



encit 2020



18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0575

EXPERIMENTAL STUDY AT HYPERSONIC SHOCK TUNNEL OF A 3D PROTOTYPED SCRAMJET POWERED WITH HYDROGEN

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Abstract. *The involvement of several research centers, around the world with studies, on supersonic combustion, to apply as hypersonic airbreathing propulsion, for an aerospace vehicle is due to its ability to make space access more economical. The scramjet 14-X waverider is a strategic project of the Brazilian Air Force and is being developed at Laboratory of Aerothermodynamics and Hypersonics Prof. Henry T. Nagamatsu, at Institute of Advanced Studies (IEAv). This vehicle aims to demonstrate the scramjet and waverider technologies in flight at geometric altitude of 30 km and a speed corresponding to Mach number 10. The experimental study of supersonic combustion, performed at the Hypersonic Shock Tunnel T3, at Nagamatsu Laboratory, on a scramjet model, is presented. The model is approximately 1.2 meters long and was instrumented with 24 pressure transducers along the geometry. Tests without injection of fuel are compared with injection of hydrogen as fuel to verify differences in the pressure profile obtained by the pressure transducers installed not only in the combustion chamber, but also after the combustion chamber.*

Keywords: *scramjet, supersonic combustion, hypersonic airbreathing propulsion, experimental investigation*

1. INTRODUCTION

The effort in research and development of scramjet technology, in several research centers around the world, is due to the potential to increase the payload and reduce the cost of satellite launch vehicles. One possibility to achieve this goal is to use a scramjet vehicle that achieves high Mach numbers in the Earth's dense atmosphere (**Doherty et al., 2012**).

The research of scramjet vehicles has been developed for over 40 years, with the objective of carrying out flight tests. Theoretical studies using computational codes (CFD) require experimental flight data to validate the results obtained in CFD and, consequently, assist in the design of the scramjet vehicle geometry (**Pulsonetti e Stalker, 1996**).

Several scramjet vehicles using different fuels have been tested on flights with different Mach numbers. During the flight with Mach number 5, at about 30 km of altitude, the X-51 burned the JP-7 hydrocarbon fuel in the combustion chamber. While, for two X-43 flights, at approximately 30 km of altitude, and Mach numbers 7 and 10, the supersonic combustion was demonstrated using hydrogen (**Jackson et al., 2014**).

A lot of efforts to study hydrogen-fueled scramjet engines was done simulating flight conditions with Mach number 4, 6 and 8 at Ramjet Engine Test Facility (RJTF) in Japan Agency Exploration Agency (JAXA), Kakuda Space Center. These studies allowed to identify two different combustions mode: weak and intensive combustion mode. In the first mode the pressure rise in the combustor was low but the combustion was indicated by the heat flux in the downstream of the combustor. Also, in this mode the boundary layer was almost attached in the combustor wall and the scattering of fuel was within or near the boundary layer. In the intensive mode, the pressure rise caused by combustion was high and propagated from the combustor to isolator, the boundary layer was largely separated around the fuel holes and most of the fuel burned between the separation region of the boundary layer and the mainstream (**Ryou et al., 2008**).

The most important of the scramjet engine technology are the flame holding method and the control of drag and aerodynamic heat. Since 2005 KARI (Korea Aerospace Research Institute) studied the scramjet technology. The first

scramjet engine model (called S1) was used to collect data of fundamentals physics and characteristics of the scramjet engine. The S1 scramjet engine model was tested simulating flight at altitude of 31 km and Mach number 7.6 varying components (shape of cowl) and equivalence ratios (Soo et al 2011).

The success of X-43A flight experiments showed that an air-breathing scramjet propulsion system to fly at Mach 10 by its own net thrust is possible, also, indicated that this technology can then be applied in the development of vehicles for fast transportation or in stages of low orbit launchers (Riva et al., 2019).

This scientific article aims to report the experimental study of supersonic combustion performed in the Hypersonic Shock Tunnel T3, at Laboratory of Aerothermodynamics and Hypersonics Prof. Henry T. Nagamatsu, at Institute of Advanced Studies (IEAv), of a 3D printed scramjet model with 1.2 meters long instrumented with 24 pressure transducers along the geometry.

This experimental campaign aims to obtain the pressure profile during the tests with injection of hydrogen fuel and comparing these results with experiments without injection of hydrogen.

2. BIBLIOGRAPHIC REVIEW

The theoretical definition of a hypersonic flow is Mach number is greater than five. When an object is in a supersonic and/or hypersonic flight a shockwave is established. Temperature, pressure, and density of the airflow are increased through the shockwave, while flow Mach number and flow velocity decrease. The shock wave is an extremely thin region, in the order of 10^{-5} cm (Vilela, 2016).

