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SWIRL INJECTOR FOR PREMIXED COMBUSTION OF HYDROGEN-METHANE MIXTURES

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Abstract

Among the present domains of interest in scientific research, the field of combustion gained more and more attention, especially the search for new greener and more efficient fuels. One idea that is intensely studied worldwide is 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, like the risk of flashback, the effects of higher temperatures and the modification of the flame front. Hence new solutions are needed.

In this context, this paper presents a new developed and patented type of injector designated to the combustion of premixed hydrogen-methane fuel in various proportions. Based on the characteristics and dimensions of an existing combustion chamber of Garrett GTP30-67 gas turbine, different types of swirled injectors were numerically simulated and compared. After the analysis of the simulation results, plastic models were produced using 3d printing technology. The preliminary conclusions lead to a final pilot injector, made from titanium alloy.

The new type of swirled injector was tested on a low pressure rig designed to have similar dimensions to the combustion chamber of the initial gas turbine. For the experiment only natural gas was used as fuel. Finally, the experiments showed a stable and efficient working flame can be obtained with the new type of injector. Moreover, the results confirmed the possibility of developing and improving the new found type of swirled injector for other types of combustion applications.

1 Introduction

The paper presented here is a part of the doctoral research of the first author and also the work for a Romanian Government founded research program called HIDROCOMB (UEFISCDI nr 76/2014). The work is aimed at studying the turbulent flames fuelled by Hydrogen / Methane mixtures. 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. For brevity, their conclusions are omitted here, but the interested reader can find pertinent information in, e.g., References [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 Numerical simulations CFD

To achieve the proposed goal, burning hydrogen gas mixtures, one aspect that was mainly taken into consideration was avoiding the appearance of flash-back phenomenon that occurs at various regimes due to high speed burning rates. For this reason, in an initial embodiment, starting from a classical type (Figure 1a), a new idea came into light, a constant radial exit-section swirled injector (Figure 1b). The flow channel is basically a convergent nozzle and the speed in the exit section is higher than the burning speed. In this way are avoided the uneven velocities between the base section and tip section at the exit of the channel and at the same time, obtain higher flow speeds, which removes the danger of flash-back phenomenon.

