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NUMERICAL INVESTIGATION OF THE FLOW INSIDE A PILOT SUPERSONIC COMBUSTOR TEST BENCH

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Abstract. *The supersonic combustor test bench (SCTB) is a ground test facility for the study of supersonic combustion. It simulates the in-flight flow conditions at the entrance of the combustor of a scramjet (supersonic combustion ramjet), which is an aspirated engine with a supersonic combustion-type reactor. The SCTB used in this study is composed by a combustion chamber, or vitiated air generator (VAG), used to heat the air, coupled to a supersonic nozzle which accelerates it. The study looks for a relationship between the desired conditions of temperature, Mach number, and the oxygen content, equal to 21%, at the SCTB exit, and the mass flow rate of the reagents (NGV, air and oxygen) at the entrance. For this purpose, the behavior of the hot and cold flow along the test bench is numerically evaluated to generate the desired conditions at the entrance of the scramjet combustors to be tested. The expected result is the development of a methodology to manipulate the valves of the three reagents (O_2 ,air, NGV), at the entrance of the SCTB, to control the test flow at its exit, with the desired temperature and Mach number and also with O_2 to maintain a 21% concentration at the outlet. The results can also provide data for the future analysis of the effectiveness of the nozzle geometry in generating the desired conditions.*

Keywords: scramjet, computational simulation, ground test facility.

1. INTRODUCTION

There is a great effort by several countries in the development of vehicles capable of reaching ever faster speeds (SUTTON, 2001). It is, in this scenario, that we can see the need for the development of aspirated engines as supersonic combustion ramjets, called scramjets. The study of supersonic combustion has become even more relevant, with the supersonic combustor test benches (SCTB), being widely used for this purpose, making its use important as the ground test facility for study of supersonic combustion. The SCTB can generate the same flow conditions at the entrance of the scramjet's combustor in a real flight. The flow inside the combustor has high temperatures and speeds with Mach number around 2.6. Therefore, the test bench is basically composed of a combustion chamber, or vitiated air generator

(VAG), which serves to heat the air, and this VAG is coupled to a supersonic nozzle that accelerates the heated air to the desired test speed. The Institute for Advanced Studies (IEAv), has a pilot SCTB where the air, inside the VAG, is heated by combustion, using natural gas vehicle (NGV) as fuel. In this process the oxygen is consumed, and the problem is that at the exit of the bench, the oxygen content of the air test flow must be equal to 21%. Thus, before the combustion process, the air is enriched with oxygen to replace what will be consumed during this heating process.

One of the main problems to be solved is to find the relation between the desired conditions of the flow (temperature, Mach number and oxygen content) at the SCTB exit and the mass flow rate of the reactants (air, NGV and oxygen) at the entrance of the VAG.

The objective of this research is to evaluate the flow behavior along the pilot IEAv's SCTB, to be able to control the mass flow rates of the reagents at its entrance. For this purpose, the combustion process inside the VAG and flow inside the nozzle will be analyzed using the commercial softwares Fluent and Chemkin, and also the Cantera and Pyton, to create a methodology to control the flow test conditions through the manipulation of the reagents flow rates at the entrance of the pilot SCTB. This methodology will help in the development of the present bench and also will contribute to the study and assembly of other ones in the future.

2. METHODOLOGY

2.1 The SCTB pilot unit

Supersonic combustion researches and hypersonic flow studies require ground test facilities such as shock tunnels, hypersonic mass accelerator and supersonic combustor test benches (SBTC) (LEITE at al., 2004). Among these facilities the Institute for Advanced Studies (IEAv), in São José dos Campos, has some hypersonic shock tunnels and one hypersonic mass accelerator. To complete the set of ground test facilities for the supersonic combustion studies the IEAv is assembling a SBTC with a vitiated air generator (VAG) coupled to a nozzle, as shown in the schematic drawing in Fig. 1, where the combustor to be tested will be directed connected to the nozzle exit of the outlet of the bench.

