different systems. The main system is responsible for wind tunnel operation (starting and stopping the runs), recording its parameters, but also for coordinating the other systems, including the data acquisition systems. In addition to the tunnel parameters (Mach, pressure, temperature), the model parameters from the installed sensors were recorded such as axial forces measured by the balances, pressure on different points of the engines and model and temperatures on the critical engines areas.

The recordings of the model parameters are made for relevant testing conditions, when the flow is stabilized inside the testing section. Thus, the pressure and temperature data recording time was of four seconds (when the engines were operating). Since the time needed for the flow conditions to be stabilized is variable, the main system triggered the other data acquisition systems in order to record the signals.

The recorded data highlighted several important aspects. The actual pressure ratios obtained in engine simulators will depend upon the pressure losses in the connection pipes and the pressure available at the fuel supply system. The pressure variation recorded at one testing case, by the sensors of each engine simulators mounted on the settling chambers (four engines model configuration), depending on the pressure supplied by the HTP supply system, is presented in the **Fig. 7**. For example, it is shown that for 20 bar at the system exit (HP 20 bar) approximate 11 bar are on the engines.

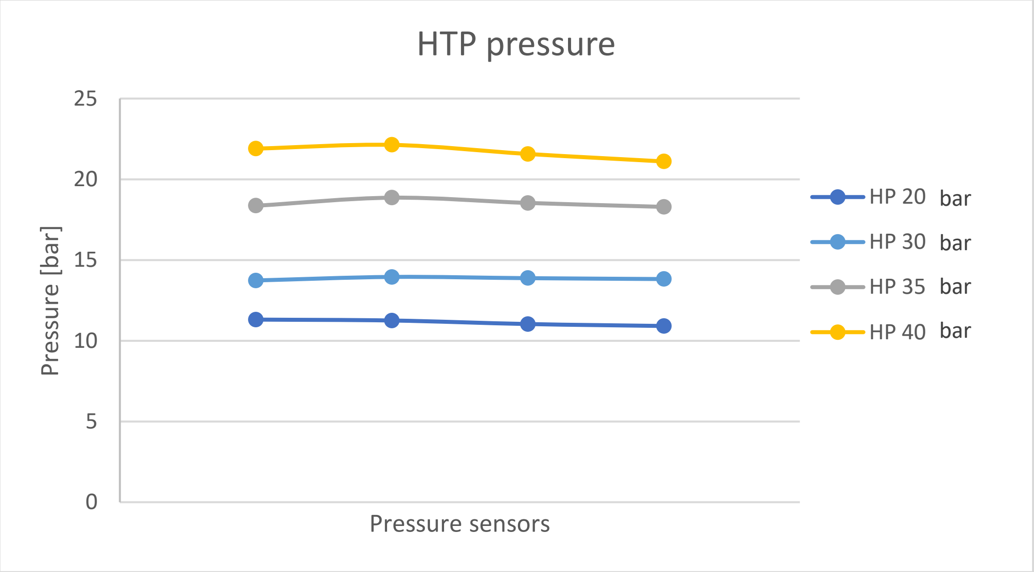

Fig. 7 - Engine stilling chambers pressure (4 engines configuration at Mach 3)

The following two figures **Fig. 8** and **Fig. 9** are showing how the forces evolve as function of Mach number and HTP feeding pressure, for the single engine configuration. Force 1 is measured by the balance where is attached the fuselage of the wind tunnel model (B1) and force 2 is measured by the balance where the engines and the model base plate are attached (B2). The feeding pressure is directly correlated with the settling chamber pressure and in this way with exhaust gas expansion of the jet flow at the nozzle region. During similar studies differences in flow characteristics and base drags were observed with over or under expansion conditions by the nozzle. In the overexpansion condition, the base pressure decreases as expansion is generated in the upper region of the base, and the base pressure further decreases with increasing freestream Mach number as the expansion becomes strong. In the under-expansion conditions, a shock wave is generated around the base by the influence of the nozzle flow, which is increasing the base pressure, and the effect is growing as the chamber pressure is higher. If the chamber pressure is constant, as the free-stream Mach number increases, the base pressure decreases as the shock wave generated at the base moves downstream [1], [4]. The base flow affects the aerodynamic main characteristics, by changing the axial force, and the heat loading at the base of the vehicle may be significant [2].

