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DEVELOPMENT OF A DEVICE FOR ANALYZING THE FLOW IN COLD CONDITION AT THE EXIT OF A SUPERSONIC COMBUSTION TEST BENCH

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Abstract. *The study of hypersonic flow and supersonic combustion is conducted using ground test facilities such as shock tunnel, hypersonic mass accelerator and the direct-connected supersonic combustion test bench (SCTB). The present work will use a SCTB, one of the most commonly equipment used for the study of supersonic combustion and aerothermodynamics tests, which the main advantage is the time duration of the tests, compared to others ground test facilities, and also the fact that flow test can be performed both in cold or hot conditions .The SCTB simulates the same flow conditions inside a Scramjet's combustor in actual flight. It consists basically of a combustion chamber or vitiated air generator (VAG), where the flow is heated to the desired temperature, and a supersonic nozzle, where the heated air is accelerated to supersonic speeds. In this context, the objective of this paper is to develop a device that can be capable to measure the speed of the cold flow at the outlet of the supersonic nozzle. For this it will be used a wedge, located in front of the supersonic flow, at the exit of the nozzle and the schlieren technique to visualize shock wave angle over the device to be tested.*

Keywords: *supersonic flow, ground test facilities, supersonic nozzle.*

1. INTRODUCTION

Currently, in the Aerospace sector, several countries are in increasing search for advanced technologies to develop hypersonic vehicles, which consist of Air-Breathing Propulsion Systems and Supersonic Combustion Ramjet (Scramjet). In Brazil, a technological demonstrator called 14-X is being developed and conducted at the Institute for Advanced Study (IEAv) by the PROPHIPER (hypersonic propulsion) project with the objective of demonstrating the concepts of air-breathing propulsion and supersonic combustion, encompassing two types of technologies: the waverider and scramjet. This project consists of some stages of studies and research as computer simulation, ground tests and flight tests. All these steps are important, however the preliminary studies on the ground are fundamental to characterizing all the conditions to which this vehicle will be submitted in actual flight. For these ground tests, the IEAv have some equipments, such as: hypersonic shock tunnels, hypersonic mass accelerator, also known as "Zarabatana", and the supersonic combustion test bench (SCTB), specially used for testing scramjets supersonic combustors.

The experimental study of supersonic combustion has been of interest to several countries since the 1950s (CURRAN, 2001). The technology required for the supersonic combustor's development involves great challenges, mainly regarding the maintenance of combustion in steady and continuous conditions, in high speed flows. This is due to the fact that the fuel must be injected, mixed the oxidizer, undergo ignition and be burned in a supersonic air flow (BRANDÃO, 2017). The supersonic combustion test bench (SCTB) is the ground test facility that simulates the conditions of the flow at the entrance of a scramjet's combustors, becoming a ground facility of great interest for research centers. One of the main advantages of this facility is the test time, which is in the order of a few seconds, while, for example shock tunnels, they are in the order of milliseconds, and this allows the studies of the ignition and maintenance of the supersonic combustion.

Therefore, the present paper aims to characterize the cold flow and its thermodynamic properties (pressure and temperature) at the outlet of the pilot SCTB convergent-divergent nozzle, using a device, with wedge shape and a Pitot tube, for the experimental data to compare with the theoretical-analytical studies, considering the gas as calorically perfect. With this, it will be possible to compare the values of the supersonic flow conditions, at the outlet of the nozzle, with the ones obtained with another methodology used before, and thus obtaining the appropriate conditions for future ground tests with the combustors and for the improvement of the experimental apparatus.

2. METHODOLOGY

2.1 Experimental apparatus

All over the world, research centers in several countries as U.S.A, India, European countries, and Brazil are focused on the development and utilization of this equipment seeking a larger study in supersonic combustion, because one of the great challenges in relation to the research involving the scramjet is to ensure that the combustions process will occur in a steady and continuous conditions inside a supersonic speed flows, obtaining the ignition and the desired combustion stability of the engine.

In this context, the it is essential and very important to characterize the test flow and instrument the SCTB, due to provide the better flow test conditions for the study and analysis of the ignition inside the scramjet's combustor to be tested.