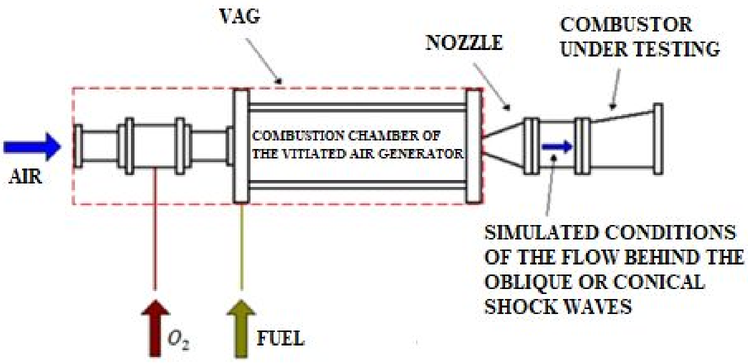


Figure 1. Schematics of a direct-connected supersonic combustion test facility (LEITE, 2006).

To simulate the same air conditions at the entrance of a scramjet combustor, in this ground test facility, oxygen enriched air is heated, by combustion, inside the vitiated air generator unit and then accelerated through a nozzle, thus feeding the combustor, under testing, with a "vitiated air" containing the desired flow properties, plus the combustion products, generated in the heating process, while keeping the desired atmospheric oxygen content.

The heart of the direct-connected scramjet combustor test facility is the vitiated air generator unit. It consists of an axisymmetric cylindrical chamber where the air is first enriched with oxygen and then heated by the combustion of a fuel (here NGV), yielding the desired stagnation temperature before flowing through a nozzle to be accelerated to the desired Mach number. Figure 2 shows the complete scheme of a VAG and the nozzle.

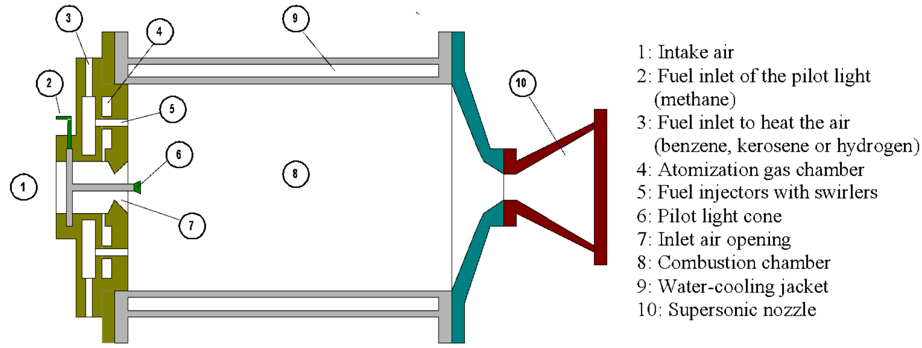


Figure 2. Schematics of the vitiated air generator with the nozzle (LEITE, 2006).

One advantage of this bench is the duration of the test time, because for the shock tunnel and the mass accelerator, the time is about 1 millisecond and for the SCTB it is around 20 or 30 seconds.

In parallel with the main bench assembly, one SCTB pilot unit (Fig. 3) was built for studies and data acquisition that will help the development of supersonic combustion researches and also to the mounting of the main bench laboratory.

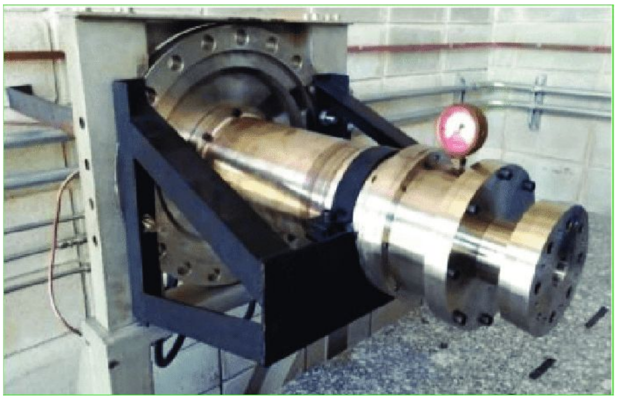


Figure 3. The SCTB pilot unit

The purpose of the present work is the numerical investigation of the flow inside the SCTB pilot unit to find a relationship between the conditions of the flow at the bench exit and mass flow rate of the reagents at its entrance, to be able to control the test flow conditions only manipulating the valves of the reagents that feed the system.

