THE OPTIMIZATION OF A SWIRL INJECTOR FOR COMBUSTION OF HYDROGEN FUEL MIXTURES

Razvan CARLANESCU[1], Tudor PRISECARU[2], Radu KUNCSER[3], Elena POP[4] *

This paper aims to study how an injector conceived specifically for combustion of hydrogen fuel mixtures, here blended with methane, can be modeled and optimized. This new type of injector has been designed to remove some of the problems found in the literature, such as flashback and it contributes to the reduction of pollutant emissions by stabilizing the flame. Numerical experiments and simulations with this model were conducted. Aspects regarding manufacturing configurations and materials that fit the use of hydrogen were studied. This new type of innovative injector, through promising results, opens the possibility of using it in similar industrial applications.

Keywords: hydrogen, swirl, injector, combustion, gas turbine, mixture

1. Introduction

The global energy landscape is experiencing major changes caused by current economic developments. There is a growing pressure to provide more gas and oil to support the global energy needs. The economic implications of global dependence on fossil fuels are major. In 2010, imports accounted for 52.7% of fossil fuel consumption in Europe [1]. This figure is expected to reach 65% by 2030. To ensure the safety of fuel resources, taking into account the limited resources of fossil fuels and the increased attention to environmental protection, there is a growing need to look for more efficient fuels and for lower pollutant emissions.

Simple solutions to reduce pollutant emissions include energy conversion efficiency, or the use of carbon-neutral fuels by using renewable energies.

The addition of hydrogen to the natural gas mixture is considered worldwide as a possible solution for increasing economic efficiency in the production of energy from renewable sources [2]. It should be underlined that current hydrogen

[1] Eng., Dept. of Combustion chambers, Romanian Research and Development Institute for Gas Turbines COMOTI, Bucharest, Romania, e-mail: razvan.carlanescu@comoti.ro
[2] Prof., Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania, e-mail: tudor.prisecaru@upb.ro
[3] Eng., Dept. of Combustion chambers, Romanian Research and Development Institute for Gas Turbines COMOTI, Bucharest, Romania, e-mail: radu.kuncser@comoti.ro
[4] Ş.L. Elena Pop, The Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania, e-mail: elena.pop@upb.ro
* *Corresponding author*, e-mail: elena.pop@upb.ro

production methods from fossil fuels are not sustainable alternatives and are additional sources of greenhouse gas production [3]. Therefore, attention should be directed to the production of hydrogen from alternative sources based on renewable energies. Thus, excess electricity obtained from renewable sources during periods of reduced consumption can be used to produce hydrogen and the latter can be introduced into the already existing pipeline network for the transport of natural gas. In this way, the problem of the widespread use of hydrogen as a fuel, namely transporting through the use of the existing gas infrastructure, will be solved easily. This process will result in a new type of gas fuel consisting of natural gas and hydrogen, which will feed industrial applications, perhaps even ordinary users. An energy application of interest in this respect is the industrial use of gas turbines for the production of electric and thermal energy.

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 [4], based on this approach. Also, the multinational energy provider E.ON, Essen, Germany recently completed the construction of a pilot plant in Falkenhagen [4], 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 fueled turbine power plants for operation with 10% hydrogen mixture [5].

However, hydrogen enrichment of natural gas significantly alters the flame characteristics of this mixture [6] and so, the effects on combustion efficiency and flame stability require a careful assessment.

For instance, it has been shown [7] 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 thermoacoustics. Also, the addition of hydrogen in gaseous mixtures has been proved to increase the laminar flame speed, with a linear variation depending on the amount of hydrogen [8]. All these effects can be reasonably expected to impact on the flame stability and the pollutant emissions, which will influence the performance and the reliability of the hydrogen-enriched natural gas fueled gas turbine driving the power plant.

