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NUMERICAL SIMULATIONS FOR DIFFUSIVE COMBUSTION OF HYDROGEN-METHANE MIXTURE, INSIDE OF A GAS TURBINE COMBUSTION CHAMBER

BY

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Abstract. Nowadays major preoccupations in the field of combustion are to find new greener and more efficient fuels. One idea that is more and more studied worldwide is the usage of hydrogen, since new technologies for producing and transporting it developed lately. Important studies are trying to validate the possibility of hydrogen transport using the existing natural gas distribution network, mixing the two gases. The properties of the new mixture influences the combustion parameters, so, depending on the application, the main issue is to find the maximum hydrogen percentage that can be added in the mixture, for safe and efficient usage, without the modification of the combustion systems, or finding new solution for burning more hydrogen in the same equipment. This paper is reproducing the results of numerical simulations, using the Reynolds Averaged Navier – Stokes approach, inside of the combustion chamber of a Garrett GTP30-67 gas turbine. Three approaches regarding the way to mix the two gases are presented, as well as different

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results depending on the composition of the mixture, with regard to the percentage of the hydrogen used. With increasing of the hydrogen in the mixture, the temperature raises and the flame front is getting closer to the entrance of the combustor. This can damage the elements of the rig. Also the higher temperature leads to higher thermal NOx production.

Key words: hydrogen; gas turbine; combustion; mixture; RANS simulation.

1. Introduction

In the context of the worldwide growing need for gradual replacement of traditional fuels, given the limited resources and increasingly stringent requirements in terms of protecting the environment, there is an increased concern lately in finding alternative fuels which are cheaper, less harmful to the environment and eventually improve the current performance of combustion processes. An increased interest in the use of renewable resources can be noted, for example, European Commission is aiming for the 2020 agenda to reduce by 20% the greenhouse gas emissions and to cover at least 20% of the energy consumption by using renewable sources (COM, 2011). One of the less polluting and high efficient fuel is the hydrogen and the idea of using it is not new at all, but the main issue so far was the production and transport of this fuel, which was not cheap, nor green to produce and if the costs of classic transportation are accounted the alternative is not viable or efficient at all.

Alternative fuels can also be produced by non-conventional, renewable energy sources, such as wind or solar power. One of the problems with these sources is that they produce a constant amount of energy, independent of the power need, so without a storage solution, their efficiency is diminished. An economically viable idea is to use this extra energy to produce the hydrogen and then transport it using the natural gas distribution and supply network, by mixing the two gases. At the delivery point, the hydrogen can be separated from the natural gas, or the new mixture can be used as it is. In this last case, a careful approach is needed, since the new mixture has different physical and chemical properties that influence the combustion characteristics and, depending on the application, can damage the existing facilities. New solutions must be taken into considerations, or the need to narrow the percentage of the added hydrogen in the mixture. The existing literature gives various percentages for safe margins, pointing at 10-15% (in volume) of hydrogen. For example, Siemens Industrial Turbomachinery developed the SGT-700 and SGT-800 series turbine power plants for operation with a mixture of natural gas and 10% Hydrogen (Larfeldt & Heimdal Nilsson, 2014). Also, E-ON recently revealed their new already developed project of a pilot plant in Falkenhagen, Germany, based on the same idea (Hampton, 2013). As expected, the addition of hydrogen to natural gas is leading to a new mixture, which affects drastically the turbulent combustion's characteristics and stability. For example, a study (Cozzi & Coghe, 2006) is showing clearly that by using this type of mixture there are important changes in the flame front position and in the mean values of the temperature. They mark here also the need of closer investigations regarding the combustion of CH4-H2, for ameliorate the pollutant emissions, without affecting the stability of the combustion. Therefore, a more detailed view and more studies are needed in this new field, to be able to help us have a better understanding of the complete processes that emerge in the hydrogen enrichment combustion process.

The paper presented here is a part of the doctoral research of the first author and also the work for a government founded research program called HIDROCOMB (Carlanescu *et al*., 2015). The authors attempted some numerical simulations, aiming to highlight the main characteristics of the combustion of hydrogen-methane mixture, inside of the combustion chamber of a Garrett GTP30-67 gas turbine (Technical Manual, 1974), pointing the differences between the cases, related to the percentage of the hydrogen in the mixture.

