THE ANALYSIS OF THE COMBUSTION OF PREMIXED METHANE-HYDROGEN MIXTURES STABILISED BY AN INOVATIVE SWIRL INJECTOR

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Abstract

The work presented in this paper is starting from the search of new, greener and more efficient fuels, a need which is more and more present in the scientific research, especially in the field of combustion. One idea revived in the past few years regarding the possibility of using hydrogen, since new ways for producing and transporting it developed lately. Different studies are trying to confirm the possibility of hydrogen transport using the existing natural gas distribution network, by mixing the two gases. Because the properties of the new mixture influence the combustion parameters, using the existing equipment would face new problems.

In this context, this paper presents a new developed type of injector for the combustion of partial premixed hydrogen-methane fuel in various proportions. Based on the characteristics and dimensions of an existing gas turbine combustion chamber of Garret GTP30-67, numerical simulations were carried out using the RANS approach, with the help of ANSYS CFX commercial software. After the analysis of the simulation results, it was concluded that a new solution is needed. Starting from the classical type, a new idea came into light, a constant radial exit-section swirled injector, which was produced from titanium alloy, using 3D printing technology.

After the CFD simulations, the new type of swirled injector was tested on a low pressure rig designed to have similar dimensions to the initial combustion chamber of the initial gas turbine. The fuel used was a mixture of volume parts of hydrogen 0%, 10%, 20%, 40%, 60% with the rest as methane. The experiments showed promising results regarding the flame stability, compared to the existing literature for swirl type combustors and a close correlation with the CFD results. Moreover, the results confirmed the possibility of developing and improving the new type of swirled injector for other combustion applications.

1. Introduction

The presented paper is focusing on the analysis of the swirled stabilized flames fuelled with different methane/hydrogen mixtures, in an existing modified combustion chamber.

The study is motivated by the present trends in the energy production industry, demanding the use of higher efficiency, less polluting fuels, and, in the same time, a reduction in the dependency on fossil fuels [1], and particularly on foreign resources (from outside the EU) [1].

One way to cope with these issues is to increase the degree of using non-conventional, renewable, environmentally friendly energy sources, such as wind, solar, or geothermal. One of the most significant problems related to these alternative energy sources is the fact that they produce roughly the same amount of energy irrespective of the actual demand on the power grid, raising the need to store the produced energy during the low energy demand hours, in order to allow the power plant operation at full capacity, and, therefore, its economic viability.

A solution to the storage problem, currently considered by some of the most important energy producers [2], is the use of the excess energy to produce Hydrogen from water, and to mix it with natural gas, using the existing natural gas transport and supply infrastructure. Thus, a consortium of energy providers and users, including Vattenfall, Enertrag, Deutsche Bahn, Total and Siemens recently opened a 6 MW pilot plant in Prenzlau, Germany [2], based on this approach. Also, the multinational energy provider E.ON recently completed the construction of a pilot plant in Falkenhagen, Germany [2], based on the combustion of Hydrogen enriched natural gas in conventional gas turbine power plants. Within the same trend, Siemens Industrial Turbomachinery recently certified the SGT-700 and SGT-800 series natural-gas fuelled turbine power plants for operation with 10% Hydrogen mixture [3].

However, the addition of Hydrogen into the fuel mixture affects significantly the turbulent combustion characteristics of the natural gas based fuel [4]. For instance, it has been shown [5] that the addition of Hydrogen in the natural gas fuel in a swirl-stabilized gas turbine combustor affects the flame shape and luminescence, as well as the turbulent burning velocity, and the flame thermo-acoustics. All these effects can be reasonably expected to impact on the flame stability and pollutant emissions, which will influence the performance and the reliability of the Hydrogen enriched natural gas fuelled gas turbine driving the power plant.

Therefore, a need to study the impact of Hydrogen enrichment upon the turbulent flame characteristic arose, and the work presented here is part of this research effort. In this field, several theoretical and experimental studies were earlier carried out worldwide [6-14].

A first step of the authors in this direction was the study and numerical simulation of the combustion mixtures of hydrogen and natural gas in an existing combustion chamber, known experimental data, in order to be able to validate the results [15].