A SCTB consists basically of a vitiated air generator (VAG), with a high enthalpy, to heat the air, coupled to a convergent-divergent supersonic nozzle to accelerate it to the required flow test conditions.

There are two models of high enthalpy vitiated air generator, the first use electric arc (Fig.1) to generate the desired stagnation conditions and the other model (Fig.2) uses combustion for the same purpose.

To heat the air inside de VAG it can be done using a heated with the electric arc (Fig. 1) is basically a higher voltage source connected to the ends of the vitiated air generator, causing an electric arc that heated the air and then is accelerated by a nozzle to the desired test conditions. The disadvantage of using this is that the operational cost is more expensive.

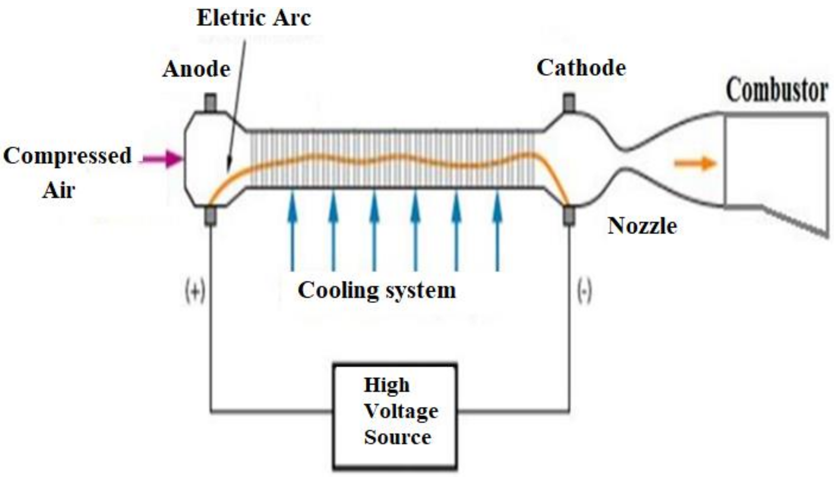

Figure 1. Arc-heated scramjet test facility.
(adapted from PLASMA TEST & DIAGNOSTICS LABORATORY,2017).

Another way to heat the air inside the VAG is by combustion (Fig 2) which is a simpler and cheaper option compared to the electric type, but this type requires an appropriate and safe laboratory for combustion test.

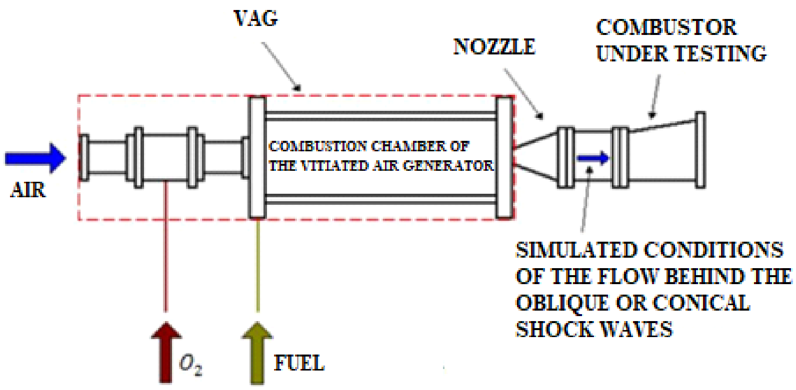

Figure 2. Direct-connected supersonic combustion test bench with heating combustion (LEITE, 2006).

In Brazil, the first SCTB with the heating by combustion was developed at INPE but it was disabled for security reasons. Therefore, IEAv began to develop a new Supersonic Combustor Test Bench, a direct-connected SCTB type, which requires an appropriate and safe laboratory that is being designed at this moment. In order to obtain the parameters for the main laboratory, a pilot unit of the SCTB (Fig.3) was developed as part of a master's dissertation of BRANDÃO, 2017, and it was assembled in order to continue the researches of combustion diagnostic techniques and the supersonic combustion, and also obtain data that will help in the installation, instrumentation and operation of the main SCTB (GUIMARÃES, 2018). This equipment is of great relevance for the PROPHIPER project, as this will make it possible to analyze and study the propulsion system of technological demonstrator 14-X in an estimated experimental test time of at least 30 seconds.

