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NUMERICAL INVESTIGATION OF GAS TURBINE BURNERS OPERATING WITH HYDROGEN AND HYDROGEN-AMMONIA BLENDS

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ABSTRACT

Attractivity of carbon-free fuels, like hydrogen or ammonia, has recently increased, as they can be produced with zero carbon emission via electrolysis and thus supporting further expansion of renewables sources adoption through energy storage concepts.

Gas turbines combustion system incremental developments are pointing to hydrogen use and some demonstrations of potential in abatement of the greenhouse gas carbon-dioxide have been already achieved and documented. Concerning the ammonia, low technology level or conceptual studies only are available: as a matter of fact, a proven technology is nowadays still unavailable for the abatement of NOx emissions.

Hydrogen-ammonia blending is of interest as it can be used to overcome the storage and transport limitations of pure hydrogen, although a few examples of applicability are nowadays available.

Main objective of this paper is to investigate the capability of real gas turbine burners to operate with hydrogen and hydrogen-ammonia blends.

The impact on gas turbine operability is reported alongside the evaluation of NOx emissions. Numerical models have been used for prediction of NOx emissions at relevant gas turbine operating conditions, leveraging available data from full scale annular combustor rig test with hydrogen-air mixtures. Models include 1D freely propagating flame, a basic chemical reactor network and a 3D computational fluid dynamic setup. The latter, already used in the ambit of hydrogen combustion, has been upgraded to predict NOx emissions when hydrogen-ammonia blends are provided to real burner geometries.

The discussion on operating constrains is addressed in this paper leading to the definition of a viable hydrogen-ammonia blend for an existing combustion system architecture.

INTRODUCTION

Among the possible ways to reduce the anthropic carbon footprint to climate change, one of the most effective passes through the complete removal of carbon from the combustion processes. Hydrogen has represented the most evaluated option for several years (Chiesa et al., 2005). However, in the last few decades, ammonia have been drawing much attention as a promising alternative (Zamfirescu and Dincer, 2009). In fact, ammonia can act as a clean energy carrier and storage medium: due to the high hydrogen content it can in principle be burnt in an environmentally benign way like the pure hydrogen, yielding only water and nitrogen when completely combusted (Wang et al., 2013).

In principle, both hydrogen and ammonia can be produced from renewable energy resources such as wind power, solar energy, biomass, etc. However, unlike hydrogen, for which storage and transportation problems still are cause of concern, ammonia can be easily stored, and there are already established infrastructures and experiences in producing, distributing, and handling it. Hence, ammonia has the potential to play an influential role in future energy systems as an energy storage medium and as a green fuel.

Indeed, combustion performances of ammonia fired gas turbine has received attention since the sixties of the last century (Pratt, 1967). Nevertheless, only in the last years, some studies have been undertaken, leading to significant progress in science and technology of ammonia combustion (Kobayashi et al., 2018) and providing experimental evidence and numerical analyses regarding the exhaust emissions (Li et al., 2014).

The effective use of ammonia and hydrogen-ammonia blends as an alternative carbon-free fuel is under investigation in many different sectors, from naval, aero and vehicular transportation (Comotti and Firgo, 2015) to some typically hard-to-abate industrial applications.

While pure ammonia represents a poorly burnable fuel due to its low reactivity, partial ammonia cracking results in a fuel mixture consisting of a hydrogen-nitrogen-ammonia blend that may exhibit suitable combustion properties. Off-the-shelf catalysts, based on already available commercial products, can be deployed to crack the target ammonia fraction using some of the gas turbine waste heat.

Many studies unveiled the challenges of burning fuels containing ammonia. In particular, the low reactivity and the poor stability drove Pugh et al. (2020) to rely on highly swirled burners to stabilize the flame. Moreover, it was agreed among different researchers that conventional lean premixed technology would fail in keeping the overall NOx emissions to few tens of ppm, due to the presence of fuel-bound nitrogen. Nevertheless, containment strategies like the humidification of reactants might help in reducing both NOx and unburnt NH_3, but they are expected to be effective only if combined with the air staging, as shown by Pugh et al. (2019).

As stated above, the introduction of ammonia, hydrogen or ammonia-hydrogen blends in existing combustion systems is not a straightforward practice, unless performance targets change with respect to natural gas operation. Regardless, a minimum required set of changes can be defined for an existing combustion system architecture to make it suitable for the combustion of such green fuels. This preparatory step is an effective and economically controllable approach to launch environmental-friendly technologies and enable evaluations not only at gas turbine module level, but also at industrial plant and final user levels.

Moreover, a complete retrofit of the new technical solutions into existing systems, is paramount standing the not immediate green ammonia high availability.

As for the hydrogen, the ammonia supply chain could represent the limiting factor to further growth of the so called zero emissions energy market: for the hydrogen, price cyclic fluctuations registered over the last decades have prevented continuous investments for gas turbine technology development.

Indeed, Baker Hughes has worked together with ENEL to the development of a fully hydrogen fuelled gas turbine, to be integrated into a combined cycle power plant, located in Fusina (Venice, Italy). Cocchi et al. (2008) demonstrated that operating either with pure hydrogen or natural gas was possible for a single shaft 10 MW gas turbine, featuring a single silo combustion system, equipped with a diffusion flame burner.