The scramjet is an aerospace vehicle using a hypersonic airbreathing propulsion system. The air flow captured by scramjet inlet is compressed, heated and decelerated by the shock waves (generated during the hypersonic flight) and the airflow is conducted to the combustion chamber at supersonic speed (Mach number higher than 1), where the fuel (at least sonic speed) is injected, mixed with the supersonic airflow and the supersonic combustion starts. The combustion products leave the combustion chamber and are accelerated to hypersonic speeds through the exhaust nozzle generating the thrust needed to realize the hypersonic flight (Denis, 2011). The schematic of a scramjet is show in **Erro! Fonte de referência não encontrada..**

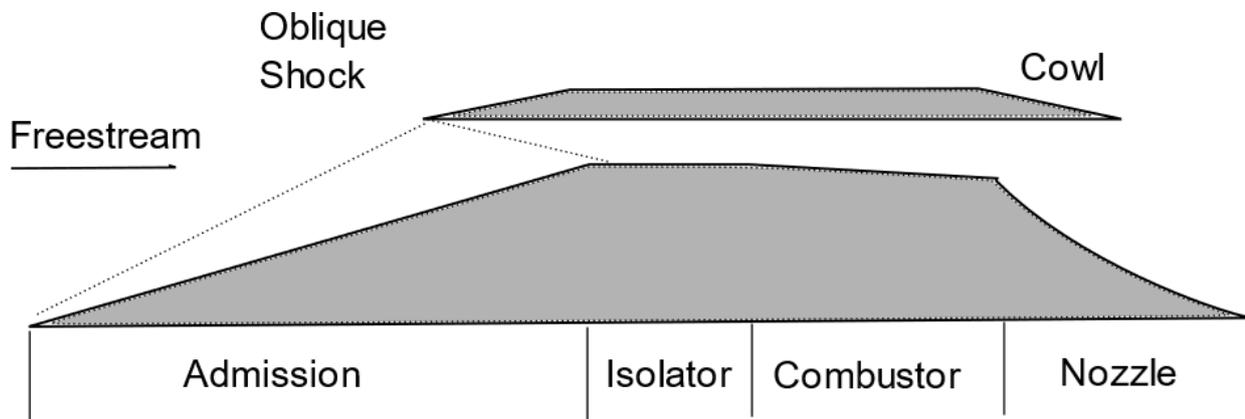


Figure 1. Scramjet geometry representation (Adapted of Heiser and Pratt, 1994).

A hypersonic shock tunnel is the best tools to experimentally simulate the hypersonic flow over a scramjet engine at flight conditions (Martos, 2017). A shock tunnel consists of a shock tube coupled to a convergent-divergent section where the flow is accelerated to hypersonic velocity, which is enclosed by a clamped section where the model to be tested is accommodate. The shock tube is formed by two reservoirs with different pressures (driver and driven, reservoirs at high and low pressures, respectively) separated by one or more diaphragms. At the end of the driven is installed a diaphragm to separate the driven and the test section (Romanelli et al., 2011). During the test, the incident shock wave generated in the driven section encounters a diaphragm at the end of the driven section. This shock wave breaks the diaphragm and the airflow at quasi-stagnated condition is accelerated at the convergent section up to Mach number 1 and accelerate to hypersonic Mach number at the divergent (Cardoso, 2016). **Figure 2** shows the T3 Hypersonic Shock Tunnel, of the Prof. Nagamatsu Laboratory, at the IEAv. This hypersonic shock tunnel was designed to operate at Mach numbers from 7 to 25 (Romanelli et al., 2011).

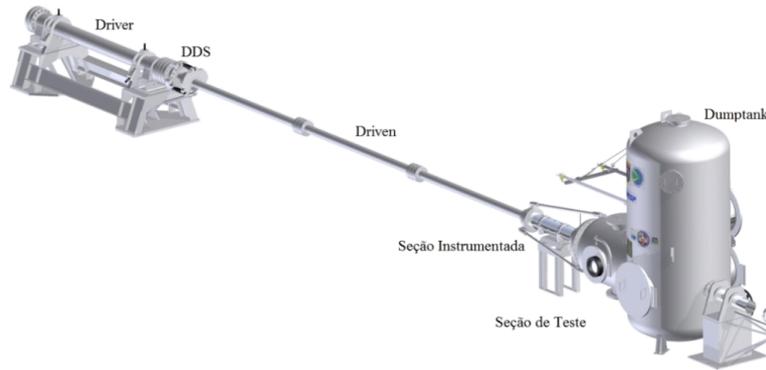


Figure 2. T3 Hypersonic Shock Tunnel (Romanelli et al., 2011).

2.1 Experimental Study

For the experimental study, a 3D prototyped academic scramjet model with three compression ramps, an isolator and two expansion ramps, was prototyped by a 3D printer. The design of this academic model is presented by Martos (2017). Figure 3 shows the identification of all pressure transducers used, twenty-four installed along the geometry, two installed to measure the injected gas and six installed as pitot tube. The region analyzed in this paper is the combustion chamber, where the P13 to P24 pressure transducers are installed.