2. The Setup of the Parameters

2.1. Computational Grid and Boundary Comditions

With the help of Solid Edge and ICEM CFD, licenced commercial software, the combustor chamber was represented in fine details. In order to reduce the computational power requested, the grid was simplified and divided in half, using symmetry and periodicity conditions available in the software.

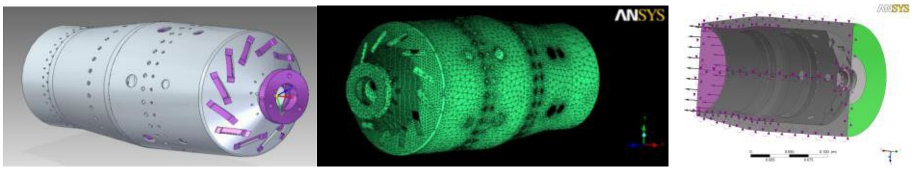


Fig. 1 − The 3D CAD model and the computational grid.

In this way, a domain made of tetrahedral finite volumes resulted, with a discretisation grid consisting of 1,029,166 elements and 169,250 nodes, with an average cell size of 1 mm. The grid was more dense in the flame area, near the injector. The boundary conditions were imposed based on the known data of the gas turbine (Technical Manual, 1974).

At the exit of the combustor an outlet pressure of 3.05 bar was set.

At the inlet the following parameters were set: inlet air mass flow rate 0.2 kg/s, inlet air temperature 430 K, inlet fuel temperature 360 K.

The numerical simulations were made using steady state, RANS analysis, with ANSYS CFX licenced commercial software. The turbulence model K-ε was used and for the combustion we choosed model Flamelet Probability Density Function (FPDF). The variation of the percentages of CH4-H2 in the mixture was made using the Reacted Integrated Flamelet (RIF) – flamelet library generation tool, as option of ANSYS CFX.

2.2. Three Different Approaches for the Variation of the Fuel Mixture Composition

The logical goal in changing the type and the composition of the fuel is to maintain the same performances of the motor, having in mind that the target is simulating a combustion chamber which must produce the same power, for a given constant load. Still, the existing literature (Tomczak *et al.*, 2002) take different approaches, so we decided to simulate and to point the differences between them:

Case A – Constant combustion power

The combustor thermal power was kept constant at 70.0126 KW, corresponding to the mass flow rate 1.4 g/s of the Garret GTP 30-67 (Technical Manual, 1974).

$$P = m_c * Q_i \qquad (1)$$

where: P – theoretical combustor power, [KW]; m_c – fuel mass flow rate, [kg/s] Q_i – calorific fuel power, [Kj/Kg]

Also, the percentage of hydrogen was changed for each case.

Case B – Constant volumetric flow

In order to have a constant volumetric flow, since the section is fixed, only a constant speed had to be set for the fuel inlet.

$$Q = v * A \qquad (2)$$

where: Q – volumetric flow rate, [m^3/h]; v – inlet fuel speed, [m/s]; A – section at fuel inlet, [m^2]. The speed of fuel inlet was set to 49.073 m/s, measured in case A. Also, the percentage of hydrogen was changed for each case.

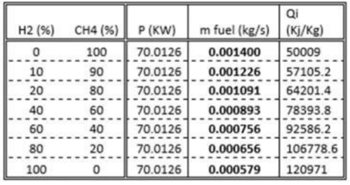
Case C – Constant mass flow

The mass flow rate was kept constant at 1.4 g/s.

Also, the percentage of hydrogen was changed for each case.

