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DEVELOPMENT OF A MEASUREMENT SYSTEM OF TEMPERATURE AND PRESSURE IN THE COMBUSTION CHAMBER OF A TORCH IGNITION SYSTEM

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Abstract. *The Chemical Propulsion Laboratory (CPL) at UnB/FGA is developing a prototype of a torch ignition system (project of FAPDF - 03/2015) in order to implement it into a hybrid rocket test motor for the SARA platform (AEB Program - Uniespaço - II). This system is of fundamental importance to a reliable operation of a rocket motor. After the preliminary analysis of the system, it was verified that an advanced analysis is required at the characterization of temperature and pressure sensors since they produce perturbations in the flux and combustion processes. This study has as main objective an analytical and numerical analysis of the sensors impact on the operating parameters of the system, such as the temperature and pressure distribution inside the combustion chamber of the igniter. After the study of the technical characteristics of the sensors used, this research evolved the numerical simulation based on the Navier-Stokes equations and combustion modeling applied to the problem in consideration, which makes possible the definition of the flow parameters of the igniter. The validation of analytical and numerical results is based on the experimental studies provided by the project team. As final result, this study presents the possibility of having an adequate method of modeling and measuring of the data with good confidence.*

Keywords: *torch ignition, thermocouple, hybrid rocket motor, fluent combustion*

1. INTRODUCTION

The research on the Torch Ignition System was started by the team of the Chemical Propulsion Laboratory of the University of Brasilia (UnB) in order to develop the reliable multi-use system for the hybrid rocket motor for the SARA (Brazilian reentry satellite, project Uniespaço-II) platform. Since the ignition of the hybrid rocket motor requires the relatively high power for the propellants melting and evaporation for the combustion initiation, the development of the compact and powerful system was the main goal of the current project. Various schematics and types of the igniter were analyzed, including the torch, pyrotechnic, electric, resonance systems, etc. (Judson Jr., 2015), (Tian H., 2006), (Welland H.M., 2010). The advantages and disadvantages of each system allowed to identify two perspective systems, from our point of view: pyrotechnic and gas torch. The limitations of the size, mass and electric power on-board were considered as the most important characteristics for the current development.

The pyrotechnic igniter developed at UnB was fabricated in cooperation with the Brazilian aerospace industry, which allowed to prove the reliability of the ignition around 99,7%. However, the relatively high cost, dependence on the fabrication technology and the single ignition per charge did not allow to satisfy all the requirements of the project and testing at the laboratory conditions.

The gas torch ignition system was considered as better choice from the point of view of multiple ignition possibility. The main disadvantage of such system is its complexity, and as a result higher probability of the failure, compared to the pyrotechnic ignition system. The complexity also influences on the total weight and size of the system. To solve these problems, it was decided to use the main oxidizer of the hybrid motor (oxygen or nitrous oxide) as the propellant for the ignition system. The choice of the fuel for the ignition system was based on the necessity of low energy of activation and self-pressurization properties. The gaseous methane (CH_4) was chosen as the main fuel for the igniter. The process of the methane-oxygen combustion was widely studied earlier by different authors: (I. Glassman, 2008), (J. Warnatz, 2006).

On order to achieve the long lifetime of the system it was decided to use vortex-type combustion chamber with the self-cooling effect by swirl injection of the oxidizer. The first prototype of the system shown on figure 1 had simple design with two oxidizer injectors and one fuel injector. Two pressure sensors and one temperature sensor were integrated to the design for the automatic control system implementation using the DAQ of National Instruments.

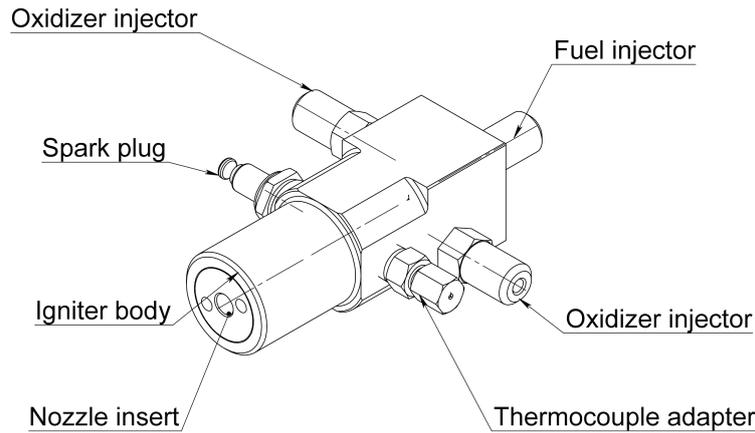


Figure 1. The first prototype of the torch igniter (Shynkarenko *et al.*, 2016)

First tests of the system showed the complexity of the solution: the three-injector system required additional housing, the assembling of the system with the motor was complicated. Also, was found a necessity of having the pressure measurement for the study of the flow inside the combustion chamber of the igniter. However, the first prototype allowed us to study the operation of the system analytically and numerically and prove the concept for the future development. As a result of this analysis, was built a new igniter with the simplified fast connections and simple assembling with the hybrid motor system, shown on figure 2. Also, were implemented the following modifications:

- The flow of the propellants is controlled by the digital servo valves, it allows to have a precise control of the propulsion process;
- The pressure and temperature measurements inside the combustion chamber are provided simultaneously using the universal sensor interface. The temperature of the flow can be measured in the arbitrary point along the radial direction of the combustion chamber, which opens wide possibilities for the system validation using the numerical simulation methods.

