

Hydrogen Combustion for an Industrial Gas Turbine Burner: OH* Chemiluminescence Preliminary Measurements

Christian Romano¹, Emanuela Gallo¹, Lorenzo Miris¹, Giulia Babazzi¹

¹ Baker Hughes / Nuovo Pignone Tecnologie s.r.l.

Via F. Matteucci 2, 50127, Firenze, Italy

christian.romano@bakerhughes.com; emanuela.gallo@bakerhughes.com; lorenzo.miris1@bakerhughes.com;
giulia.babazzi@bakerhughes.com

Abstract – In order to meet future decarbonization objectives and limit the negative effect on climate change looking at the energy production sector, gas turbine combustion plays a key role to get the “most” and the “best” energy from smart and clean fuels. Gas turbine combustors typically designed and operated with traditional fuels like natural gas and diesel oils, could meet several challenges when facing carbon-free fuels like hydrogen or ammonia; the high reactivity of hydrogen could lead to flashback issues in premixed flames and the nitrogen-bound nature of ammonia could lead to unacceptable levels of exhaust NO_x emissions. Understanding the behaviour of an existing combustion system when fuel nature is radically modified, is fundamental since it allows to identify the effort level for a potential design modification of the baseline or to conclude that a jump to a different combustion technology is necessary.

In this paper an innovative industrial gas turbine burner has been characterized in atmospheric conditions in terms of NO_x exhaust emissions together with a qualitative structure of the flame through OH* chemiluminescence imaging with pure hydrogen or hydrogen/methane mixtures as fuel. The present information represents also a good starting point in validating Computational Fluid Dynamics (CFD) codes, especially when non-conventional fuels are involved.

Keywords: combustion diagnostics, gas turbine burner, premixed flames, hydrogen combustion, OH* chemiluminescence

1. Introduction

In the last couple of decades combustion diagnostics techniques and, in parallel, combustion CFD simulations, have reached an extremely high level of complexity that changed radically the paradigm of both experiments and predictive models as already noted in the far 2009 by Connelly et al. [1].

Combustion CFD simulations proceeded through the development of different techniques depending on the spatial/temporal scale to be investigated (especially where turbulence/mixing plays a dominant role in the combustion process) and depending if any additional transport/chemistry mechanisms must be introduced: DNS should be in principle the most complete approach [2] but the computation effort in terms of CPU time could be excessively expensive such that RANS and LES approaches are preferred in some case to simulate specific flames' behaviours.

Regarding the experiments discipline, combustion science has a long tradition that considered the experimentation as the best way to explore and characterize flame behaviours, to validate new measurements techniques and to validate new combustion systems. Several measurement approaches have been developed along the years moving from intrusive techniques like physical probes to optical systems significantly less intrusive like direct emission analysis and excited emission analysis through lasers sources (typically considered not intrusive up to a certain level of laser power), [3].

Flame spectral analysis has been extensively used to provide qualitative information on the flame structure, shape, and position [4]. Chemiluminescent emissions occur when excited radicals such as OH*, CH*, C₂*, formed within the flame front, return from an excited energy state to a lower energy state by emitting light at a characteristic wavelength (e.g. OH* emits light around 310 nm); these radicals are typically considered as representative of the heat release rate from the flame and the light emission intensity can be correlated even with equivalence ratio (flame temperature) in certain conditions [7]. Today some research is also dedicated to find the best chemiluminescent signal ratio (between two different radicals e.g. OH*/C₂* for hydrocarbon combustion or OH*/NO* for ammonia combustion or with a spectral band intensity like violet from 350 nm to 400 nm for hydrogen combustion) that could support the development of compact smart devices to monitor combustion in industrial applications [8].

In Baker Hughes, the validation process adopted during the development of a gas turbine (GT) combustor runs through a series of test with increasing complexity from a first single-phenomena characterization up to the final

validation on the engine. The increasing complexity of gas turbine combustion systems and therefore the increasing costs of testing, the need to adopt fuels quite different from the traditional hydrocarbons, and the succeeding development of innovative CFD approaches, impose a new balance between experiments and modelling allowing modelling to replace in some case the experiment itself. This can be done if preliminary experiments provide appropriate and focused measurements for model calibration: some of these could be the OH* chemiluminescence.

