Modifications of an existing microturbine to use hydrogen as fuel

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ABSTRACT

Distributed energy technologies are playing an increasingly important role in the energy portfolio given that they can be used to meet power demands, as well as cooling and heating needs. Distributed power generators typically rely on natural gas or renewable resources, therefore these generators can be quieter and less polluting than large power plants, which makes them suitable for on-site installation.

Hydrogen would be an alternative fuel in the mid-term future due to its energy properties and its production potential by means of different sustainable and environmentally friendly methods. The objective of the present work is to show the steps that were taken in order to use hydrogen as fuel in a conventional microturbine operating with natural gas, with a maximum output power of 30kW. If the use of microturbines for distributed generation can lead to improved efficiency and lower energy costs, particularly in combined cooling, heating, and power (CHP) applications, the use of hydrogen as its operational fuel will additionally lower the environmental impact of these systems.

The results of the work will provide knowledge about how to adapt these systems to its use with hydrogen as fuel, and will contribute to the hydrogen penetration in the global economy.

Keywords: Hydrogen, microturbine, fuel, modification, generator

1. Introduction

Nowadays there is a great concern about the depletion of conventional energy sources, the energy dependence and the effects that these energy sources have on the climate. There are numerous researches that study the problems of increasing atmospheric CO_2 concentrations in the Earth´s atmosphere and the possible future climatic changes which may ensue [1]. In this context, hydrogen appears as the preferred energy carrier in the mid-long term [2][3], as it can be obtained from renewable energy sources in a distributed manner and its combustion does not produce CO_2 emissions.

On the other hand, there are several technical and economical barriers that must be overcome before a worldwide use of hydrogen is achieved [4]. One of the main barriers is the need to set up new infrastructures, because this increases enormously the cost of hydrogen technology implementation if it is compared with conventional energy technology.

Currently the majority of electric power production systems use combustion to transform the chemical energy bound in the fuel into thermal energy that can drive a piston or turn a turbine. Microturbine generators (MTGs), are ideal devices for distributed power generation applications which have demonstrated thousands hours of operation. By generating power where it is needed (e.g., tertiary sector), the use of MTG's can increase the reliability of the electrical power and allows use the waste of heat to meet other energy requirements at the site, increasing the efficiency of energy fuel use. [5][6] and then reducing the emissions. MTGs offer an attractive option for reducing pollutant emissions in comparison to reciprocating systems [7].

The use of hydrogen as fuel for MTGs yields as the only emissions water vapor and NO_x when air is used as oxidizer [8]. Water vapor also contributes to greenhouse effect if it is released in the upper atmosphere, but its residence time is much less than CO_2. On the other hand, NO_x must be limited, because it is a precursor for photochemical smog, contributes to acid rain, and causes ozone depletion.

As hydrogen combustion produces gas temperatures around 125K greater than natural gas combustion for a given equivalence [9] and thermal NO_x production doubles for every 90K temperature increase when the flame temperature is about 2200K [10], the NO_x production could be a problem that must be controlled when hydrogen is used as fuel. In this study the hydrogen combustion temperature is controlled by injecting more air in the combustion zone than what is needed for CH_4 combustion.

This research tries to pick out the necessary modifications that must be implemented in a commercial natural gas MTGs to use hydrogen as fuel. This way this project contributes in a direct approach to the introduction of hydrogen in the current economy, as costly and new infrastructures are not needed. The paper contains a first phase of the work devoted to the CFD (Computational Fluid Dynamics) study that was developed previously to apply and to test the modifications needed to adapt the selected MTG to use hydrogen.

2. System description and CFD modeling

For this study a market study was conducted to select a microturbine that meets the following criteria:

- Commercial and reliable technology with thousand hours of work
- Many successful installations.
- Not expensive equipment.

As a result a 30kW natural gas microturbine with millions of documented runtime operating hours was selected (hereinafter "the MTG").

Analyzing the results of several characterization tests of the MTG done by the manufacturer, some modifications were proposed in order to adapt the microturbine to use H_2 as fuel. To check that the modifications worked properly, two CFD simulation of the combustion chamber were carried out and compared between them. One simulation with CH_4 as fuel and the actual geometry of the combustion chamber and the injectors and another whit H_2 as fuel and taking into account modifications of the geometry. The findings of this study will be shown in the following paragraphs.