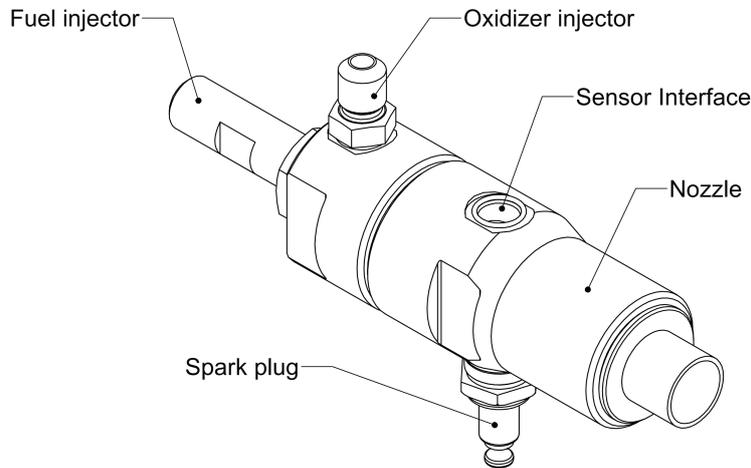


Figure 2. Current ignition system structure (Shynkarenko *et al.*, 2016)

The test model of the igniter was developed and calculated analytically and numerically. This system architecture has as main advantage the possibility of multiple ignitions and the reutilization of the motor oxidizer of the propulsion system. After the first phase of this research, the analysis of the operation of temperature and pressure sensors was required in order to validate the numerical calculations, since these sensors cause a perturbation in the flow and combustions processes inside the combustion chamber of the torch igniter.

2. EXPERIMENTAL PROCEDURE

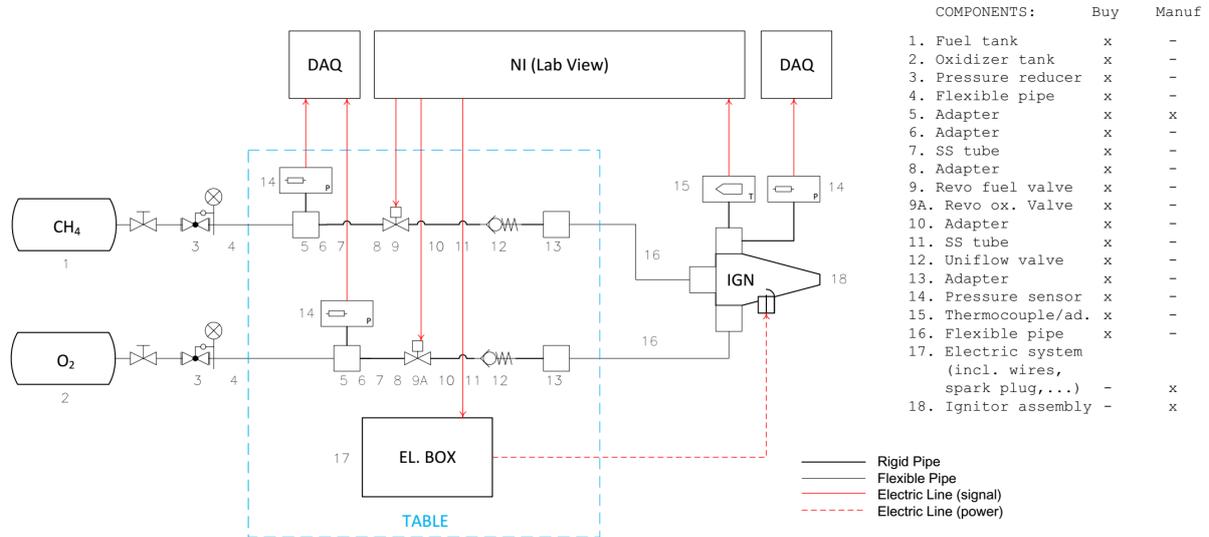


Figure 3. Design of the torch ignition system developed at CPL UnB/FGA (Shynkarenko *et al.*, 2016)

As seen from the figure 3, the torch ignition system is complex, since it needs a considerable amount of components for its operation. The components 1 and 2 showed on figure 3 are the methane and oxygen tanks, respectively. The other components are the pressure reducers of the tanks (components 3), the stainless steel hoses (components 4, 11 and 16) of the feed system, adapters (components 5, 6, 8, 10 and 13), rigid tubes (components 7), valves (components 9 and 12), pressure sensors (components 14), temperature sensor (component 15), electric box (component 17) and the igniter (component 18). The igniter components, already manufactured, are shown in figure 4.