Objective of this paper is to illustrate a preliminary experience done in Baker Hughes with OH* chemiluminescence on a gas turbine burner that is under development for the dry-low-NOx hydrogen combustion.

2. Experimental Facility

BlueRig test bench in Baker Hughes (BH) Nuovo Pignone Florence plant is a single-cup atmospheric combustion rig where BH executes explorative and preliminary test on fuel burners for its GT products.

The core of the test-bench (the test-article) is made by an internal flame-tube in Hast-X surrounded by a flow-sleeve and an outer vessel in AISI 310S; at the inlet section (right side of the Figure 1) fuel burner is engaged and the outlet section discharges exhaust gases towards the stack.

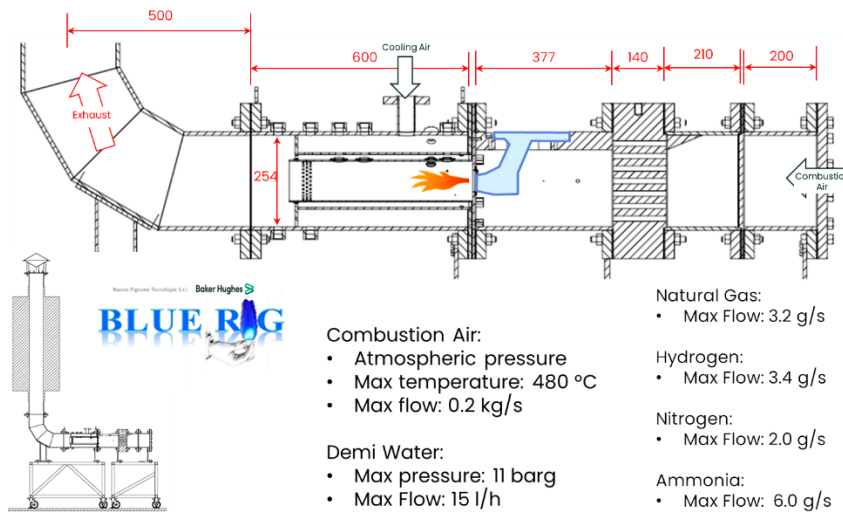


Fig. 1: Test-article cross-section, general dimensions, and test-bench capability
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In Figure 1, together with the test-article cross-section, some capability data are reported. A conceptual schematic of the test bench is made of air from plant network split into two mainstreams, one typically used for combustion and the other for test-article cooling. Fuel system is organized in such a way that each line to the fuel burner is equipped with a mixing pipe where different species can be fed; hydrogen and ammonia have their own skid for staged expansion, heating, flow controlling and safety. The tested fuel burner is a modification of the standard component of NovaLT™16 and NovaLT™12 and it is already described in previous papers [5, 6]; it is a fully premixed type made by four channels integrally printed in Additive Manufacturing with the main fuel injection in the premixer channel (Line 1) and a secondary injection downstream close to the burner tip (Line 2).

The optical access to the Flame-Tube is guaranteed through a plane quartz window 22 cm long from the burner tip. The Flame-Tube depicted in Fig. 2, is a square section made by four angular bars and four plates in the downstream zone (while in the upstream zone quartz glasses are interchangeable with metal plates).

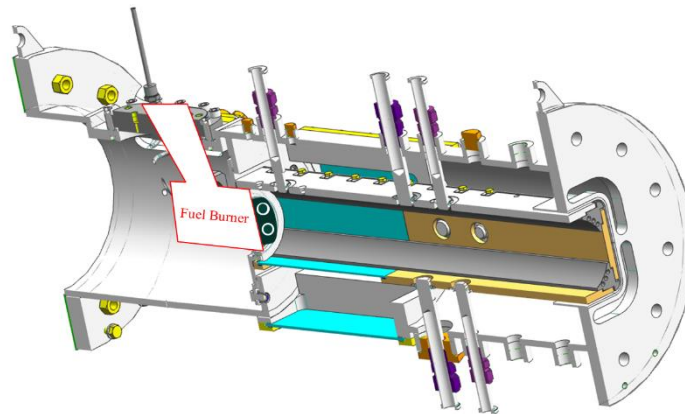


Fig. 2: Flame-Tube cross-section.
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Ignition of the test article is realized through an electric spark-plug (Champion) typically used on GT combustors. After ignition phase, the test bench is brought to test point conditions targeting the burner pressure drop and flame temperature according to the test-matrix indications; variations are realized through control of the air and fuel mass flows.