Table 1

The Three Approaches for the Fuel Mixture Variation

<table>
<tr><td>Case A</td><td>Case B</td><td>Case C</td></tr>
<tr><td>Constant combustion power</td><td>Constant Volumic flow</td><td>Constant mass Flow</td></tr>
<tr><td>P = mc * Qi

<table>
<tr><th>H2 (%)</th><th>CH4 (%)</th><th>P (KW)</th><th>m fuel (kg/s)</th><th>Qi (Kj/Kg)</th></tr>
<tr><td>0</td><td>100</td><td>70.0126</td><td>0.001400</td><td>50009</td></tr>
<tr><td>10</td><td>90</td><td>70.0126</td><td>0.001226</td><td>57105.2</td></tr>
<tr><td>20</td><td>80</td><td>70.0126</td><td>0.001091</td><td>64201.4</td></tr>
<tr><td>40</td><td>60</td><td>70.0126</td><td>0.000893</td><td>78393.8</td></tr>
<tr><td>60</td><td>40</td><td>70.0126</td><td>0.000756</td><td>92586.2</td></tr>
<tr><td>80</td><td>20</td><td>70.0126</td><td>0.000656</td><td>106778.6</td></tr>
<tr><td>100</td><td>0</td><td>70.0126</td><td>0.000579</td><td>120971</td></tr>
</table></td><td>Q = v * A
v = 49.073 m/s
H2 variation – 0-100%</td><td>mc = 0.0014 Kg/s
H2 variation – 0-100%</td></tr>
</table>

The results are as logically anticipated: (Table 1)

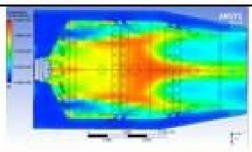
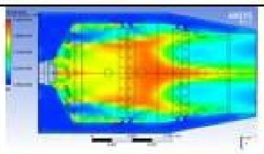
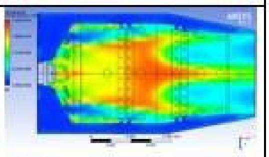
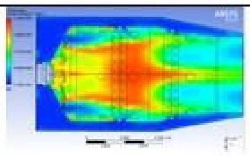
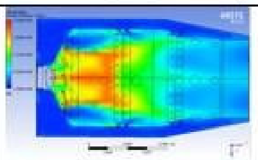
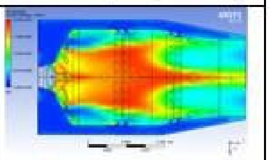
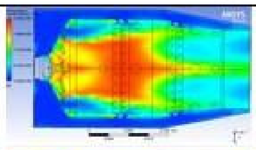
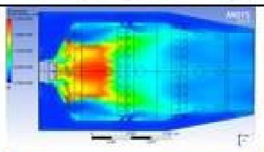
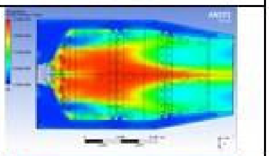
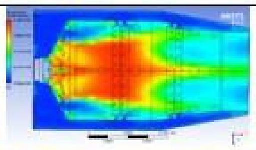
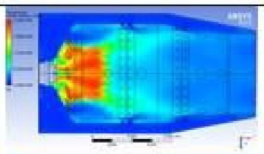
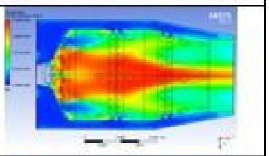
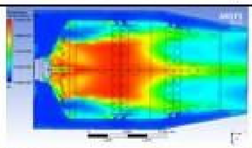
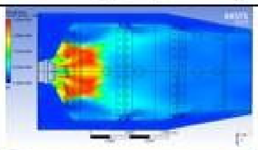
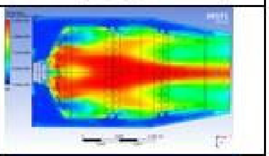
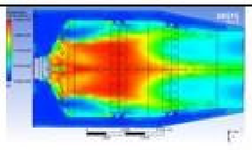
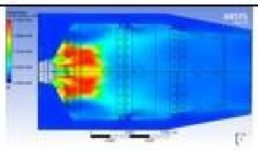
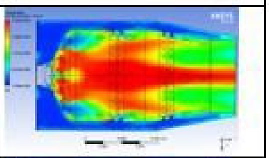
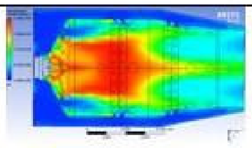
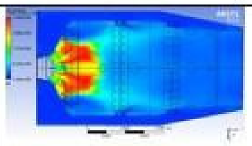
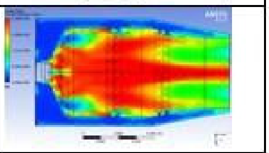
– For case A, the temperature increases by adding more H2 and the flame front is getting closer to the combustor injector and to the front walls.