The pilot SCTB unit (Fig.3) consists basically of a vitiated air generator (VAG), with a high enthalpy, coupled to a convergent-divergent supersonic nozzle, so the VAG has the purpose of producing the stagnation condition at the nozzle inlet, that is, high temperature and pressure. These properties must be high enough to expand along the nozzle and generate the ideal test flow conditions at the nozzle exit. This test flow will feed the scramjet combustor to be tested, as shown in Fig. 2.

The test and studies at SCTB can be carried out with both cold and hot (with combustion) flow.

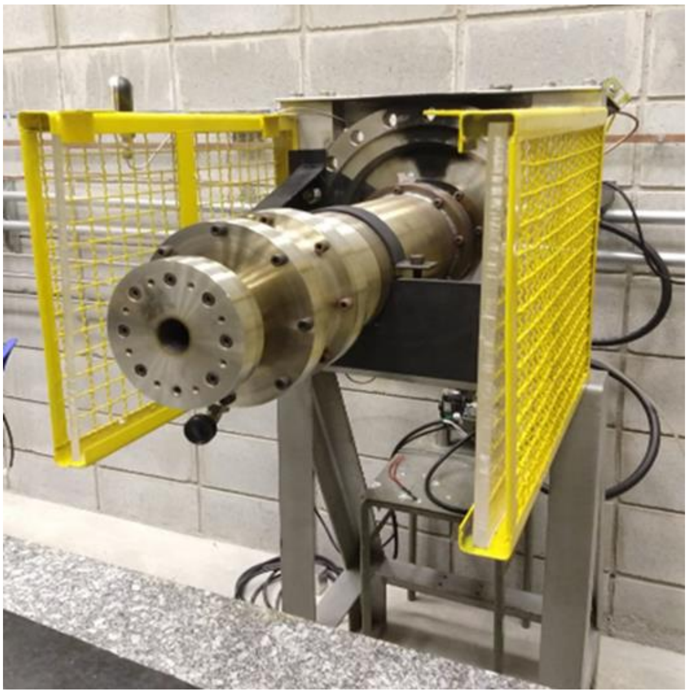

Figure 3. Supersonic combustion test bench pilot unit.

The complete pilot SCTB laboratory assembly configuration is shown in Fig 4.

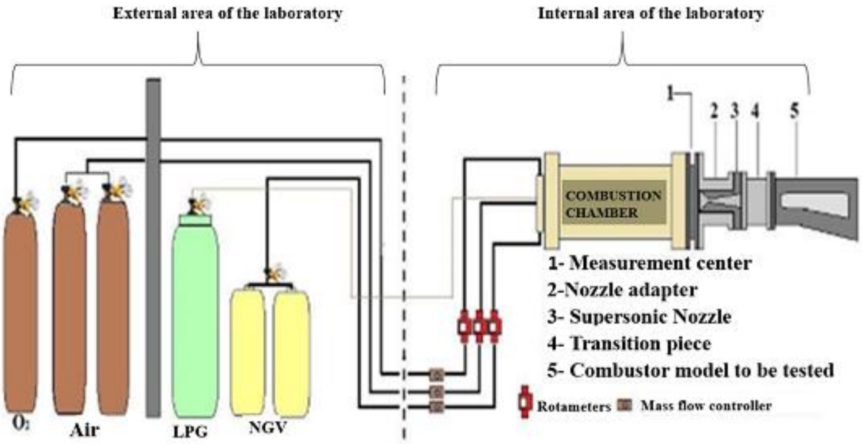

Figure 4. Scheme of the complete experimental apparatus for carrying out tests at SCTB (GUIMARÃES, 2018).

In Fig. 4, it can be seen from the left to the right, at the external area of the laboratory, the oxidants and fuel used for the combustion process of heating the air inside the VAG, and this feeding system containing: 1 cylinder of oxygen, 2 cylinders of compressed-air, 1 cylinder of liquefied petroleum gas (LPG) and 2 cylinders of natural gas vehicle (NGV). Also in Fig. 4, at the internal area of the laboratory, there are: the mass flow controller and the rotameters, the vitiated air generator (VAG), a section called measurement center, where the pressure sensors are placed, the convergent-divergent supersonic nozzle, a transition piece and the combustor model to be tested.