2.2 The scramjet and the supersonic combustor

The scramjets use the air from the atmosphere to burn the fuel and its combustion chamber is supersonic and the flow at the entrance of the combustor (Fig. 4) has the conditions of the flow behind the oblique or conical shock waves formed ahead of vehicles flying at hypersonic speeds, and these are the conditions that should be simulated at the exit of the SCTB. These conditions are; high temperature, supersonic speed ant 21% of O_2 content.

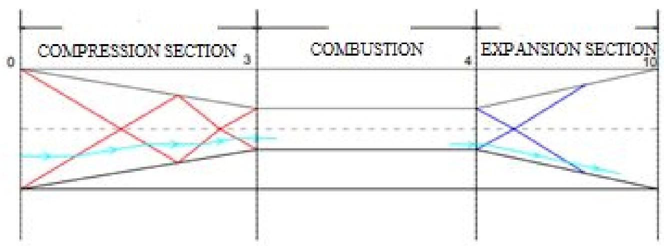


Figure 4. Schematic drawing of the scramjet combustor. (Adapted from HEISER and PRATT, 1994).

Among the advantages of scramjets it can be mentioned: reduced high temperature effects; allows for long distance travel in a shorter time due to its hypersonic regime; as it is an aspirated engine, it only carries the fuel it and not the oxidizer, reducing the vehicle's payload and it has no moving parts for air compression.

In the present study, the conditions referring to the exit of the SCTB are the same conditions at the entrance of the combustor of a scramjet in real flight as shown in Fig. 5.

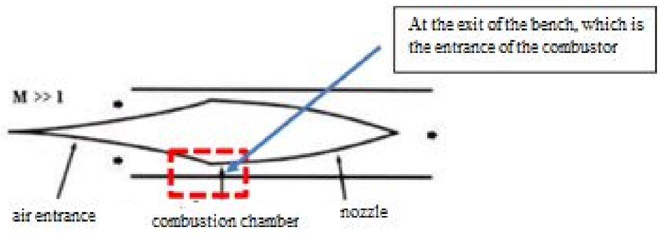


Figure 5. Schematic diagram of a scramjet engine (AVIATION INTERNET GROUP, 2018).

As a state-of-art about the studies and technological demonstrators of scramjets, it can be mentioned many cases all over the world for the last 8 years from 2012 to 2020. Among the most recent studies on scramjet we have the following countries: 2012 United States (BBC NEWS, 2012), 2016 India (FIRSTPOST, 2016) and the most recent, in 2019, India reaching Mach 6 for 20 seconds (BUSINESS STANDARD, 2019). Currently, in Brazil, the IEAv is developing the 14-X Technological Demonstrator which is expected to reach Mach 7 for 20 seconds.

As a major challenge faced in relation to supersonic combustion reactor research is to ensure that the combustion occurs in a stable and continues manner. So, the SCTB will help in this research, because as the time of the test is about 30 min, it is possible to study the ignition and the maintenance of the supersonic combustion.

2.3 Numerical evaluation of the flow inside the SCTB

For the study of the flow conditions along the SCTB it was necessary to use four different software and one more to create system/methodology that will make possible to control the test flow condition at the exit of the bench. The five software are listed below:

• AUTODESK INVENTOR to make the geometry of the model to be studied;
• CANTERA: In order to understand/define all possible chemical reactions during combustion process inside the VAG using PYTHON language;
• CHEMKIN: To be able to understand all possible chemical reactions during combustion.
• FLUENT ANSYS: For the numerical study of the behavior of the flow along the complete geometry of the SCTB, to obtain the conditions of the flow at exit of the bench, using as input conditions the ones generated by the software CHEMKIN or CANTERA.
• LABVIEW: To create a methodology to control the conditions that will be measured at the exit of the SCTB nozzle manipulating the mass flow rate of the reagents (opening of the valves) at the entrance of the bench. This one will not be used in this work.