– For case B, the temperature also increases, but the flame is diminished drastically. Due to the considerably lower density of H2, keeping volumetric flow constant, by adding more H2, the massic flow decreases.

– For case C, the temperature and the shape of the flame are substantially increased, because by adding more H2, the calorific power of the fuel is raised.

Table 2

The Temperature Diagrams for the Three Approaches

	A – Constant power	B – Constant volumetric flow	C – Constant mass flow
H2 0% CH4 100% (mass fractions)			
H2 10% Ch4 90% (mass fractions)			
H2 20% CH4 80% (mass fractions)			
H2 40% CH4 60% (mass fractions)			
H2 60% CH4 40% (mass fractions)			
H2 80% CH4 20% (mass fractions)			
H2 100% CH4 0% (mass fractions)			

3. Results

As mentioned before, having in mind the need of keeping the same performances of the combustor, the paper is focusing on the results of the first case, in which the theoretical thermal power is kept constant.

Table 2 is showing the variation of the mean temperature field, as the percentage of added hydrogen is changed in the composition of the fuel. The shape of the flame is changing more till the 20% hydrogen limit and after this it remains approximately the same. But the big differences between H2 0% and H2 100% can be seen in Fig. 2.

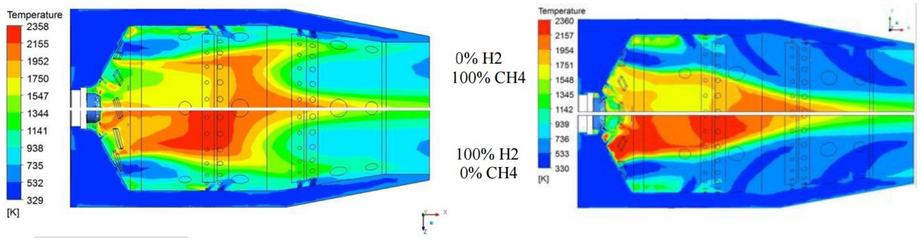


Fig. 2 – Mean temperature fields in two longitudinal sections.

The temperature was measured for all the cases also by a longitudinal axial line in Fig. 3. The movement of the flame front can be observed and the increasing temperature for higher concentrations of hydrogen.

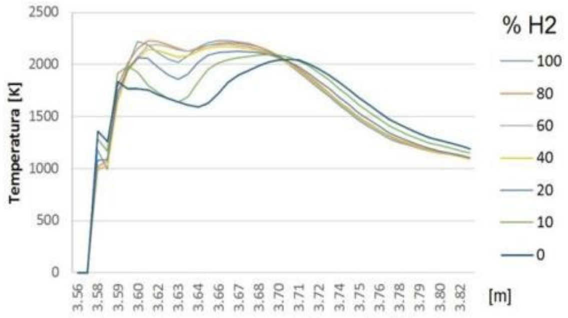


Fig. 3 – Temperature variation for an axial measurement line.

The differences between the two types of fuels can be further studied in a transversal plane, in Fig. 4. The temperature field is not symmetrical here, an unsteady effect that is caused probably by the low resolution grid. A more dense mesh of the grid can lead to better results, but with higher computational power needed, which are not available for the moment.