Fuel burner is fed through one fuel line with variable fuel composition in terms of methane, hydrogen, and ammonia. Emission measurement probe is located at 2000 mm along the flow path from the fuel burner; the probe sucks a uniform exhaust gas mixture from the cross section of the stack. Gas mixture is first dried and then analyzed by the devices listed in the Table 1 with the related physical principle of measurement and expected accuracies in the measurement ranges.

Table 1: Exhaust emission measurement devices characteristics.

Chemical species	Analyzer / Principle	Range of measurement	Expected accuracy
NO _x	CAI Noxmat 600 / Chemiluminescence	0 – 30 ppmvd	0.3 ppmvd
O ₂	Siemens Oxymat 6E / Paramagnetic	0 – 25 % vol	0.4 % vol
CO ₂	Siemens Ultramat 6E / Infrared	0 – 5%	0.1 % vol

Fuel mass flows are measured and regulated through Bronkhorst mass-flow-controllers while combustion and cooling air flows are measured by Coriolis devices and regulated through control valves; devices are listed in Table 2.

Table 2: Mass flow meters for all the fluids entering the test-article.

Fluid	Mass flow device	Accuracy
Comb. Air	Emerson CMFS075	0.5% of reading
Cooling Air	Yokogawa RCUS38S	0.3% of reading
CH ₄	Bronkhorst F-202AI-M20	3% FS
H ₂	Bronkhorst F113AI-1M0	3% FS
NH ₃	Bronkhorst F-113AI-M50	3% FS

The test rig is equipped with other sensors like thermocouples, static pressures, pressure pulsation probes and flame detector, all necessary for the safety and control of the test bench.

Methane fuel has a purity of about 98.7% in volume, the rest being high-hydrocarbons and 0.5% CO₂ (analysis provided from the natural gas plant network and verified through microGC PGC490 gas chromatography).

The test rig has been characterized in terms of air splits along with the internal flow path: some dedicated flow test allowed to implement a flow network in Altair® Flow simulator™ [10] to retrieve the flow split along the test rig. Combustion air is divided between the air flowing into the burner and the air used for the heat shield and angular bars cooling. The cooling air is instead partitioned between the leakage at the instrumentations interface and the cooling rows placed at the end of the flame tube. The model is run imposing the combustion and cooling air mass flow inlets and a pressure at the outlet of the test rig. All the geometric features are simplified in a series of orifices, considering the actual

test rig geometry. The effective area of some of the orifices composing the flame tube were tuned to match the experimental pressure drop along the combustion chamber. The chamber flow split is then retrieved from the flow network.

For all test points, 80% of the total combustion air feed the flame primary zone while the remaining 20% is used the angular bars dedicated cooling.

Measurements of chemiluminescence from the OH* radical were employed to detect the reaction zone and its position in various operating conditions, as its emission can be considered a heat release marker [27–29]. In order to carry out this type of measurements, a camera coupled with an image intensifier has been used. The camera Phantom VEO-640L, was coupled with the IRO-x image intensifier through a relay lens. In addition, a Nikon UV 85 mm f /2.8 lens together with a bandpass filter (OD= 4.0; CWL = 310 +/- 2 nm; FWHM = 10 +/-2 nm) were mounted on the image intensifier to be able to capture the OH* transition, which has its peak emission intensity in the UV spectrum. OH* chemiluminescence images were acquired at 400 Hz recording about 1000 images. The instantaneous snapshots were time-averaged to remove the influence of any unsteady phenomena and analyse the flame steady state structure. In addition, the averaging process smooths out the chemiluminescence intensity peaks associated with unsteady structures and reduce the measurement noise. Throughout this test campaign, the intensifier gain was kept constant while the gate was varied between 0.4 ms and 2 ms depending on the flame luminosity (i.e., tested conditions). In order to make a truthful comparison, for the cases acquired with different intensifier gate values, each averaged test condition was normalised over its maximum intensity value. Thanks to this operation, the aforementioned cases were compared in terms of flame shape and position and extension of the reaction zone.