More recently, the impact of hydrogen enrichment has been assessed on lean premixed combustion systems of a new gas turbine, namely the double shaft 17 MW NovaLT16™, manufactured by Baker Hughes. It consists on an annular combustion chamber and a piloted premixed fuel burner, as described by Cerutti et al. (2018). A new set of emissions data has been made available, after a dedicated test campaign with pure hydrogen in a full annular rig. NOx emissions data at gas turbine relevant pressure were used to assess different numerical approaches and calibrate the models. The capability of the developed numerical model in predicting NOx emissions and flame stabilization mechanisms of real gas turbine burners, when operated with hydrogen-rich fuels, was presented in by Meloni et al. (2020).

With the aim of investigating the hydrogen-ammonia blends burning capabilities of the combustion system mentioned above, such a model has been updated to deal with hydrogen-ammonia fuel blends.

Summarizing, this paper deals with:

- The definition of the impacts on combustion system of the NovaLT16™ of a credible ammonia supply scenario;
- The evaluation of a possible operational profile of the combustion system, based on a basic chemical reactor network analysis;
- The evaluation of NOx emissions through 3D computational fluid dynamic (CFD) model of the combustion system at gas turbine relevant conditions.

NOMENCLATURE

Symbols

$\dot{m}/\dot{m}_0$	Normalized Mass Flow Rate
$\dot{m}_f$	Fuel Mass Flow Rate (kg/s)
$\dot{m}_{a,S}$	Secondary Air Mass Flow Rate (kg/s)
P/P_0	Normalized Power
PMX/PMX_0	Normalized Premixed Fuel Split
Q/Q_0	Normalized Thermal Input
Sl_u	Unstrained laminar flame speed (m/s)
W	Molecular Weight
X	Molar fraction (%)
Y_c	Progress Variable
Y	Mass Fraction

Greeks

α	Thermal Diffusivity
Δ	Cell Size
ϕ	Equivalence Ratio
η	Normalized Efficiency
τ	Residence Time (ms)

Acronyms

CFD	Computational Fluid Dynamic
FGM	Flamelet Generated Manifold
FTT	Flow Through Time
LES	Large Eddy Simulation
PDF	Probability Density Function
PLT	Pilot
PMX	Premixed
RANS	Reynolds-Averaged Navier Stokes
TFSC	Turbulent Flame Speed Closure

ANALYSIS SCENARIO

The aim of the investigation reported in this paper is to provide an analysis-based description of the impacts of using hydrogen-ammonia blends as fuel in a real gas turbine combustion system, namely the NovaLT16™ one. As mentioned in the introduction, the fuel interchangeability potentially affects both the operability and the emission characteristics.

Concerning the gas turbine performances, Table 1 summarizes the main impacts of the ammonia blend into hydrogen for the gas turbine, assuming no changes are made on the control strategy, namely assuming the same exhaust temperature as long as the pressure ratio increases.

		Pure H_2 (ref)	H_2-NH_3 blend	Pure NH_3
Fuel H_2 mole fraction	%	100	70	0
Fuel NH_3 mole fraction	%	0	30	100
P/P_0		1	1.09	1.12
η/η_0		1	1.03	1.04
$\dot{m}/\dot{m}_0$		1	1.03	1.04
Exhaust N_2 mole fraction	%	73.4	73.6	73.7
Exhaust O_2 mole fraction	%	14.8	13.3	12.9
Exhaust H_2O mole fraction	%	10.9	12.2	12.6
Exhaust CO_2 mole fraction	%	0.0	0.0	0.0
Exhaust Ar mole fraction	%	0.9	0.8	0.8

Table 1: performance summary

It has to be stated that an increase in the generated power (P) and the efficiency (η) is already been expected for the pure hydrogen combustion (reference case in Table 1) with respect to the standard natural gas, due to the higher specific enthalpy. However, as soon as the ammonia starts to blend into hydrogen, a further increase in power and efficiency may be obtained, mainly due to the increment of the mass flow expanding through the turbine.

Table 1 shows the change in both O_2 and H_2O mole fractions in the exhausts: this aspect affects the pollutant emissions representation, as those are typically reported on dry basis and corrected at 15% O_2. However, for the gas turbines considered in this work, large differences in the raw NOx emissions content are expected between the reference and the investigated blend cases, so that the correction is supposed not to play a significant role in the discussion.

Considering a gas turbine suited for pure hydrogen operation (Meloni et al., 2020), the availability of an ammonia stock for blending potentially affects:

- The fuel supply pressure, because of the reduced lower heating value of the blend;
- The flame stability, due to the lower reactivity of the blend;
- The NOx emissions, since a fuel-bound nitrogen driven significant increase is expected for increasing ammonia content in the blend.

Given the burner architecture of Figure 1, the way this system allows to adapt the fuel supply pressure to fuel changes is the variation of the fuel split between the two lines, namely the pilot and the premixed.

Indeed, the quantity of fuel through the premixed line can be limited for a specific blend for a twofold flame stability related aspect.

In the case of natural gas, the amount of premixed fuel flow is a regulation parameter to achieve a proper balance between NOx emissions and lean blow out margin, as reported by Cerutti et al. (2018) for the same burner subject of this survey. Moreover, according to results of Romano et al. (2019), the fuel split can be optimized to handle fuel composition changes.