Figure 4. Torch igniter components: from left to right - nozzle, combustion chamber, cover, fuel jet injector in assembly with oxidizer swirl injector

The sensor used for temperature measurements was a thermocouple, which is a sensor with field contact and made by the association of different materials that convert thermal energy in electrical energy by the *Seebeck* effect (Garnier *et al.*, 2011). The thermocouple used is a KMQLS-125U-6 model from OMEGA, type K, with 3.2mm diameter, 150mm length and grounded junction. It supports temperatures as high as 1335°C and has stable temperature deviation lower than 2.5°C in 25 weeks (Omega, 2017).

Some of the first tests of the igniter system had the main task of investigating the mean temperature measured by the thermocouple with the optimum case of the igniter operation (pressure of 3 bars in the feeding system) defined by the previous tests. So, by using statistic methods, the CPL team reach an average result for the measurement of temperature, as shown in table 1:

Table 1. Statistical test results

| | |
|------------|-----------|
| T_{mean} | 651,744°C |
| σ | 23,598°C |
| T_{min} | 457,8°C |
| T_{max} | 991,2°C |

The analysis of the system showed that all tests with the temperature outside of the region $T_{mean} \pm 3\sigma$ were received with the fuel injector malfunction due to the erosion process during combustion. After the previous tests, with the data of temperature only on the igniter center, the temperature measurement in other points was considered an important task in order to study the thermocouple response. After the adjusting position of the spark plug to have more reliable ignition, the flow in the combustion chamber was changed. Breaking of the boundary layer because of the spark plug presence results in increase of the temperature in the measured zone. Some tests varying the thermocouple radially were done by the CPL team, varying from the wall until the center of the combustion chamber, producing the results showed of figure 5. The tests were made fixing of the thermocouple at each position during 20 seconds of burning. It could guarantee the formation of the stationary flow and stabilization of the temperature inside the thermocouple. Basing on the previous statistical tests, the standard deviation of the experimental data is expected to be around 4% of the mean measured values, the thermocouple position error is ± 0.01 mm.

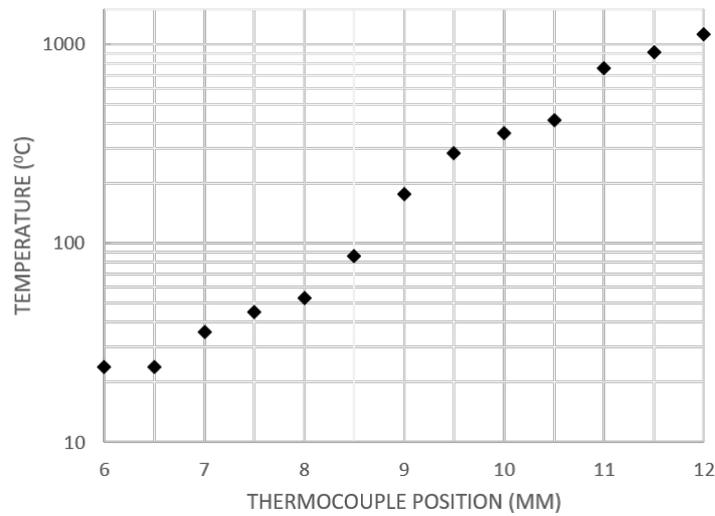


Figure 5. Collected data from the test in which the thermocouple was moved

As we observe from the figure 5, some small rise of the temperature happens at 7-8 mm thermocouple position, which corresponds to the heat diffusion process in the gas. At 8-9 mm the thermocouple starts to enter into the transition zone between the flow of the fuel and oxidizer. At 9-10.5 mm thermocouple enters to the intensive combustion zone where the rapid rise of the temperature occurs. After 10.5 mm the thermal probe destroys the central jet of the fuel flow, intensifying the turbulence and the combustion inside the igniter. The maximum temperature of 1115°C was observed in the central position of the thermocouple, when its influence to the flow structure is maximum.

3. FLUID PERTURBATIONS CAUSED BY THERMOCOUPLE PRESENCE

The thermocouple presence inside the combustion chamber of the torch igniter causes perturbations on the fluid because of the space filled by the sensor and the conduction heat losses by the thermocouple walls. These phenomena were investigated by Rabin (1998) and Khine et al. (2013).