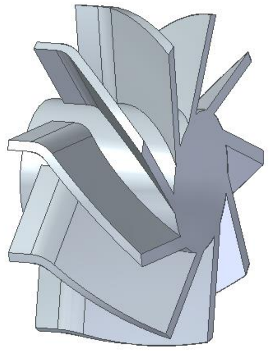


Fig. 1a: Swirled injector - Classical type

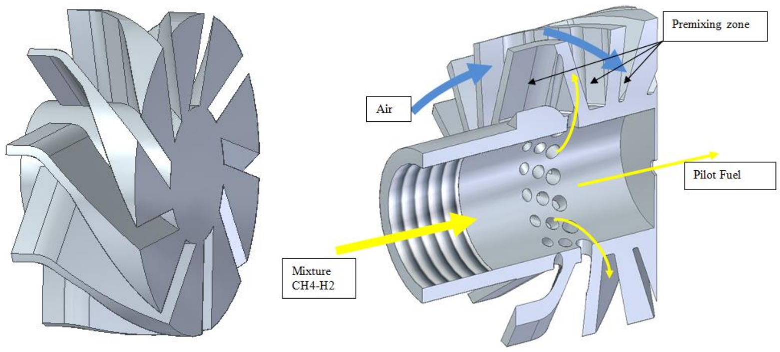


Fig. 1b: Swirled injector - New type

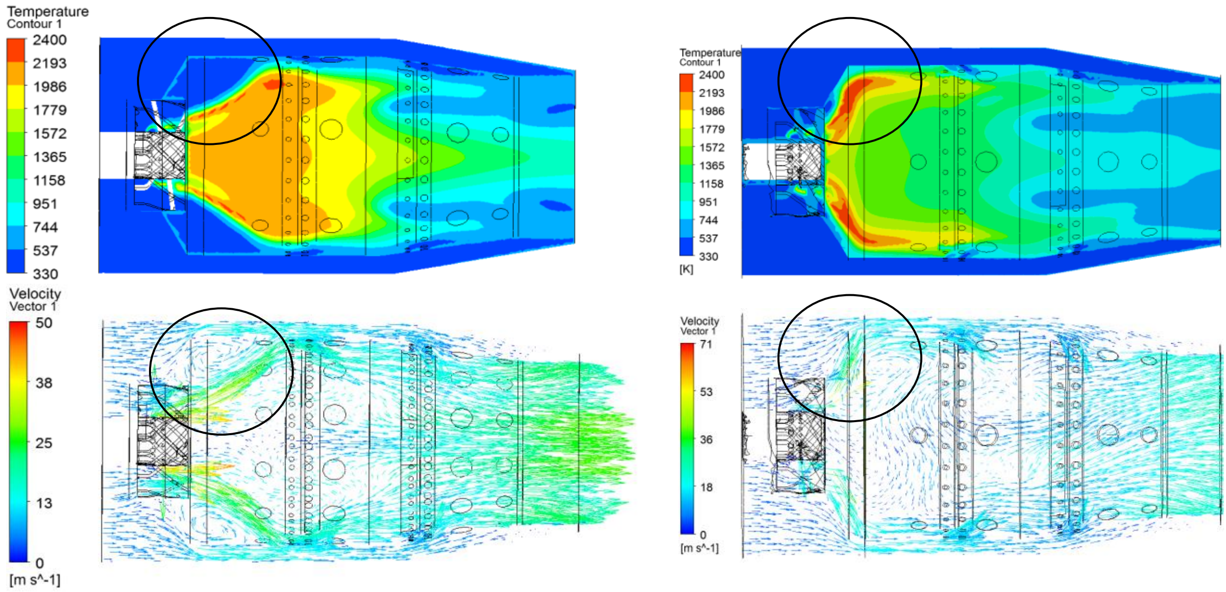
Inside the chosen combustion chamber, using the classical type and the new model, with the characteristics specified above, numerical simulations were made, with the help of commercial software ANSYS CFX.

To highlight the differences between the classic and the new type of injector, same boundary conditions were kept as in the simulations made with the combustion chamber for initial input CFD calibration [15]:

- Air: annular inlet surface of A = 7175 mm^2, T = 430 K, flow rate m = 0.2 Kg / s.
- Fuel mixture: different proportions of hydrogen-methane (0-100%), T = 330 K.
- Exit P = 3.05 bar

The numerical simulations were carried out using steady-state RANS 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 [16].

The simulations focused on comparing the results for the two types of swirled injectors at different percentages of natural gas and hydrogen mixture. Below are the results of our Hydrogen 100 %:



a. classical type *b. new type*

Figure 2: Numerical simulations for the 2 types of swirled injectors

An increased degree of turbulence it is observed in case b. In this temperatures chart it can be seen that for the new type, the flame is more dispersed sideways and the reaction is consumed faster. On the other hand, for the classical type, the flame has a larger field, but also closer to the body of the swirler, which is undesirable as it may lead to its destruction. In the figure above, in the circle marks, it is shown that the new type uses better the space is more efficiently used. At the same time, there are high temperature values near the walls, where the excess air is lower. These observations, proved partially by simplified experiments presented below, has led ultimately to shape the design of a new whole combustion chamber, which is still under developing and resulted as a patent [17] with already high international appreciation [18].

With the help of these simulations it was measured that the amount of air in the inlet of the swirled injector was 25% (for both cases 0.114 kg/s). Knowing the amount of primary air is very important in experiments, for finding an optimal working regimen by adjusting the measured data with the required parameters.

3 Low pressure experiments

In order to check the low-pressure combustion characteristics for the new type of swirler a special designed experimental setup was build (Figure 3). The physical model for the swirl injector used in this setup was made by 3D printing from a titanium alloy. In this phase, the design was intended to be simple, reliable and not expensive, because the aim was to find out about the behavior and the general characteristics of the new concept. The experiments were conducted using natural gas as a first phase.

