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INVESTIGATION OF A SUPERSONIC COMBUSTION CHAMBER USING A SHOCK TUBE

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Abstract

Hypersonic flow research and studies of supersonic combustion demand the use of ground test facilities, such as Ram Accelerators, Shock Tunnels and Supersonic Combustion Test Benches. In addition, Shock Tubes are capable of generating high temperatures and supersonic velocity flows, simulating the real flow conditions at the entrance of a Scramjet engine combustor (Supersonic Combustion Ramjet), enabling studies of supersonic combustion. In this work, aerothermodynamic and supersonic combustion tests were performed using a Shock Tube, in order to replicate the flow conditions at the entrance of a Scramjet engine combustor. The experimental arrangement consisted of the T1 Shock Tube, a device with a high-pressure section (Driver) and a low-pressure section (Driver), separated from each other by a diaphragm. When the diaphragm is ruptured, the flow propagation occurs, which is accelerated to supersonic speeds through a two-dimensional nozzle connected to the supersonic combustion chamber. The methodology adopted enabled the analysis of the flow inside the supersonic combustion chamber of the Scramjet engine, generating flows with Mach number equal to 2.7 at the entrance. The Schlieren imaging allowed the visualization of the initial flow behavior without fuel injection.

Keywords: *Shock tube; Supersonic flow; Supersonic combustion; Scramjet*

Nomenclature

M – Mach number
P0 – Stagnation pressure
P – Pressure inside
Pi - Injection pressure
θ – Wave deflection
μ – Mach cone opening
He – Helium
H_2 – Hydrogen
T1 – Shock Tube
DDS – Double Diaphragm Section
IEAv – Institute for Advanced Studies

1. Introduction

In the global scenario, several countries have been carrying out research and development of vehicles capable of achieving high-speed regimes. In this context, the development of aspirated engines of supersonic combustion reactor-state type (Scramjets) occurs based on technological demonstrators [1].

Scramjets vehicles are capable of achieving hypersonic speeds (Mach number > 5) through supersonic combustion. These vehicles represent a variation of the Ramjets, having as main difference the velocity of flow in combustion. In Ramjets vehicles, the air flow inside the combustion chamber reaches subsonic speeds. Nonetheless, in the combustion chamber of Scramjets vehicles, the speeds are supersonic [2].

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The Brazilian government, through the Ministries of Defense and Science and Technology, has established priorities and strategies based on R&D in aspirated air propulsion and hypervelocity regimes. The key objective is to promote national technological equality with other foreign nations [3]. Research in the field of aspirated hypersonic propulsion is concentrated in the Institute of Advanced Studies (IEAv). There, researchers are developing the 14-X vehicle and conduction experiments in propulsion and hypersonic.

The progress of hypersonic vehicles demands computer simulations, as well as the execution of flight and ground tests. As a consequence of technological advances and software implementation, computer simulations are the starting point for R&D, saving time and resources. However, even the most effective computational models do not substitute field tests, for they are mandatory to validate hypersonic vehicles technology. Flight tests provide reliable and accurate results because data are obtained in the proper operating environment. However, they are considered expensive investigations, with long preparation times and several risks associated.

As an alternative, ground tests allow the simulation of several flight parameters at more modest costs, therefore enabling the costly projects of hypersonic technologies. In experimental aerothermodynamic and hypersonic, ground test facilities like Ram Accelerators, Shock Tunnels and Supersonic Combustion Test Benches are available. [4;5]

Supersonic combustion studies are carried out by means of experiments in Shock Tunnels. In these tests, a Scramjet model is coupled to the Shock Tunnel, generating a hypersonic flow that moves along its aerodynamic geometry and produces a shock wave. The shock wave then decelerates the flow to the supersonic conditions required at the entrance of the combustion chamber of the Scramjet model.

1.1. Shock Tube

A Shock Tube allows the study of wave propagation phenomena in gaseous media under controlled conditions. In these devices, it is possible to evaluate the rapid exhaustion of gases, with associated temperature gradients over a broad range of flow Mach numbers. A Shock Tube in its simplest configuration (**Fig.1**) consists of a long tube with two sections, whose individual reservoirs have different pressures and are separated by a membrane known as diaphragm.

This diaphragm separates the high-pressure section (Driver) from the low-pressure section (Driven). When it is ruptured, a shock wave propagates in the Driven section and an expansion fan in the Driver section. The shock wave constitutes the border between two regions with different pressures and temperatures [6].