2.1 System description

Table 1 shows the main technical characteristics of the MTG:

Net Power Output	30 ± 1 kW net
Net Efficiency (Lower Heating Value)	26 ± 2%
Nominal Net Heat (Lower Heating Value)	13,800 kJ/kWh

Table 1: Main technical characteristic of the MTG

The MTG has an annular combustion chamber with three injectors. Each injector delivers fuel from two inlet points, directly from the pilot tube, or through the premix tube. The pilot tubes supply fuel directly into the combustion chamber where it mixes with air. When the premix tubes are used the air/fuel mix is done prior to entering the combustion chamber. The operation mode of the injector varies at different power levels.

- Below 7kW, the microturbine operates with a single pilot injector.
- From 7kW to 22 kW, all three pilot injectors are switched on.
- Above 22 kW, all three injectors are feed only by premix tubes.

In this study the turbine will only be operated with hydrogen between 0-22kW in order to avoid working in premix mode. In future studies the operation of the MTG with premixed H_2/air will be considered.

2.2 CFD modeling

The commercial CFD tool ANSYS Fluent was used to simulate the behavior of the combustion chamber.

Prior to develop the simulation was necessary to define the geometry and the boundary conditions of the combustion chamber.

Geometry of the combustion chamber.

The dimensions and geometry of the actual combustion chamber and injectors were obtained from technical documents and doing in-situ measurements.

Fig. 1: Geometry of the combustion chamber

ANSYS ICEM CFD software was used to generate two meshes, one with the actual geometry and another including the modifications:

Actual geometry mesh properties (CH_4):

- Number of cells: 4.042.015
- Mean quality: 0,7765557
- Minimum quality: 0,0162283

Modified geometry mesh properties (H_2):

- Number of cells: 4.973.062
- Mean quality: 0,7585809
- Minimum quality: $8{,}67252 \cdot 10^{-5}$

The quality of the meshes can have important implications in the numerical solution of the CFD problem. A bad quality mesh can cause convergence difficulties, bad physic descriptions and diffuse solutions. [11]

Boundary conditions.

Boundary conditions are a key point for accurately CFD modeling. So to determine in accurately way the temperature and mass flow of inlet gases in the combustion chamber it was necessary to take into account some tests results provided by the manufacturer. Basically the tests consisted in the determination of the temperature and mass flow rate of the exhaust gases for several net power levels for an inlet air temperature of 15ºC. Applying these data in the following equation system and solving it, the inlet and outlet temperature of the gases at the combustion chamber were calculated. In this equation system the effect of fuel mass in the whole flow was neglected.

(1) $$\frac{T_{i\_ad}}{T_{amb}} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

(2) $$\eta_r \cdot \dot{m} c_p \cdot \left(T_{f\_exh} - T_{i\_exh}\right) = \dot{m} c_p \cdot \left(T_{f\_ad} - T_{i\_ad}\right)$$

(3) $$\Delta \dot{Q}_{fuel} = \dot{m} c_p \cdot (T_{f\_comb} - T_{i\_comb})$$

(4) $$-\Delta P_{elect} = \eta_c \cdot \eta_t \cdot \eta_m \cdot \eta_g \cdot \dot{m} c_p \cdot (T_{f\_turb} - T_{i\_turb})$$

(5) $T_{i\_exh} = T_{f\_turb}$

(6) $T_{f\_ad} = T_{i\_comb}$

(7) $T_{f\_comb} = T_{i\_turb}$

Where:

T_{amb}: Ambient temperature = 15ºC

p_2/p_1 : Compressor pressure ratio = 3,7

γ: Air adiabatic coefficient = 1,4

c_p: Air heat capacity ratio, *f (T, p)*

η_r : Recuperator effectiveness = 0,85

η_c : Compressor efficiency = 0,78

η_t : Turbine efficiency = 0,85

η_m : Mechanical efficiency = 0,99

η_g : Generator and inverter efficiency = 0,90

ΔQ_{fuel}: Fuel flow energy

ΔP_{elec}: Net electrical power

$\dot{m}$: Exhaust mass flow

T_{i_ad}: Inlet air temperature after compressor

T_{f_ad}: Inlet air temperature after recuperator

T_{i_comb}: Inlet air temperature before combustion chamber

T_{f_comb}: Combustion gases temperature after combustion chamber

T_{i_turb}: Combustion gases temperature before turbine

T_{f_turb}: Combustion gases temperature after turbine

T_{i_exh}: Combustion gases temperature before recuperator.