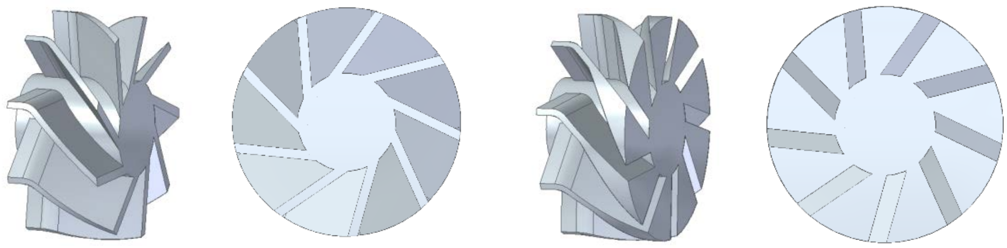
Therefore, a need to study the impact of hydrogen enrichment upon the turbulent flame characteristics arose and the work presented here is part of this research effort. The authors propose to study a new type of injector and modify it so that it can work in optimal conditions with methane-hydrogen mixtures. Since the natural gas has in its composition an important amount of methane (~90%), the authors decided to use methane (CH_4) for numerical calculations and experiments.

2. Determining the optimal dimensional shape

Starting from a classic swirl injector, the geometric shape it was changed to function with methane-hydrogen mixtures (Fig. 1). In reshaping of the new type of swirl injector, the theory that an intense swirling would lead to better burning parameters was counted. But consideration has also been given to avoiding the flashback phenomenon, well known in the case of hydrogen combustion, due to the higher reaction rate of hydrogen compared to other combustible gases. For example, the rolling velocity for hydrogen is 1.9 m/s, compared to 0.38 m/s for methane [9].

For the classic injector (type 1 from Fig. 1), the channel sections are approximately constant considering the channel length, and the output section have significant differences in geometry across the swirl radius, resulting in radial flows and uneven velocities between the base and the peak, that will make the downstream recirculation currents more difficult to control. The most important disadvantage of constant dimension of the channels is the possibility of flashback, especially in the case of fuels with very high combustion speeds, such as hydrogen [10].

In the case of the new type 2 injector, presented in Fig. 1, the disadvantages described above are eliminated, with a geometry in which the channels have constant radial cross-section at the exit and have a minimum section at the outlet, so it can be sized such that, depending on the operating regimes, it can have higher speeds in the exit regardless of the way of mixing and of the percentage of methane/hydrogen (CH_4/H_2). Thus, due to the increased flow rates through the channels, it is intended to eliminate the main danger, namely the flashback.



Type 1 Type 2

Fig. 1. The two types of injectors compared in CFD simulations for non-reactive flow.

The final shape of the injector is shown in Fig. 2. It can be observed the way of operation and the way in which the fuel is partially premixed with the air, before leaving the injector channels [11].

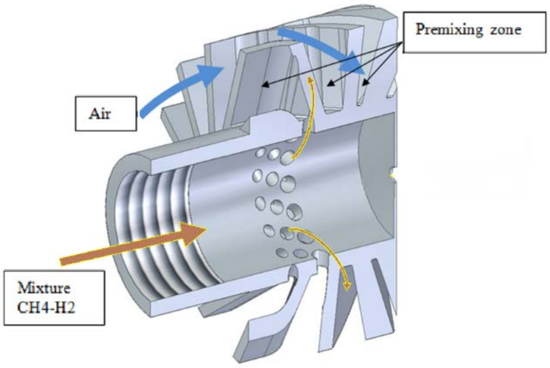
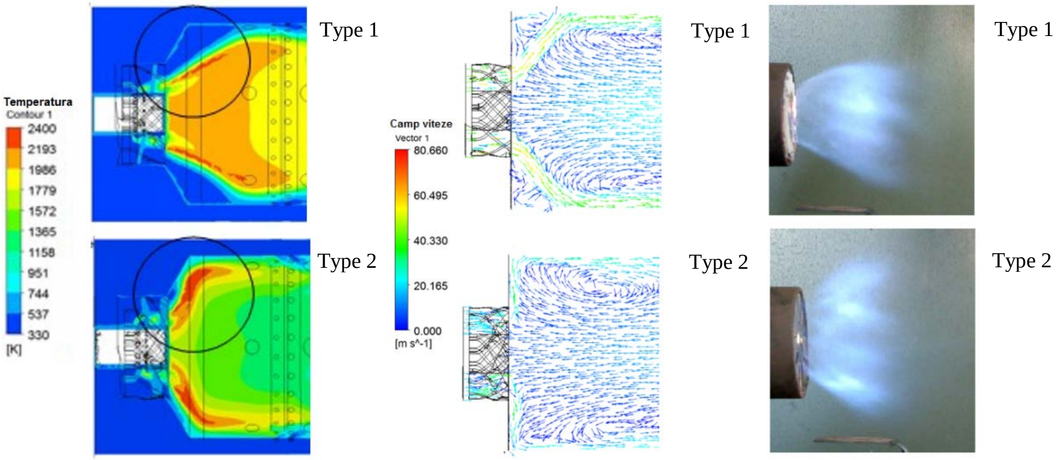