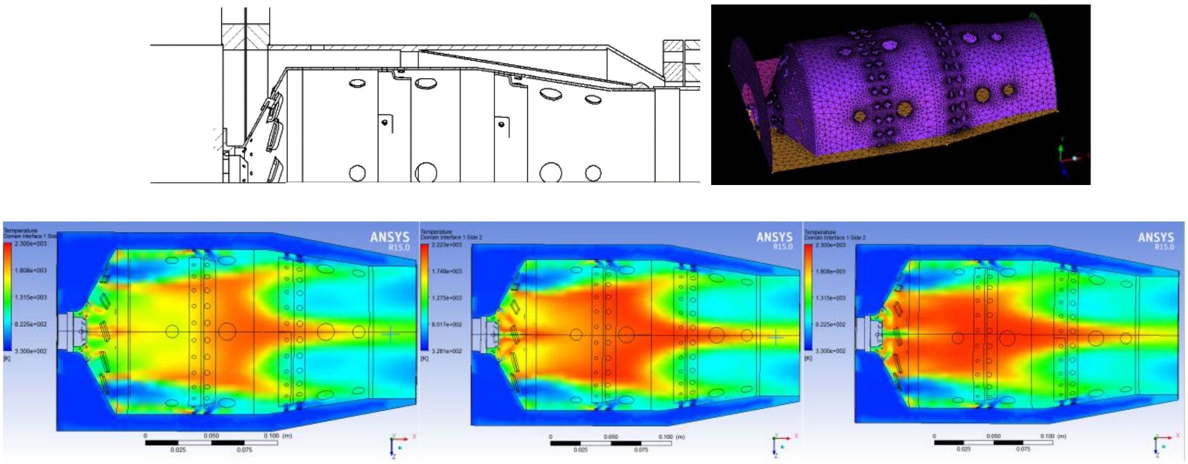
A second step is described in this paper and it is referring to the developing of a new type of swirl injector that will fulfill the purpose.

2. Initial CFD numerical simulations for nominal high pressure regimens

Starting from the initial intent of modifying a known combustion chamber in order to be able to work with a mixture of hydrogen and methane, the initial numerical simulations had the boundary conditions set to the parameters of the nominal regimen:

- Air: annular inlet surface A = 7175 mm2, T_{air} (T2) = 430 K, flow rate m_{air} = 0.2 Kg/s.
- Fuel mixture: different proportions of hydrogen-methane (0-60%, volume parts of H2), T_{gas}(T3) = 330 K, P_{exit} (P3)= 3.05 barg

The numerical simulations were carried with the help of commercial software ANSYS CFX, using steady-state Reynolds Averaged Navier – Stokes numerical analysis. The turbulence model used for the simulations was the k - epsilon model, while the combustion model was the Flamelet Probability Density Function (FPDF) model, using CFX-RIF flamelet generation tool library that provides kinetic reaction schemes for CH4-H2 (mixture- mixtures of methane and hydrogen, using LCSR mechanism without NO), choosing components for fuel (CH4, H2) and Oxidizer (N+O) [16]. The results are presented in Fig. 1.



0% H2 10% H2 20% H2

Figure 1. CFD results for the original combustion chamber

As it can be observed in the figure above, the increased percent of hydrogen in the mixture leads to the modification of the flame front. The shape of the flame and the maximum temperature areas are getting too close to the front walls and that could result in a damage of the combustion chamber. Also, getting close to the injector is increasing the possibility of flashback phenomenon. For this reason, in an initial embodiment, starting from a classical design (Fig. 1), a new idea came into light, a constant radial exit-section swirled injector (Fig. 2)

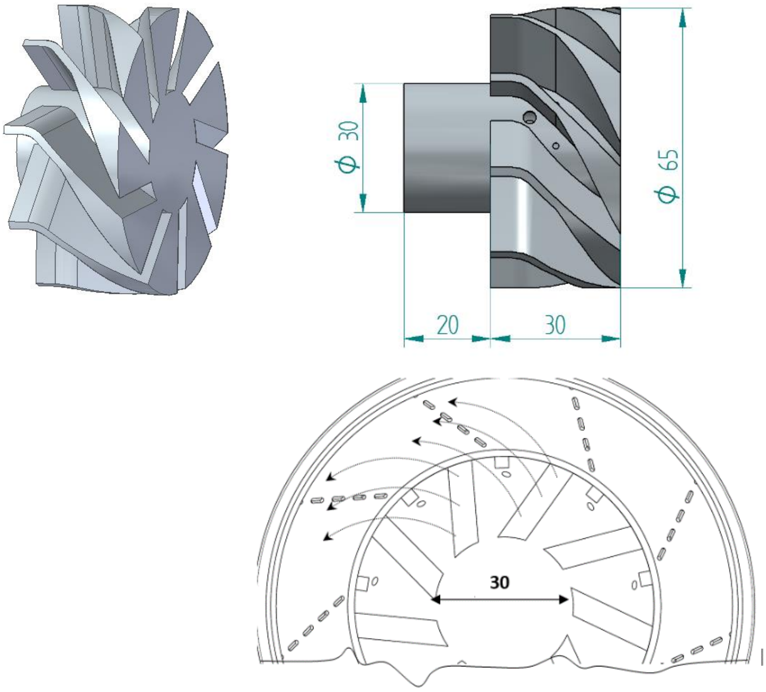


Figure 2. Swirled injector – new type, constant radial exist section

The flow channel is basically a convergent nozzle and the speed at the exit section is higher than the burning speed. In this way, uneven velocities are avoided, between the base section and tip section at the exit of the channel. Also higher flow speeds are obtained, fact that reduces the risks of flash-back phenomenon. In the same time, it was observed that the flame is composed by little separated flamelets and the swirling is made through flamelets that compose a turbulent confined co-flowing diffusion flame, with enhance combustion characteristics [26].