T_{f_exh}: Combustion gases temperature after recuperator, exhaust gases temperature

The parameter values were obtained from technical reference manuals of the MTG. The temperatures locations can be seen more clearly in the Fig. 2

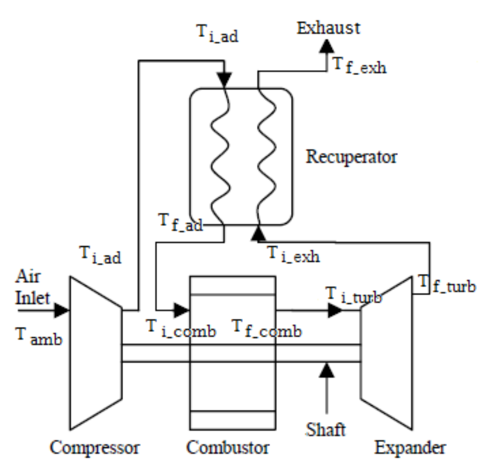

Fig. 2: Temperature locations

Using these temperatures and the actual geometry of the combustion chamber, the inlet and outlet velocities of the gas flow in the combustion chamber and the temperature of combustion chamber walls were estimated.

2.2 Validation

To validate these boundary conditions, the T_{f_turb} was measured for different net powers and compared with the CFD simulation results (Fig. 3). The simulated T_{f_turb} was calculated applying equation (4) on the simulated T_{f_comb}.

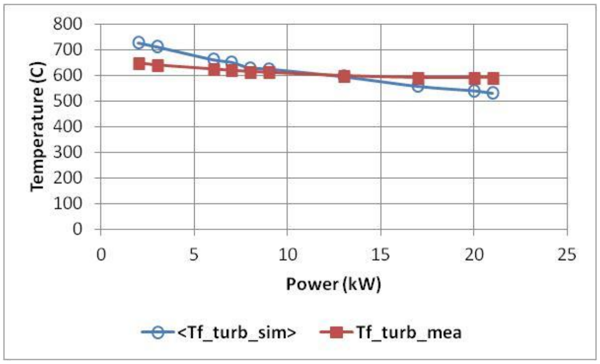

Fig. 3: Comparison of the mean simulated T_{f_turb} (<Tf_turb_sim>) and the measured T_{f_turb} (Tf_turb_mea)

As can be seen in Fig. 3, both curves present the same behavior; both temperatures decrease with the power, but the simulated one do it faster. If relative mean and max error are calculated:

- Mean error: 4 ± 3%
- Max error: 7% for 2,0kW and 21kW

So the mean relative error for this magnitude is below 5% and the differences of both temperatures can be partially explained, because the simulated one is a mean value while the experimental was measured in one point.

Comparing the simulated and measured maximum temperature, T_{f_turb} , the last one is always lower that the first one (Fig. 4).

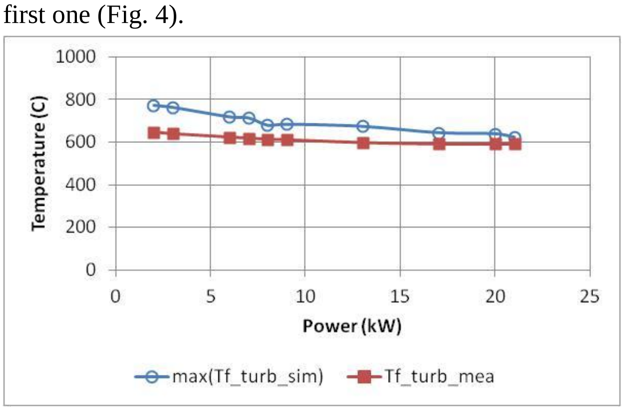

Fig. 4: Comparison of the max simulated T_{f_turb} (<Tf_turb_sim>) and the measured T_{f_turb} (Tf_turb_mea)

Once the CH_4 simulations were validated, the simulated field of temperatures and velocities were analyzed in order to understand the behavior of the combustion chamber and to elaborate proposals to adapt the microturbine to use hydrogen as fuel.