2.3.1 Geometry of the tested model

The geometry of the model was made following all the parameters and values of the pilot unit of the IEAv's SCTB parts. The geometry was designed in 3D using the software "Autodesk Inventor version 2021" as shown in Fig. 6, where, at the right end of the VAG there is the fuel injection plate with 8 holes (the swirlers) and at the other end there is the nozzle.

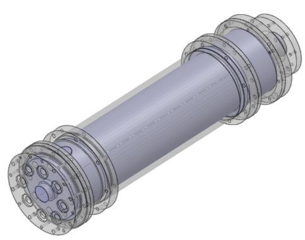


Figure 6. Isometric view of the SCTB geometry.

The bench works with two different nozzles: one with the diameter of the throat equal to 7 mm and another one with the diameter equal to 21 mm. In Fig. 7 is shown the detail of the 7 mm throat.

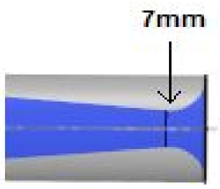


Figure 7. Nozzle with 7 mm throat.

The 8 holes (swirlers) at the entrance of the VAG combustion chamber, are the representation of the reagents injection (air+NGV+ O_2) area.

2.3.2 Problem considerations

The domain used for the complete study is the region on blue (Fig. 8), which represents the flow into the chamber through the swirlers, the combustion chamber (VAG) and the nozzle.

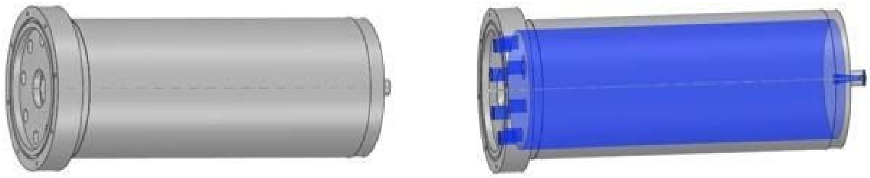


Figure 8. Domain for the study (swirlers + combustion chamber + nozzle with 7mm throat).

1) For the study using CANTERA and CHEMKIN:

These two softwares are used to understand the combustion process inside the VAG, and with this obtain the reactions (mechanism) of NGV (Methane) and air. This mechanism obtained will be used for the calculation of the entire domain (Fig. 8). With CANTERA and CHEMKIN the domain is only the combustion chamber (VAG) because the objective is the combustion process.

So, for the calculations using CANTERA and CHEMKIN, it was considered:

- One dimensional flow;
- Viscous flow;
- Reactants: air + Methane;
- Domain: only the combustion chamber (VAG).

2) For the study using FLUENT ANSYS:

This software is used to calculate the conditions of the flow at the exit of the SCTB. With the combustion reactions (mechanism) obtained with the softwares CANTERA and CHEMKIN it is possible to calculate the flow conditions at the VAG exit, which are the stagnation conditions for the nozzle, and with this it is possible to obtain the flow test conditions at the nozzle exit.

So, for the calculations using CANTERA and CHEMKIN, it was considered:

- Flow equilibrium;
- PRS reactor;
- Plug Flow reactor;
- Reactants: air + methane;
- Entire domain: swirlers + combustion chamber (VAG) + nozzle with 7mm throat.

The first step of the study was based on obtaining basically the chemical reactions mechanism for Methane and air using the software CANTERA, considering the combustion process incomplete, and the gas inlet condition as ideal gas. The studies considering the combustion process as rich and the poor mixtures can also be done, in order to see how to solve the problem more efficiently.

3. RESULTS

3.1 Combustion Methane CH_4 + Air (Using CANTERA with PYTHON)

For the study of the combustion process of Methane (CH_4) and air, it was used the composition of the atmospheric air of Tab 1. The values expected for the flow temperature and pressure conditions, at the end of the combustion process, must be equal to 2500 K and 20 atm respectively. These are the required stagnation conditions, at the entrance of the nozzle, or at the exit of the VAG, to obtain the desired flow test conditions, of temperature, T = 1200 K, Mach number = 2.5 and pressure, p = 1 atm, at its exit.

Table 1. Composition of atmospheric air (NASA, 1976).