Inside the chosen combustion chamber, using the new model, with the characteristics specified above, after the numerical simulations, low pressure experiments were made, in an initial try to define the working and combustion characteristics of the new type of combustor. The idea was to validate the correct working, independently of other factors like dilution air, cooling, etc. These observations, proved partially by the experiments presented below, has led ultimately to the design of a whole new combustion chamber, which is still under developing.

3. Experimental setup

Given the above observations, it was considered necessary in this stage to perform simulations and experiments at low pressure, also from costs reasons. The combustion takes place in the same dimensional space, using just the fire tube in Figure 1. No air dilution, the entire flow of air and fuel being introduced through the swirled injector. The aim was to determine the stability characteristics and efficiency and to compare the results with the existing data in the literature.

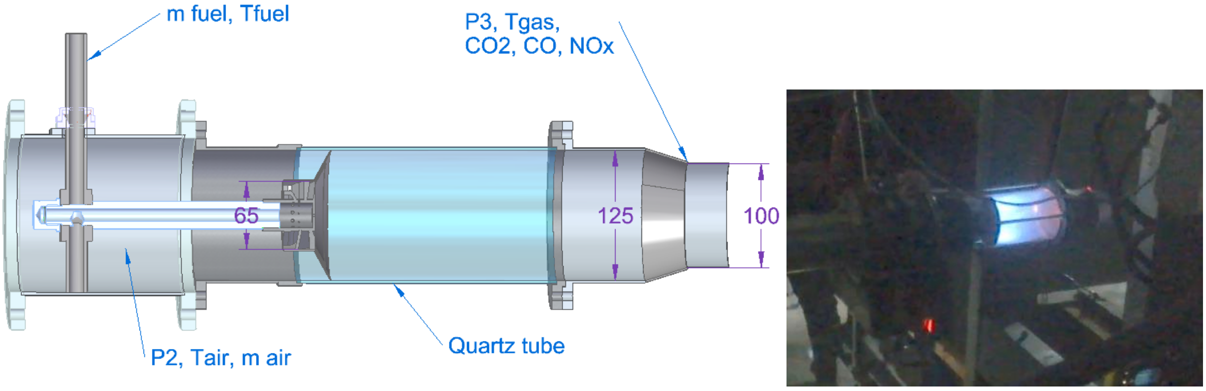


Figure 3. Experimental rig

The inlet for air was delivered by a centrifugal blower. The gaseous H2-CH4 mixture fuel was provided by 200 bar cylinders of 0%, 10%, 20%, 40%, 60% H2 in volume percentages.

Airflow was measured with diaphragm flowmeter and for the fuel, a Bronkhorst In-Flow mass flow meter/controller was used. The burned gases analysis was made using a MRU analyser.

For calculations and checking the following equation was developed and used:

$$\alpha = \frac{1-y+CO2-0,5*y*CO2}{4,76*CO2*(2-1,5y)} \qquad (1)$$

Where: α – air excess;
y – volume parts of H2 in the fuel mixture, (20%H2-Y=0.2);
CO_2 – volumetric concentration of CO2 in the dry exhaust gases

For calculating of the low heating value of the mixture, the equation below was used:

$$Hi = 50.000 * \frac{[(1-y)*16+2,4*y*2]}{[(1-y)*16+y*2]} \text{ [Kj/Kg]} \qquad (2)$$

Where: *Hi*- low heating value;
Hi Ch4 = 50000Kj/kg;
Hi H2 = 120000Kj/kg.

The swirled injector used for numerical simulations and for the experiments was the one shown in Fig. 2, with 9 blades and 45^o for the angle of the air flows at the exit of the channels between the blades. The calculated swirl number for the swirl injector is S_N=0.76.

4. Low pressure non reacting regimens (CFD + measured)

Non reacting regimens: P atm = 1026 mBar, t aer =10^oC, airflow = 0.08 - 0.02 kg/s.