Four different solutions were proposed but only the results of the best solution are going to be shown in this paper. The proposed modifications of this solution can be summed as follow:

- Increase the mass air flow in the injection area to dilute the effects of high hydrogen combustion temperatures.
- Reduction of the inlet H_2 velocity to keep it lower than air velocity and use the air to envelope the fuel in order to protect combustion chamber walls.

To do this, only the injectors were modified.

3. Results and discussion

CFD simulation is a powerful tool that facilitates the analysis and reduces the number of experimental test on combustion chamber. The CFD based on the Finite Volume Method, has been widely used for the analysis of annular and tubular combustion chambers [12]. Basically two kind of CFD simulation were carried out to check if the above mentioned modifications meet the objective of emissions reduction and, at the same time, keep the structural integrity of the combustion chamber:

- Temperature fields CFD simulation
- NO_x production CFD simulation

3.1 Temperature field CFD simulation:

The temperature fields of CH_4 and H_2 were compared for several power outputs in order to find the exact hot spots and quantify them. The most significant cut planes to study the temperature field are represented in the Fig. 5.

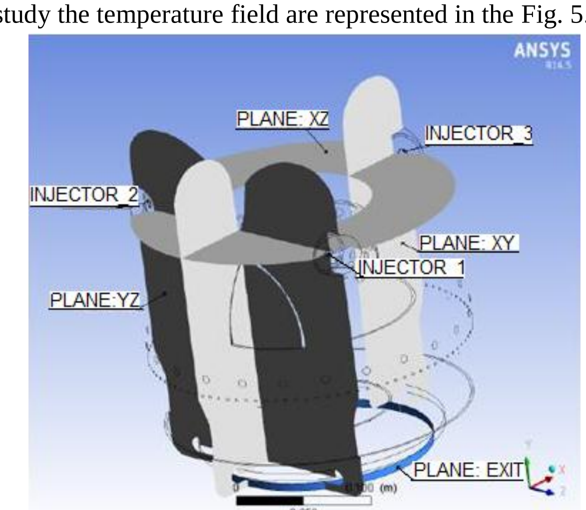

Fig. 5: Analyzed Cut planes of the temperature fields

Temperature field in the combustion chamber was analyzed in a detailed way for the phases of the MTG operation and associated power outputs as indicated in Table 2:

MTG operational phase	Analyzed power outputs
Only 1 injector operative	2, 3 and 6 kW
Transition 1 to 3 injectors	7 and 8 kW
3 injectors operative	9, 13, 20 and 21 kW

Table 2: Combustion chamber temperatures: Case studies

The above mentioned case studies cover entirely the behavior of the combustion chamber for MTG operation with the pilot tubes as indicated in paragraph 2.

From the analysis of the simulations results, the behavior of the combustion chamber can be explained in three ranges of power output:

- Less than 6kW:

Fig. 6 shows the zones where the H_2 combustion temperature is higher than CH_4 temperature. In general this doesn't happen near the combustion chamber walls. In some small regions of the vicinity of the walls, the H_2 combustion temperature is only slightly higher than the one for CH_4 (less than 10%).

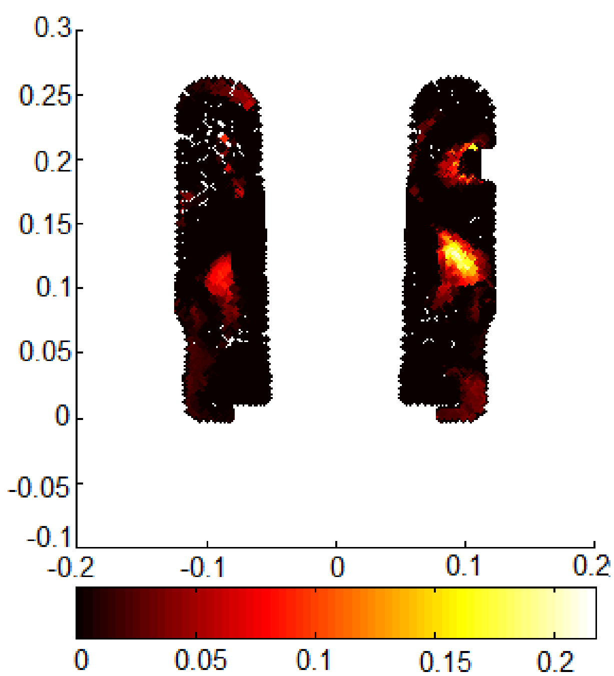

Fig. 6: XY plane for 2kW. Relative variation of the H_2 temperature for the regions where the H_2 temperature is higher than CH_4 temperature.