Fig. 2. Swirl injector and working principle [11]

Next, with the help of a commercial CFD software, ANSYS CFX (Version 12, license of INCDT COMOTI), the injector was simulated in the two variants, first for cold flow, observing the speed and recirculation fields and then for reacting flow, trying to highlight the differences between the flame shapes by viewing the temperature fields. Finally, the two types of injectors were produced in simplified versions and physically tested, in order to observe the differences (Fig. 3).

For the numerical simulations, the authors used the RANS (Reynolds Avereged Numerical Simulation) approach, the k-e turbulence model, and the Eddy Dissipation (EDM) combustion model, as part of ANSYS CFX software.

An increased degree of recirculation is observed for type 2. In the temperatures chart, it can be seen that for the new type, the flame is more dispersed sideways and the reaction is consumed faster. Also, in the experimental images, it can be observed the same thing. For reducing the lateral dispersion, a possible solution would be the modification of the angle of the blades for the injector, in order to reduce the swirl number [11]. The modification of the swirl number will also affect the inlet turbulence intensity, with a substantial impact on the axial decay of mixture fraction and temperature, velocity, and strain rate [12],thus with possible changes in combustion characteristics. Still, some interesting results of Pourhoseini and Asadi [13] suggest that it is not the case that a rise in the swirl number leads always to an increase in temperature and combustion efficiency, but there is an optimum angle for swirling vanes at which the combustion efficiency, temperature, and radiation heat transfer of the flame stand at their maximum. Also, in the paper [14], the authors highlight the importance of changing the geometry of a post-combustion burner and its influence on the degree of turbulence, swirling motion and implicitly on the reduction of NO_x emissions. Another aspect to be considered



a. Temperature field b. velocity fields (cold simulation) c. Images during experiment

Fig. 3. Comparison of CFD numerical results and visualization during the experiment

is the influence of the chosen combustion model for the CFD calculation (in this case EDM), since different models can lead to big differences in the results [15]. For this case, the model produced good results that are in concordance with the experiments, but when changing the geometry and the turbulence rate, other combustion models might be considered.

On the other hand, for the classical type, the flame has a larger field, but it is also closer to the body of the injector, which is undesirable as it may lead to its destruction. The observations on the recirculation zones are important, because it was demonstrated that the increase in residence time of the fuel will favor the decrease of CO emissions; therefore, the critical geometrical parameters that determine the flow field and the pattern of the recirculation areas will directly affect the combustion characteristics [13] [16].

From the *Table 1*, the measured data from the cold numerical simulations, the advantages of the new design are clearly observed, with higher speeds for the new type. These results confirm the hypothesis of channels with constant radial section at the exit and the advantages of adopting it.

Table 1

Numerical simulation results for the two types of injectors

	Inlet air	**Injector exit**	**Comb zone exit**
Type 1	V = 40 m/s	V = 66.49 m/s	V = 19.2 m/s
	p = 0.023 bar	p = 0.0022 bar	p = 0 bar (input)
	m_{air} = 0.151 kg/s		
Type 2	V = 40 m/s	V = 152.14 m/s	V = 22.4 m/s
	p = 0.16 bar	p = 0.0056 bar	p = 0 bar (input)
	m_{air} = 0.153 kg/s		

3. Design, production and materials considerations

After the injector's dimensional calculation, the setting of the angles and constructive elements, and the use of CFD calculations in choosing the optimal injector solution, the injector was ready for physical production, needed for experiments. Several important aspects are worth considering.