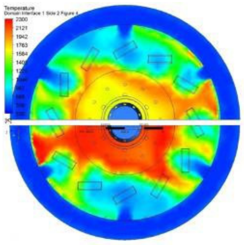
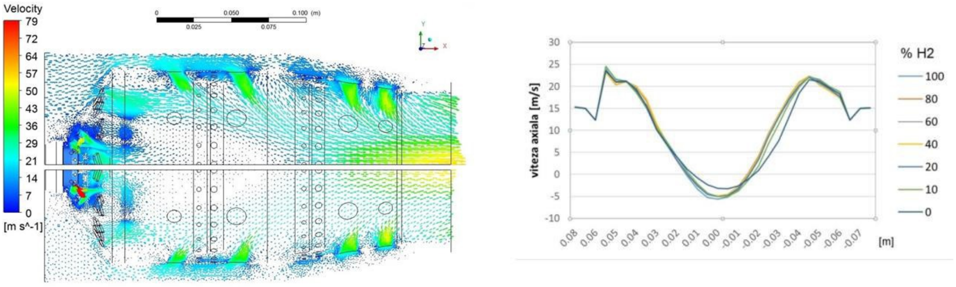


Fig. 4 − Temperatures field at a transversal section (75 mm from the injector).

The mean velocity field representation (Fig. 5*a*) is showing the recirculating zones that influence the shapes of the flame for both types of fuel. For methan 100% it is clearly observed that the velocity values are bigger at the exit of the combustor than those for hydrogen 100% and this can be explained by the different temperatures of the flames: the energy added to the combustor that is transformed more in kinetic energy in the first case, for the second case it is transformed more to internal energy, due to higher temperature. Through a transversal measurement line no major differences are observed between the velocities, with the variation of the fuel composition (Fig. 5*b*).



a *b*

Fig. 5 − Velocity vectorial field (*a*) and transversal measurement lines at 350mm from combustor (*b*).

4. Conclusions

The presented results are showing very clearly some of the main differences and the changes in the characteristics for the combustion of the mixtures of methane and hydrogen, in various proportions.

The existing literature presents distinct methods regarding how to change the composition of the mixture. The paper presented and simulated three main approaches, but still we consider more relevant to keep the same characteristics of the combustion chamber, by targeting a fix value for the thermal power. Therefore this solution is adopted and studied for the results.

Even if the RANS simulation method is not considered 100% accurate and as other simulating methods has its limitations, it can still conduct us to obvious conclusions: the temperature is clearly rising and the flame front is moving towards the injector and closer to the front walls of the combustor. This is an unwanted effect that can have negative results, like lowering the resistance of the materials and even damaging the combustion chamber. Without changing the constructive design of the combustor, new solutions of cooling and reducing the temperature are needed, or redesigning the injection system. The installations and existing devices that aim to benefit from the hydrogen enrichment of natural gas must take all these into consideration.

Other predictable effect of the hydrogen addition to the mixture can be the increase in production of thermal NOx, since higher temperatures lead to thermal dissociation. Unfortunately, the chemical mechanism used for this numerical simulation is not able to mark any result in this direction, but references to this fact can be found in the literature (Cozzi & Coghe, 2006).

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SIMULĂRI NUMERICE PENTRU ARDEREA DIFUZIVĂ A UNUI AMESTEC DE HIDROGEN-METAN, ÎN INTERIORUL UNEI CAMERE DE ARDERE A UNEI TURBINE CU GAZE

(Rezumat)

Articolul descrie rezultatele simulărilor numerice, folosind abordarea Reynolds Averaged Navier – Stokes, în camera de ardere a unei turbine cu gaze de la micromotorul Garrett GTP30-67. Modelul de turbulenţă folosit este K-ε, iar modelul de combustie ales este Flamelet Probability Density Function (FPDF). Sunt prezentate trei abordări diferite pentru a varia compoziția amestecului de combustibil, amestecând CH4 şi H2, în procente de la 0% la 100%. Aceste trei cazuri sunt comparate, apoi sunt detaliate rezultatele numai pentru primul dintre ele, deoarece se urmăreşte păstrarea parametrilor funcţionali ai motorului la valorile originale. Din diagrama alăturată, care reprezintă comparaţia între 0% H2 şi 100% H2, dar şi din mai multe rezultate cuprinse în articol, se poate trage concluzia că la o cantitate mai mare de hidrogen, temperatura creşte, iar frontul flăcării se deplasează către partea frontală a camerei, apropiindu-se de injector. Acest lucru poate duce la distrugerea echipamentului. De asemenea, o temperatură mai mare duce la creşterea emisiilor de NOx.