The main parameters of the tested conditions are summarized for each test point in the table below. For proprietary reason, the flame temperature was scaled with a typical gas turbine base load flame temperature:

Table 3: Flame conditions for each test points (TP) where OH* chemiluminescence has been gathered.

TP	Fuel [% vol]	Line1 [-] / Line2 [-]	Tflame* [-]
2	H2	1/0	0.86
3	H2	1/0	0.92
4	H2	1/0	1
9	H2	0/1	1
8	H2	0.2/0.8	1
7	H2	0.4/0.6	1
6	H2	0.6/0.4	1
5	H2	0.8/0.2	1
11	NG	1/0	1
10	NG (10) / H2 (90)	1/0	1

Combustion and Cooling air temperature was maintained constant at 390°C while pressure drop across the flame tube was running between 3.6 and 4% of inlet pressure.

3. Results and Discussion

Normalized NO_x at 15%O₂ (due to proprietary reason) have been plotted versus normalized flame temperature with 100% hydrogen as fuel fed through the Line 1 (fully premix). As depicted in fig.3, NO_x shows an increasing trend with flame temperature; this is expected according to the typical chemical mechanism “thermal-NO_x” [9]. OH* images show that increasing the flame temperature, the anchoring edge of the flame (the inception of OH* radicals’ formation) moves closer towards the burner tip. In addition, the flame length slightly reduces while maintaining the same overall shape. For each image, an average chemiluminescence intensity is calculated and plotted against the flame temperature as showed in the upper graph of Figure 3. According to the increase in NO_x emissions, as the flame temperature rises, the averaged OH* intensity grows linearly.

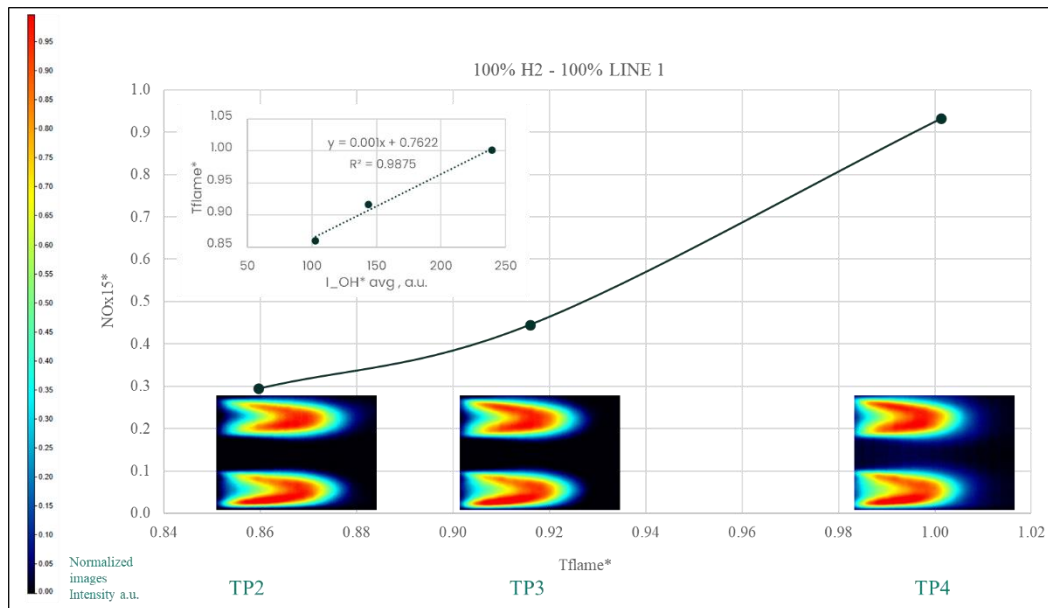


Fig. 3: Sensitivity of normalized NOx at 15%O2 versus normalized flame temperature (solid circles). OH* images for the three test-points (normalized images). In the top-left box it is reported the normalized flame temperature versus average OH* intensity in a.u.

At the same flame temperature, some test-point has been gathered by changing the fuel mass flow ratio between Line 1 and Line 2. In fig.4 the trend of normalized NOx at 15% O2 versus Line 1 flow split has been reported. According to the expectations, NOx decreases as the combustion mode moves from partially premix to fully premix. The OH* images show an interesting behaviour with respect to the combustion mode highlighting the flame change in shape and position; in partially premix mode the flame structure is characterized by a small zone with the highest OH* concentration and a wider area where OH* is still present at lower intensities. When Line 1 reaches 80%, the OH* dispersion reduces significantly toward a full containment in the fully premix flame zone.

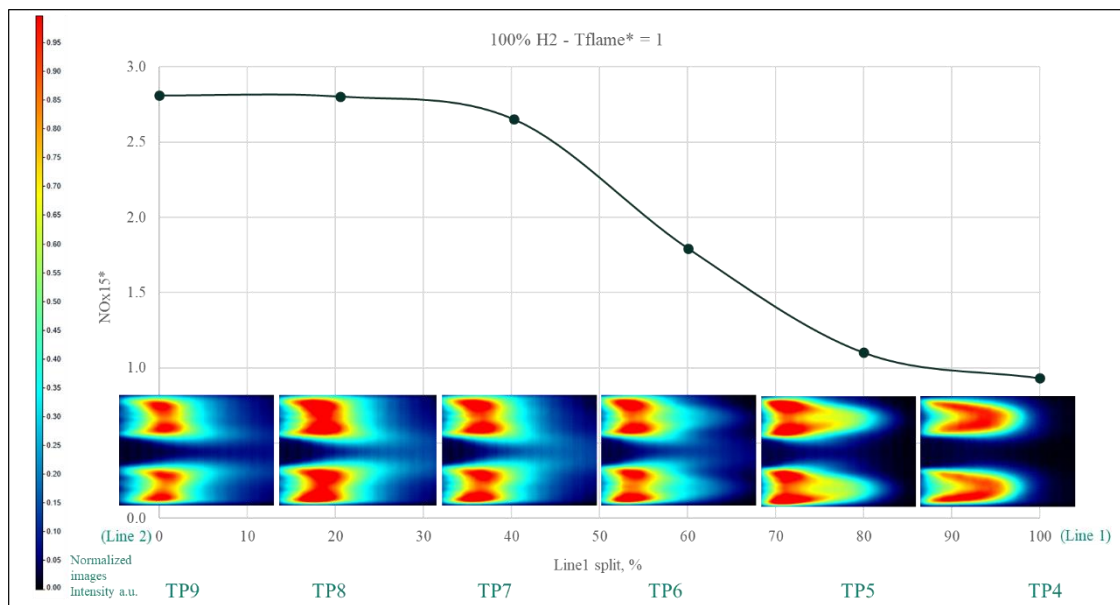


Fig. 4: Sensitivity of normalized NOx at 15%O2 versus Line 1 fuel mass flow split (solid circles). OH* images for each test-points (normalized images).

Finally, some sensitivity to the fuel composition has been explored through mixing natural gas with hydrogen toward full natural gas as reported in fig. 5. As expected, normalized NO_x emissions are significantly higher with pure hydrogen; the NO_x factor between pure hydrogen and pure methane is higher than the expected (i.e., Zeldovich mechanism would predict 3.5 while test data show a number around 7). An important contribution is due to the slightly difference found on the flame temperature between natural gas and hydrogen during post-processing, but in any case, a better investigation would be required. As the hydrogen content decreases, the flame length start increasing as can be seen comparing the OH* distribution of TP 10 and TP 4. OH* images present a radical change of in the flame shape when 100% natural gas is reached, and a flame front cannot be properly detected. Indeed, methane combustion is no more confined in a certain region but spreads all along the flame tube