Since hydrogen is a long-standing fuel in various applications, its properties are well known and also the problems that can arise in transport, in storage and in the processes. There are safety standards in this area and special hydrogen characteristics require strict adherence to them.

One of the most important properties to be taken into account is very low density and the low molecular weight, which can pose serious problems with seals, with the possibility of unwanted leaks, even though compact materials [17]. With regard to metals, it is advisable to avoid cast iron, soft steels, and for liquid hydrogen it is advisable to avoid using nickel [18].

At high temperatures and pressures, hydrogen attacks low-alloy steels, producing degradation and increased brittleness. Thus, special materials and technologies are needed to transport and store hydrogen at high pressures [17].

Uncontrolled plant leaks and hydrogen accumulation are absolutely to be avoided due to the very high flammability potential of hydrogen in the oxidant environment. Flammability limits of 4-75% and very low minimum ignition energy (10 times lower than CH_4) [9], make hydrogen use very dangerous in any kind of experimentation. Special detection, ventilation and emergency stop measures are necessary, because previous experiences show that leaks and gas accumulations sometimes occur even with the most careful efforts in hydrogen sealing [19] [18]. Some authors [20] [3] draw particular attention to safety issues, experiencing experimental problems with explosion prevention methods, having to pursue a series of tests and preliminary tests before determining the optimal position and injection angle of hydrogen to the injector head.

Therefore, in addition to the special safety measures and specific equipment used in the preparation of the experimental setup (one-way valves, hydrogen flame arresters, pressure reducers, safety valves), all these considerations have been taken into account when producing the injector.

Due to the rather complicated geometry resulting from the design, with complicated geometric shapes and narrow channels, it was chosen to produce the injector by 3D printing, using titanium powder as material (Fig. 4). This material is in the safe area and it is compatible with the hydrogen, according to the industry standards [18].

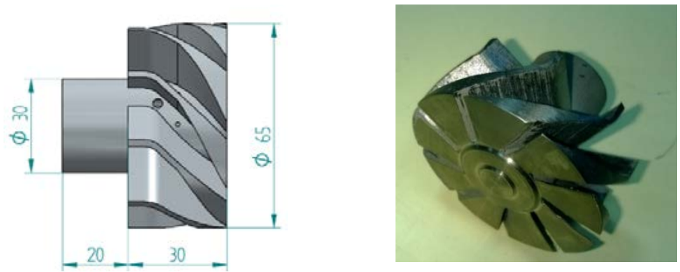


Fig. 4. The injector experimental model

From the point of view of hydrogen permeability, the performed tests were satisfactory. In this case, given the geometry of the combustion chamber and the way the air and fuel flow through the injector, the leaks are not important, taking place in the fuel injection area.

Using 3D printing technology, microscopic particles are deposited layer by layer with laser technology, the roughness of the material being directly dependent on the size of the particles used. Thus, it was considered necessary to study the quality of the surface, with the help of an efficient microscope (Fig. 5).

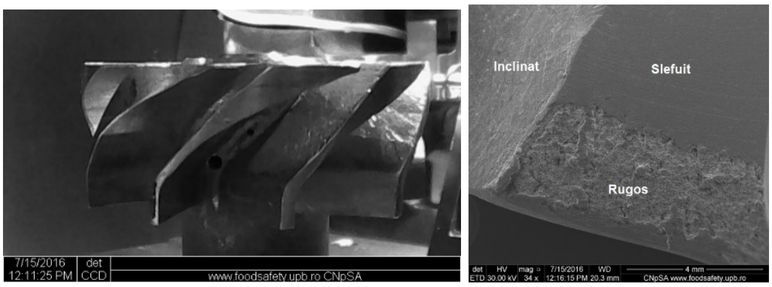


Fig. 5. Microscope study of the resulting surfaces

The irregularity of the dimensions (4µm – 10µm) and the random distribution of the particles (Fig. 6) question the idea of using this technique in the part production for hydrogen environment, but for this case and for the studied application, it proved to be a fast, cheap and viable solution.