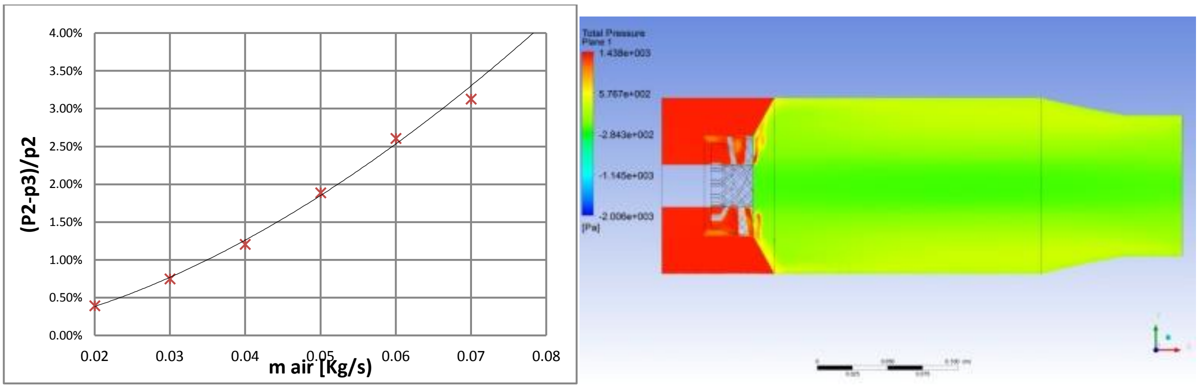


Figure 4. Total pressure loss

At input air 0.04 kg/s, the total measured pressure loss was 1.21 %, compared to the 1.23%, resulted from CFD (Fig. 4).

For calculating aerodinamical characteristics and similitude, pressure loss factor is calculatet with the equation [17]:

$$PLF = \frac{p2-p3}{ma^2/(2*p2*Am^2)} = K1 + K2 * [(T3 - T2) - 1] \tag{3}$$

Where: PLF – pressure loss factor
P2/P3 – inlet/outlet total pressure [Pa]
R – gas constant value for air (0.287 kJ/kg K)
Am – characteristic section [m2]
T2 /T3 – inlet/outlet total temperature [K];
K1, K2 – constants

Using the measured data and calculating PLF, the pressure loss at nominal regimen can be calculated by: [17]

$$\frac{p2-p3}{p2} = PLF * \frac{R}{2} \left(\frac{ma\sqrt{T2}}{Am*P2}\right)^2 \tag{4}$$

Where: R – gas constant value for air (0.287 kJ/kg K)

For calculating the pressure loss, it can be considered that the loss given by the temperature increase is around 0.5% to 1.0% from P3. [18]

With the measured data and calculations above, for an air flow rate at low pressure of 0.04 kg/s at 330K, with measured pressure loss of 1.21%, for a corresponding nominal regimen of 0.2 kg/s at 430 K, and 3.05 barg, it results a pressure loss of 5.34%.

This is the air flow rate chosen (0.04 Kg/s) for numerical simulation, as aerodynamically optimal. For experimental measurements at low pressure, some more flow rates will be measured around this value (0.02-0.08 kg/s), for the determination of the combustion parameters progress.

5. CFD numerical simulations

Using the same CFD model, numerical simulations were fulfilled for m_{air} = 0.04 Kg/s, swinging the air regimens with fuel mixtures of volume parts of hydrogen 0%, 10%, 20%, 40%, 60% with the rest as methane.

Having in mind the need of keeping the same performances of the combustion chamber, the imposed constrain was to keep the same theoretical thermal power as a constant. For example, in the figure below the presented results are for the case of excess air α=3.5, the same thermal power 33.3 KW (resulted initially at H2 0%), with the variation of H2 volumetric percentage.

m_{air} 0.04 kg/s; 0% H2 m_{air} 0.04 kg/s 20%H2

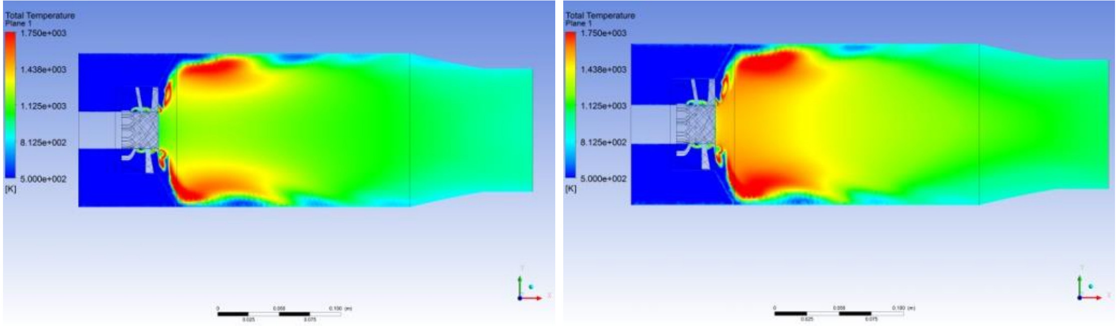


Figure 5. Temperature field for m_{air} 0.04 kg/s - 0%H2 and 20%H2. Excess air 3,5