- 6kW to 7kW:

Fig. 7 represents the relative temperature fields for H_2 and CH_4 combustion. The H_2 temperature field is 10% higher than the CH_4 temperature field in a very localized zone next to the walls. In this case the flow is tangential to the walls and the wall is refrigerated by the air from the recuperator.

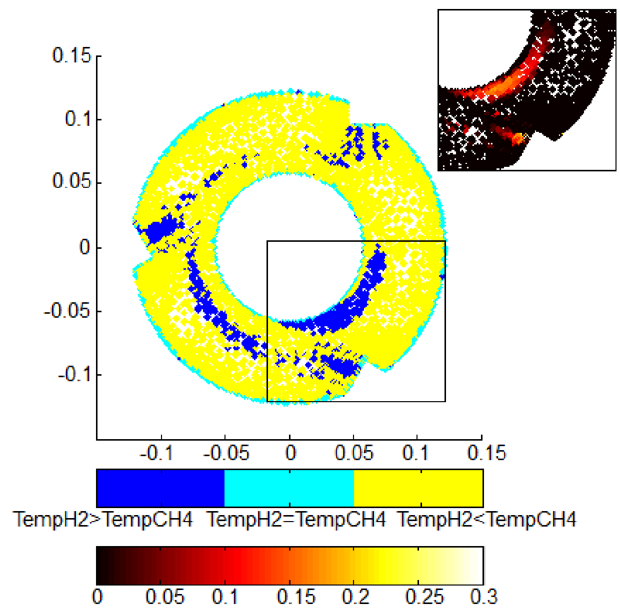

Fig. 7: XZ plane for 7kW- Regions where the H_2 temperature is higher than CH_4 temperature. Boxed figure, relative variation of the H_2 temperature for the zones, where the H_2 temperature is higher than CH_4 temperature.

- 8kW to 21kW:

As shown in Fig. 8, in the power range from 8kW to 21kW, where the three injectors are operative, there isn't any problem. The few regions where the H_2 temperature field is higher than CH_4 temperature field, the flow direction points to the interior of the combustion chamber.

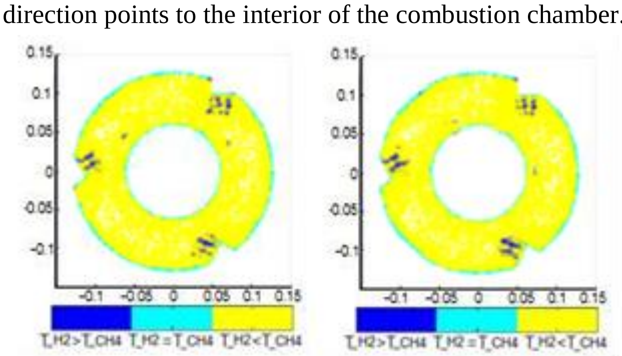

Fig. 8: XZ plane for 8kW (left) and 21kW (right) Regions where the H_2 temperature is higher than CH_4 temperature.

In summary, it was only found at power levels between 6,0 and 7,0 kW a very localized area where the H_2 temperature field is higher than CH_4 temperature field in the vicinity of the combustion chamber walls. But in this area the combustion gas flow is tangential to the wall and the wall is refrigerated by air from recuperator, so it is expected that this area does not jeopardize the structure of the combustion chamber. Therefore, from the CFD simulations it can be stated that with the modified injectors the combustion chamber of the MTG works properly with hydrogen as fuel.