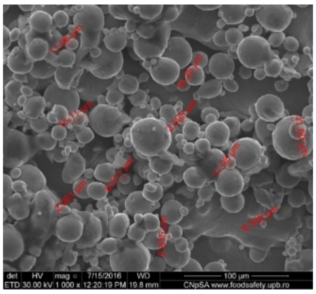


Fig. 6. Microscope injector surface - 1000x multiplication

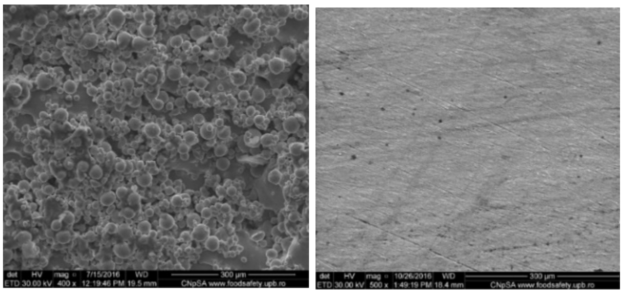


Fig. 7. Surfaces before and after polishing - 400x multiplication

In the case of a high roughness of the surface, the issue of influencing the flow in the boundary layer near the walls can also be raised. In an attempt to find out how there was an influence in this regard, the surfaces of a flow section between two blades of the injector were mechanically polished and the flow rates were compared at different points with the other similar sections of the other channels.

Velocity measurements were made using a Pitot tube and for the minimum, mean and maximum radius, the values for each channel were recorded in *Table 2*.

Table 2

Measuring the velocities in the injector flow sections

Air flow kg/s	Channels→ Radius ↓	9→1	1→2	2→3	3→4	4→5	5→6	6→7	7→8	8→9
		Polished								
		velocity [m/s]								
0.02	R min	9.50	11.10	11.40	10.60	11.00	11.90	11.10	10.90	11.00
	R avg	11.00	11.30	11.50	10.40	11.20	10.80	10.50	10.30	11.10
	R max	10.30	9.90	9.70	9.80	10.00	8.50	10.10	9.80	10.30
	average	10.27	10.77	10.87	10.27	10.73	10.40	10.57	10.33	10.80
0.04	R min	21.00	21.50	23.20	22.60	22.40	22.70	22.20	22.00	21.90
	R avg	21.50	22.80	22.30	22.00	22.30	22.00	22.20	22.20	21.90
	R max	19.90	21.90	20.60	19.50	19.90	18.50	20.20	20.30	20.00
	average	20.80	22.07	22.03	21.37	21.53	21.07	21.53	21.50	21.27
0.06	R min	38.10	38.10	38.20	37.70	38.40	37.90	37.10	38.80	38.00
	R avg	38.90	38.70	38.60	38.90	37.90	38.00	35.10	38.40	38.40
	R max	38.40	36.10	36.10	35.10	31.50	35.20	35.60	34.80	36.30
	average	38.47	37.63	37.63	37.23	35.93	37.03	35.93	37.33	37.57
0.084	R min	54.50	53.50	53.60	54.50	54.90	53.20	53.80	53.50	53.80
	R avg	54.90	54.40	55.80	55.30	55.50	54.10	53.30	54.70	54.70
	R max	51.00	51.30	50.50	50.20	49.80	49.30	51.60	51.10	51.00
	average	53.47	53.07	53.30	53.33	53.40	52.20	52.90	53.10	53.17

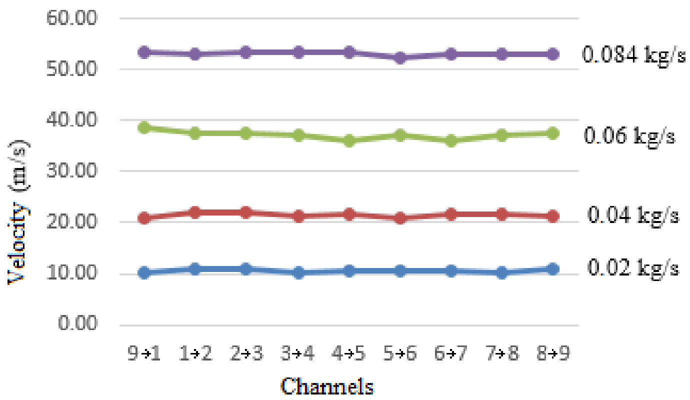


Fig. 8. Average velocity values at different air flows

Fig. 9. Measuring channels' velocities

No notable differences can be observed for section 9→1, the one that was polished. One possible explanation would be the widening of the channel and the increasing of the total flow section, along with the mechanical surface rectification, which would lead to a decrease in channel flow velocity. Thus the possible gain by improving the surface could be lost by decreasing the speed, due to the increase of the section. Furthermore the method chosen for measuring is not the most accurate for the case of boundary layer flows.