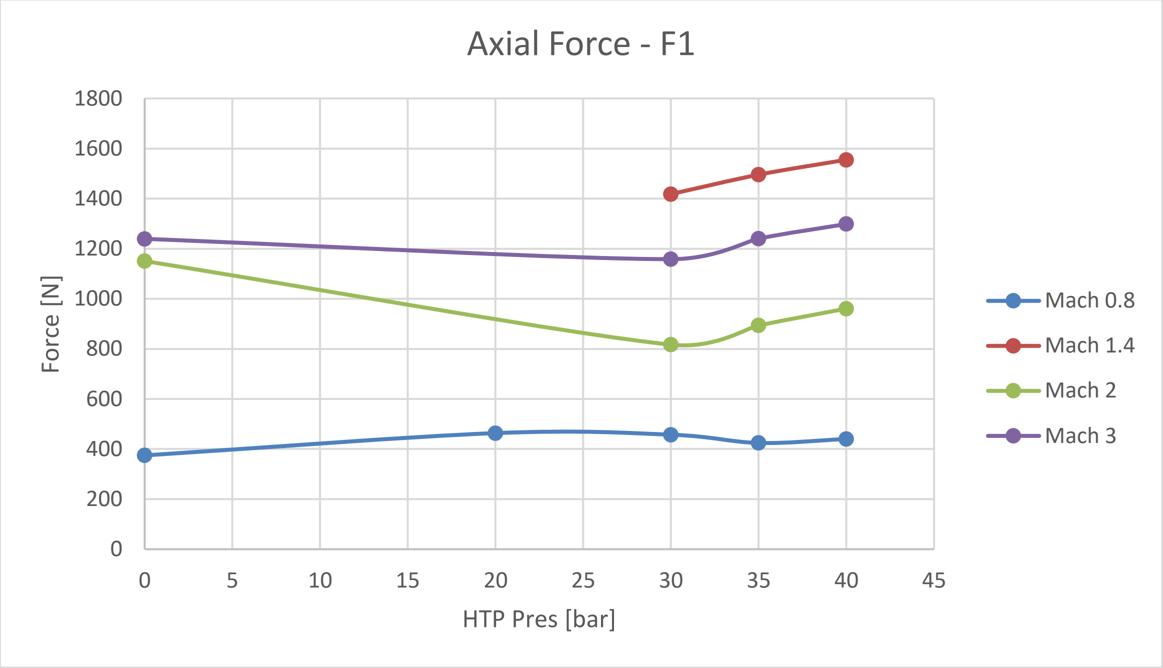

Fig. 8 - Axial Force F1 (1 engine configuration - SF = OFF)

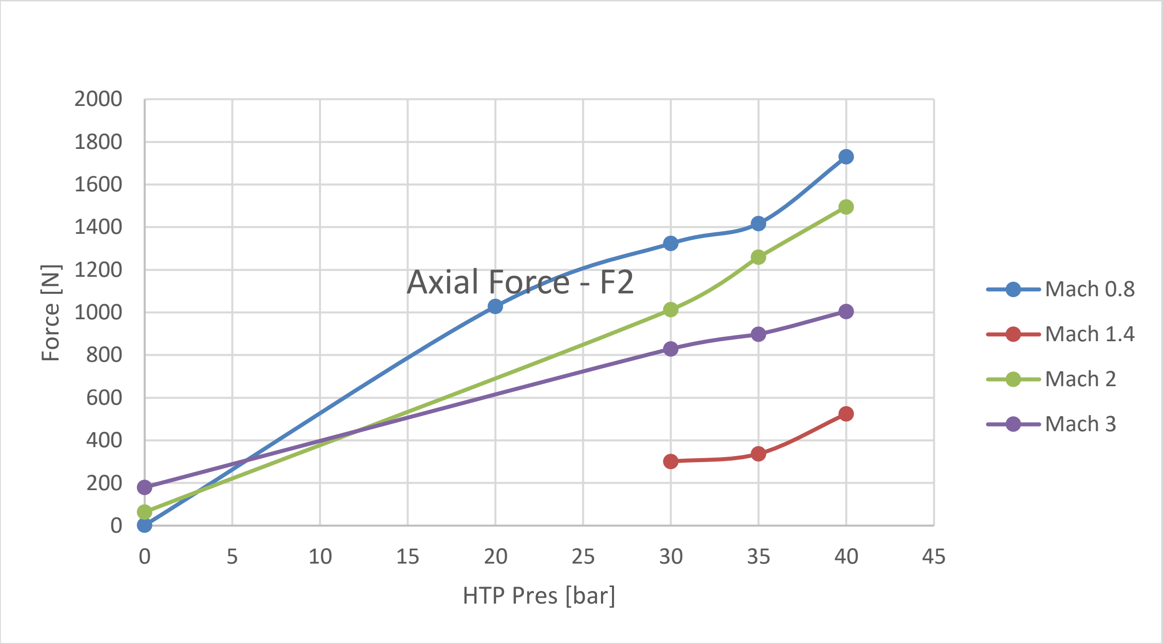

Fig. 9 - Axial Force F2 (1 engine configuration – SF = OFF)

During the tests, the maximum temperature recorded at the exit from the engine settling chamber slightly exceeded 600 degrees Celsius (873 Kelvin). Due to the engine's walls thermal inertia, that affected the sensors measurements, we estimate that a higher temperature was inside the chamber, where the decomposition process takes place.

Due to the new information that is available using this type of testing, improvements of correlation parameters for better predictions are possible. It is known that the shear layer structure is important for the base pressure level. In general base pressure coefficient used in both compressible and incompressible flow is defined as:

$$C_{Pb} = \frac{P_\infty - P_b}{P_\infty} \cdot \frac{1}{\frac{\gamma}{2} M_\infty^2} \qquad (1)$$

Comparing this with the general form of the base pressure parameter given above, we find that $P_{ref} = P_\infty$ and f(M) = M^{-2} is the scaling function of Mach number. However, in the hypersonic regime, large values of Mach number in the denominator of this equation tend to mask small variations in the base pressure ratio that P_b/P_∞. Frequently, such small variations indicate important physical mechanisms. Thus, we should consider velocity parameters other than Mach number. In the traditional way, in compressible flow usually include four common dimensionless velocities for a perfect gas:

$$M = \frac{V}{c} = \frac{V}{(\gamma RT)^{1/2}} = \frac{V}{[\gamma RT_0(T/T_0)]^{1/2}} \tag{2}$$

$$M_0 = \frac{V}{c_0} = \frac{V}{(\gamma RT_0)^{1/2}} \tag{3}$$

$$C = \frac{V}{V_{Max}} = \frac{V}{(2C_pT_0)^{1/2}} = \frac{V}{\left[\gamma RT_0\left(\frac{2}{\gamma-1}\right)\right]^{1/2}} \tag{4}$$

These defining relation show that for constant T_0, Crocco number is related linearly to local velocity. In contrast, the velocity - Mach number relationship is nonlinear because the value of T/T_0 is itself a function of Mach number and, therefore of, velocity. We notice that the temperature at the base plays an important role and at the same time there is little test data for base heat transfer because such measurements are more difficult to make than corresponding pressure measurements [3].

5. Conclusions

During this testing campaign, because of the combined rough conditions, like high temperatures, high pressure reached and hydrogen peroxide presence, several issues occurred.

During activities of mounting/dismounting of the pressure sensors, contamination with hydrogen peroxide (liquid) was observed on the inside of some of the connecting tubes. This phenomenon was noticed especially on the lines from the engines. Due to the high pressure and temperature in some cases the plastic tubes were damaged. Also, it has been noted that engine simulator residual heat can be a problem when installed near instruments.

The initial plan was to perform tests up to Mach 3.5. It was observed that as the Mach number reached 3.25, the vibrations of the model became dangerous, and the balance measurement looked affected in some cases. This phenomenon seems to be related to effect of engine's jet starting that induced instabilities at the model back producing the model's strong vibrations. Therefore, it was decided to limit the testing conditions at Mach 3.25.

During testing it was noticed a higher than initially estimated pressure loss between the feeding hydrogen peroxide supply system and the engines. To compensate that, it was necessary to increase the pressure of the feeding system up to its limits.

Also, at some tests it was observed the forces generated by the engines were lower than expected compared to the other similar cases. This phenomenon was connected to hydrogen peroxide different properties like inhibitor presence or concentration variation.

Due to corrosive effects of HTP, special materials were used for storing and handling concentrated hydrogen peroxide. Precautions were taken to prevent contact with skin, different wind tunnel components and other devices, since hydrogen peroxide is not compatible with many organic and inorganic materials. During the test campaign, it was observed that the walls paint was affected as a result of hydrogen peroxide interaction and the high temperature on that area, and when the test were finished it was necessary to repaint the entire testing section.

The testing campaign was successfully performed and shows that this type of testing, using active models with engines based on HTP, is possible at Trisonic WT. Considering the high novelty and interest for this testing concept, there are several points that need to be improved in the future at the model level but also related to the engines feeding system.

Despite the reported problems an aerodynamic database was initiated for in transonic and supersonic regimes, consolidating experimental capabilities for future testing of launch vehicles models under similitude conditions.

The activities performed addresses the need for new ways of testing that will lead to better understanding of certain phenomena, anticipating a detailed design approach for new developing propulsion systems or for future improvements of space vehicles. Thus, new testing capabilities and the supportive infrastructure was developed, providing ESA and European companies or institutions a new testing possibility and approach.

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