3.2 NO_x production CFD simulation:

To estimate the NOx production two CFD simulations were done, one using CH_4 as fuel and another using H_2. NOx concentrations were analyzed at surface PLANE Exit (Fig. 5).
Firstly to compare the results of both CFD simulations, the CH_4 simulation results were validated comparing them with the experimental results of Ref. [13] (Fig. 9)

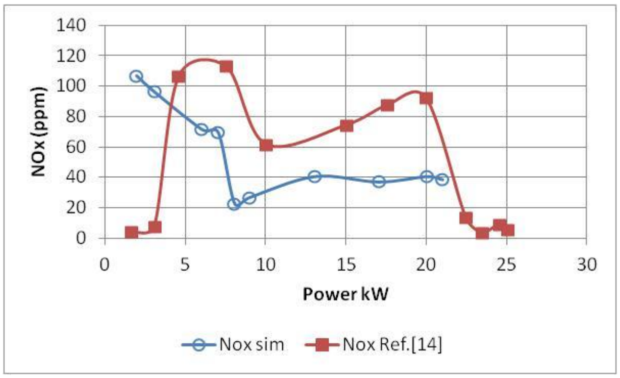

Fig. 9: NOx production for CH_4 simulation (NOx sim) and for measured results (NOx Ref. [13]).

As can be seen in the Fig. 9, the simulated NO_x production is approximately the half of measured NOx production in accordance with the results of Ref. [13]. But the CFD simulation is able to reproduce the behavior of NOx production for different power levels.

Table 3 and Table 4 gather the CFD results of NOx production for CH_4 and H2 combustion,

Power (kW)	NOx Emis (ppm)	Power (kW)	NOx Emis (ppm)
2	107,02	9	26,55
3	95,74	13	40,21
6	71,47	17	36,95
7	69,24	20	40,10
8	22,81	21	38,11

Table 3: NO_x concentrations at surface PLANE Exit for methane CFD simulation.

Power (kW)	NOx Emis (ppm)	Power (kW)	NOx Emis (ppm)
2	1848,92	9	57,27
3	1508,16	13	51,13
6	--	17	40,77
7	1586,98	20	38,21
8	49,26	21	34,73

Table 4: NO_x concentrations at surface PLANE Exit for hydrogen CFD simulation.
Table 3 and Table 4 show that NO_x concentration for H_2 combustion is between 15-18 folds higher than CH_4 combustion for power levels from 2 to 7kW.(only one injector operative). When three injectors are used the difference is not so dramatic, even for 20kW and 21kW the NOx concentration is lower for hydrogen than for CH_4.

These results are consistent with the evolution of the maximum temperature inside the combustion chamber (Fig. 10).

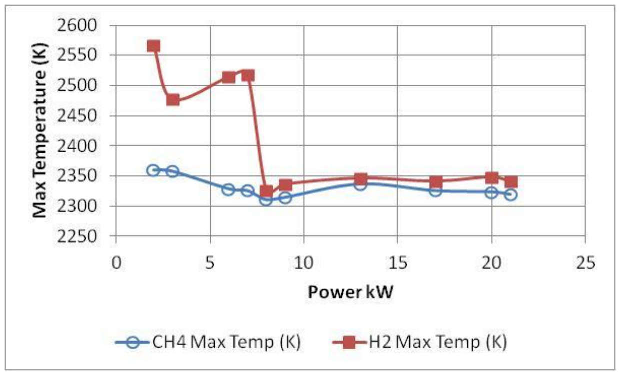

Fig. 10: Max temperature evolution of the combustion chamber for CH_4 simulation and H_2 simulation.

According to the calculation results, we can say that the proposed changes in the geometry of the injectors are good enough to ensure similar levels of NOx emissions than those obtained with CH_4 when the three injectors are operative.

4. Conclusion

This research demonstrates that is technically feasible to use H_2 as fuel in a commercial turbine, only modifying the injectors.

CFD simulation is a powerful and useful tool to analyze the performance of combustion chambers. Although with CFD simulation is not always possible to quantified NOx production in accurate way, however it is a good tool to simulate the general behavior of NOx production and to compare the emissions of two different combustion processes.

At the time of writing this paper, the selected MTG has been operated up to 10kW using hydrogen as fuel and the original CH_4 injectors with no apparently damages in the combustion chamber. The modified injectors adapted for H_2 use are being made.

Acknowledgements

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