To obtain the desired flow test conditions, of temperature, pressure and Mach number, at exit of the nozzle, the stagnation condition, at its entrance, must be around: T_0 = 2500 K e p_0 = 20 atm (2.027e+6 Pa), and in addition, the oxygen mole fraction must be equal to 0.21 at the nozzle exit, because it simulates the flow condition at the entrance of a scramjet combustor in actual flight.

Before beginning the test with the hot flow, it is necessary to characterize the flow inside the SCTB in cold condition. In the case of cold flow, which is the subject of this work, the conditions at the outlet of the nozzle is: p_1 = 1 atm (101325 Pa), because the equipment is directly open to the atmosphere and the temperature, and the stagnation condition T_0 = 298.15 K. For the studies involving cold flow, the cylinders of fuels will not be used and the one of oxygen will be replaced by a compressed air one.

2.2 Flow velocity characterization at the supersonic nozzle exit

The purpose of this paper is the characterization of the flow velocity at the outlet of nozzle using basically the relations of the normal and the oblique shock waves, measuring the total and static pressures and applying the Rayleigh's equation, from the normal shock wave theory, and at the same time measure the shock wave angle formed over the wedge, using the schlieren technique, and with this obtain the Mach number of the test flow by the *θ-β-Mach* relation, from the oblique shock wave theory. In his paper the flow will be considered as calorically perfect, because is cold flow study case.

Using the AutoDesk Inventor Professional 2017 student version commercial software, the model to be studied was design, and it consists of a wedge geometry and a blunt body located under it to assemble the Pitot tube, as shown in Fig. 5.

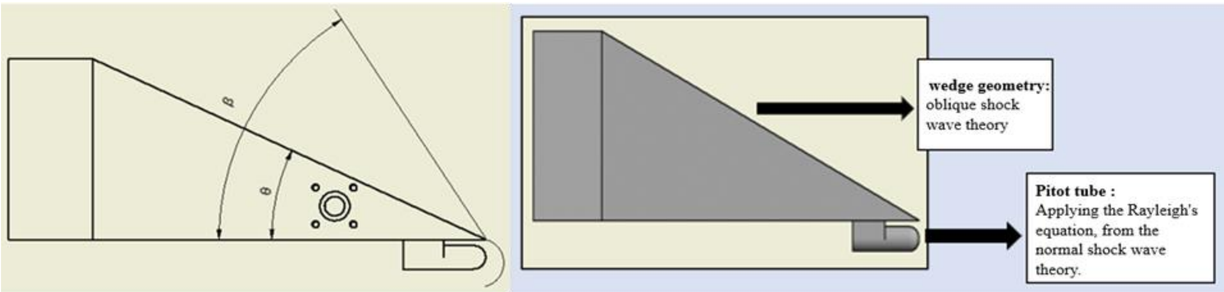

Figure 5. Model of the device to be studied, the shock wave angle formed over de wedge and shock wave formed over a blunt body.

This device will be mounted in front of the supersonic flow that comes out of the nozzle exit and at the same time that the oblique shock wave is formed over de wedge, the total pressure is measured with the Pitot tube. So, it is possible to compare two different methodologies to obtain the velocity or Mach number of the test flow at the exit of the SCTB, as shown in Figs. 5 and 6.

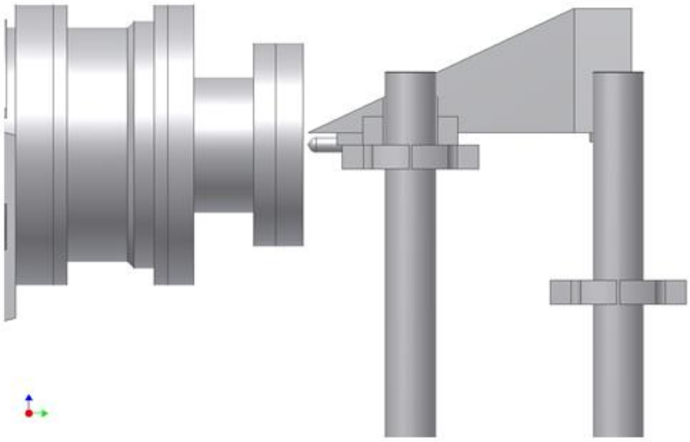

Figure 6. Configuration of the device to be studied in front of the test bench nozzle