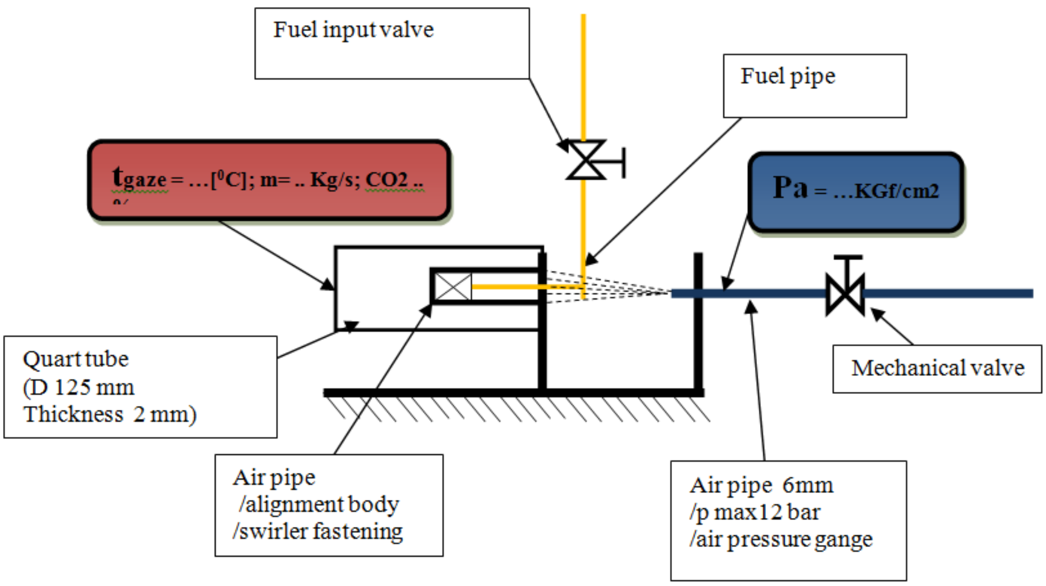


Figure 3: Low pressure experimental setup

As shown in the setup diagram (Figure 3), the feeding of the air is made by ejection and it is delivered by a high pressure piston compressor. For finding the air flow, measurements were made using a laboratory Pitot tube, type KIMO / diameter 3 mm / 1% precision class.

Thus, knowing the predefined air pressure of the tube air and the speed, the flow rate was determined, the same working regimens being used also for the reaction experiments (Figure 4).

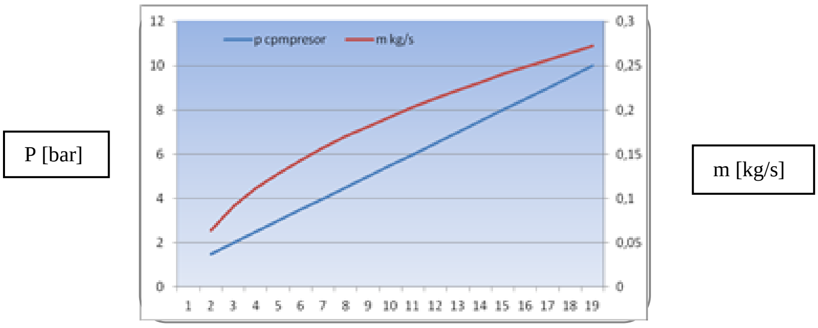


Figure 4: Air flow determination - different regimens

Although the method is not the most accurate, the next phase will include low and high pressure experiments with laboratory precise measurement, including laser PIV and LIF.

In these conditions described above a number of starts/stops were made and the results and parameters are presented below (Figure 5).

