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COMPARATIVE ANALYSIS OF THE FLOW INSIDE A SUPERSONIC COMBUSTION TEST BENCH USING TWO DIFFERENT LENGTHS FOR THEIR VICIATED AIR GENERATOR.

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Abstract. *The supersonic combustion test bench (SCTB) is a ground test facility for the study of supersonic combustion. The SCTB simulates the flow conditions in actual flight at the entrance of the combustor of a scramjet (supersonic combustion ramjet), which is an aspirated engine with supersonic combustion reactor. For the supersonic combustion experimental researches, the Institute for Advanced Studies (IEAv) has a pilot SCTB. This pilot SCTB consists of a combustion chamber, or vitiated air generator (VAG), to heat the air, coupled with a supersonic nozzle that accelerates the heated air to the desired test speed. For the studies of supersonic combustion, the combustor, to be tested, is coupled immediately after the nozzle exit, for this reason this test bench is called directly connected. For a better flame stability inside the VAG, a 1000 mm long SCTB is being designed and, for that, it was necessary to study it considering the same conditions at the entrance of the current 430 mm long SCTB. This study seeks a relationship between the desired conditions of temperature, Mach number and oxygen content, equal to 21%, at the exit of the SCTB, for both lengths, and the mass flow rate of the reagents (NGV, air, and oxygen) at their entrance, with the intention of making a comparative analysis between the two lengths of the SCTB in order to better understand how to reach the desired flow conditions at their exit. For this purpose, the behavior of the hot flow along the test bench is numerically evaluated to compare the results obtained for the two different lengths of the SCTB. With the results it is possible to analyze what is the best relationship between the inlet and outlet flow conditions of the bench to, in the future, create a methodology to manipulate the mass flow rate of the three reagents (O2, air, NGV), at the entrance of the SCTB, in order to control the test flow at its exit. The results can also provide data for future analysis of the effectiveness of the nozzle geometry in generating the desired test conditions.*

Keywords: *scramjet, computational simulation, ground test facility, vitiated air generator*, supersonic combustion test bench.

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 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), 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 find a relationship between the desired conditions of temperature, Mach number and oxygen content, equal to 21%, at the exit of the SCTB, for both lengths, 430 and 1000 mm, and the mass flow rate of the reagents at their entrance, with the intention of making a comparative analysis between the two lengths of SCTB in order to understand the behavior of the flow inside de SCTB for both lengths to see which is better considering the flame stability and consumption of reagents.

For the study of combustion inside the VAG and the flow inside the nozzle, it were used the commercial softwares Fluent and Chemkin, as well as Cantera and Phyton, to create a methodology to control the flow test conditions, manipulating the reagents flow rates at the inlet of the pilot SCTB. This methodology will also contribute to the design of the main SCTB unit that will be assembled the future.

2. METHODOLOGY

2.1 The scramjet

The scramjets use the air from the atmosphere to burn the fuel and inside the combustion chamber the flow speed is supersonic. At the entrance of the combustor the conditions of the flow are the ones behind the oblique or conical shock waves formed ahead of vehicles flying at hypersonic speeds as shown on the image below (Fig. 1).

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 inside it and not the oxidizer, reducing the vehicle's payload and there are no moving parts for the compression of the air.

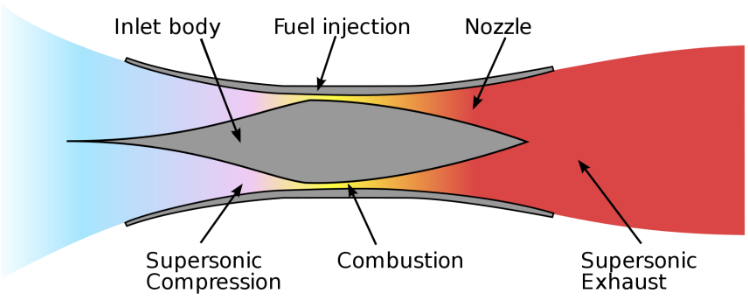


Figure 1-Schematic diagram of a scramjet engine (EMOSCOPES,2005).

Supersonic combustion research and hypersonic flow studies require ground test facilities such as shock tunnels, hypersonic mass accelerator and supersonic combustor test benches (SCTB) (LEITE at al., 2004). Among these facilities, the Institute for Advanced Studies (IEAv), in São José dos Campos, has some hypersonic shock tunnels and a hypersonic mass accelerator. To complete the suite of ground test facilities for the supersonic combustion studies, the IEAv is assembling a SCTB with a vitiated air generator (VAG) coupled to a nozzle, as shown in the schematic drawing (Fig. 2), where the scramjet combustor to be tested must be directed connected to the nozzle outlet of the bench.

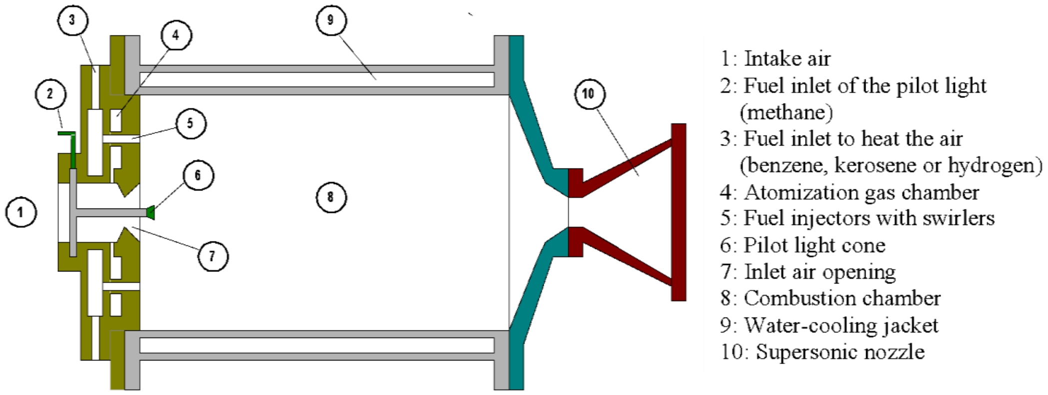


Figure 2- Schematics of the vitiated air generator with the nozzle (LEITE, 2006).

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 seconds, it is possible to study the ignition and the maintenance of the supersonic combustion.

2.2 The supersonic combustion test bench (SCTB)

The conditions of the flow at the exit of the SCTB are the same conditions at the inlet of the combustor of a scramjet in real flight, namely with: high temperature, supersonic speed and 21% of the O_2 content.

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 (VAG) unit. It consists of a 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 conditions of temperature and pressure at the entrance of the nozzle where the flow is accelerated to the desired Mach number. Figure 2 shows the complete scheme of a VAG and the nozzle.

One advantage of this bench is the duration of the test time, because the others ground test facilities used to study the supersonic combustion, as shock tunnel and the mass accelerator, the test time is about 1 millisecond and for the SCTB it is around 20 or 30 seconds.

In parallel with the main bench design and installation, a SCTB pilot unit 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.

2.3 Numerical evaluation of the flow inside the SCTB

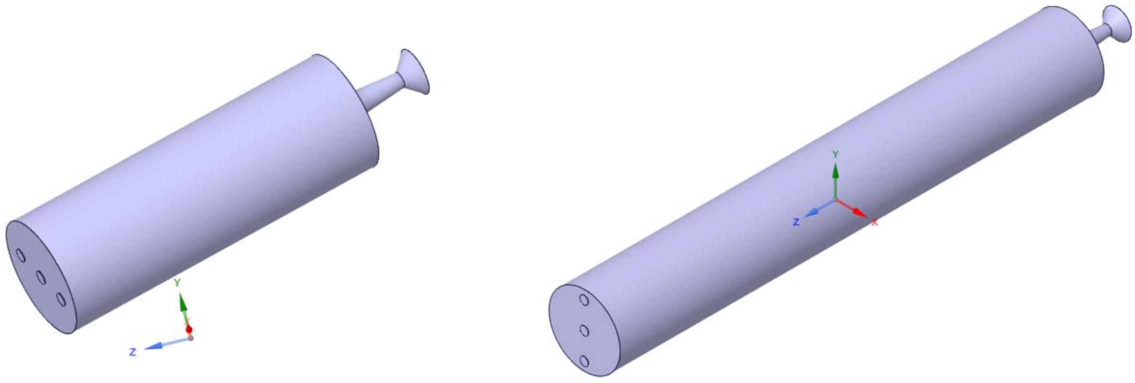
For the study of the flow conditions along the two SCTB studied, with lengths of 430mm and 1000mm, it was necessary to use four different softwares, as shown in (Tab. 1), and one more to create a system / methodology that will enable to control the test flow condition at the SCTB exit.

Table 1-Softwares used in this work.

NAME OF THE SOFTWARE	TASK PERFORMED
Autodesk Inventor	Geometry
Cantera	Combustion reaction
Chemkin	Combustion reaction
Fluent Ansys	Combustion Simulation

2.3.1 Geometries used for the study

The geometry was drawn in 3D using the "Autodesk Inventor version 2021 and 2022" software, where, at the left end of the VAG, there is the fuel injection plate with 3 holes (the swirls) and at the other end there is the nozzle.
The model 1 (Fig. 3(a)) was designed following the values of the current SCTB IEAv's pilot unit (SCTB with a length of 430mm). The model 2 (Fig. 3(b)) was designed using the values of the future pilot unit (SCTB with a length of 1000mm)



(a) (b)

Figure 3- (a) SCTB with a length of 430mm and (b) SCTB with a length of 1000mm.

The bench works with two different nozzles: one with a throat diameter equal to 7 mm and another with a diameter equal to 20 mm. In this work it we used the nozzle with the 20 mm throat.

2.3.2 Problem considerations

To calculate the flow conditions at the output of the SCTB it was used the FLUENT ANSYS software, with the combustion reactions (mechanism) obtained with the CANTERA and CHEMKIN software. The mechanism used was provided by Chemkin itself within the Ansys software for the air + methane combustion. So, it was possible to calculate the flow conditions at the outlet of the VAG, which are the stagnation conditions at the entrance of the nozzle, and with this it is possible to obtain the flow test conditions at its exit.

considered:
- PRS reactor;
- Plug Flow reactor;
- Reagents: air + methane;
- Entire domain: swirls + combustion chamber (VAG) + nozzle with 20 mm throat.

considering the incomplete combustion process and the gas inlet condition as the ideal gas.

For the study of the combustion process of NGV (Natural Gas Vehicle) and air, it was considered Methane (CH_4) as the fuel, because the NGV has about 90% of CH_4 in its composition, and for the air it was used the composition of the atmospheric air of (Tab 2.)

Table 2- Composition of atmospheric air (NASA, 1976).

Composition of atmospheric air	
Species	Molar fraction
N_2	0.780840
O_2	0.209476
Ar	0.009365
CO_2	0.000319

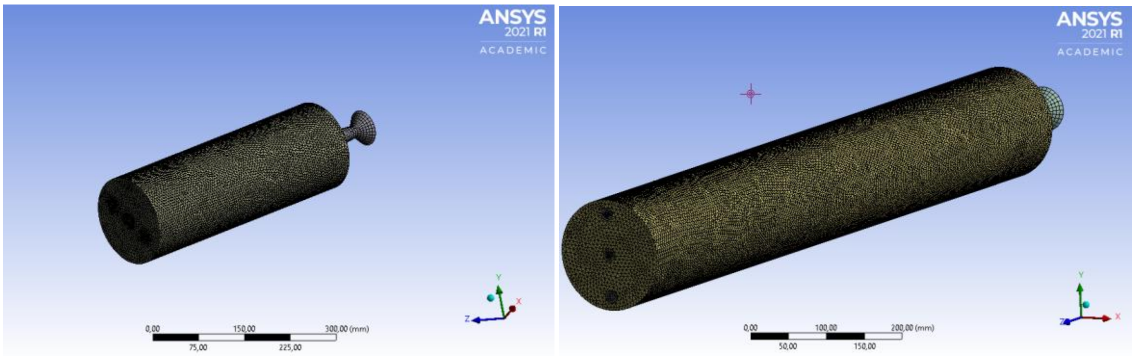
3. RESULTS

3.1 Preliminary results

3.1.1 Mesh

3.1.1.1 Refinement of the mesh

After studying the two geometries that would be used for the study, a refinement of the mesh of the entire domain to be used for the calculations in the FLUENT software was carried out. For this study it was necessary to prepare the domain for calculating the flow conditions throughout the entire SCTB, including the VAG for the case of the 430 mm long combustion chamber and for the case of the 1000 mm long one and the 20 mm nozzle, using the FLUENT software. (Fig. 4(a)) shows the mesh with the element size equal to 5E-003 for the VAG 430mm long and (Fig. 4 (b)) the refinement with the element size equal to 5E-003 of the VAG 1000 mm long mesh.



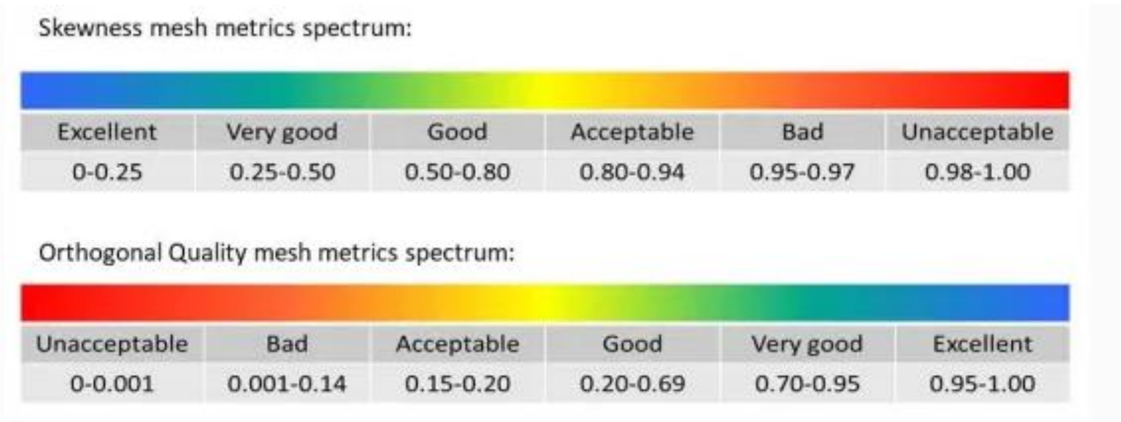
(a) (b)

Figure 4 -Mesh generation (a) and refinement (b) using FLUENT software.

3.1.1.2 Mesh quality verification

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

In (Fig. 5) it is possible to observe in the spectrum of skewness and in the orthogonal quality spectrum which values are considered suitable for the mesh.



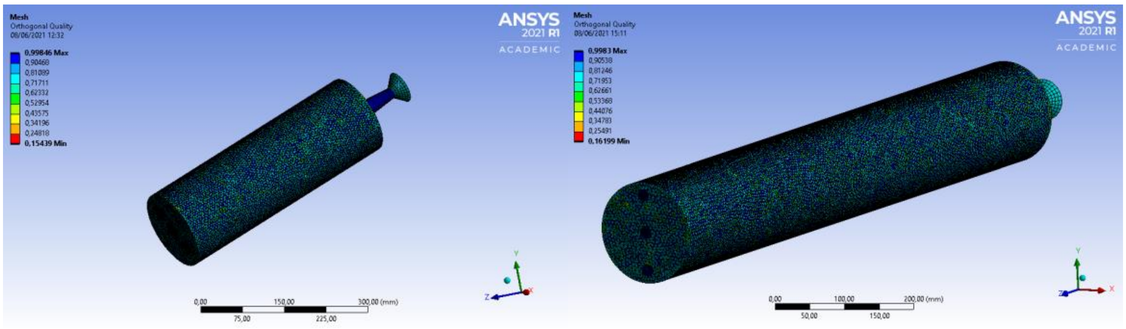
Skewness mesh metrics spectrum:

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:

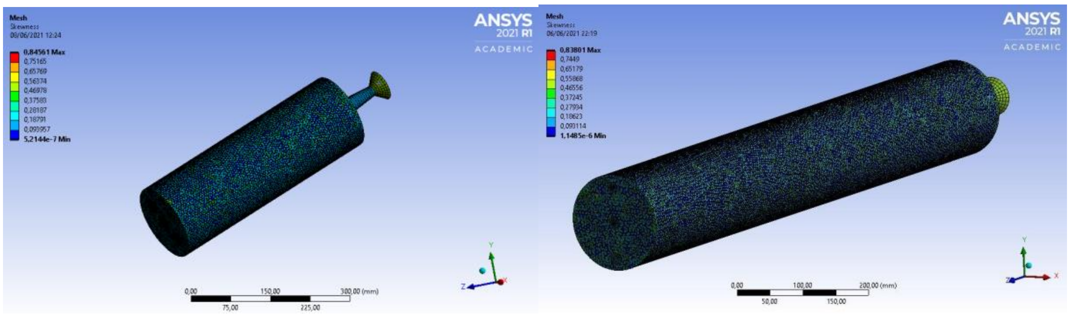
Unacceptable	Bad	Acceptable	Good	Very good	Excellent
0-0.001	0.001-0.14	0.15-0.20	0.20-0.69	0.70-0.95	0.95-1.00

Figure 5 -Mesh quality statistics (SMITH, 2017).



(a) (b)

Figure 6 - Orthogonal quality for de VAG 430mm (a) and 1000mm (b).



(a) (b)

Figure 7 - Skewness for de VAG 430mm (a) and 1000mm (b).

For the two geometries studied in this work, the asymmetry values skewness obtained were between 0 to 0.845 (Fig. 7(a)) are considered from acceptable to excellent and between 0 to 0.838 (Fig. 7(b)) are also considered from acceptable to excellent. The values for the orthogonal quality obtained were between 0.15 to 0.99 (Fig. 6(a)) and were considered very good and from 0.16 to 0.998 (Fig. 6(b)) were considered excellent as well.

The work is still in progress, so the next step to be carried out will be to refine more the mesh and run the program in the Institute's cluster, where it will be possible to do this, thus being able to carry out the a comparison with all the results obtained. In this way, a more detailed study will be possible to do and it will allow to observe whether the mesh would have a good refinement or not.

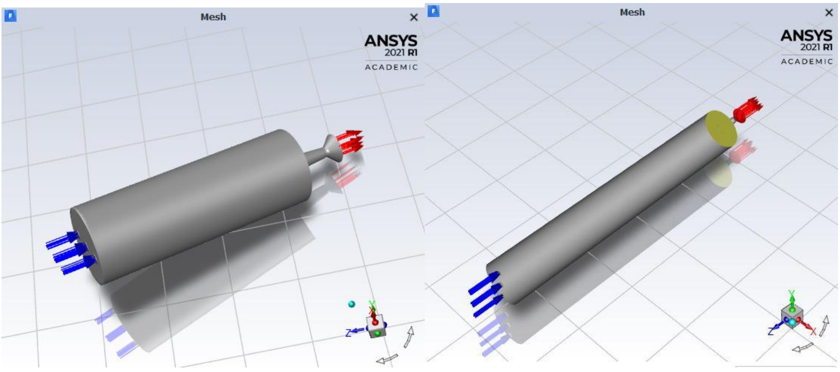
3.1.2 Setup of the program (using ANSYS- FLUENT)

The reactor model used for the study, using the software FLUENT, was the "Non-Pre-Mixed Combustion" reactor, due to the oxidant and the fuel do not enter together in the same mixture inlet, and the fluid was considered in equilibrium and adiabatic because there is no exchange of heat with the walls of the VAG. In Table 3 it is possible to see the boundary conditions used in the setup.

Due to previous work carried out for the SCTB, the mass flow used for air was 0.4 kg/s, for CH_4 it was 0.1 kg/s and for O_2 it was 0.15 kg/s. It is possible to see the representation of the flow inside the SCBT with the VAGs 430 mm and 1000 mm long in Figures 8 (a) and (b) respectively.

Table 3-Setup of the boundary conditions

SETUP	
Boundary Conditions	
Combustion model	EDC (Eddy dissipation concept)
Turbulence model	Finite- Rate/Eddy- dissipation
state	transitional
Entry limit condition	P= 101325Pa , T= 300K
Wall boundary condition	adiabatic

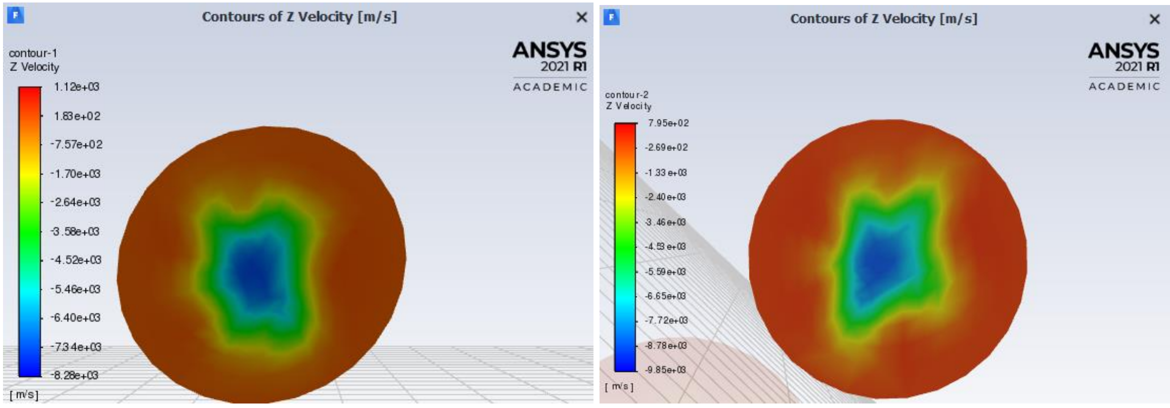


(a) (b)

Figure 8 - Representation of the flow inside the SCBT with the VAGs 430mm (a) and 1000mm (b) long.

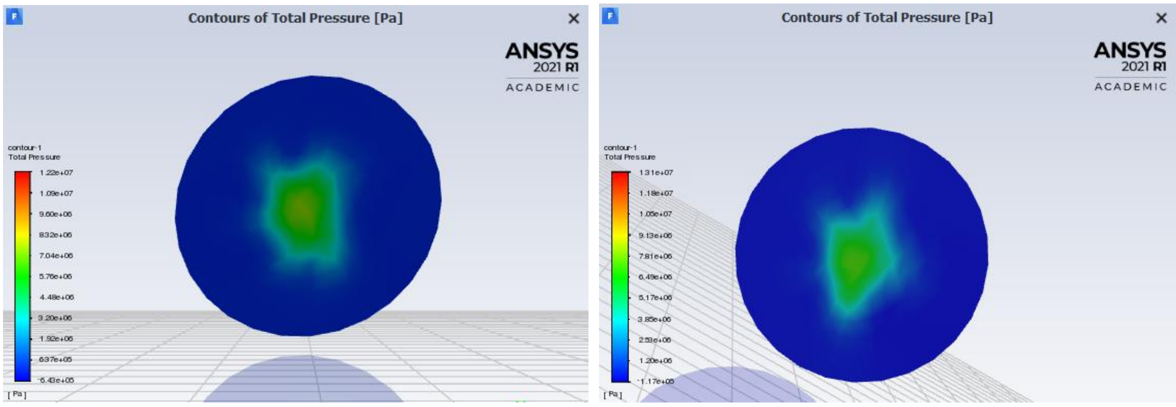
3.2 Final results

Figures 9 (a) and (b), 10 (a) and (b) and 11 (a) and (b) show the results obtained for the velocity (Vs), pressure (Ps) and molar fraction of O2 respectively at the exit of the SCTB.



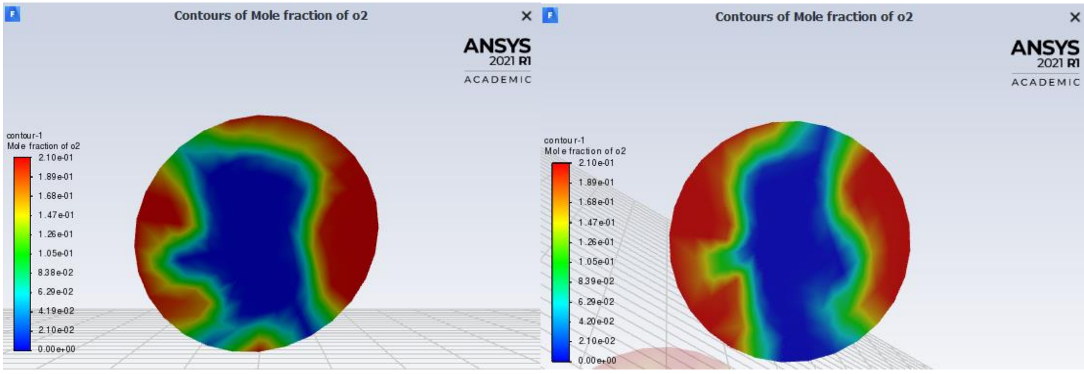
(a) (b)

Figure 9 - Velocity calculated values at the SCTB exit for the VAGs of 430mm (a) and 1000mm (b) long.



(a) (b)

Figure 10 - Pressure calculated values at the SCTB exit for the VAGs of 430mm (a) and 1000mm (b) long.



(a) (b)

Figure 11 - Molar fraction of O2 calculated values at the SCTB exit for the VAGs of 430mm (a) and 1000mm (b) long.

In (Fig. 12) is shown the representation of the total temperature distribution along the VAG with 1000 mm long to allow us to see the flow behavior during the combustion process inside it.

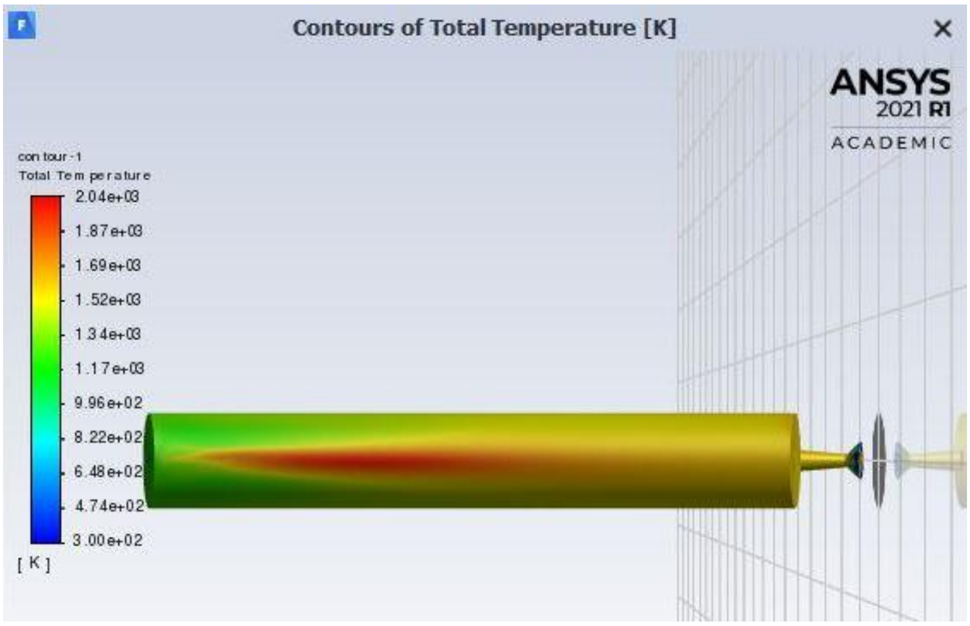


Figure 12 - Representation of the total temperature distribution along the SCTB (1000 mm).

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 for the VAGs with 430mm and 1000mm long. The values of pressure (Pe), total temperature (Te), Mach number (Me) and % of O2 at the outlet of the nozzle are shown in (Tab. 4.)

Table 4- Values obtained for SCTB exit.

PROPERTIES	VAG 1000mm	VAG 430mm
P_e (atm)	9.03	8.2
T_e (K)	1106	1012
M_e	2.1	1.86
molar fraction O2	0.1038 (10%)	0.1007 (10%)

4. DISCUSSIONS

Considering the values obtained in the present work, it was possible to see that all the input parameters at the inlet of the combustion chamber or VAG of the SCTB have a great influence on the flow test conditions at the nozzle exit or at the SCTB exit. The desired flow test conditions at the output of the SCTB for both lengths, of 430 mm and 1000 mm, for the development of experimental research on supersonic combustion at this moment, are: T_e= 1200 K, M_e = 2.5 with 21% content of O_2. For both cases studied in this paper it was not possible to reach the oxygen content of 21%, with the mass flow rate of the reactants used for the calculations. At the SCTB exit it was only reached 10% which means that it will be necessary to enrich the air flows at the SCTB inlet with O_2 until it the test flow can achieve the desired 21% content of O_2 at the SCTB exit. It was also possible to observe that the total temperature for the two estimated lengths was very close to 1200K and the Mach number was not satisfactory, being below the required value. It is expected to reach the appropriate Mach number value by adjusting the reactants flow rate values at the entrance of the bench.

The next steps to be taken in the study as mentioned in the methodology in section 3.1.1.2, is the mesh refinement test, using the Institute's cluster, which will be used to check if it has a better refinement for the case study or if the refinement showed in his work is enough. After all this is done, a more accurate result can be observed and the program can be validated. Showing that, the methodology developed now can be improved and validated, to be applied as a tool for future works.

Thus, the next step is to apply this methodology and all the tools developed in this work, to run many cases with different combination of reactants using: oxygen, air, methane and also nitrogen to better control the temperature desired values at the nozzle output.

This methodology will assist in the development of the current pilot SCTB (430mm), to help in the design of the new pilot unit (1000mm) and will also contribute to the study and assembly of the main unit. With this done it is possible to say that a complete methodology is ready to be used in order to manipulate the mass flow rate of the reagents at the entrance of the SCTB, in order to control the test flow at its exit. This will be a great contribution to the experimental research of the supersonic combustion.

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