However, the method of producing the injector, the roughness and the chosen material may influence normally to a certain extent the parameters of the flow of the injector, but these experiments and the chosen method show too little differences to be able to conclude in this matter.

4. Numerical and experimental testing of the injector

Experimental study is required for the operation of the newly chosen injector resulting from the above work. Tests and measurements were carried out with the 1:1 scale injector, in a combustion chamber that respects the dimensional proportions of an existing micro gas turbine combustion chamber. Parameters were calculated by Mach similitude method for atmospheric pressure, starting from the known flow rates and values for the micro gas turbine [21]. The simple operation of the injector is studied here, without the addition of dilution air, all the air is passing through the injector. The outer wall was made of a quartz tube, to be able to view the flame shape and estimate its stability. Measurements are made at various points for pressures, temperatures, pollutant emissions.

In Fig. 10, the schematic of the combustion chamber setup and an image during the experiments are presented.

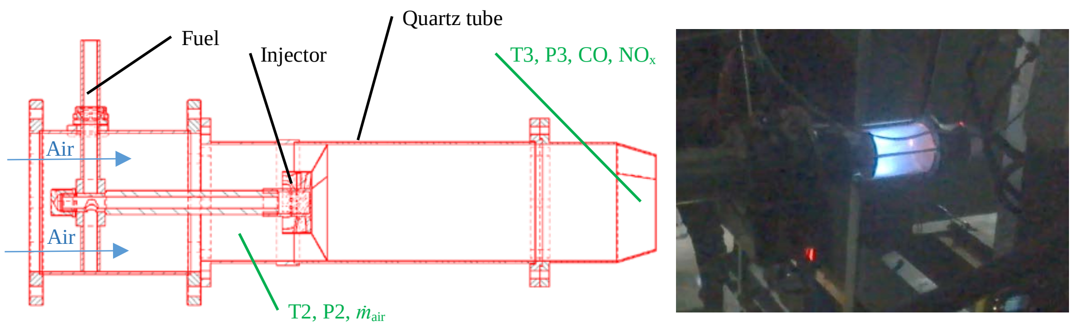


Fig. 10. Arrangement of the combustion chamber for experimentation

Starting from the idea that this injector can be used in mixed hydrogen-methane mixtures in various proportions, for these experiments, the injector works with methane/hydrogen mixtures with volumetric fractions of 0% and 40% hydrogen (the rest methane). The chosen experimental conditions: thermal power

33.3 kW, excess air 3.5, $\dot{m}_{air}$ = 0.04 kg/s, values considered to be representative for micro gas turbines in this range [21]. The focus was on the differences in aspect and stability of the flame and on the main combustion characteristics. The main values taken as input in the calculations are presented in *Table 3.*

Table 3

The main input values used to set the test regimes

	Air flow kg/s	Fuel flow kg/s	Calorific Value kJ/kg	Thermal Power kW	Excess Air
H_2 0% CH_4 100%	0.04	0.00066	50000	33.3	3.5
H_2 40% CH_4 60%	0.04	0.000601	55384	33.3	3.5

The calorific value was calculated with the help of this relation:

$$H_{i\,fuel} = H_{iCH_4} \frac{\left[(1-y)\cdot 16 + 2{,}4 \cdot y \cdot 2\right]}{\left[(1-y)\cdot 16 + y \cdot 2\right]} \quad [kJ/kg] \tag{1}$$

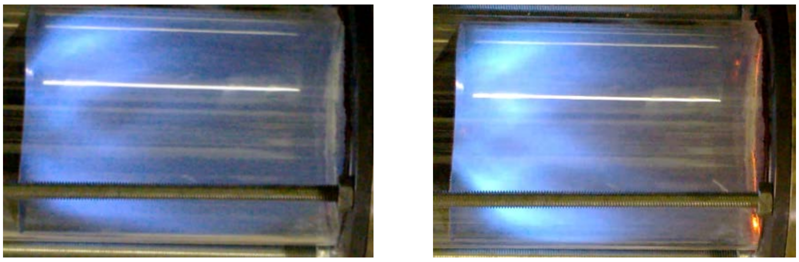
where: H_{iCH_4} - the calorific value of CH_4, y – volumetric fraction of H_2.