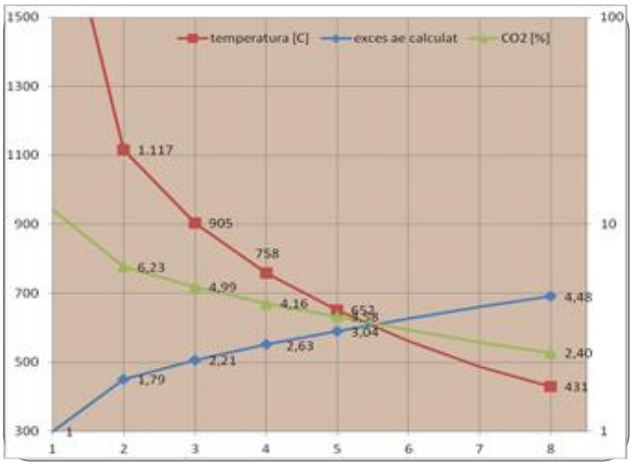


Fig. 5: Measurements at the output for low pressure experiments

A first observation is the high flame stability, having an air excess of 4.48 is sufficient to ensure the input temperature of a real scale turbine in a turbine engine. Actually, it can be estimated that the secondary dilution air can be reduced as the combustion chamber can use only the premixed air-fuel coming through the swirl injector.

In Figure 6 it is presented a view of the setup working at operating regimen no. 3 (905 ^{o}C).

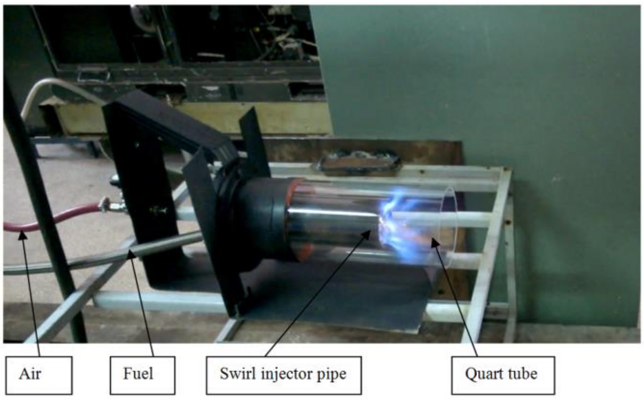


Figure 6: Experimental setup

In Figure 7 we can see the experiment running at operating regimen no. 2 (1117 ^{o}C) and in Figure 8 a recording with Fluke infrared thermo-vision special camera.

Figure. 7.

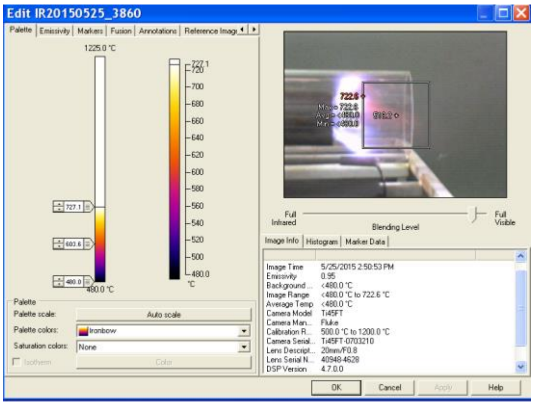


Figure 8.

A slight staining near the quart wall can be observed (the interruption of the flame front when touching of the wall) and this lead to the idea of a need for film surface cooling of the wall. This idea emerged also from the above CFD calculations. A classic cooling means a large air intake with large penetrations, not suitable for this case. One possible way is the cooling by effusion.

So, for this purpose, a perforated metal sheet with 0.5 mm holes at a pitch of 1.5 mm was used as a first technological attempt. (Figure 9)

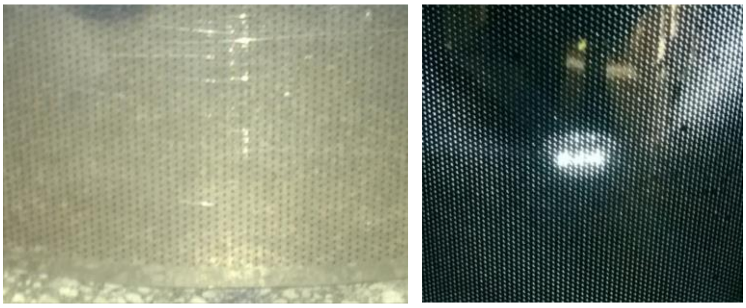


Figure 9: Effusion holes in the wall of the combustion chamber

The advantage of this solution with a hollow area of 4.9 mm2 / 100 mm2, being the boundary flow layer, is that the additional air flow penetration is extremely low, with reduced coefficient of pressure loss, so the quantity of intake air is extremely small. Precise future determinations will be made to find penetration and flow rate per unit area, optimization if needed, even by modifying the hole size, which can go as low as 0.2 mm with available technology.