It can be observed that the flame shape changed, for 20 Vol% H2 the flame is more compact. For 0% there is a discontinuity area next to the injector. As it will be shown in the experimental results, this regimen is close to stability limit for 0% and stable at 20%.

m_{air} 0.04 kg/s; 0% H2 m_{air} 0.04 kg/s 20%H2

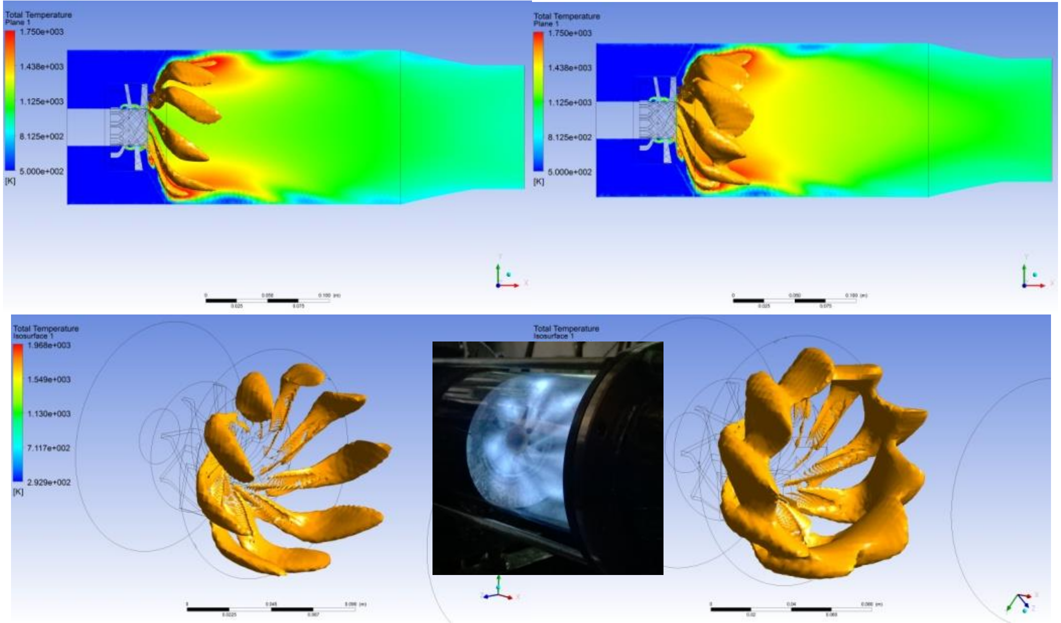


Figure 6. Isometric views for m_{air} 0.04 kg/s - 0%H2 and 20%H2. Excess air 3,5

The same differences can be observed also in Fig. 6, where an isometric view of the simulated flame can be related to the shape of the flame captured during the experiments.

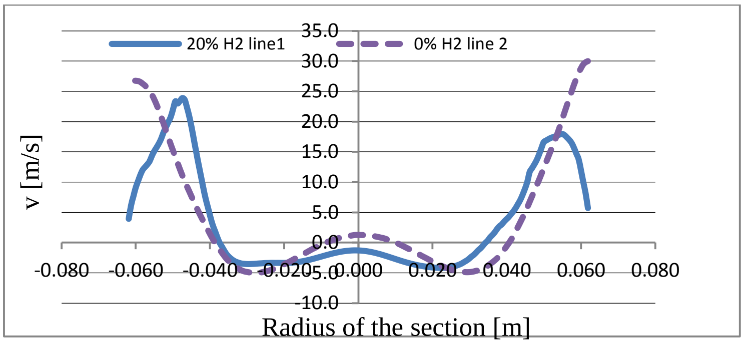


Figure 7. Axial velocity variation

In Fig 7, the variation of axial velocity in the transversal section can be observed. If we neglect the density variation, the fact that the mean value for negative values is -2.16 m/s for 0% and -2.76 for 20% is suggesting an increasing in the recirculating flow by 21.7% for the case of 20% H2.

The velocity field is different from the classical swirl cases reported in the literature [20]. In [25] the authors refer to "the higher combustibility of hydrogen makes […] expands the reaction zone to consequently reduce the recirculation flow". Although the experimental conditions in [25], as well as the swirl injector are not identical, the conclusion drawn from the numerical simulations is to be validated in a subsequent step, using laser PIV measurement techniques.