The fuel flow rate of the mixture was calculated by keeping the thermal power as constant in the relation:

$$P = \dot{m}_f \cdot H_{i\,fuel} \quad [kW] \tag{2}$$

where: $\dot{m}_f$ – masic flow rate of the fuel mixture.

During the tests, a very good stability was observed, characteristics with lean blowout limits at 306°C for 100% CH_4 and 180°C for H_2 40% CH_4 60%. Therefore, at the same air flow rate, a considerable improvement in stability is observed when adding hydrogen. Images showing the shape of the flame front in operation can be seen in Fig. 11. It was found that the shape of the flame changes at 20% H_2, becoming at the same time more compact and intense. For 0% H_2 there is a discontinuity area right next to the injector, because for the same air flow rate this regimen is less stable.



a. 0% H_2 100% CH_4 b. 20% H_2 80% CH_4

Fig. 11. The experimental injector at the same power, at 0% H_2 and 20% H_2 (the remaining CH_4)

A numerical simulation of the two experimental cases was also attempted, with similar results as the experiments, in terms of temperature fields (Fig. 12). The same intensification and the same increase of the temperature can be observed in the case of addition of hydrogen. The numerical simulations were carried out using the same RANS k–epsilon turbulence model, while the combustion model was the flamelet probability density function model, using CFX-RIF flamelet generation tool inside ANSYS, a library that provides kinetic reaction schemes for CH_4-H_2 (mixture of methane and hydrogen, using LCSR mechanism without NO), choosing components and fractions for fuel (CH_4, H_2) and oxidizer (N+O) [22] [11].

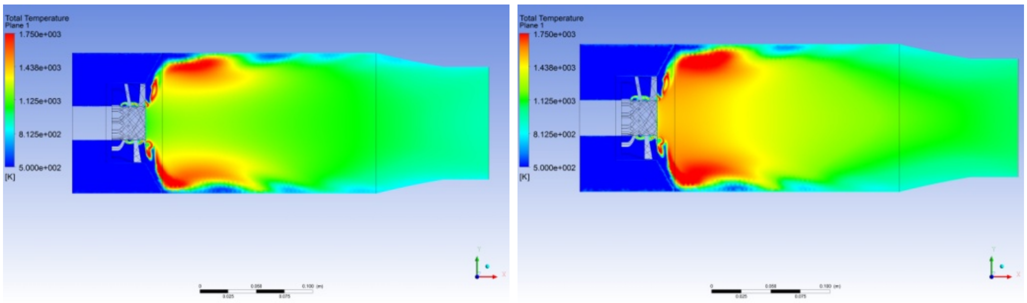


Fig. 12. Temperature field for 0%H_2 (left) and 40%H_2 (right). ($\dot{m}_{air}$ 0.04 kg/s, excess air 3,5)

In the experiments the values of the main pollutant emissions were also measured, using a portable gas analyzer (MRU Varioplus). Two mixtures were observed: 0%H_2 and 40%H_2, with the rest CH_4. The regimens were modified by varying the flow rate of the mixture fuel between the limits of rich and lean blowout. The results are presented in Fig. 13. As observed below, the lean blowout for 40% H_2 is reached at a lower temperature than for 0% H_2. This increase of the working range at lower temperatures can lead to better stability of the flame.