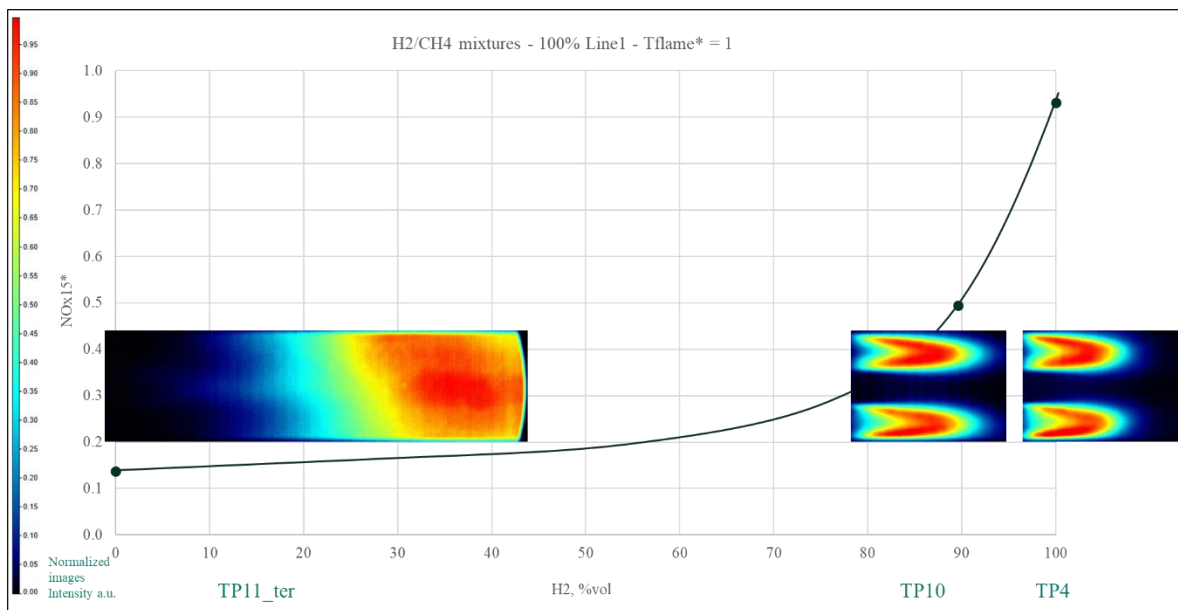


Fig. 5: Sensitivity of normalized NO_x at 15% O₂ to hydrogen content in hydrogen/methane mixture fuel (solid circles). OH* images for each test-points (normalized images).

4. Conclusion

Hydrogen flame conditions of an industrial gas turbine burner have been explored in atmospheric pressure looking at the NO_x emission as global parameter and OH* chemiluminescence as a marker of the flame shape and position.

Three main parameters have been modified along the test campaign: the flame temperature, the mass flow split between fully premix and partially premix line and the hydrogen volumetric concentration in mixture with natural gas.

While NO_x emission present expected behaviour in accordance with the well-known mechanisms, flame structure shows interesting results summarized here below:

- In hydrogen premix mode, the increase of equivalence ratio (i.e., the flame temperature) causes the approach of the flame (in particular the OH* inception region) to the burner tip without significantly modifying the flame structure (the shape remains the same, but the length slightly reduces).
- Moving from fully premix to partially premix mode, the flame structure changes significantly since OH* radical peak concentrates in a smaller region closer to the burner tip and the spatial distribution covers a bigger area respect to premix mode.
- Introducing natural gas into a mixture with hydrogen, the flame shape begins to change in terms of length (evident increase at 90% vol). With pure natural gas the original flame structure is completely lost, the OH* radical formation is farther from burner tip and a very “diffused” combustion is present quite similar to a flameless mode. A possible step forward will be the investigation of the transition mixture by testing different hydrogen/natural gas blends.

- Finally, a preliminary correlation of the average OH* intensity with combustion parameter like flame temperature (but also NOx) showed an interesting premise for future applications since it could allow a better understating of the mechanism behind the formation of the high temperature regions mostly responsible for the NOx formation.

As indicated in the title, this work is preliminary, but for the industrial reality of Baker Hughes that moves toward the continuous research of the best technologies for the energy optimization, it opens new doors for the development process of gas turbine combustion technologies; in particular, these experimental data collection effort helps to capture the flame structure allowing the validation of combustion models useful to predict the behaviour of complex phenomena like combustion instabilities and flashback.

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