6. Experimental results

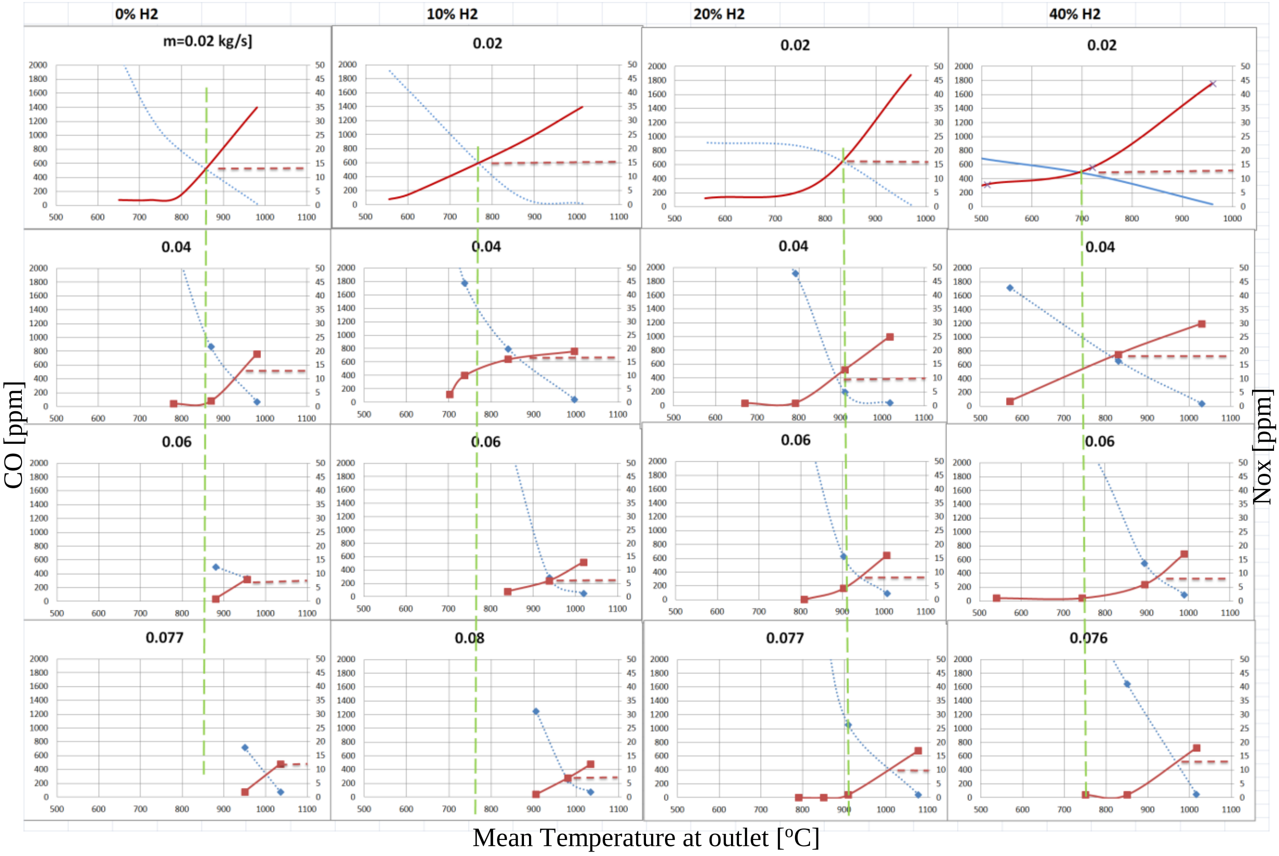


Figure 8. Burned gases measured pollutant emissions

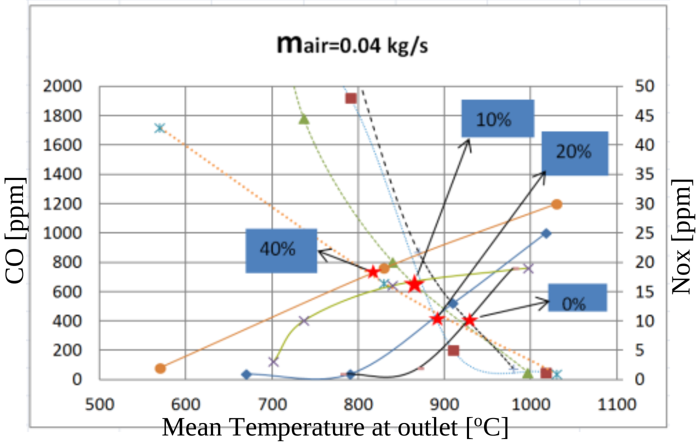


Figure 9. Comparison for burned gases measured pollutant emissions

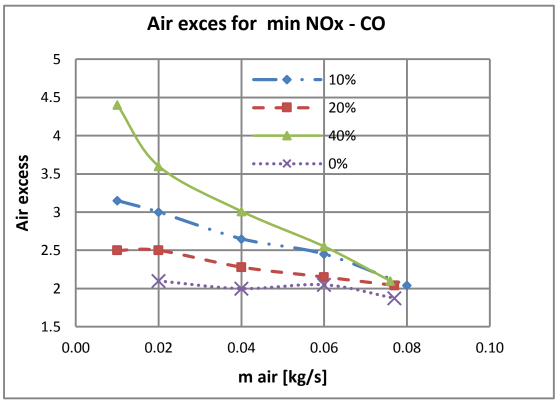


Figure 10. Air excess at “optimal” CO-NOx

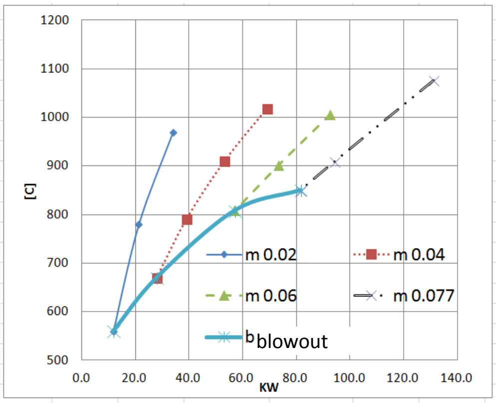


Figure 11. Blowout limits

As expected, in Fig. 8 it can be observed a displacement of the intersection of CO-NOx (optimum) towards higher temperatures, as the air flow rates regimens increase. In Fig. 9 there is a synthesis representation for m_a = 0.04 kg/s, where we can see that the NOx values are increasing by higher H2 percentages. In Fig. 10 the excess air for the optimal values resulted from the intersection of NOx and CO curvers in Fig. 9 are represented for all mass air flow regimens. In Fig. 11 contains data regarding the variation of blowout limits as temperature values depending on the thermal power in KW.

Regarding the relatively high concentrations of CO, it should be noted that these values can decrease by adding dilution air, and by working at nominal regimen (430K and 3 bar), due to the possibility of continuation of the combustion process. From this point of view, the NOx values are depending only on temperature (Zeldovichi mechanism). Even without the dilution effect, the pressure increase is beneficial [17]. In the real case, the full scale combustion chamber will be developed and tested in nominal regimens in the next phase. So a decrease in the pollutant emissions values is expected. As seen in Figure 5, areas with extreme low temperatures indicate the possible location of the introduction of the dilution air.