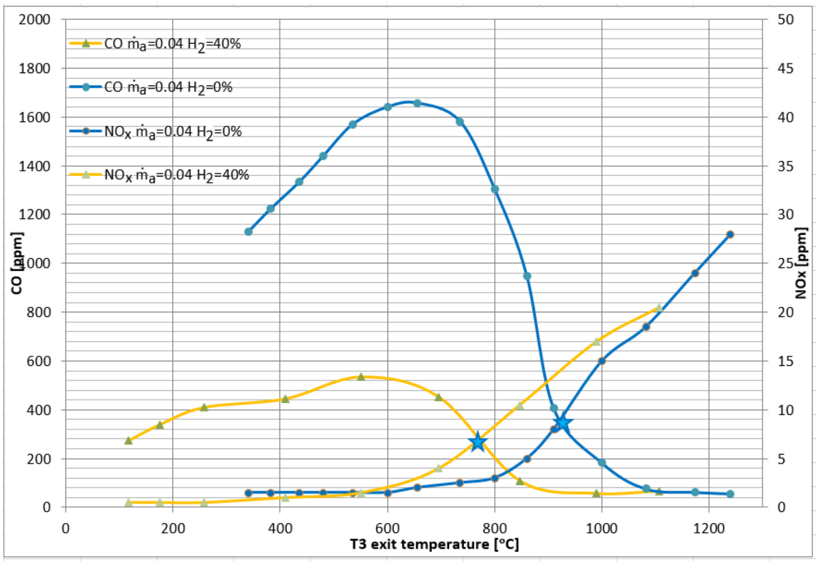


Fig. 13. Variation of CO and NO_x pollutant emissions for 0%H_2 and 40%H_2.
(air mass flow rate at 0.04 kg/s)

Regarding the CO concentrations, a clear decrease is observed with the increase in the percentage of hydrogen in the fuel mixture. Also, it can be observed that by the addition of hydrogen, the NO_x emissions are increased for the same corresponding temperature. This can be explained by the higher maximum combustion temperature, resulted from the specific higher adiabatic flame temperature of hydrogen, with a direct dependence on the Zeldovich kinetic mechanism, which leads to the formation of thermal NO_x on temperature rising, due to thermal dissociation [3] [20] [23]. At the same temperatures, NO_x increased between 20% and 120% in the area of interest, with a clear point to the need of considering NO_x reducing measures (steam or H_2O) for future works.

These experiments were performed on similitude calculated parameters and based on other studies [24] it can be concluded that for actual operating regimes with increased air pressures, temperatures and airflow rates, flame stability will improve and CO emission values will be reduced. Increased operating pressure in real modes is expected to have a positive influence on NO_x formation, too.

From the point of view of pollutant emissions, if things are to be considered for the turbine combustion chamber, the purpose of this work, but also by extension, for the injector as a possible industrial burner, the data must be evaluated against the updated pollution regulations and by the legislation. Certain limits of the optimal functioning can be settled using, for example, the Romanian Law no. 278 of 24/10/2013 [25]. This regulation provides NO_x limits of 100 mg/m^3_N for the industrial burners and 50-75 mg/m^3_N for gas turbines, and CO limits of 100 mg/m^3_N for both cases. After the transformation and comparison of the norms with the obtained results, it can be seen that the injector studied in this paper operates within acceptable limits as pollutant emissions.

5. Conclusions

Starting from the need to find an injector specially designed for burning hydrogen-methane mixtures, a classic model and a geometrically optimized type were studied comparatively for this purpose. Its production has taken into account material aspects and safety concerns, attempting methods to improve the surfaces of interest. Experiments were made by burning this specific fuel mixture in the new type of injector, comparing with 100% methane operation.

It was shown that different geometry of the injector influence the flame characteristics. Also the manufacturing method and the quality of the surfaces, even if in this case did not make an impact to be considered, still they can have an influence, depending on the geometry of the part and on the application.

With regards on the flame stability, good performance of the injector has been observed, through reduced lean blowout limits, with the improvement of them as the percentage of hydrogen increases. Acceptable emissions values have been recorded, leading to promising conclusions.

Since the experiments were performed on similitude reduced parameters, it is expected that for nominal regimes with increased air pressures, temperatures and airflow rates, flame stability and the pollutant emission will improve.

It can be said that the premises and the results obtained are generally positive, with good combustion characteristics, stability and the possibility of building a partially premixed combustion chamber with this injector that meets the standard requirements in the field, with low pollutant emission characteristics. The data obtained confirms the possibility of future development and improvement of this new type of injector and combustion chamber, for optimization and use in other potential industrial applications.

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