According to Rabin (1998), the temperature $T_w(0)$ measured by a thermocouple insert in a fluid is affected by the presence of the own thermocouple, since it conduces heat from or to the measured point, cooling or heating the fluid. He investigated this thermal effect of conduction between the sensor and the fluid, and presented a correction based on the assumption that the fluid has a uniform temperature T_s .

Later, Khine et al. (2013), investigated the same phenomenon and presented a correction to the measured temperature but, this time, considering that the fluid could present a non-uniform temperature. This models are showed on figure 6, where T_m is the fluid temperature at the measured point.

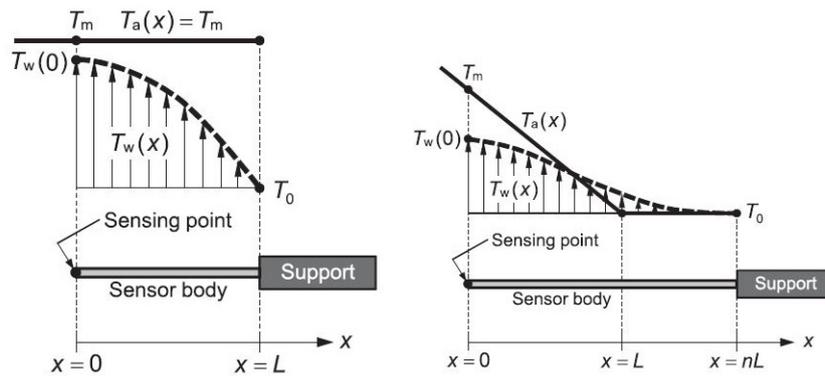


Figure 6. Comparison of the conventional model of heat conduction by the thermocouple, and the model which considers a non-uniform temperature of the fluid, respectively, (Khine *et al.*, 2013).

In order to apply the models presented on figure 6, some properties of the thermocouple and the investigated flow must be known, such as the coefficient of heat transfer by convection, density, thermal conductivity and specific heat of the thermocouple material. Because of the difficulty to correct measure these properties, it was decided to observe the fluid perturbations caused by thermocouple presence numerically, as presented on the next section.

4. NUMERICAL MODELING

For the numerical study of the fluid behavior inside the torch igniter with the presence of a thermocouple, as well as the numerical acquisition of the temperatures on some measured points for comparison with experimental data, six simulations were done by using the software *Ansys Fluent*®. There were simulated five positions of the thermocouple varying it from 0mm (at the wall) to 12mm (at the igniter center axis) with intervals of 3mm and with the thermocouple at 10.5mm since it is expected to have the flame at this region.

First, the mesh with the sensor tip at the igniter center was constructed by using two tools from *Ansys*®: the *Design modeler* and *SpaceClaim*. They allowed the extraction of the fluid control volume from the igniter CAD, as well as the treatment of this control volume in order to facilitate the mesh generation. The final mesh for this configuration is shown in figure 7 and have 1422356 elements. The mesh was refined near the central-axis because of the flame formation that would be generated on this region, and near the walls because of turbulence-model and to better calculate the properties inside the boundary layer.

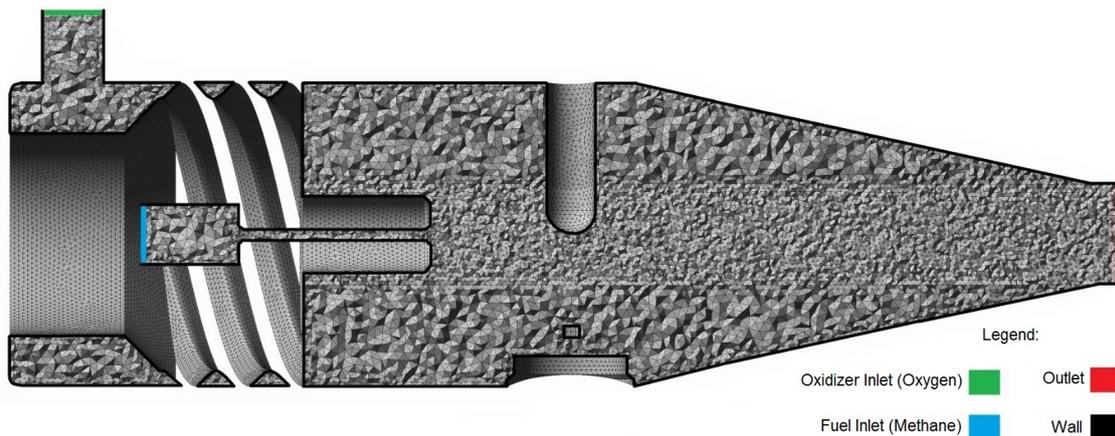


Figure 7. Mesh elements and boundary conditions on the central plane of the igniter.

4.1 Boundary Conditions

The boundary conditions applied to the 3D domain are shown on figure 7, where the fuel and oxidizer inlet were defined as mass flow inlets, with a mass flow rate of 0.351g/s for methane and 2.03g/s for oxygen from the experimental data at 300K, and the chemical species mass fraction were determined accordingly. This boundary condition allows the static pressure to vary in order to adequate the solution and, consequently, it is a preferable boundary when the mass flow rate is a parameter more important to match than the total pressure (Fluent, 2009, section 7.3.5). Moreover, the control

volume outlet was defined as a pressure outlet, with a zero gauge pressure, and all the walls were defined with a non-slip adiabatic condition.

The operation conditions was set at 2.5 bars as the expected mean pressure of the flow. Therefore, it is important to notice that "*all pressures computed or reported by Ansys Fluent are gauge pressure*" (Fluent, 2009, section 8.14.2) and, in order to have the absolute pressure the following equation must be applied:

$$P_{abs} = P_{op} + P_{gauge} \quad (1)$$

where the absolute pressure is the sum of the operating and gauge pressures.

4.2 Turbulence and Viscosity Model

The $k-\varepsilon$ model was chosen for the turbulence and viscosity calculations since it has a relatively easy implementation and more stable solutions, which converge fast. However, it is worth highlighting that this model can be applied only to fully turbulent flows (Karthik, 2011).

According to Salim and Cheah (2009), $k-\varepsilon$ method is coupled with wall functions for the near-wall treatment instead near-wall modeling because this model is valid only for turbulent flows and, therefore, the flow far from the walls. For this reason, it is desired values of y^+ between 30 to 60 at the walls, which characterizes a fully turbulent or log-law region.

Based on these observations, the y^+ values at the present simulations were specially observed on the thermocouple's tip, expecting values around 35 to have an acceptable solution, since the mean temperature at this region would be compared with the experimental data. However, the observed y^+ values on the domain were very low around the thermocouple and on most of the walls, for this reason, it was applied the scalable wall functions to the $k-\varepsilon$ model in order to force the usage of the log law. This scalable method introduces a limiter in the y^+ calculations and if somewhere y^+ is lower than this limit, the limit value is assumed. It's worth pointing out that the y_{limit}^+ on Fluent is 11.225, from which the log-law is employed (Fluent, 2009, section 4.12.2).

4.3 Cold Flow and Non-Premixed Combustion Simulations

Initially, a cold flow simulation was done in order to capture the mixture formation process and fluid development without any reaction, therefore, the only species present were methane and oxygen. The species transport model was applied with the volumetric reactions disabled. This first approach induces better the convergence of the reaction simulation and makes possible to have an initial visualization of the likely flame region and ignition probability.

Then, the non-premixed combustion model was applied to the control volume in which the kinetic scheme of oxy-fuel combustion and the thermo-chemical data were retrieved from GRI-Mech 3.0 library (Smith *et al.*, n.d.). The total number of species simulated was 20, and the flamelet approach was used in order to have faster results.

The flamelet approach considers the chemical reactions as infinitely fast and happening on an infinitely thin laminar interface at the surface of stoichiometric mixture, where its inner layer is the flamelet, and can be described by one dimensional model flame (SAS, 2015). As Claramunt *et al.* (2005) says, despite reducing computational costs, this approach fails to model extinction, re-ignition, lift-off, blow-out and others non-equilibrium effects, and it can over-predict the mass fraction of some intermediate species involved in slow reactions. As result, this concept can lead to higher temperatures than expected.

4.4 Numerical Results and Discussion

After the cold flow simulations converged with approximately 500 iterations and the combustion simulations with approximately 1800 iterations and residuals between $10e-7$ and $10e-4$, the results could be analyzed and compared with the experimental ones. An important observation is that, for a combustion simulation to be considered converged, as important as the residuals is the monitoring of a probe parameter such as temperature. On this case, the probe was put at a point where the igniter central axis crosses the thermocouple central axis, in order to compute the temperature variation along the iterations. This convergence study can be seen on figure 8, where the first peak of all curves appear at the cold flow and just after it, the simulations converged with the expected temperature of approximately 300K since the reactions were not yet started. The second peak shows the transition from the cold flow to the combustion simulations, followed by an increase in temperature due to the flame propagation and converging at, approximately, 850K.