Composition of atmospheric air	
Species	Molar fraction
N_2	0.78084
O_2	0.209476
Ar	0.009365
CO_2	0.000319

The first results for the combustion process the studies of Methane (CH_4) and air, using the CANTERA software with the PYTHON language, gave as a result: 325 chemical reactions with 53 species, generating the graph, for various equivalence ratios, shown in Fig. 9.

In the graph (Fig. 9), the two curves represent, the complete combustion process, in blue color, and the incomplete combustion process, in orange color, for the case of the present study. Another observation is that with the equivalence ratio Ø > 1 it will have excess of fuel (CH_4) in the reaction (rich mixture) and with Ø < 1 it will have excess of oxygen in the reaction (poor mixture).

It was noticed that to obtain the desired stagnation of temperature equal to 2500 K, for p = 20 atm, the equivalence ratio would be approximately 0.7.

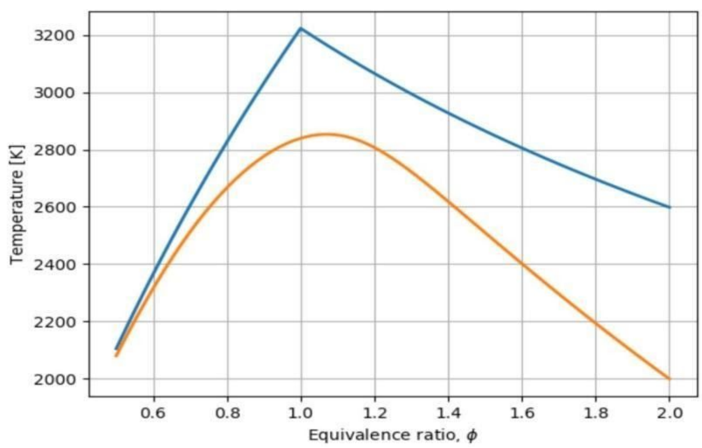


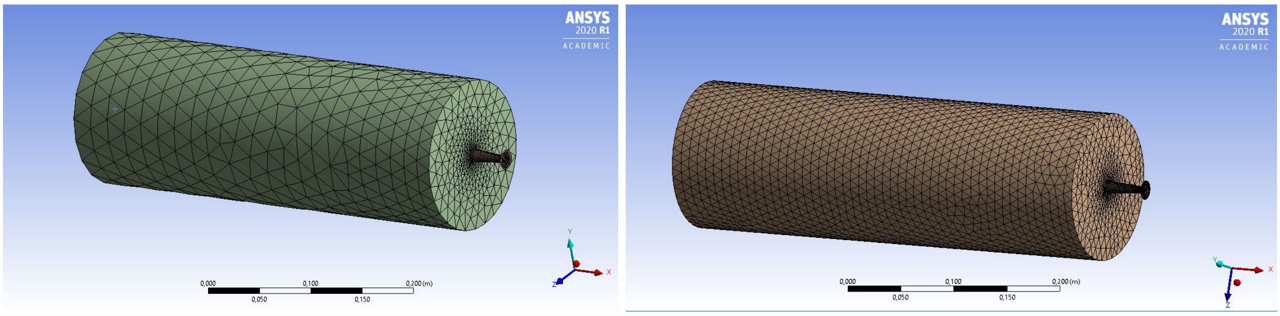
Figure 9. Temperature x equivalence ratio.

3.2 Mesh (using ANSYS- FLUENT)

3.2.1 Refinement of the mesh

In parallel to the calculations using the CANTERA software, a study was done on the refinement of the complete domain mesh to be used for the calculations using the FLUENT software.

This study was necessary to prepare the domain for the calculation of the flow conditions along the entire SCTB, including the VAG and the nozzle, with FLUENT software. Figure 10(a) shows the mesh with the element size equal to 3E-002 and Fig. 10(b) the refinement with the element size equal to 1E-002.



(a) (b)

Figure 10. Mesh generation and refinement using FLUENT software.

3.2.2. Mesh quality verification

Mesh quality statistics can be a good way to assess mesh integrity. They are not a surefire method for creating an accurate mesh, but they can give an idea of how well it will converge (SMITH, 2017).