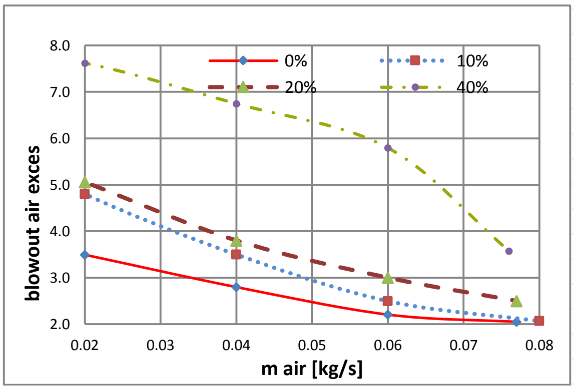


Figure 12. Blowout limits

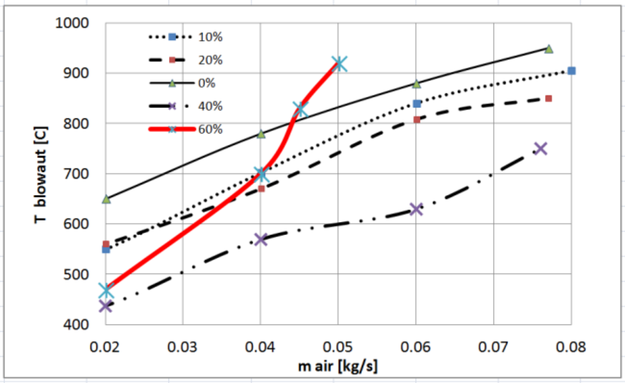
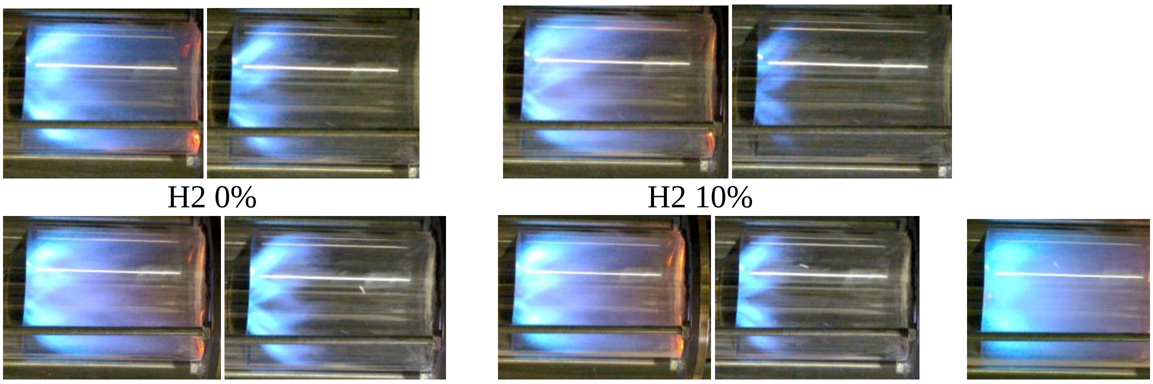


Figure 13. Blowout limits

The Figures 12 and 13 feature synthetic data of the experiments, from the viewpoint of the limit of extinction. It is noted that the limit of extinction is decreasing in temperature values, as the airflow is higher (higher excess air, lower dosage). Data collected in a similar system to the one used in this paper are presented in [13], the only difference is that in that paper there is a total premixing, compared to the partial premixing here. If we analyze the data in Figure 12, compared with the data of [13], a better blowout limit is observed for these experiments. Thus, at the minimum regime of [13], the excess air at blowout limit is between 2.6-2.8, while in the presented experiments, this limit is exceeded even for the maximum regimens (0.08 kg/s). Also, due to the different sections, at the maximum regimen in [13], their equivalent airflow rate by similitude would be 0.022 kg/s. The comparison seems favorable, but it should be regarded with caution, because the reference uses perfect totally premixed air-fuel mixture with a classical swirl injector with 8 blades at 45 degrees inclination, with the swirl number 0.98, while for the present experiments, the number of blades is 9, the angle of 45 degrees is in a non-classical shape and the swirl number in the case is 0.76. However, the excess air at blowout limit for the studied case, both in CFD and experiments, is 3.8, at 20 vol% H2, which appear promising in this phase. In [20] it is shown that the addition of 20% of hydrogen lead to an excess air of 2,5 at blowout. In [21] it also showed that the mixture of 20% hydrogen and 80% methane, by volume, can extend the lean blowout limit typically by 10%, compared to the pure methane, at high-pressure conditions (ex.5bar). So, as stated above, future high pressure experiments will lead to better results.

Also, the regimen of 60% volume H2 has been tried (Figure 13). In this case a major deviation from the general trend was noted. Data could not be registered for all the planned variations of the regimen, because of experimental major vibrations and high frequency noise, with obvious destructive tendencies. This phenomenon worth to be studied separately in a subsequent stage. In [22] and [23] it is signaled, that for the comparison between 0 and 50% H2, there is a drastic change in the frequencies within a wide range of load conditions. Also in [24] the authors found similar issues. Other study [19] mentions that the improvement of stability can be achieved only up to 41% H2.



H2 0% H2 10%

H2 20% H2 40% H2 60%

Figure 14. Experiments with various percentage of H2

Figure 14 is presenting photographic visual comparison between the regimens used in the experimentation. Visually there is a generally good match with the temperature fields resulted in CFX. The luminosity is slightly increasing by adding H2. The exception is for 60% vol H2, where at the appearance of noise and vibrations, the flame front decreased and the luminosity notably increased.

7. Conclusions

Starting from the study and CFD numerical simulation of a known combustion chamber, the goal was to calibrate and validate the numerical solutions, and to experimentally define the working characteristics at low pressure, comparing to known literature, in order to improve and develop a new concept of swirl injector and combustion chamber, capable to work with premixed mixtures of natural gas and hydrogen in varying proportions.

A new type of swirled injector for the combustion chamber was designed and developed, which proved to have various advantages. The first experiments validated the calculations and conducted to new ideas for developing more the assembly and for improving the swirl injector.

The results have shown good blowout limits, compared to the known literature results. The NOx values had the expected results, relatively adequate, considering the partial premixed and depending on the flow regimens and on the proportion of CH4-H2. The final solution of the combustion chamber, it is estimated that will lead to results in the acceptable limits.

Undergoing experiments will continue and will lead to an optimized, viable and efficient final solution.

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