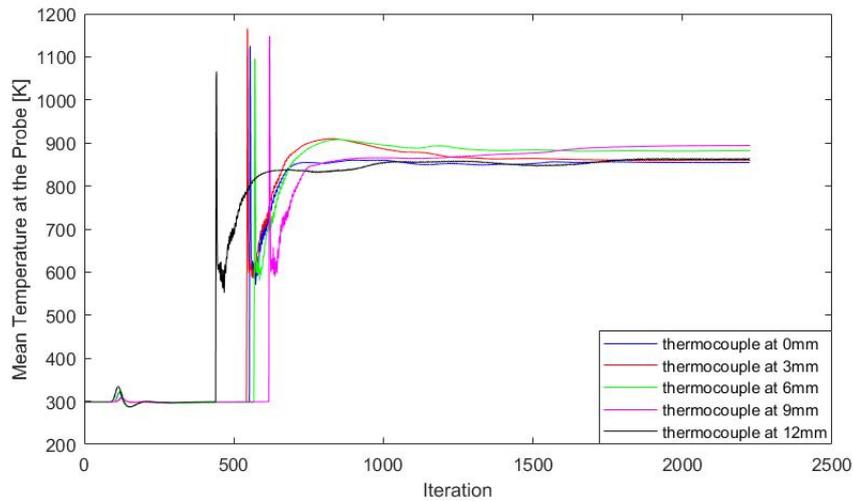


Figure 8. Convergence study.

The contour of temperature and velocity at the central plane of the igniter can be seen on figure 9 below for three configurations of the non-premixed combustion simulations. On these contours it is clearly observed the influence of the thermocouple on the fluid structure and heat transfer. On the velocity contours it is possible to notice the methane jet being deflected by the thermocouple and, because of the lower velocities downstream, it is observable an increase on the flammable region causing higher temperatures.

When the sensor is fully immersed on the flow, as seen on the third temperature contour at figure 9, a higher temperature field is generated near the fuel injector showing some heat transfer backwards to the flow. Moreover, the sensor is embraced by hot gases. In order to better understand what happens near the thermocouple, an iso-surface plot for temperature was generated as shown on figure 10.

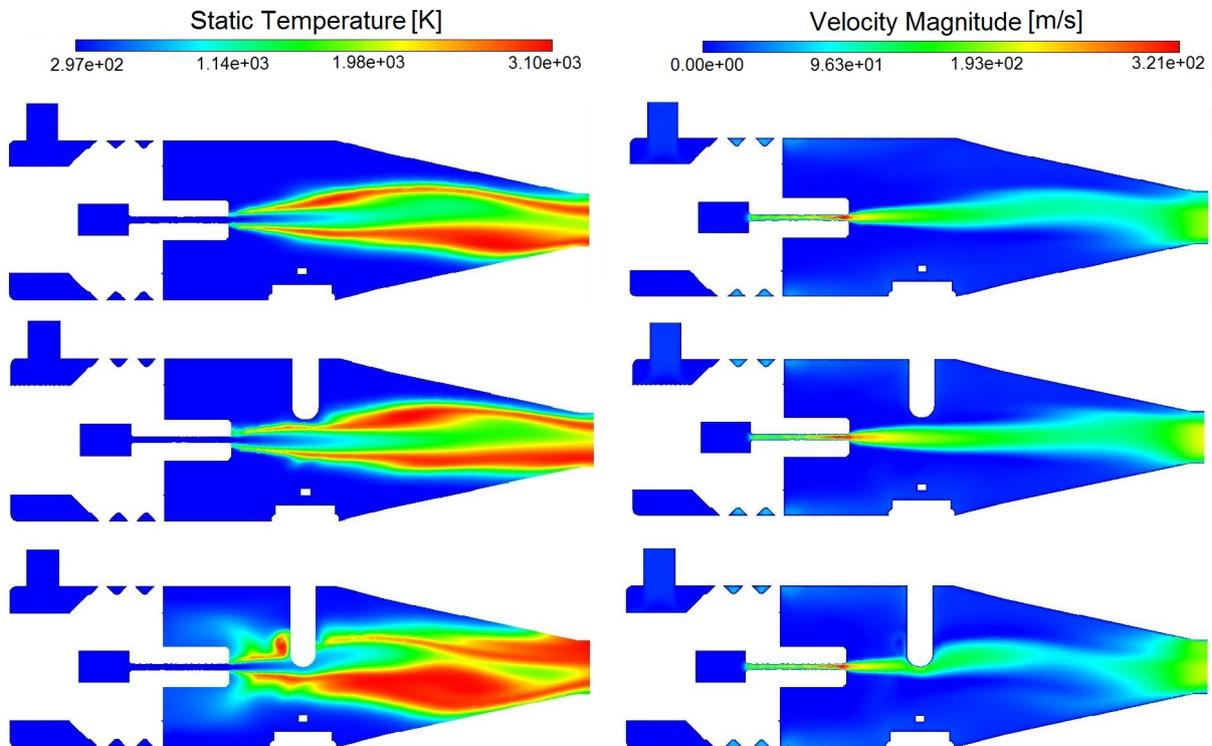


Figure 9. Temperature and velocity contours at the igniter's central plane

When the thermocouple is completely immersed in the fluid (at 12mm), it is noticed, as shown on figure 10, that the thermocouple does not experience the high temperatures generated on the combustion, since a colder layer is formed around the sensor protecting it from temperatures higher than 1335°C which would damage the sensor. Therefore, these numerical results show that the thermocouple does not suffer erosion despite the high combustion temperatures inside the torch igniter chamber. However, the temperature field of the flow is very disturbed by the sensor presence and the measured temperatures do not correspond directly to the real flow temperatures, as explained before according to the study of Rabin (1998) and Khine et al. (2013).

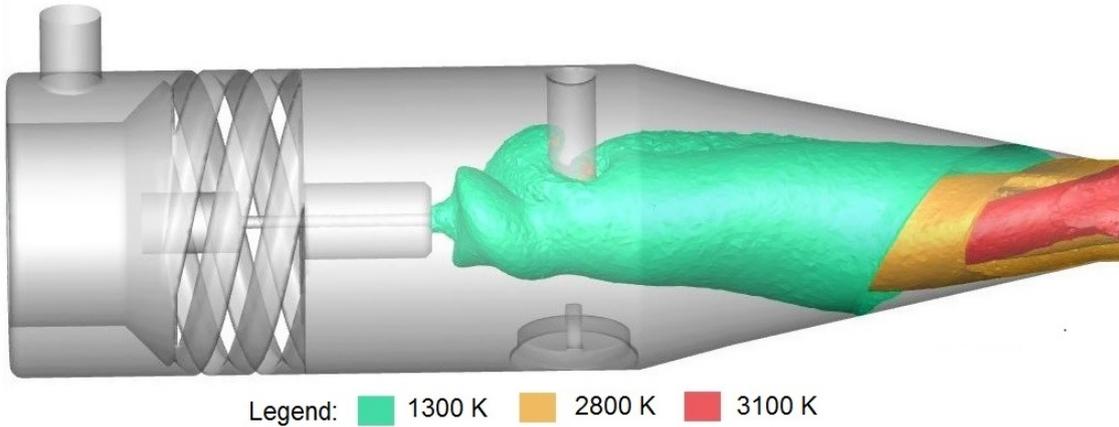


Figure 10. Isosurface plot for three temperatures.

Since the highest temperatures are expected to be at the stoichiometric regions where the mean mixture fraction is 0.2 for methane/oxygen combustion, this is an important region to be studied. As shown on figure 11, the stoichiometric region is close to the center of the igniter and, therefore, the walls are protected from the high temperatures caused by the combustion. This results are the consequence of the high and swirling mass flow rate of oxygen that ensures low temperature at the walls. However, with the presence of the thermocouple, mixing is intensified due to turbulence around the sensor and near the fuel injector resulting on the process shown on figure 9 where heat travels backwards to the flow direction.

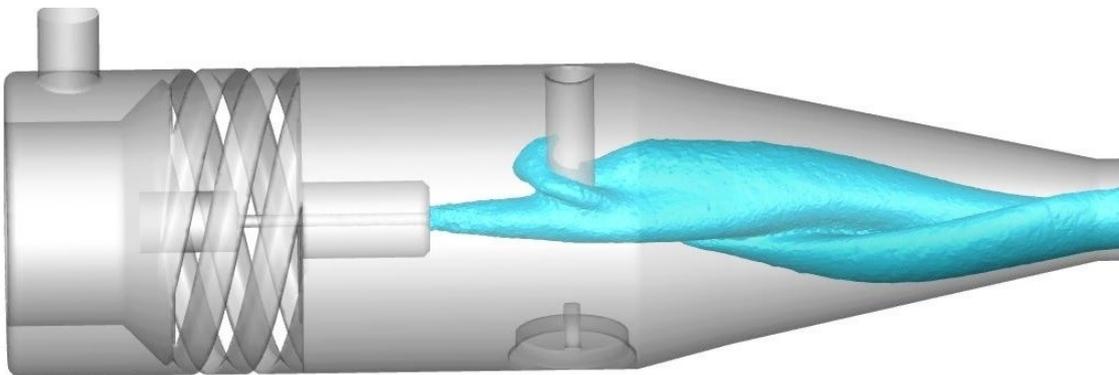


Figure 11. Isosurface plot for mean mixture fraction of 0.2.

Another important parameter to observe is the pressure distribution along the control volume of the torch igniter. The pressure contour, as can be seen on figure 12, is quite similar for all of the simulations since the chamber pressure is not considerably affected by the thermocouple's presence. As explained before, since the boundary conditions for the flow inlet were the corresponding mass flow rates, the pressure is a consequence that depends also on the temperatures settled. As result, the pressure inlet of the fuel and oxidizer jets are nearly 4.65 bars and 2.86 bars, respectively. Comparing with the experimental data of 3 bars at each inlet, the numerical results are quite matching the oxidizer inlet but is over-predicting the pressure at the fuel inlet.

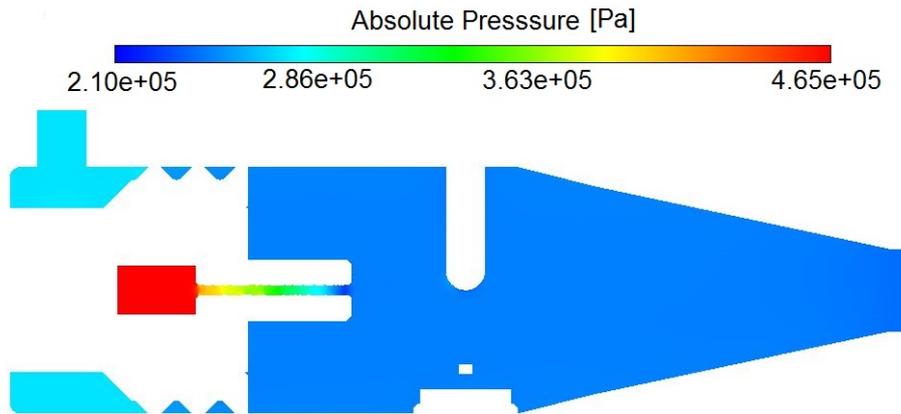


Figure 12. Pressure contours at the igniter's central plane

In order to compare numerical and experimental data, there were collected two types of the numerical results. The first one were the area averaged temperature at the thermocouple's tip for all the six simulations, and the second was the area averaged temperature at the thermocouple's surface accounting for a length of 2 times the sensor diameter. As seen on the figure 13, the experimental data is clearly different from the first numerical data acquired, but it is more similar to the second one. This indicates that the thermocouple readings are based not only on its tip temperature, but also on the mean temperature of a great part of the sensor surface. Therefore, the curves experimental and numerical 2 does not really match the real temperature profile inside the torch igniter. On the other hand, the curve numerical 1 describes better the temperature profile, where the peak is not at the central axis, but must be at the region where the oxygen and fuel meet and have near stoichiometric ratios as expected looking to the temperature contours showed on figure 9.

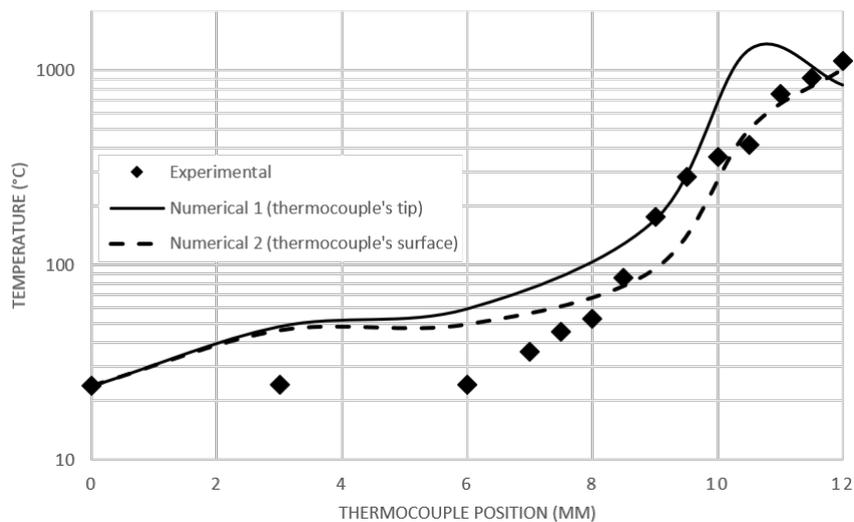


Figure 13. Comparison of experimental and numerical results.

A remarkable difference between the numerical and experimental results was the temperature profile far from the flame, where the numerical results pointed higher temperatures. This can be a consequence of the combustion model used since, as explained before, it can over-predicted some species formed in slow reactions.

The simulations must be improved in order to better match the experimental temperature and pressure values, because only these matches together can fully validate the numerical study and enable further studies. Since the simulation gives more data for analysis than analytical or experimental methods, with its validation it will be possible to observe better the process and its more significant parameters, in addition to the optimization of the torch ignition system based on the variation of these parameters.

5. CONCLUSIONS

In view of the presented results, a more in-depth investigation of the torch ignition system have been made possible. This initial experimental, analytical and numerical analysis already allowed the emergence of some conclusions such as the importance of the measured temperature correction according to each experimental test, and the impact of limits imposed by numerical and analytical analysis on the solutions.

For future works, more statistical experimental data is needed to confirm the repeatability of the thermocouple insertion and the accuracy of the data. Moreover, the numerical simulations must be improved in order to better match the experimental and analytical results, such as using methods that accounts for slow reactions, non-equilibrium effects and flame turbulence, despite the computational cost. These future researches will be supported by experimental pressure measurements, which could improve the quality of experimental data and consequently, analytical and simulation results.

6. ACKNOWLEDGEMENTS

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