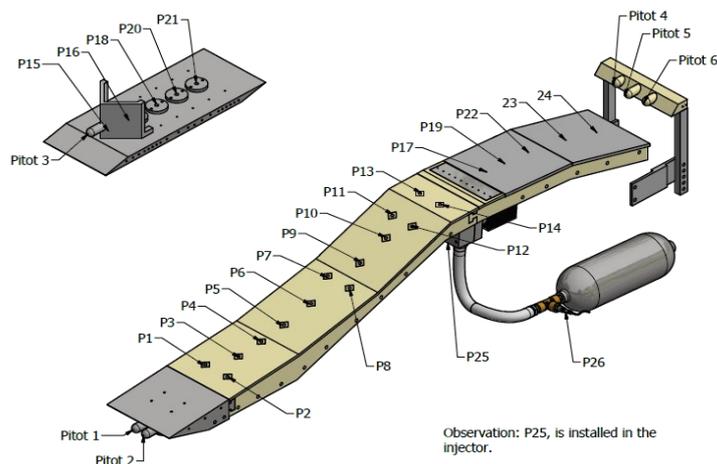


Figure 3. Identification of the pressure transducers installed in 3D prototyped academic scramjet model

The 3D prototyped academic scramjet model installed in the section test of the T3 Hypersonic Shock Tunnel is illustrated in Fig. 4. The position represented in Fig. 4 was chosen to provide Mach number 7 at the leading edge of the model and to the combustion chamber to be within the visualization window of the T3 Hypersonic Shock Tunnel.

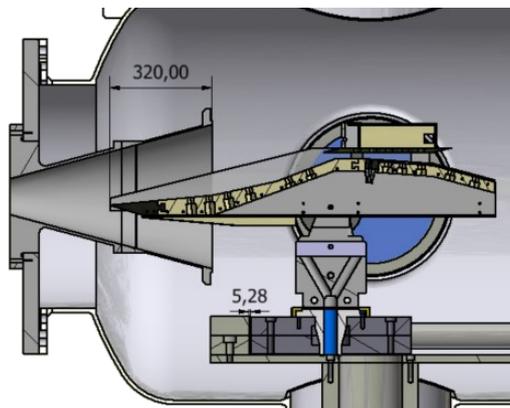


Figure 4. 3D prototyped scramjet model installed in test section of the T3 Hypersonic Shock Tunnel.

3. RESULTS

The experiments carried out have basically three different configurations: without injection (baseline), injection of helium, and injection of hydrogen. The helium injection was done to present the pressure behavior after injection but without burn. The experiments configurations used are presented in **Tab. 1**.

Table 1. Experiments injection setup

Experiment	Injection	Pressure
#1	No injection	-
#2	No injection	-
#3	No injection	-
#4	Hydrogen	15 atm
#5	Hydrogen	14 atm
#6	Hydrogen	8 atm
#7	Hydrogen	14 atm
#8	Hydrogen	14 atm
#9	Hydrogen	5 atm
#10	Hydrogen	5 atm
#11	Helium	14 atm
#12	Helium	14 atm
#13	helium	14 atm

A combination of the normalized measurement collected by a pressure transducer (in blue) with the median of this same measurement (in red) is presented in **Fig. 5**. To facilitate the visualization of measured values, the graphs presented shows only the median of each transducer pressure.

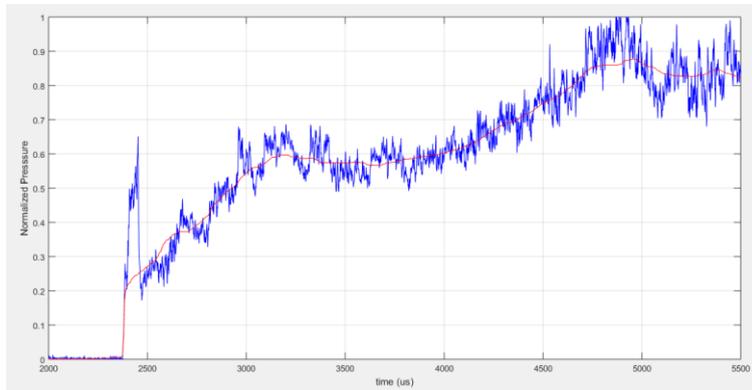


Figure 5. Measurement example with median.

The normalized pressure is calculated by the ratio of the pressure measured in the combustion chamber with the flow pressure at the leading edge of the model, calculated by an inhouse software using the measure obtained by the pitot installed in this region.

The injection occurs inside the combustion chamber and 820 mm from the leading edge. It is important to say that the pressure mentioned in the description of the experiments is the pressure of the fuel in the fuel system with the pressure measured during the experiment being approximately half of the value informed.

Figures 6 and 7 show the comparison of measurements obtained in the upper and bottom walls of the combustion chamber for experiments without injection of fuel (#1 and #2) with injection of helium (#12 and #13).