Skewness mesh metrics spectrum:

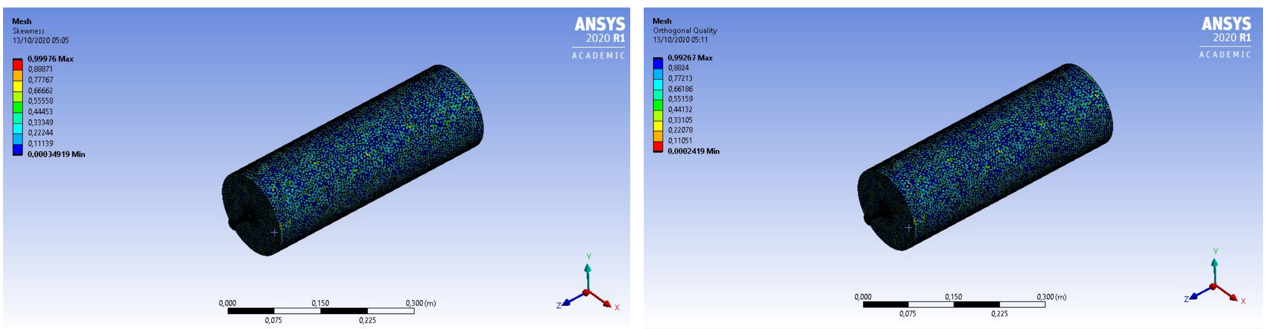
Excellent	Very good	Good	Acceptable	Bad	Unacceptable
0-0.25	0.25-0.50	0.50-0.80	0.80-0.94	0.95-0.97	0.98-1.00

Orthogonal Quality mesh metrics spectrum:

Unacceptable	Bad	Acceptable	Good	Very good	Excellent
0-0.001	0.001-0.14	0.15-0.20	0.20-0.69	0.70-0.95	0.95-1.00

Figure 11. Mesh quality statistics (SMITH, 2017).

Figure 11 shows at the spectrum of skewness and at the spectrum of orthogonal quality which values are considered adequate for the mesh. For the geometry of this work the values for the skewness, obtained between 0.1 and 0.94 (Fig 12a) are considered acceptable. There are some elements that were in the low range from 0.95 to 0.99 but they were found for a very small area, so they were disregarded. The values for the orthogonal quality, obtained between 0.15 and 0.99 (Fig 12b) were considered very good, but there are some elements with low values, from 0.002 to 0.14, which, in the same way, were disregarded because, as they have very small area, they did not influence in the study.



(a) (b)

Figure 12. Skewness and orthogonal quality.

3.3 Setup (using ANSYS- FLUENT)

3.3.1 Reactor model conditions

The reactor model used for the study was the "Partially Premixed Combustion", due to the oxidizer and the fuel will enter together through the same inlet mixing in this way and the fluid was considered in equilibrium and adiabatic.

3.3.2 Boundary and initial conditions

In previous works for the SCTB, the mass flow rate used for the air was 0.3888 kg/s and for methane was 0.1 kg/s, with an equivalence ratio equal to 4.42 at the combustion chamber entrance, so it means that it is a rich mixture as already explained in section 3.1. Because it is necessary to obtain 21% of O_2 at the outlet of the SCTB, a study of the inlet mass flow rate was made to obtain an equivalence ratio values less than 1, to have a poor mixture as shown in Table 2. For this study the mass flow of the mixture methane + air, chosen to start the calculations, was 0.4888 Kg/s, which was maintained constant while the flow rates of the air and the methane flow were being modified separately.

Table 2. Study for the mass flow rates inlet values.