Next there are presented some aspects regarding the open-air running (the quartz tube was removed)

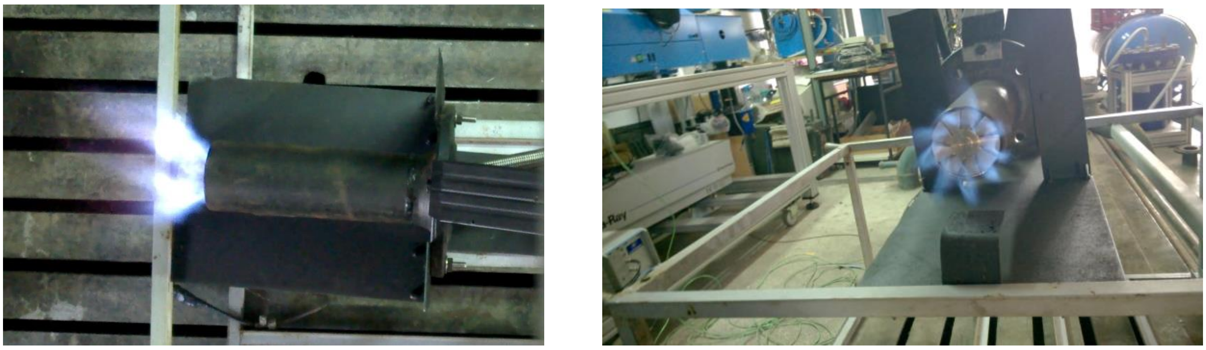


Fig. 10: Open air testing of the swirl injector

Due to the output constant section, compared to the classic swirlers, there are areas of clear separation between flame fronts, which allows that in the intense recirculation process to have some extra injected gaseous mixture that leads to increased stabilization.

Not least, these early experiments validate the CFD calculation results and assumptions, burning only natural gas being a disadvantage compared to mixed H2-CH4, or only hydrogen, at least regarding the burning speed rates.

The results of the evaluation of the flame characteristics seem to be promising. The burned gases analysis is a bit uncertain because of the length of the tube quartz in which combustion occurs, having an irregular flow zone at the outlet of the rig. In subsequent phases the authors will proceed to experiments on complex testing setups, as mentioned before, with multiple possibilities for adjustments and measurements. Anyhow, the current measurements indicate as pollutant emissions CO and NOx, with concentrations between 5 and 18 ppm.

4 Conclusions

The current paper is part of the work for a Romanian Government founded research program called HIDROCOMB (UEFISCDI nr 76/2014), with the partners "Politehnica" University of Bucharest and GE Aviation (Unison Engine Components Bucharest) and conducted by The Romanian Research and Development Institute for Gas Turbines COMOTI. Also the paper is connected to the doctoral work of the first author.

It started with the study and CFD numerical simulation of a known combustion chamber, with the goal to calibrate and validate the numerical solutions, in order to improve and develop a new concept of combustion chamber, capable to work with pre-blended 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 new idea was patented and appreciated [17, 18] (Fig. 11). The first experiments validated the calculations and conducted to new ideas for developing more the assembly and for improving the swirl injector.

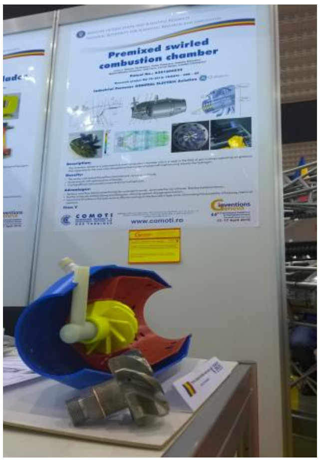


Fig. 11

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

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