It is expected the measures of the P15 (**Fig. 6**) and P13, P14 (**Fig. 7**) to be close to each other since these pressure transducers were installed before the injection point, however is possible to see that the measurement in P13 are P14 are almost the double of P15. The variation of the measurements, for the experiments with injection of helium are higher in pressures transducers P15 (**Fig. 6**) and P14, P19 and P22 (**Fig. 7**). For experiments without injection the pressure transducers in **Fig.6 and Fig. 7** obtained measurements close to each other, except in P13 and P14. It was expected that the pressure transducers in experiments with injection of helium to be higher than in those without injection, however the pressure transducers installed in the bottom wall presented a variation higher than those in the upper wall of combustion chamber. P23 and P24 not answer as expected and not obtained measurements in almost all experiments carried out.

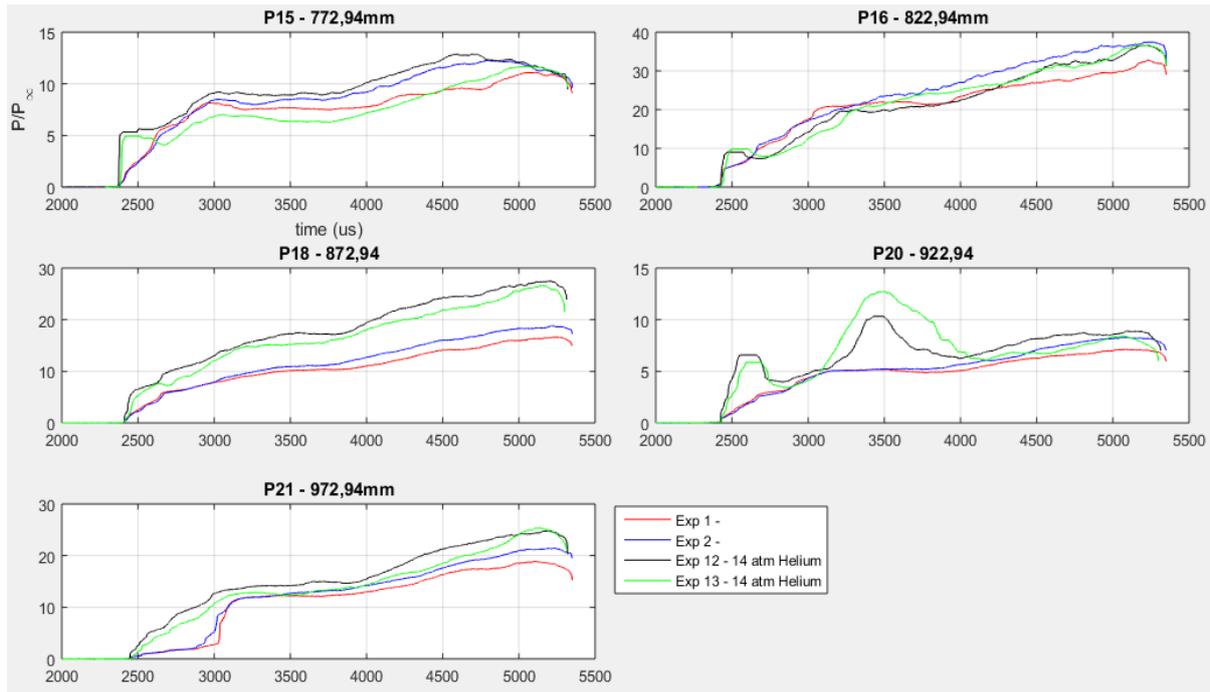


Figure 6. Upper wall pressure normalized comparison of experiments #1, #2, #12 and #13.

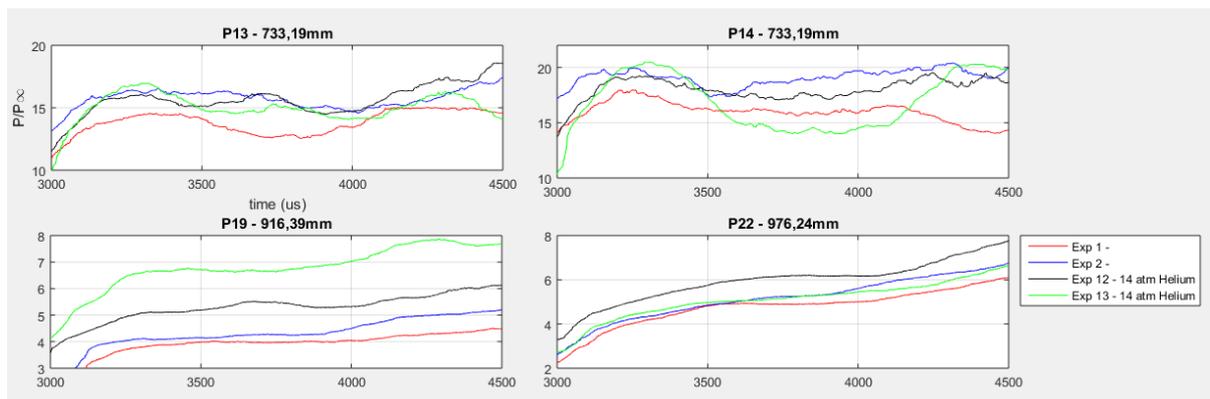


Figure 7. Bottom Wall pressure normalized comparison of experiments #1, #2, #12 and #13.

Figures 8 and 9 shows the normalized pressure along the upper wall and bottom walls of the combustion chamber comparison between experiments without injection (#1 and #2), with injections of helium (#12) and 8 atm hydrogen (#6).

Comparing the value obtained by the P19 pressure transducer (**Fig. 9**) is showed a higher value for the experiment with hydrogen injection, however comparing this measurement with the **Fig. 7** is possible to see that the pressure is close to each other. Only P21 and P22 showed higher value in the comparison, even if comparing with **Fig. 7**.

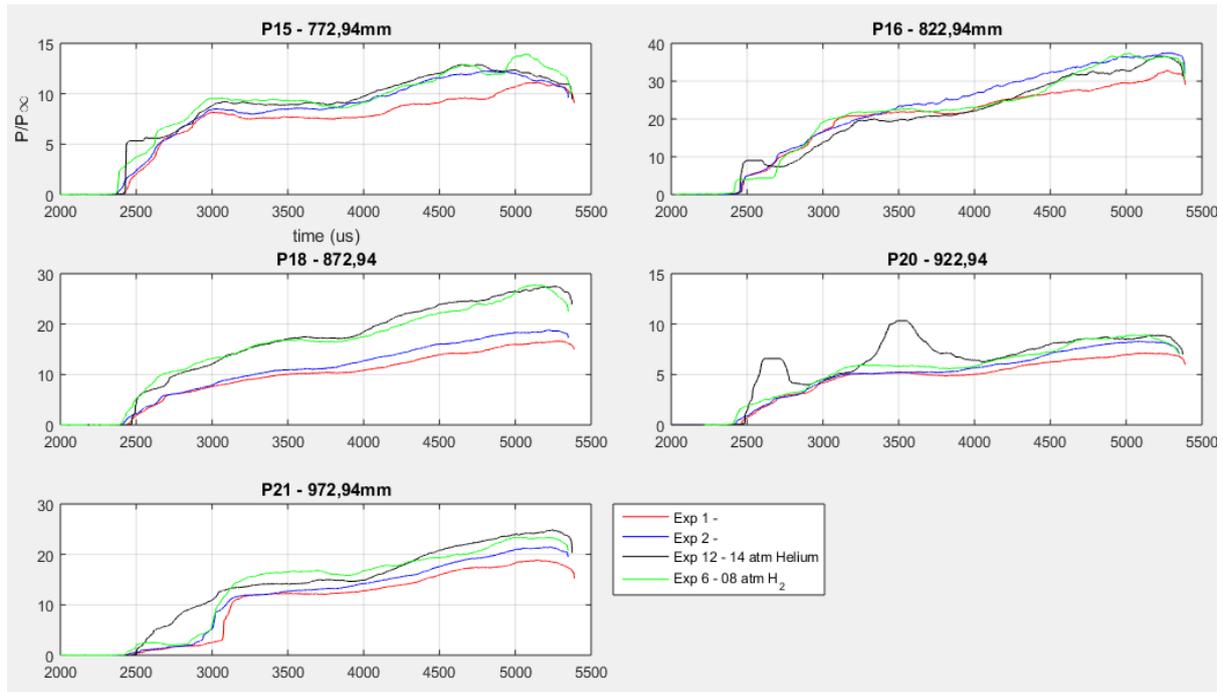


Figure 8. Upper Wall pressure normalized comparison of experiments #1, #2, #6 and #12

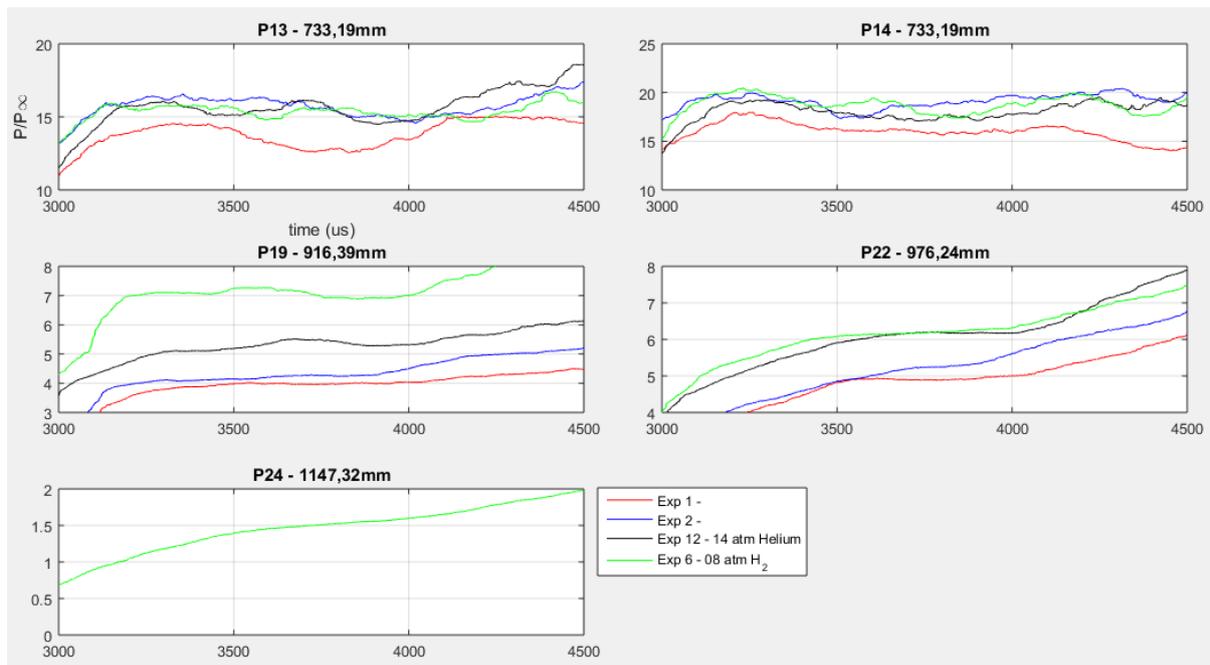


Figure 9. Bottom Wall pressure normalized comparison of experiments #1, #2, #6 and #12

Figures 10 and 11 show measurements obtained along the upper and bottom walls of the combustion chamber comparison between experiments with 15 and 14 atm hydrogen injection (#4 and #5), with injection of helium (#11) with without injection (#1). The measurement obtained by the P15 pressure transducer (Fig. 10) is close to all experiments in this comparison, however this behavior is not repeated in P13 and P14 (Fig. 11). Again, as in Fig. 6 and Fig. 8, the P15 obtained almost half measure then P13 and P14.

The pressure transducers P18 (Fig. 10) and P19 (Fig. 11) showed higher values for experiments with injection, however, the measurement obtained in experiment with helium injection are practically the same of those with hydrogen injection. The measure obtained by P22 and P24 (Fig. 11) showed a little difference with the values from experiments with hydrogen injection being a little higher than of helium injection.

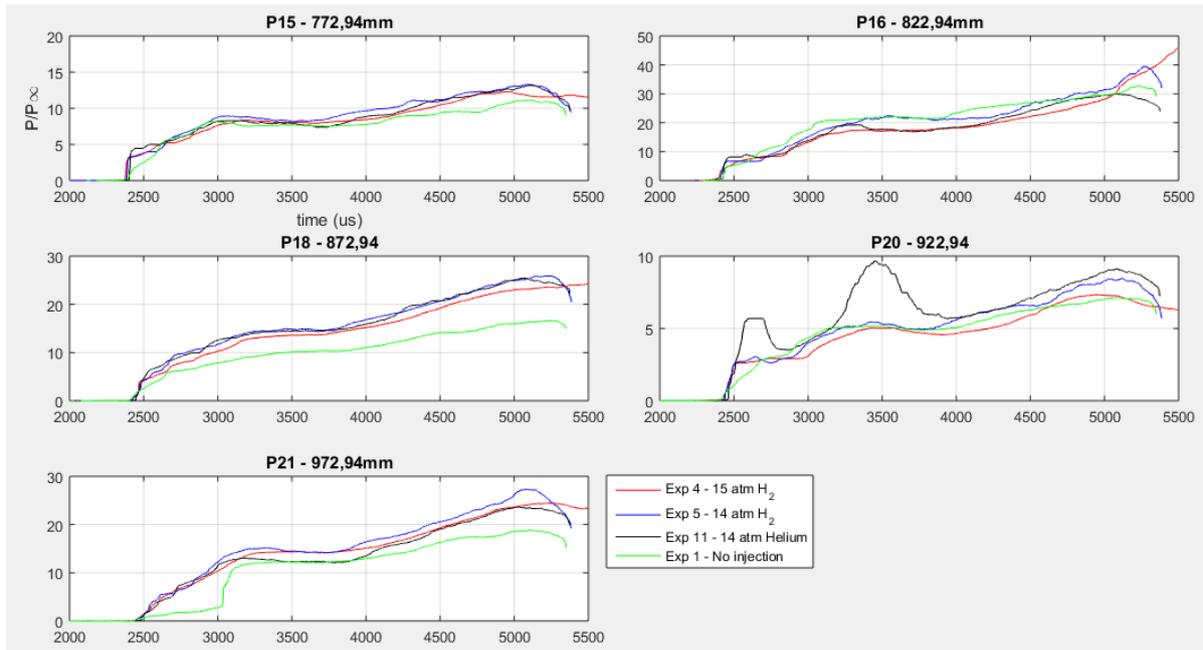


Figure 10. Upper Wall pressure normalized comparison of experiments #1, #4, #5 and #11

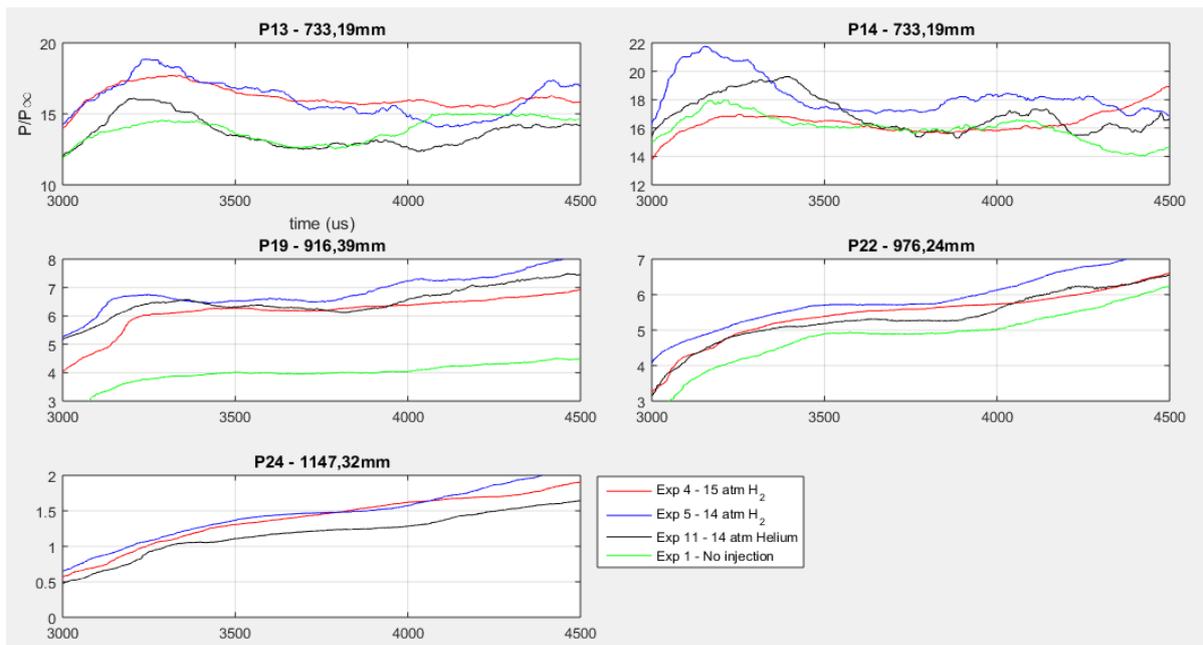


Figure 11. Bottom Wall pressure normalized comparison of experiments #1, #4, #5 and #11

Figures 12 and 13 show comparison of measurements obtained along the upper and bottom walls of the combustion chamber between experiments without injection (#1, #2 and #3) with 14 atm hydrogen injection (#7 and #8), with 5 atm hydrogen injection (#9 and #10).

The measures obtained in the upper wall (Fig.12) are initially (P15) higher in experiments without injection (#1, #2 and #3), however as it advances inside the combustion chamber it decreases until reaching the same value as the experiments with injection (Fig. 12). Also, this figure shows that only P18 showed a little higher value for experiments with hydrogen. Pressure transducers P20 and P21 obtained lower measurements in experiments with hydrogen injection.

In Fig. 13 the pressure transducer P19 for experiments #7 and #10 showed a higher measurement, however in the P22 all measurements of experiments with hydrogen injection are lower than without injection.

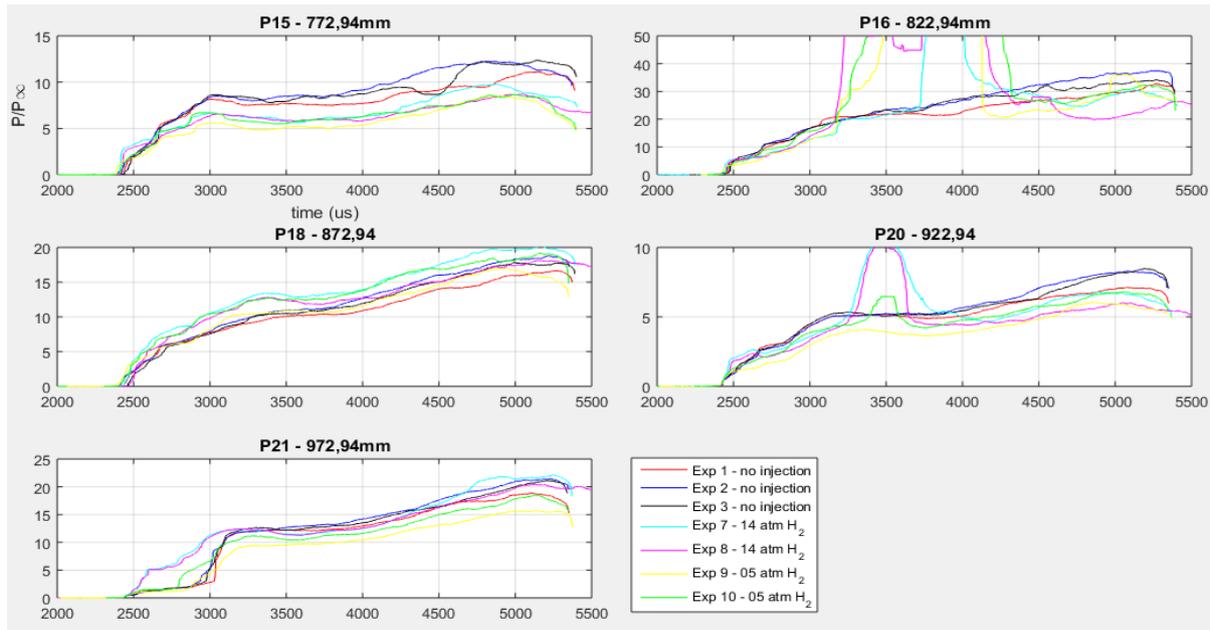


Figure 12. Upper Wall pressure normalized comparison of experiments #1, #2, #3, #7, #8, #9 and #10

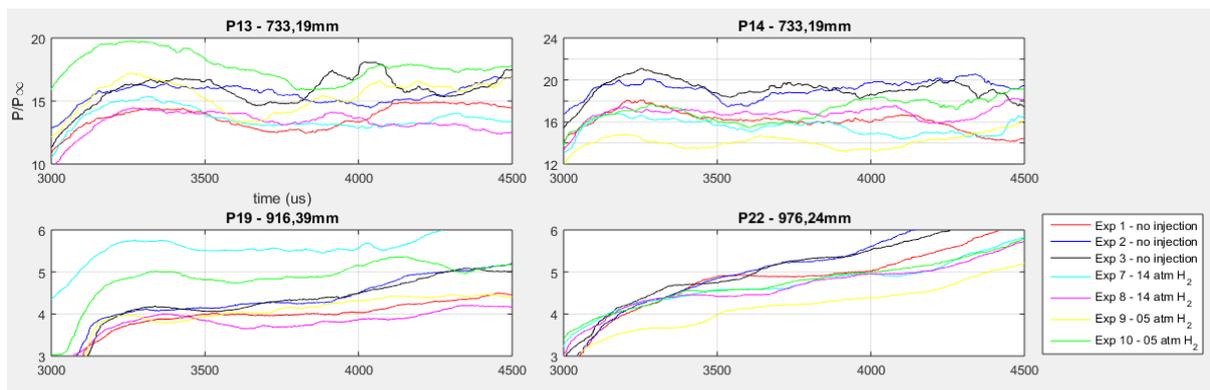


Figure 13. Bottom Wall pressure normalized comparison of experiments #1, #2, #7, #8, #9 and #10

4. CONCLUSIONS

The scramjet engine technology has high potential in increasing the payload and reducing the cost of launch-to-orbit vehicles. Experimental studies involving the simulation of flight conditions in scramjet engines are an important tool for the design of this type of technology.

This paper shows the experimental study of a 3D prototyped academic scramjet model tested in the T3 Hypersonic Shock Tunnel, at the IEAv. A total of thirteen experiments were carried out, three experiments without injection, seven experiments used hydrogen injection varying the fuel injection pressure (5 atm, 8 atm, 14 atm and 15 atm) and other three experiments with 14 atm helium injection. The experiments without injection (baseline) were done to allow the comparison with experiments with hydrogen injection and helium injection. It was expected that the pressure measured after the injection (820 mm from the leading edge of the academic model) would be higher and spread through the combustion chamber when compared with the experiments without injection.

The measurements obtained on the upper wall, at the combustion chamber, after the injection point, showed higher variations in the pressure transducer P18 for experiments with injection (helium or hydrogen) except for experiment #8 when compared with experiments without injection. The pressure transducers P16, P20 and P21 also showed variations, however lower than those obtained by P18. Comparing the results obtained by these three pressure transducers is possible to see that in P16 and P20 experiments with helium or hydrogen injection are lower or almost the same of experiments without injection, and in the P21 the measurements obtained in experiments with injection of hydrogen (#4, #5 and #6) and helium (#12, #13) are higher than those without injection.

The measurements obtained on the bottom wall after the injection point, showed higher values in the pressure transducer P19 for experiments with injection of hydrogen (#4, #5, #6, #7 and #10) and helium (#11, #12, and #13). The

pressure transducer P22 obtained higher values for experiments #4, #5, #6 and #12. Other experiments with injection (hydrogen or helium) obtained lower or equals results than experiments without injection. The pressure transducer P24 obtained measurements only in experiments #4, #5, #6 and #11 where the first three obtained same results and higher than the last one.

After analyzing the results obtained by pressure transducers it was possible to notice that the pressure rise caused by combustion was not detected by the pressure transducers. It is important to inform that another work using a diagnostic technique has been developed, and in that work, it was identified that the supersonic combustion occurred, however, only pressure measurements do not allow this identification. Therefore, it is possible to conclude that the supersonic combustion is not conclusive by the analyzed results.

5. ACKNOWLEDGEMENTS

The authors would like to thanks the Instituto de Estudos Avançados (IEAv) the support given to complete this scientific work. The first author would like to thank prophiper project for financial supporting the experimental research. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil (finance code 001).

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