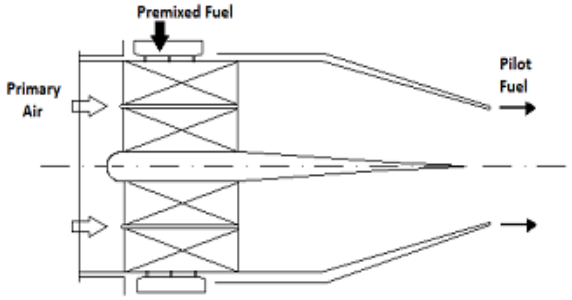

Figure 1: fuel burner scheme

Although the introduction of hydrogen would require high premixed fuel flow to maintain the NOx below acceptable values, experience done by Cerutti et al. (2014) suggests limiting the presence of flammable mixture within the burner premixing duct to reduce the flashback risk.

Considering the scenario presented in this paper, namely a hydrogen-ammonia variable fuel blend, a quantitative analysis has been performed, based on the evaluation of the unstrained laminar flame speed, Sl_u.

Calculations have been made assuming freely propagating conditions and by means of an in-house developed tool, based on Cantera libraries (Goodwin et al., 2018). The GRI-Mech™ 3 (Smith et al.) mechanism was used to provide reaction parameters to the tool.

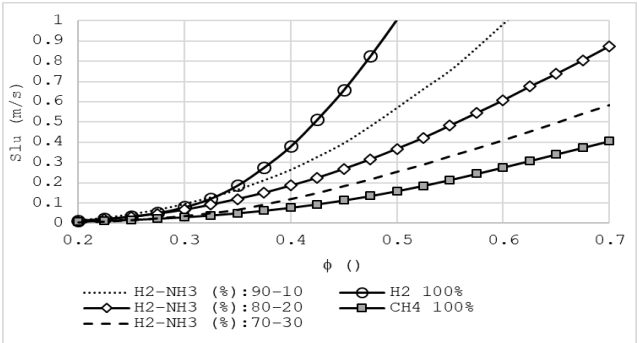

Figure 2: unstrained laminar flame speed as a function of the equivalence ratio in freely propagating conditions

For the burner subject of this survey, it can be assumed that the flame stability would not be significantly impacted by a moderate premixed fuel quantity. However, the amount of premixed fuel should be properly set to maintain stable flame, thus avoiding excessive unburnt fraction or either flashback events. As a lean mixture would probably establish downstream the premixed fuel injection, the laminar flame speed could provide an adequate indication of the fuel blend reactivity at gas turbine relevant conditions. Trends are shown in Figure 2 as a function of the equivalence ratio.

An optimal premixed fuel split schedule has been assumed, aimed at maintaining the fuel supply pressure constant for increasing ammonia content in hydrogen.

Such a schedule has been then used to evaluate the most probable laminar flame speed in the premixed flame, then normalized to the one obtained in the case on pure methane.

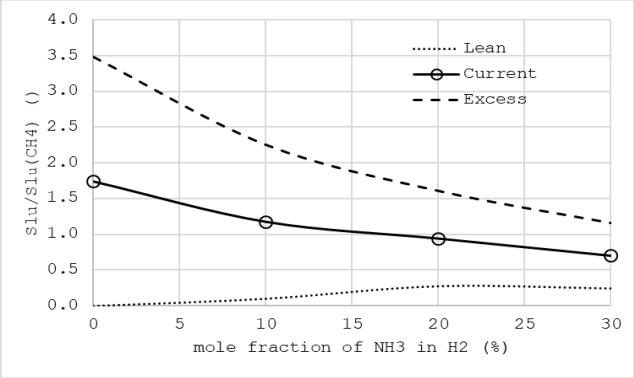

Figure 3: normalized unstrained laminar flame speed (to the Sl_u at CH_4 100%) considering the equivalence ratio corresponding to the optimal premixed fuel split for increasing NH_3 content in H_2

The normalized laminar flame speed is shown in Figure 3 as a function of the ammonia content in hydrogen: it has been evaluated as the average of two extreme cases. Assuming the pilot fuel burning in stoichiometric conditions, a premixed equivalence ratio can be calculated using the excess air content, leading to a laminar flame speed reducing with the ammonia content (Excess in Figure 3). On the contrary, an increasing laminar flame speed with the ammonia content can be attained by assuming the premixed flame able to mix with all the available air, regardless of the pilot split content (Lean in Figure 3).

It can be argued that a mixture providing the same laminar flame speed of the pure methane case ($Sl_u/Sl_u(CH_4)=1$ for Current in Figure 3) would exhibit similar characteristics of stability.

From the considerations above, the analysis scenario described in this paper assumes a 20% ammonia content in hydrogen. This choice is in line with a realistic supply scenario for ammonia blending in hydrogen in the range of 0-30%.

MODELS SETUP

Models setup description is reported in this section. First, the CFD setup is described, then the chemical reactor network. Both are aimed at providing the expected NOx emissions at gas turbine relevant conditions.

Two different chemical mechanisms represent the foundation of the combustion model, each of which being optimized for the specific fuel composition. For the cases with pure hydrogen combustion the mechanism by Li et al. (2004) was adopted. The mechanism by Xiao et al. (2016) was the reference for the cases dealing with the ammonia.

The Flamelet Generated Manifold (FGM, Van Oijen et al., 2000) model embedded into the commercial code Ansys Fluent® has been used in the present work. In the FGM model, the thermo-chemical state of the mixture is a function of both the equivalence ratio (through the mean mixture fraction) and the progress variable, convoluted in a Probability Density Function (PDF) to properly consider the turbulence-chemistry interaction. A Turbulent Flame Speed Closure (TFSC) was adopted to define the source term of the progress variable transport equation. The laminar flame speed curves, required as input, have been evaluated using the freely propagating flame model in Cantera (see H_2-NH_3:80-20 in Figure 2).

An important point introduced in the present study is the adoption of a new definition of the progress variable. Departing from the classic formulation valid for fossil fuels, the expression of Equation 1 has been adopted in this study:

$$Y_c = Y_{H2O}/W_{H2O} + Y_{N2}/W_{N2} + Y_{NO}/W_{NO} \quad \text{(Eq. 1)}$$

where W is the molecular weight of the generic species. In fact, the present formula ensures that inside the flame brush the progress variable increases monotonically.

The evaluation of the NOx emission shall follow different paths, according to the fuel blend.

For pure hydrogen mixture, only the thermal NOx contribution was here considered being the N_2O pathway negligible at the simulated operating conditions. Instead, the fuel-bound NOx contribution is expected to be dominant for the blend including the ammonia. So, in the latter case, both the formation mechanisms shall be included.

For this purpose, an additional scalar transport equation was derived from the FGM model for the NO species. Such approach allows defining both the forward and the backward formation rate of the interested species directly from the chemical mechanism where, obviously, the chemical reactions describing the formation of NOx from the NH_3 are present (Yadav et al., 2018).

The Smagorinsky-Lilly model with dynamic stress closure has been used for the sub-grid scale modelling of the compressible Large-Eddy Simulations (LES). The compressibility effect must be considered since the high Mach number at the pilot fuel injections. Such a condition has a direct impact on the time step size: the value was

determined to ensure a convective Courant number of around 1 at those locations. Moreover, the small size of the time step (o ~1e-06 s) was necessary to guarantee numerical stability to the simulations.

A dense mesh, especially in the primary zone of the combustor was built also in accordance with the Pope's criterion (Pope, 2004). The desired mesh resolution was reached applying local refinements, at the co-flow regions where the fuel is injected to better capture all the velocity gradients also related to the shear stress at the primary zone of the combustor where the flame stabilizes.

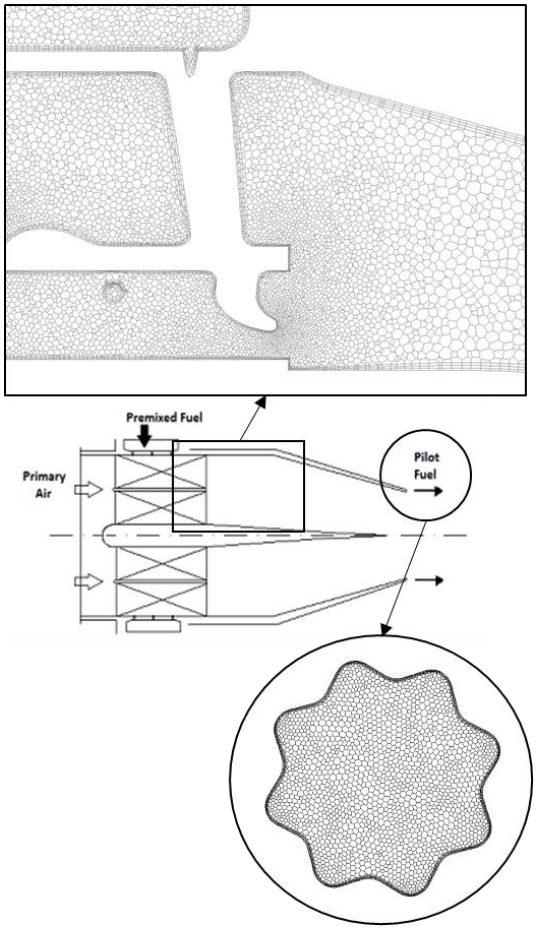

Figure 4: mesh details and local refinement in correspondence of fuel injections

The mesh is shown in Figure 4 and its count was of around 17 million polyhedral cells. Also considering the smallest time step size, each case was let running for the time needed to compute 9 Flow Through Times (FTT): 5 FTTs to let the preliminary RANS simulation to be washed-out and further 4 FTTs to collect the statistical data.

Both spatial and the implicit temporal discretization are at the second order along the SIMPLEC scheme for the pressure-velocity coupling.

The computational domain considers a single burner sector, with rotational periodicity at the cut sides. A simplified portion of the compressor discharge chamber was included to move far upstream the air inlet from the fuel injection points and to avoid any kind of numerical interaction. The combustor outlet was placed upstream the first stage nozzle and modelled as a pressure outlet. The impingement and the film cooling of the liners were considered both as mass flow inlet to reduce as much as possible the overall cell count. Constant wall temperatures have been imposed at walls.

In parallel to the CFD, a chemical network-based analysis has been carried out to provide a preliminary evaluation of the NOx emissions of the investigated combustion system. Due to the peculiar burner architecture, a relatively simpler scheme has been adopted, with respect to the one used by Hussein et al. (2019). The network is represented in Figure 4 and consists of a series of reactors.

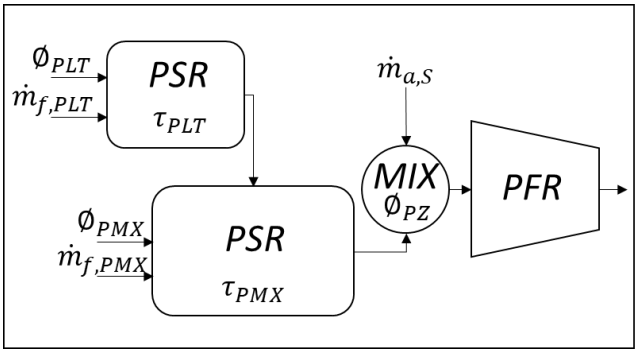

Figure 4: chemical reactor network of a low swirl piloted premixed flame

The burner subject of this work has been extensively studied over the last years. Based on numerical analyses performed by Innocenti et al. (2016), pilot fuel injection plays a fundamental role in the stabilization of the piloted premixed flame front. In fact, the counter-rotating swirler provides low swirl to the air stream, therefore the stability is demanded to the highly penetrating pilot fuel jets. As shown in Figure 4, a perfectly stirred reactor is used to simulate the pilot lifted flame, while another perfectly stirred reactor receives pilot flue gas, the premixed fuel, and the excess air. The remaining air flow is then mixed to the main gas stream before reaching the plug flow reactor, representing the secondary zone.

RESULTS

The CFD setup described in the previous section was used to simulate the flame stabilization and the NOx emissions in the case of pure hydrogen-air mixtures, as described by Meloni et al., (2020). To define the analysis cases for the hydrogen-ammonia blends, the thermal input has been kept constant for the two evaluated conditions; indeed, a certain amount of fuel was supposed to be delivered through the premixed line, to balance the fuel supply pressure increase demand. According to the considerations made in the previous section, a H_2-NH_3

mixture in the percentage volume ratio 80-20 has been set. For a smooth and direct comparison, two additional cases with all the thermal input through the pilot line have been considered too: Table 2 summarizes the analysis cases.

CASE ID	H_2	NH_3	Q/Q_0	PMX/PMX_0
	%	%		
1	100	0	1.00	0.00
2	100	0	0.91	0.00
3	80	20	1.00	0.00
4	80	20	0.91	0.00
5	80	20	1.00	0.44

Table 2: analysis cases summary

A comparison of NOx emissions in pure non-premixed combustion mode is reported in Figure 5, where emissions are normalized, for each reference thermal input, with respect to the value measured with pure hydrogen.

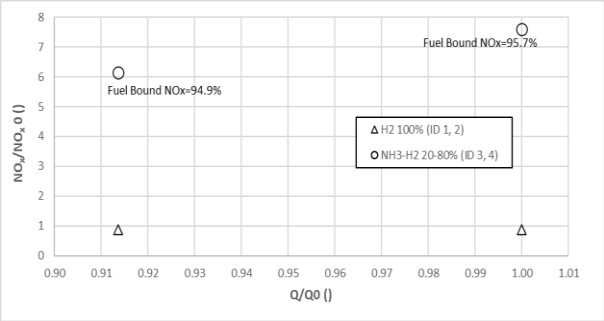

Figure 5: NOx emissions as predicted by the CFD model for all the pure diffusive considered cases (ID 1 to 4 of Table 2)

Figure 5 shows that the model is able to predict the test case emissions with fair accuracy (slight underprediction, with relative error within 10%, according to results reported by Meloni et al. (2020)) for the 100% hydrogen cases (ID 1 and 2 of Table 2). As ammonia is introduced in the fuel, the effect on NOx is twofold: on one side the fuel dilution leading to lower flame temperature and lower laminar flame speed is able to consistently reduce thermal NOx, on the other side, the oxidation of fuel-bound nitrogen is able to largely exceed this beneficial effect, leading to emissions 6-8 times higher than with pure hydrogen. The different effect of fuel composition on NOx formation mechanism is illustrated in Figure 6.

Time averaged contours of temperature are reported in Figure 7 for the investigated cases. It appears that blending hydrogen with ammonia allows a consistent reduction of temperature peaks and a moderate shift of the flame front and the high temperature post-flame region downstream, with the observed beneficial effect on thermal NOx production.

As shown in Figure 8, while in pure hydrogen flame the NOx formation is clearly related to the hot temperature region (see Figure 7 for reference), the blended fuel leads to a much higher NO mass fraction in the whole combustion chamber, due to the predominant effect of the conversion of fuel-bound nitrogen to nitrogen oxides.

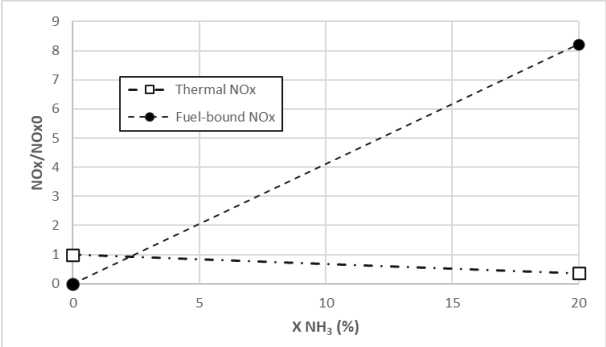

Figure 6: predicted impact of fuel composition on NOx formation mechanism (Q/Q_0=1, PMX/PMX_0=0)

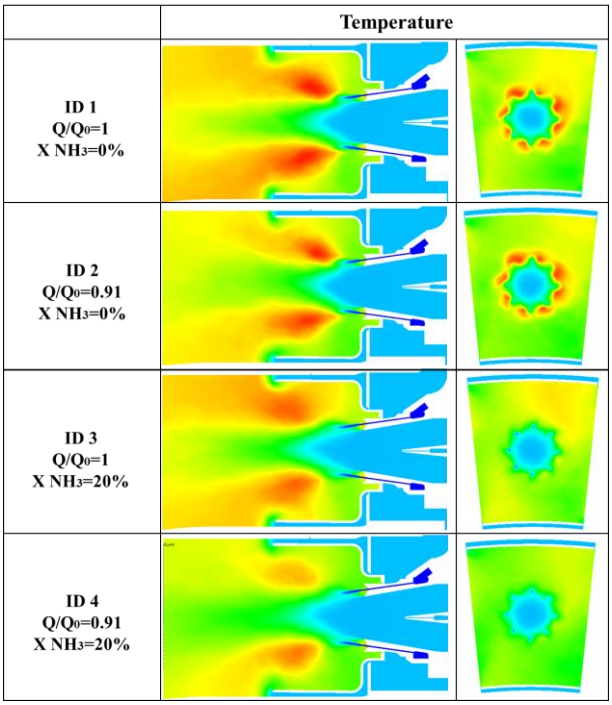

Figure 7: time-averaged contours of temperature (PMX/PMX_0=0)

The NOx formation in the case of hydrogen ammonia blends seems affected by the flame stabilization in a limited way, according to figure 8. Nevertheless, a preliminary analysis preformed with the chemical reactor network indicated the pilot equivalence ratio as one of the most impacting parameters on NOx formation. This is particularly true in the case fuel is exclusively delivered through the pilot.

The results of the sensitivity analysis are reported in Figure 9: the most influencing parameter ϕ_{PLT} has been let vary from 1 (stoichiometric) to the value at which, for pure hydrogen, the NOx emissions predicted by the CFD simulation matched the experimental data, namely 0.675.

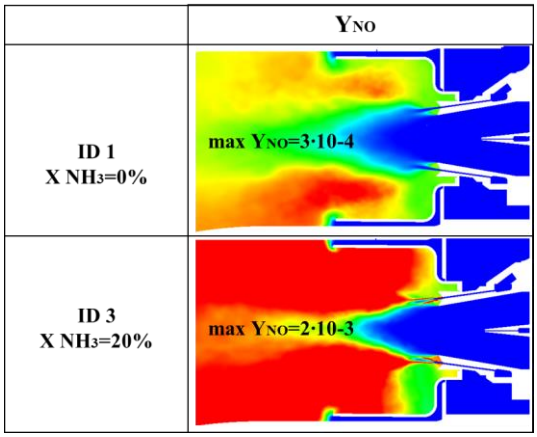

Figure 8: time-averaged contours of NO mass fraction (Q/Q₀=1, PMX/PMX₀=0)

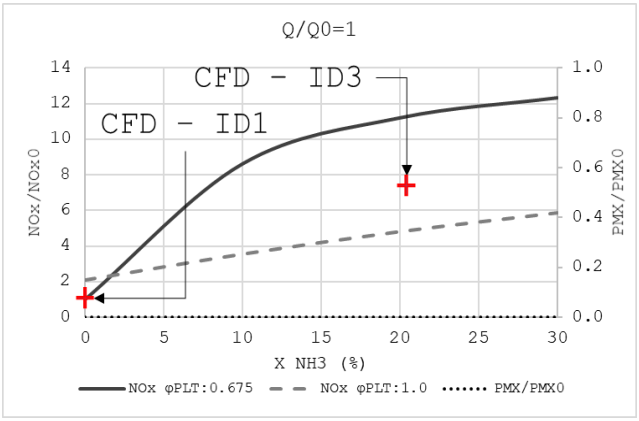

Figure 9: NOx emissions sensitivity to chemical reactor network most influencing parameter ϕPLT, compared to CFD cases (Q/Q₀=1, PMX/PMX₀=0)

Interesting insights on the effect of ammonia on NOx formation in H_2-NH_3 blends are obtained by this analysis. As the ammonia content increases, the leaner case (solid line of Figure 9) provides a significant rise in NOx emissions with respect to stoichiometric case (dashed line of Figure 9).

Although the contribution of the flame lift, here represented by an equivalence ratio lower than the unity, is lowering the thermal NOx contribution to the overall emissions, the presence of fuel-bound nitrogen plays again a major role in the result. This is qualitatively aligned with the outcomes of Hewlett et al. (2020), but not yet quantitatively aligned with the CFD prediction, which lays in-between the two curves.

In the case of the optimal premixed fuel split is assumed, as shown in Figure 10, the flame shape is moderately affected in a way that a certain reduction of the NOx could be expected. Although the reduced pilot exit velocity affecting the flame lift is responsible for higher temperature peaks with respect to fully piloted flame, the extent of such regions is reduced, leading to lower residence times responsible for thermal NOx production.

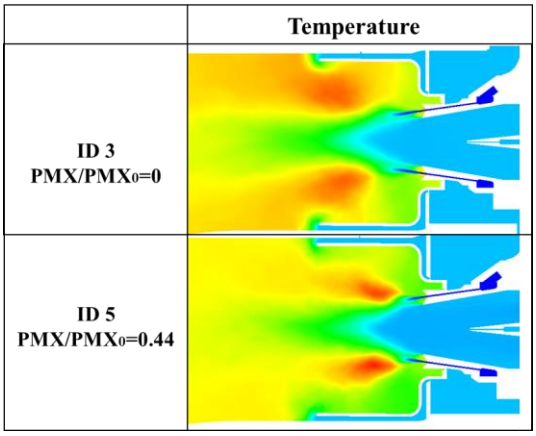

Figure 10: time-averaged contours of temperature for PMX/PMX₀=0 and PMX/PMX₀=0.44 (Q/Q₀=1)

From a comparison of the NO mass fractions, as depicted in Figure 11, the portion of the fuel which is burnt in lean premix conditions is being converted via peculiar reaction pathways that imply high ·OH concentrations. Such environment selectively promotes the oxidation of fuel-bound nitrogen to NOx, with a direct impact on emissions. Nevertheless, the lifted nature of the flame prevents the formation of stoichiometric regions in either cases. The eventual effect is a negligible reduction of the overall NOx, with respect to fully piloted flame case.

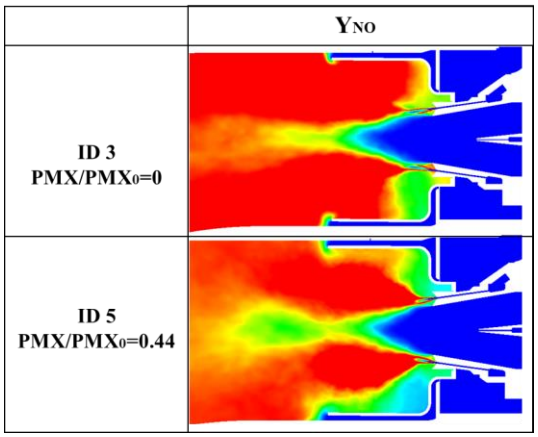

Figure 11: time-averaged contours of NO mass fraction for PMX/PMX₀=0 and PMX/PMX₀=0.44 (Q/Q₀=1)

A detailed analysis of the different NOx pathways would reveal the relative importance of thermal NOx to the totally produced by the investigated burner. Therefore, an upgrade of the model setup would be required for further assessments.

The sensitivity of NOx to the most influencing chemical reactor network parameter ϕPLT has been repeated in the more realistic case of premixed line use (see Figure 12).

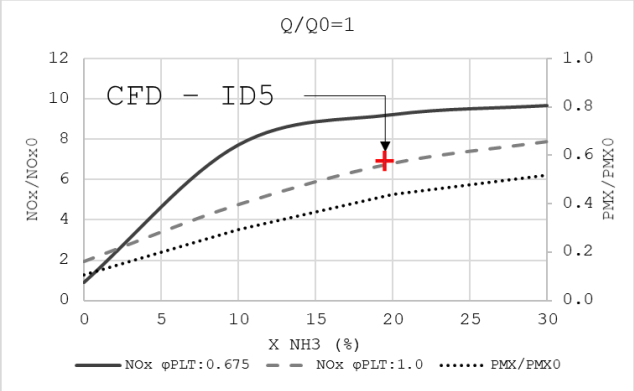

Figure 12: NOx emissions sensitivity to chemical reactor network most influencing parameter ϕ_{PLT}, compared to CFD case ($Q/Q_0=1$, $PMX/PMX_0=0.44$)

As expected, a smaller spread between the two curves is noticed. Moreover, the CFD based prediction is still within the range and aligned with the assumption of stoichiometric conditions at pilot fuel discharge, which in turn, was not able to match the emissions in case of pure hydrogen. Notwithstanding the highlighted discrepancies, models' setups can be considered adequate to describe the main trends and they would eventually benefit from future experimental data for validation and further developments.

CONCLUSIONS

An overview of potential impacts of hydrogen-ammonia fuel blends on the performances and the pollutant emissions of an existing gas turbine combustion system has been provided thought this study.

The analysis scenario has been properly selected to minimize the impact on the fuel supply pressure system, and the flame stability. Flame stability as a function of both the fuel blend and the equivalence ratio has been evaluated through the laminar flame speed, leading to the definition of the optimal operating conditions for each blend.

NOx predictions at relevant gas turbine operating conditions from a chemical reactor network model have been compared to 3D CFD outcomes. Models have been calibrated on the available data from full scale annular combustor rig test operated with pure hydrogen.

Models are aligned in ascribing to the fuel-bound NOx the dominant role in the production of pollutant emissions. Nevertheless, a validation would be required before the extensive use for real combustion systems design development.

Despite the development needed, the proposed models are able to catch main physical trends, allowing the numerical screening of viable design options to reduce the scope of dedicated test campaigns, thus revealing proper tools for high hydrogen and hydrogen-ammonia burner design and development.

REFERENCES

M. Cerutti, N. Giannini, G. Ceccherini, R. Meloni, E. Matoni, C. Romano and G. Riccio, "Dry Low NOx Emissions Operability Enhancement of a Heavy-Duty Gas Turbine by Means of Fuel Burner Design Development and Testing", Proceedings of ASME Turbo Expo 2018, Oslo, Norway.

P. Chiesa, G. Lozza and L. Mazzocchi, "Using Hydrogen as Gas Turbine Fuel," Journal of Engineering for Gas Turbines and Power, vol. 127, DOI: 10.1115/1.1787513, pp. 73-80, 2005

S. Cocchi, M. Provenzale, V. Cinti, L. Carrai, S. Sigali and D. Cappetti, "Experiemental Characterization of a Hydrogen Fuelled Combustor With Reduced NOx Emissions for a 10 MW Class Gas Turbine", Proceedings of ASME Turbo Expo 2008, Berlin, Germany.

M. Comotti, S. Frigo, "Hydrogen generation system for ammonia−hydrogen fuelled internal combustion engines", Int. Journal of Hydrogen Energy 2015, 40 (33), 10673−10686.

D. Goodwin, "Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics and transport processes", Caltech, Pasadena, 2009, http://code.google.com/p/cantera

S. G. Hewlett, D. G. Pugh, A. Valera-Medina, A. Giles, J. Runyon, B. Goktepe, P.J. Bowen. "Industrial Wastewater as an Enabler of Green Ammonia to Power Via Gas Turbine Technology", Proceedings of ASME Turbo Expo 2020, London, England

H. Kobayashi, A. Hayakawa, K. D. Kunkuma, A. Somarathne, E. C. Okafor, "Science and technology of ammonia combustion" Proceedings of the Combustion Institute 37 (2019) 109–133

N. A. Hussein, A. Valera-Medina, A. S. Alsaegh, "Ammonia-hydrogen combustion in a swirl burner with reduction of NOx emissions", Energy Procedia 158 (2019) 2305–2310

A. Innocenti, A. Andreini, B. Facchini, M. Cerutti, G. Ceccherini and G. Riccio, "Design Improvement Survey for NOx Emissions Reduction of a Heavy-Duty Gas Turbine Partially Premixed Fuel Nozzle Operating with Natural Gas: Numerical Assessment", Journal of Engineering for Gas Turbine and Power, vol. 138, pp. 011501-1-9, 2016.

J. Li, Z. Zhao, A. Kazakov, and F. Dryer, "An updated comprehensive kinetic model of hydrogen combustion", J. Chem. Kinet., No. 10, 566–575, 2004.

J. Li, Hongyu Huang, N. Kobayashi, Z. He and Y. Nagai, "Study on using hydrogen and ammonia as fuels: Combustion characteristics and NOx formation", Int. Journal of Energy Research 2014, 38:1214–1223

S. B. Pope, "Ten questions concerning the large eddy simulations of turbulent flows", New Journal of Physics, Volume 6, 2004

D. T. Pratt, "Performance of Ammonia-Fired Gas-Turbine Combustors", Technical report no. 9, 1967, University of California

D. Pugh, P. Bowen, A. Valera-Medina, A. Giles, J. Runyon, R. Marsh, “Influence of Steam Addition and Elevated Ambient Conditions on NOx Reduction in a Staged Premixed Swirling NH3/H2 Flame”, Proceedings of the Combustion Institute 37 (2019) 5401–5409

D. Pugh, A. Valera-Medina, P. Bowen, A. Giles, B. Goktepe, J. Runyon, S. Morris, S. Hewlett, R. Marsh, “Emissions Performance of Staged Premixed and Diffusion Combustor Concepts for an NH3/Air Flame with and without Reactant Humidification”, Proceedings of ASME Turbo Expo 2020, London, England.

G. P. Smith, D. M. F. M. Golden, N. W. Moriarty, B. Eiteneer, M. Goldenberg, C. T. Bowman, R. K. Hanson, S. Song, W. C. Gardiner, V. V. Lissianski and Z. Qin, “GRIMECH 3.0” Berkley, http://combustion.berkeley.edu/gri-mech/version30/text30.html

W. Wang, J. M. Herreros, A. Tsolakis, A. P. E. York, “Ammonia as hydrogen carrier for transportation; investigation of the ammonia exhaust gas fuel reforming”, Int. Journal of Hydrogen Energy 2013, 38 (23), 9907−9917.

J. A. Van Oijen, L. P. H. deGoey, 2000. “Modelling of Premixed Laminar Flames using Flamelet-Generated Manifolds”. Combustion Science and Technology, 161(1), pp. 113–137.

H. Xiao, M. Howard, A. Valera-Medina, S. Dooley, P. J. Bowen. “Study on Reduced Chemical Mechanisms of Ammonia/Methane Combustion under Gas Turbine Conditions”. Energy Fuels 2016.

R. Yadav, S. Li, E. Meeks, “A Scale Separation Method for Pollutant Prediction in Turbulent Flames Using Transported Scalars with Flamelet Generated Manifold (FGM) Method”, Proceedings of the ASME Turbo Expo 2018, Oslo, Norway.

C. Zamfirescu, I. Dincer, “Ammonia as a green fuel and hydrogen source for vehicular applications”, Fuel Process. Technol. 2009, 90 (5), 729−737.