Total flow rate	Flow rate air	Flow rate CH4	Equivalence ratio
0.4888	0.461928092358439	0.0268719076415613	1
0.4888	0.4633	0.0255	0.946136412691561
0.4888	0.4638	0.025	0.926584734799483
0.4888	0.4643	0.0245	0.907075166917941
0.4888	0.4648	0.024	0.887607573149742
0.4888	0.4653	0.0235	0.868181818181818
0.4888	0.4658	0.023	0.848797767282095
0.4888	0.4663	0.0225	0.829455286296376
0.4888	0.4668	0.022	0.810154241645244
0.4888	0.4673	0.0215	0.790894500320993
0.4888	0.4678	0.021	0.771675929884566
0.4888	0.4683	0.0205	0.752498398462524
0.4888	0.4688	0.02	0.733361774744027
0.4888	0.4693	0.0195	0.714265927977839
0.4888	0.4743	0.0145	0.525521821631879

3.4 Solution

3.4.1 Numerical simulation results - complete domain

With the values obtained in Tab. 2, , three cases were chosen: one with Ø =1 and two with Ø < 1 to be used as input data (the lines with red color in Tab. 2). These values are show in Tab. 3, where the first line shows also one case more, which was used in previous studies for Ø > 1, that will not be used in this work.

Table 3. Input values for the calculations.

Total flow rate	Flow rate air	Flow rate CH4	Ø
0.4888	0.3888	0.1	4.421
0.4888	0.461928092358439	0.0268719076415613	1
0.4888	0.4663	0.0225	0.829455286296376
0.4888	0.4743	0.0145	0.525521821631879

Figures 13, 14 and 15 show the results obtained for the mass fraction of O_2 and the temperature (T_S) and pressure (p_s) respectively at the exit of the SCTB. The images on the left (Figs 13, 14 and 15) are the results for the case of the second line of Tab. 3, the ones on de middle are for the case of the third line and the ones on the right are for the case fourth line.

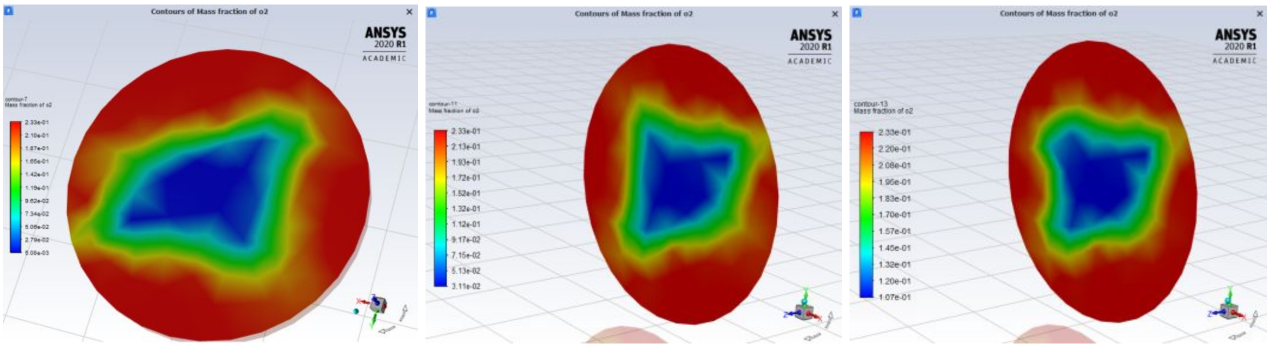


Figure 13. Mass flow of O_2 calculated values at the SCTB outlet.

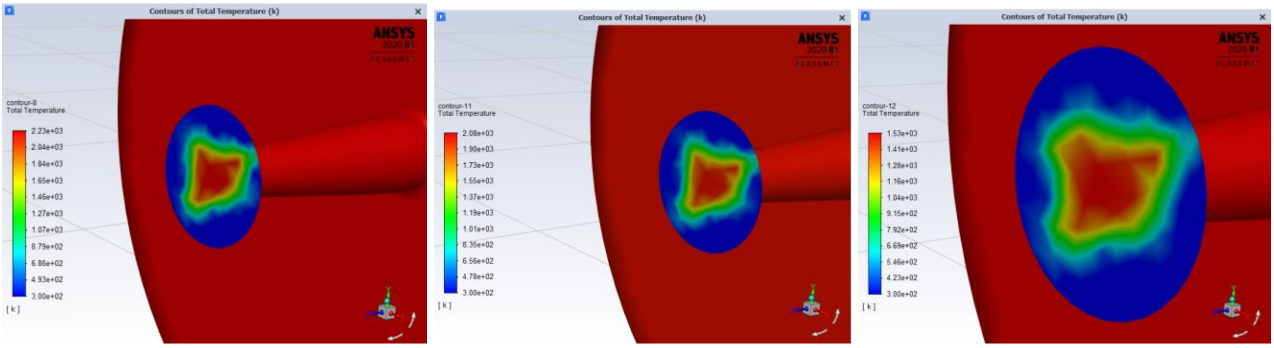


Figure 14. Temperature calculated values at the SCTB outlet.