For the flow characterization, the technique known as schlieren was used allowing the visualization of complex flows, a non-intrusive optical technique. It consists of the deviation of light when crossing a transparent medium that has gradients of the refractive index (SETTLES, 2006). For the use of this technique, some optical devices and their appropriate settings in the test section and the ideal arrangement of the equipment are necessary to obtain good quality of images. The optical devices and arrangements used are: combinations of mirrors or concave lenses, a light source, a cutting edge also known as a “knife” and a high-speed camera for recording images.

In previously experimental tests performed at SCTB, the arrangement of the equipment was used as a conventional configuration known as “Z”, as shown in the figure below (Fig 7).

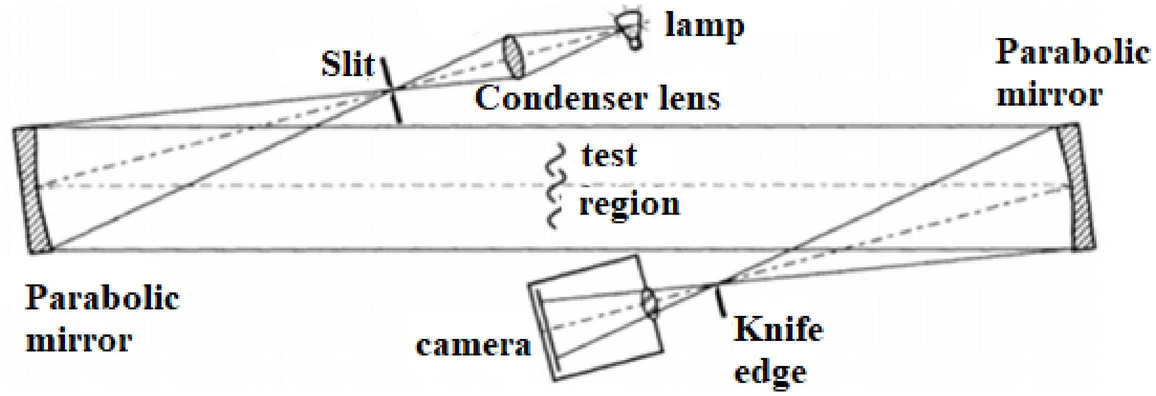

Figure 7. Schlieren technique in “Z” configuration, used to visualize the flow generated at the pilot SCTB outlet (SETTLES, 2006).

Figure 8 is an example of an analysis of the flow at the outlet of the SCTB nozzle obtained in tests carried out previously, in which it is possible to observe the behavior of the flow over a wedge geometry and the formation of the oblique shock wave, where it is possible to see the application of the schlieren technique.

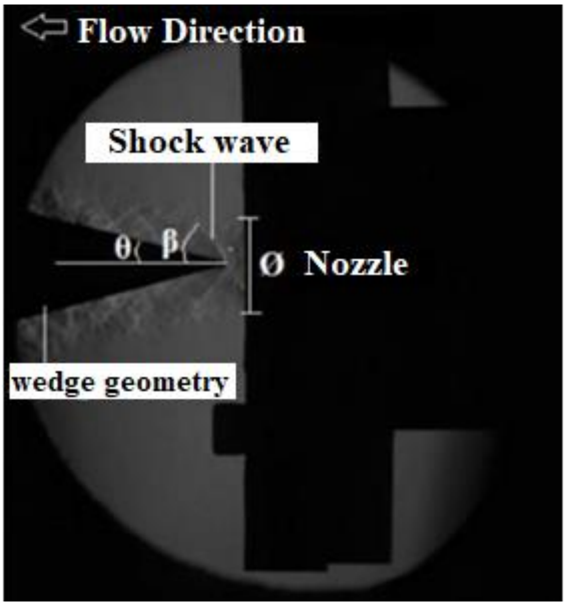

Figure 8. Exemple of the analysis of Mach number using the schlieren technique (GUIMARÃES et al, 2018)

In projects carried out experimentally, it was possible using the schlieren technique to observe the shock wave formed over the model that was tested and with the *θ-β-Mach* relation (Eq. (1)) it is possible to obtain the Mach number value at the outlet of the test bench nozzle. So, using the same method, the shock wave angle over the device to be studied can be measured, the θ angle is known and the Mach number value can be obtained analytically by Eq. (1).

$$\tan \theta = 2\, cot\beta \left[\frac{M_1^2 sin^{\,2}\beta - 1}{M_1^2(\gamma + \cos 2\beta) + 2}\right] \quad (1)$$

Previously tests performed at the SCTB used only the schlieren technique to obtain the Mach number. For this work it was necessary to develop a new geometry, which includes two types of methodologies to characterize the flow velocity; so, a Pitot tube, located below the wedge, was added for the purpose of comparing the data with the ones obtained with the old methodology and for the validation of the new methodology. The Pitot tube device, in this work, basically consists of a pressure sensor mounted perpendicular to the flow, for acquiring the total pressure data downstream of the shock wave ($p_{0,2}$) and a sensor pressure locate outside the shock wave to measure the static pressure upstream of the shock (p_1). In this work, it is important to note that this flow measurement technique uses the Rayleigh's equation for the case of supersonic flow and is related to the normal shock wave theory. Rayleigh's equation was deduced from the normal shock wave equations, considering the conditions before and after the shock wave (ANDERSON, 1991) combined with the isentropic conditions. As shown in the Eq. (2), the total pressure is represented by p0,2, the freestream static pressure is p_1 to the freestream Mach number is M_1:

$$\frac{P_{02}}{P_1} = \left(\frac{(\gamma+1)^2 M_1^2}{4\gamma M_1^2 - 2(\gamma-1)}\right)^{\gamma/(\gamma-1)} \frac{1-\gamma+2\gamma M_1^2}{\gamma+1} \quad (2)$$

Using Eq. (2) it was possible to evaluate analytically which sensor you need to carry out the experiment with precision in data acquisition and with this choose the most appropriated for the tests.

3. RESULTS

Considering the present work, which involves two different methodologies in a single experiment, and with the impossibility of executing the test flow at the SCTB laboratory in the present moment, it was necessary to use the Mach number obtained in works previously performed and validated where it was used the schlieren technique and implemented in the *θ-β-Mach* relation. In this work it was presented the development of a supersonic nozzle for the SCTB pilot (GUIMARÃES et al, 2019), where to measure the Mach number it was used a wedge with two different angles, as shown in Fig. 9, the schematic drawing of the wedge, and in Fig. 10, where it is possible to see the image of the wedge, during the experiment, using the schlieren technique.

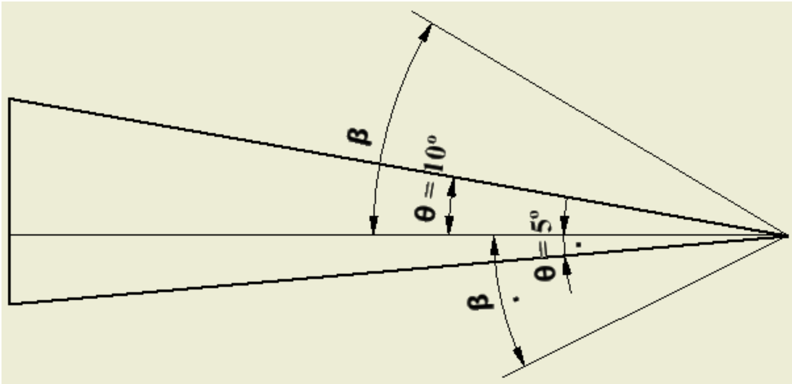

Figure 9. Schematic drawing of the wedge with two angles θ = 5º and 10 º

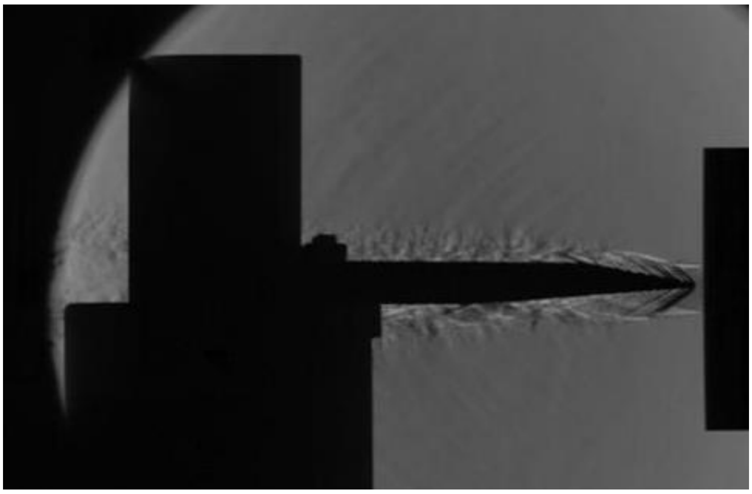

Figure 10. Image of the wedge, during the experiment, using the schlieren technique (SILVA et al, 2019).

With the images it was possible to measure the shock wave angle *(β)* and with these values, obtained with several experimental tests, for each angle of the wedges, it were calculated the respective Mach numbers, through Eq. (1). All the measured values of the shock wave angles (*β*), for the wedge angles θ = 5° and 10º, and the calculated values of Mach numbers, for each experiments are shown in Tab. 1.

Table 1. Mach number obtained through *θ-β-Mach* relation for the wedge with angles θ =5º and 10º (SILVA et al, 2019).

Image #	**Shock wave angle *β* for angle *θ* = 5° (rad)**	**Mach number calculated for *θ* = 5°**	**Shock wave angle *β* for angle *θ* =10° (rad)**	**Mach Number calculated for *θ* = 10°**
1	0.68573	1.76549	0.68892	1.99217
2	0.69474	1.74531	0.78540	1.76742
3	0.61630	1.94597	0.78540	1.76742
4	0.66964	1.80333	0.68232	2.01099
5	0.69045	1.75484	0.78540	1.76742
6	0.7474	1.79102	0.75093	1.83809
7	0.69474	1.74531	0.78540	1.76742
8	0.63108	1.90345	0.74838	1.84371
9	0.63108	1.90345	0.74542	1.85030
10	0.68573	1.76549	0.82885	1.69077
	Average	**1.81235**	Average	**1.82957**

Using the calculated Mach number values of Tab. 1, it was calculated, using these values in Rayleigh Pitot tube formula, Eq. (2), the stagnation pressure $p_{0,2}$ that must be measured at the Pitot tube located under the wedge model of the present work (Figs. 5 and 6). For these calculations, the gas was considered as calorically perfect, so γ was considered constant equal to 1.4 and the pressure p_1, at the exit of the SCTB, was considered equal to 101325 Pa.

Figure 11 shows the graphic of the values of the Mach number, calculated through *θ-β-Mach* equation, by the stagnation pressure obtained by the Rayleigh Pitot tube formula ($p_{0,2}$), for the two angles of the wedge. As the experimental tests for the present work could not be done, at least it was possible to calculate the total pressure that must be measured and with that better specify the sensor. With all that it could be shown how the purposed methodology works.

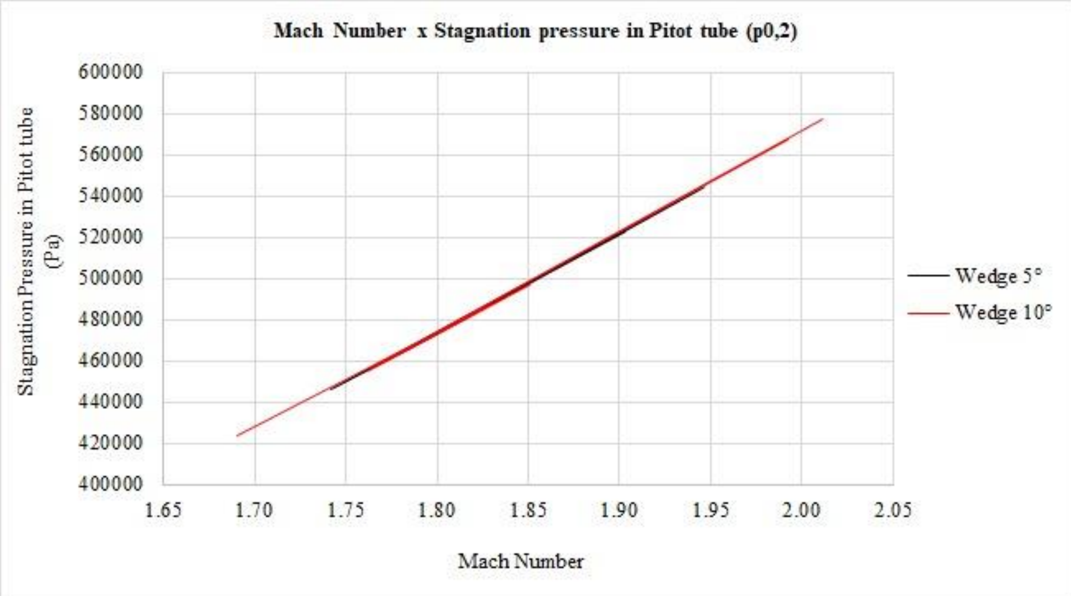

Figure 11. Mach Number x Stagnation pressure in Pitot tube.

Even though the experimental tests could not be done, and as the SCTB works with Mach numbers between 1.8 and 2.6, the values of the stagnation pressure obtained here contributed to the selection of the range of the pressure sensor that will be used in the Pitot tube and selected the ideal pressure sensor to make possible the experimental tests in the SCTB safer and more accurate.

As calculated through Eq. (2), using the average Mach numbers of each wedges, the values of the ($p_{0,2}$) that the pressure sensor in Pitot tube will measure was obtained, $p_{0,2}$ = 473138.67 Pa to M_1 =1.8 and which is M = 2.6, you get $p_{0.2}$ = 930296.01 Pa.

Considering the desired range of Mach numbers at the SCTB nozzle exit, the Model 8510B -200 piezoresistive pressure Endevco transducer is one that can be selected because its specifications meet the basic requirements to perform the test at the SCTB, as shown in the Endevco datasheet (Tab. 2)

Table 2. Datasheet Piezoresistive pressure transducer (ENDEVCO, 2020).

SPECIFICATIONS			
Dynamic Characteristics		Electrical	Environmental characteristics
Range Pressure (Pa)	Warm-up Time (ms)	Full Scale Output	Temperature (K)
0 – 1.379 e+6	1	300 ±100 mV at 10.0 Vdc	219.15 K to 394.15 K

4. CONCLUSIONS

The present work aims to use two methodologies together, at the same time, in the same experiment, to characterize the flow velocity at the exit of the convergent-divergent nozzle of the pilot SCTB, located in the IEAv laboratory, in order to improve and instrument the equipment for the ideal conditions for future experimental tests. The two methodologies consist in measuring the total and static pressures with a Pitot tube, and applying the Rayleigh's equation, to calculate the Mach number at the SCTB exit and at the same time measure the shock wave angle formed over an wedge, using the schlieren technique, and with this obtain the Mach number of the test flow by the *θ-β-Mach* relation.

Because of the difficulties to execute the experimental tests at SCTB, an analytical study was carried out using the normal shock wave relations methods with the conditions before and after the shock wave formed in front of the Pitot tube body and with the obtained data it was possible to evaluate the ideal pressure sensor for the pitot tube, meeting the specifications (pressure, temperature, time) necessary for carrying out future tests. With the obtained values it was selected the Piezoresistive pressure transducer Model 8510B -200, meeting the necessary specifications and considering that the SCTB flow is continuous, this type of sensor is not a pulsed type, with a response time in micro seconds, unlike the other models that were used in previous tests and did not obtain satisfactory data.

Even though some tests with the Pitot tube were not performed because of the present situation the biggest part of the work proposed here was done, as: the model of the wedge with the Pitot tube, with the support (Fig. 6), was manufactured and mounted at the laboratory, the schlieren technique was tested with good results, the sensor to measures the total pressure was specified, and the whole methodology was here presented. All this will contribute for the studies of the supersonic combustion that will help the researches of the hypersonic vehicle demonstrator, 14-X, that now is being developed in the IEAv.

5. ACKNOWLEDGEMENTS

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