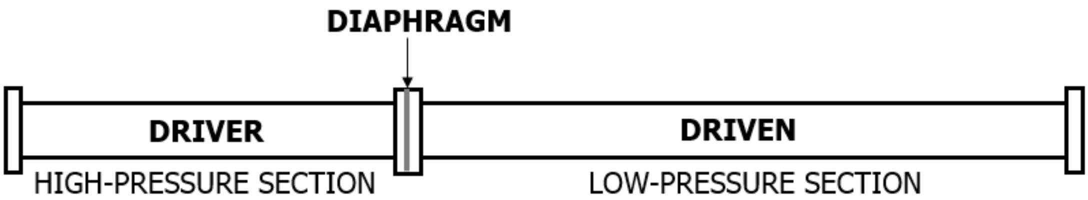

Fig 1. Initial configuration of a shock tube

Fast response pressure transducers are positioned along the tube and its ends. In this way, it is possible to determine the flow conditions generated during the test. Optical windows can also be attached along the tube. When associated with a non-intrusive diagnostic technique, they collect significant data on the flow generated.

Because of the relevance of the Shock Tube and the phenomena reproduced therein, its use in several areas stands out, such as: aerothermodynamic research, gas physics, chemical and combustion kinetics investigation, impact tests on structures and calibration of measuring instruments.

2. Development of the combustion chamber

The supersonic combustion chamber was machined from aluminum, with the flat superior part of the combustor and an expansion ramp inferior part. Ten pressure transducers were positioned throughout the model. Five of them were fixed at the top and the other five on the expansion ramp. In this way, it is possible to monitor the behavior of the pressure variation along the combustion chamber. The side parts of the model were designed to receive three optical windows each, thus forming three regions for viewing its internal area. In this manner, it is possible to employ non-intrusive diagnostic techniques that allow the visualization of the flow behavior. Between the combustion chamber and the T1 Shock Tube, a two-dimensional contour nozzle was placed, which is responsible for accelerating the flow to the desired study conditions (M 2.8).

The designed nozzle was 3D printed in ULTEM 1010. It consists of a separate block with the contour region positioned in the center. Subsequently, the nozzle was inserted in a metallic housing, to eliminate any leakage problems during the pressurization of the experiments.

In **Fig.2**, the sectional view of the designed combustion chamber is shown. The labels S1 to S10 indicate the pressure transducers used in the model. The labels J1 to J3 represent the flow visualization windows. The contour nozzle and the fuel injection point are also indicated.

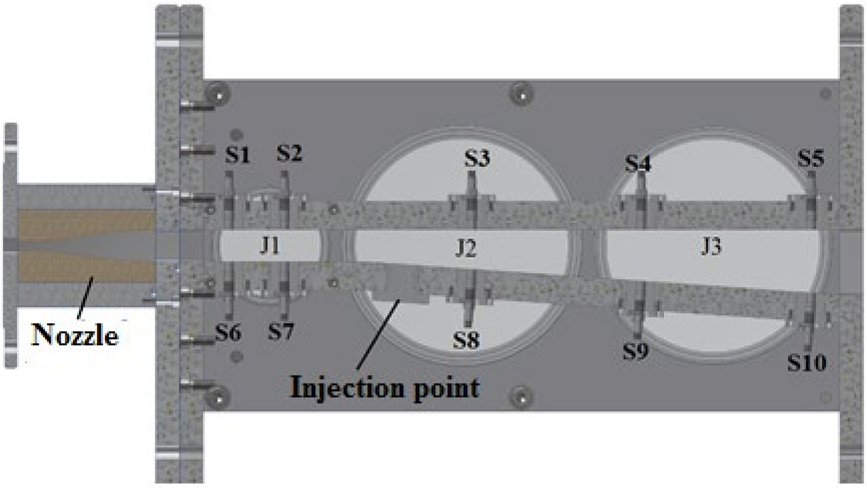

Fig 2. 2D sectional view of the combustion chamber designed to study the supersonic combustion

In **Fig.3**, a 2D sectional view of the combustion chamber connected to the T1 Shock Tube through the supersonic nozzle is shown. This configuration was initially used for tests without gas injection. For the experiments with helium and hydrogen injection, a cylinder with the respective gas was adapted before the injector, which can be released by activating a solenoid valve.

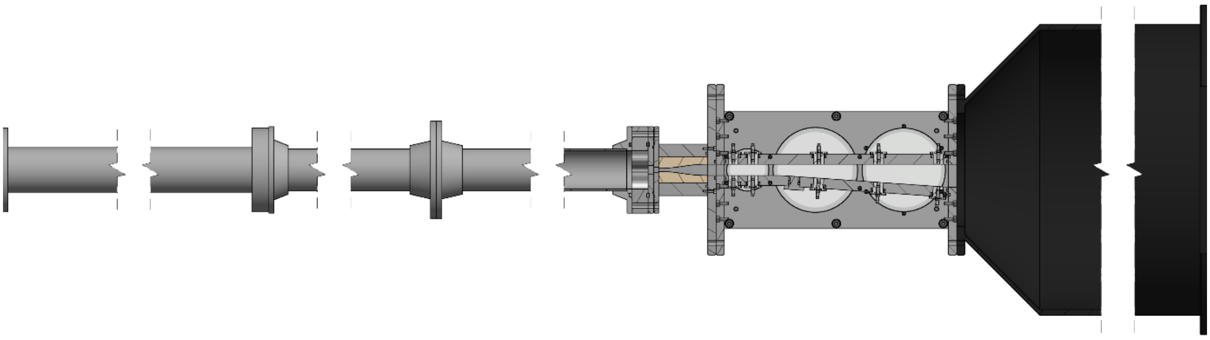

Fig 3. 2D sectional view of the combustion chamber attached to the T1 Shock Tube.

After manufacturing both the nozzle and the combustion chamber, the set was assembled to carry out the experiments. The nozzle was fixed between the T1 Shock Tube and the model. At the rear of the model, an exhaust tank was connected. The entire system employed in the experimental tests is indicated in **Fig.4**. In it, the following sections are labelled: Driver (1), double-diaphragm - DDS (2), Driven (3), the combustor to be tested (4), the exhaust tank (5), the gas cylinders (6)) used to pressurize the Driver and DDS sections, the pressurization and trigger control panel (7) and the data acquisition bench (8).

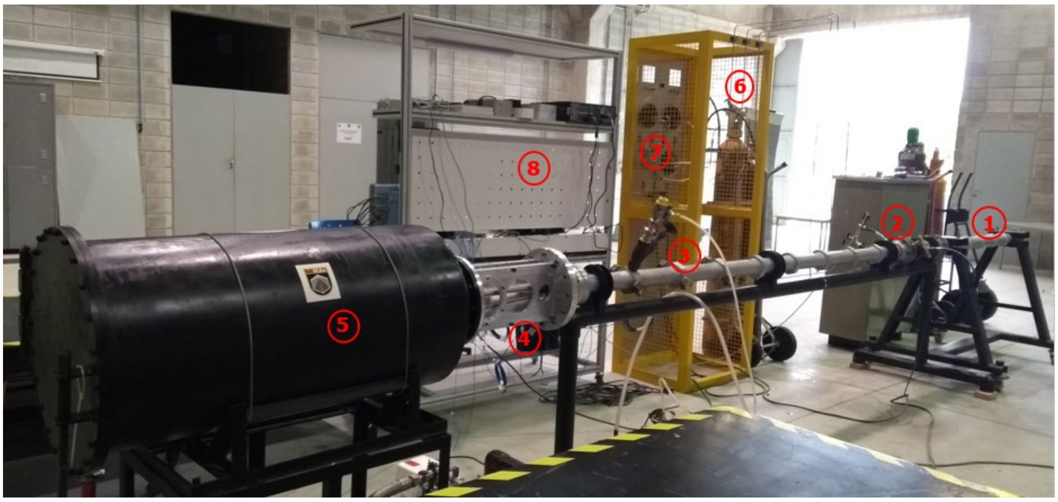

Fig 4. T1 Shock Tube used to perform the experimental tests

2.1. Optical visualization technique

The Schlieren technique was used to visualize the flow behavior inside the tested combustion chamber. It is a non-intrusive optical technique for visualizing complex flows, based on the deviation of light when passing through a transparent medium that has refractive index gradients. In it, optical devices like mirrors and/or lenses are combined, allowing visualization of the flow where the light undergoes deflection due to the refractive index gradients [7]. The deflection of the light is compared with the non-deflected light, making it possible to capture it in images with the development of the flow [8]. Thus, contrasting images are created that reveal the density variations generated in the flow under study.

In a simplified configuration, the Schlieren technique requires the light source to be as parallel as possible with the medium in which the test area is inserted. In this manner, it is possible to obtain the θ deviations more efficiently. This experimental arrangement is illustrated in **Fig.5**, in which the light source, the sets of mirrors and lenses, the spatial filter (knife) and data capture camera are observed.

In the Schlieren technique, the light source must be placed maintaining the focal length of mirror 2. Mirror 1 is used as a device to increase the optical path or also as a beam amplifier. The special filter (knife) must be positioned maintaining the optical distance with mirror 3. Therefore, producing the required contrast in the images obtained by the camera positioned immediately behind the mirror 3.

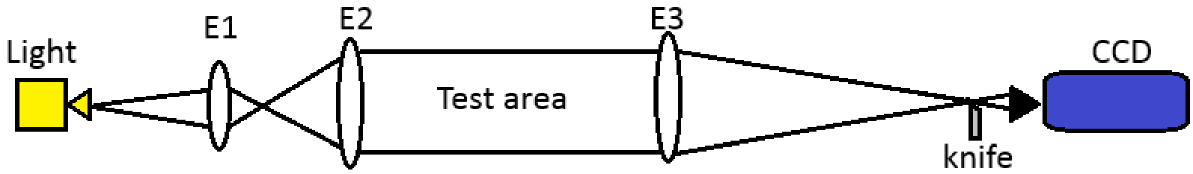

Fig 5. Example of the conventional Schlieren arrangement

A set of three mirrors were used to assemble the Schlieren technique next to the experiment (**Fig.6**). Two mirrors with a diameter of 35cm (nº2 and 3) and the other with 10 cm (nº4). The focal length used was approximately 180 cm. A LED light source (nº1), a spatial filter called "knife" (nº 5) that obstructs the deviated light rays, and a high-speed camera and a computer for data storage (nº 6 and 7). The Schlieren images were obtained through the optical arrangement in conjunction with a high speed PCO camera. / DIMAX HS.

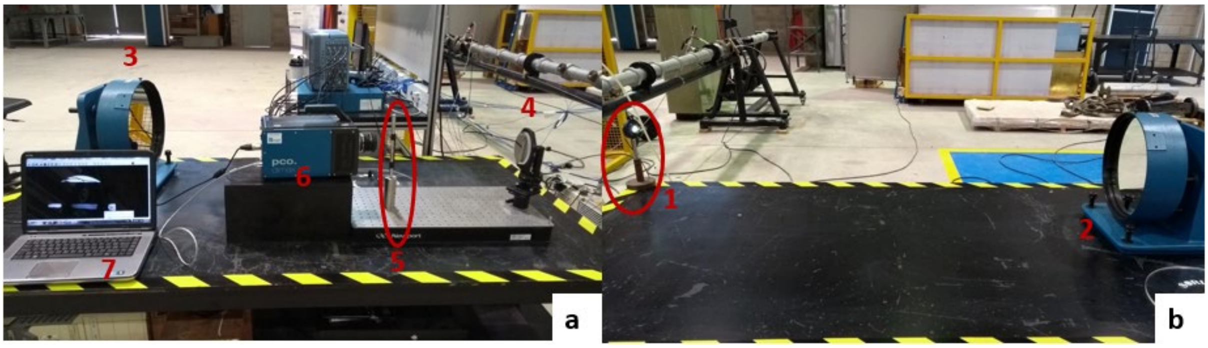

Fig 6. Schlieren experimental arrangement used during the testing campaign.

3. Partial results

After assembling the combustion chamber in the T1 Shock Tub, initial experiments were carried out to verify the flow behavior and the corresponding Mach number. In these experiments, no gas was injected into the model. However, the flow behavior could be properly observed, validating the designed nozzle.

Initially, the Driver section was pressurized with helium at a pressure of 60 bar and the Driven section was maintained at ambient pressure (≈ 1 bar). The DDS section was pressurized with argon at a pressure of 30 bar. Two types of diaphragms were employed in this stage. In the DDS section, two aluminum diaphragms with a thickness of 2 mm and a groove of 0.5 mm were employed. At the exit of the nozzle with the fuel inlet, transparent acetate sheet was used.

In **Fig.7a**, the diaphragm employed in the DDS section is shown. A diaphragms can be seen before the shot (left side) and after (right side), with its characteristic petal-shaped opening, indicating that the rupture was effective. **Fig.7b** shows the diaphragm used at the entrance of the combustor after firing. There is a rectangular opening in the center of it, which is compatible with the fuel inlet, indicating its proper functioning.

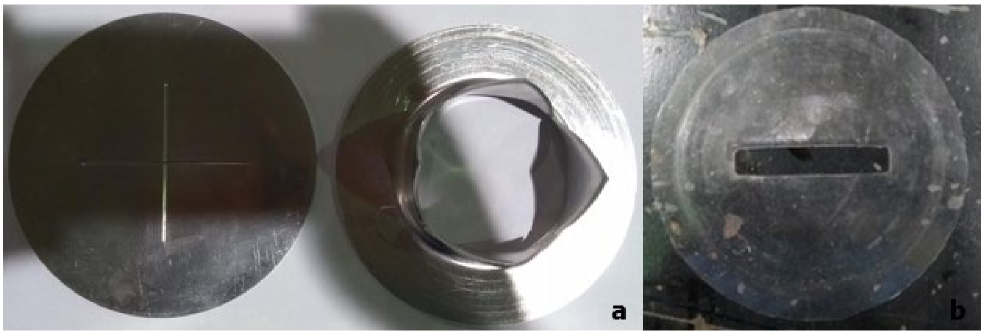

Fig 7. Diaphragm models employed in the DDS section before and after the experiment (a) and at the entrance of the combustor (b).

Analyzing the responses obtained by the pressure transducers distributed along the T1 Shock Tube and the model, a stagnation pressure (P_0) of 37 bar and a transit time of 322.5 μs were observed. The isentropic pressure equation (**Eq. 1**) can be used to determine the Mach number at the input of the model. This is possible because the stagnation pressures (P_0) and at the entrance to the combustion chamber (P) are known. In this case, the flow was considered as calorically perfect (γ = 1.4).

$$\frac{P_0}{P} = (1 - \frac{\gamma - 1}{2} M^2)^{\frac{\gamma}{\gamma - 1}} \tag{1}$$

In the experiment a pressure P = 1.92 bar and a value of Mach ≈ 2.7 were found at the entrance of the combustion chamber. The Mach number found is significantly close to the projected value for the nozzle, indicating a good system performance.

A second analysis was employed to confirm the Mach number found at the entrance of the combustion chamber. This analysis considered the images obtained by the Schlieren technique, since it is possible to visualize the Mach lines formed during the experiment. Knowing the opening equation of the Mach cone (**Eq. 2**), it is possible to find the opening angle (μ). Consequently, through trigonometric relations, the Mach number of the flow can be determined. Through the analysis, the value of M≈2.9 was obtained, which is significantly close to the projected value for the nozzle, according to the expected performance.

$$\mu = arcsin\left(\frac{1}{M}\right) \tag{2}$$

In **Fig.8**, a Schlieren image obtained during the experiment is shown. In it, it is observed the stream of the flow inside the combustion chamber and the formation of typical Mach lines.

The labels J1 to J3 represent the optical windows of the supersonic combustion chamber, and the arrow indicates the sense and direction of the flow. The image on the right, highlighted with a red circle, indicates an enlargement of the J1 window. Through this window, the flow was analyzed, and the opening angle of the Mach cone (μ) and the Mach number obtained at the entrance of the combustion chamber were identified.

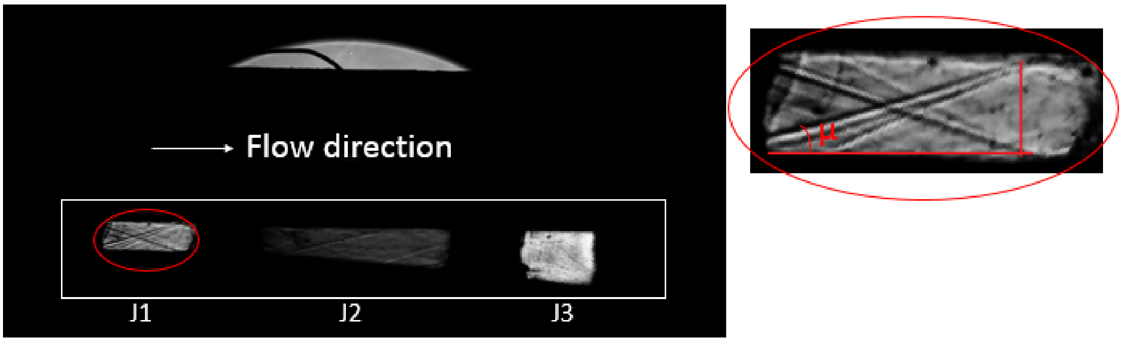

Fig 8. Schlieren image obtained during the experiments in the supersonic combustion chamber and used to determine the Mach number at its entrance.

The values of stagnation pressure (P_0) and Mach (M) found experimentally were also compared with software implemented in the Division of Aerothermodynamics and Hypersonics - EAH. This software (ShockWave) was developed by Minucci in 1986 and has as input data the flow transit time and the area ratio of the nozzle used [6]. It is known that the nozzle area ratio is A/A * = 3.5 and the transit time was 322.5 μs. Then, the output obtained in ShockWave software is M = 2.79 and P_0 = 39 bar, this value being consistent with the results obtained experimentally.

3.1. Helium injection experiment

Initially, it was decided to use Helium (He) in the combustion chamber injection system. This was necessary to identify the flow behavior generated in contact with the injected gas, as well as to verify the operation of the system.

The injection system consists of a block with three injection holes of Ø1.9mm each, connected to the bottom of the model. The injector block was associated with the solenoid valve, which, when activated, releases the gas contained in a cylinder with an initial volume of 100 ml. The injection system is activated simultaneously with the T1 Shock Tube firing. **Fig.9** shows the assembly of the supersonic combustion with the fuel.

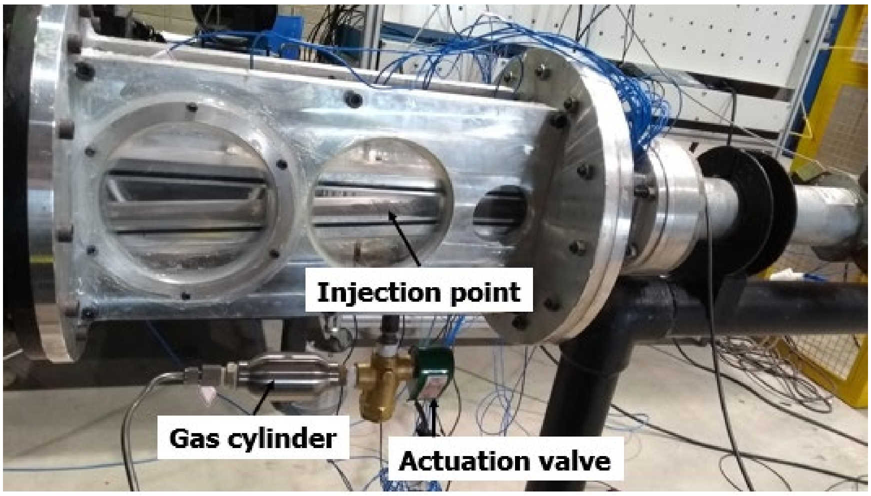

Fig 9. Gas injection system coupled to a supersonic combustion chamber.

The experiments with helium injection in the supersonic combustion chamber followed identical procedures of the ones without diaphragm models. The Driver section was pressurized with helium at a pressure of 60 bar, and the Driven section was maintained at ambient pressure (≈1 bar). The DDS section was pressurized with argon at a pressure of 30 bar. The He cylinder used to supply the injection system was set at 12 bar on the regulating valve.

Analyzing the data obtained by the pressure transducers distributed along the T1 Shock Tube and the model, a stagnation pressure (P_0) of 39 bar and a transit time of 326 μs were observed. Once more, the flow was considered to be calorically perfect ($\gamma = 1.4$). By substituting P0 in the **Eq. 1**, the Mach number of the flow at the entrance of the combustion chamber was found to be M ≈ 2.6.

The proof of the He injection in the combustion chamber was given by the registration of the pressure transducer attached to the injector. In **Fig.10**, the responses obtained by the pressure transducers of the system are shown. They are indicated by the yellow line, showing the response of the sensor fixed on the injector. The pressure value obtained at the injection was Pi = 3.50 bar.

Fig 10. Evidence of He injection during the test time of the experiment, with a pressure of P_i = 3.5 bar being injected.

The analysis of the images obtained with the Schlieren technique, in the case of He injection, followed the same methodology as the experiments without gas injection. When determining μ using trigonometric relationships, the value of M can be obtained with **Eq. 2**. Thus, the value of M ≈ 2.7 was found at the entrance to the combustion chamber. It is noteworthy, however, that the analysis of the

Mach number through the Schlieren images is performed in the J1 window before the injection of He into the combustor.

In the images obtained, there is a change (curvature) in the Mach line in the window J2. This demonstrates the injected gas is interacting with flow, promoting changes in it and indicating the proper functioning of the injection system. In **Fig.11**, a Schlieren image obtained during the experiment is shown, in which it is possible to observe the interaction of the injected He with the flow.

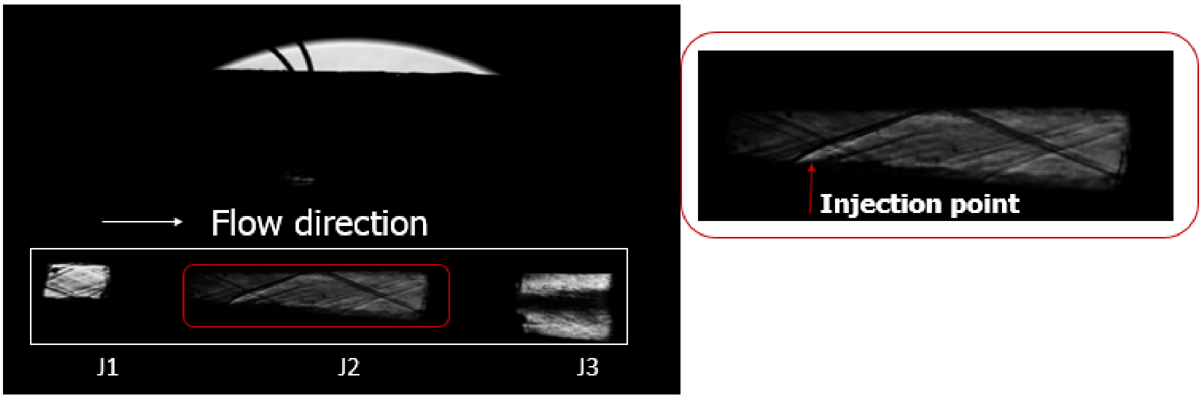

Fig 11. Schlieren image obtained during the experiments in the supersonic combustion chamber, indicating a curvature of the Mach lines through the injection of He.

The values of stagnation pressure (P0) and Mach (M) found experimentally were also compared with the results obtained through the ShockWave program.

Since the nozzle area ratio is $A/A^* = 3.5$ and the transit time was 326 μs, then the results in the SchockWave program are $M = 2.79$ and $P_0 = 39.1$ bar. These values are consistent with the results obtained experimentally.

4. Final considerations

The experimental data obtained demonstrated it is possible to study a combustion chamber directly connected to the T1 Shock Tube. This made it feasible to study the subsystem separately from the scramjet model. In this manner, it is unnecessary to generate flow conditions upstream of the scramjet model. Therefore, only the flow at the entrance of the combustion chamber must occur. The alternative turns investigations with supersonic combustors more accessible, since it is unnecessary to use a Shock Tunnel for this purpose. This would require more resources and inputs to carry out preliminary studies with combustion chambers. Once all the variables surrounding the combustion process have been exhausted, the study of the complete vehicle in a Shock Tunnel can proceed.

The preliminary results show both the two-dimensional nozzle and the projected supersonic combustion have achieved an excellent performance. From them, it was possible to visualize and characterize the flow at the nozzle outlet and in the internal region of the combustion with and without gas injection. The results obtained demonstrate adequate functionality of the injection system and the injector used in the experiments.

The Studies for the investigation of hydrogen self-ignition and its influence on flow have already started. Initially, optimistic results were obtained, allowing the self-ignition of Hydrogen to be diagnosed. Currently, efforts have been concentrated on a range of stagnation pressure variation (P_0) and injection pressures (P_i) to determine the optimal working point for the model under study. Other non-intrusive diagnostic techniques have been investigated during experiments to support the diagnosis and characterization of hydrogen combustion. One is the OH emission. The work presented is in progress and the data obtained experimentally with H2 injection will later be presented to the scientific community.

5. Acknowledgements

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