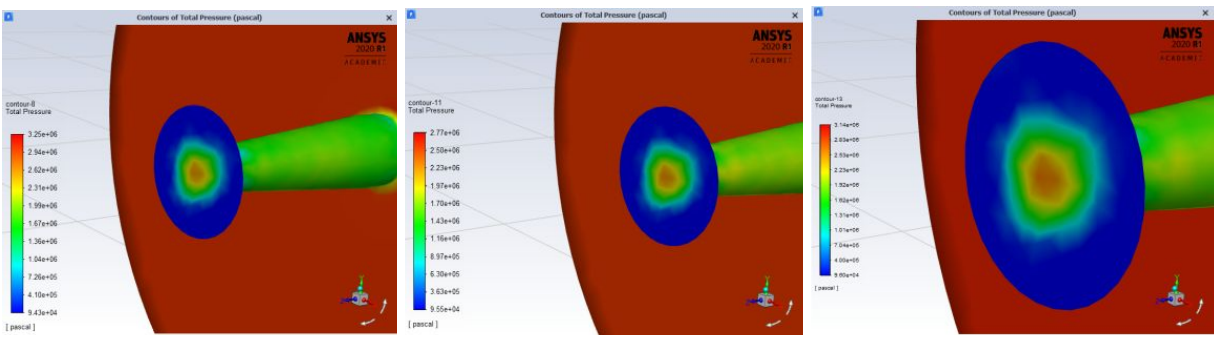


Figure 15. Pressure calculated values at the SCTB outlet.

With the results obtained with the simulation it was possible to calculate others parameters as Mach number at exit of the nozzle of the SCTB. The values of stagnation pressure (p_0) and temperature (T_0) at the entrance of the nozzle, the outlet pressure (p_s) and temperature (T_s), Mach number (M) and % of O_2 for the four cases of Tab. 3 are shown in Tab. 4

Table 4. Values obtained for the outlet.

P0(atm)	T0 (K)	Ps(atm)	Ts (K)	M	% O2 Exit
21.75	1308	4.501	745.29	1.79	3
28.99	2023	5.921	904.357	2.21	6
25.52	2040.5	5.220	817.16	2.03	8
29.76	1525.24	5.940	687.16	2.09	12.74

4. CONCLUSION

With the obtained values it was possible to clearly see that all the input parameters at the entrance of the combustion chamber or VAG of the SCTB has a great influence on the flow test conditions at the exit of the nozzle or the SCTB outlet. It is shown in Tab. 4 that when the equivalence ratio began to decrease, the stagnation temperature and pressure increased too, but if this equivalence ratio continue decreasing, at a certain point, the stagnation temperature begin to decrease. The main purpose of this work was to create a methodology to control the flow test conditions through the manipulation of the reagents flow rates at the entrance of the pilot SCTB and this goal has been achieved with all the studies and tools developed here. The desired flow test conditions at the exit of the SCTB, for the development of the supersonic combustion experimental research are around: T =1200 K, Mach number = 2.5 with 21% of O_2 content. So the next step is to apply the methodology and all the tools developed in the present work, to run many cases with various reactants mass flow rates, others fuels, and various equivalence ratios, as input values, to obtain the ones specified at the exit of the SCTB. Finally, for the case of oxygen content at the exit of the nozzle, it was observed that for the lowest equivalence ratio used in this work (Ø > 0,52), it was obtained 12% of O_2 content, so it can suggest an additional O_2 to the air, to guarantee at the exit of the nozzle the desired 21%.

This methodology will help in the development of the present pilot supersonic combustion test bench or SCTB and also will contribute to the study and assembly of other ones in the future.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE