EXPERIMENTAL AND NUMERICAL CHARACTERIZATION OF LEAN HYDROGEN COMBUSTION IN A PREMIXED BURNER PROTOTYPE

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ABSTRACT

The use of hydrogen as derived fuel for low emission gas turbine is a crucial issue of clean coal technology power plant based on IGCC (Integrated Gasification Combined Cycle) technology. Control of NOx emissions in gas turbines supplied by natural gas is effectively achieved by lean premixed combustion technology; conversely, its application to NOx emission reduction in high hydrogen content fuels is not a reliable practice yet. Since the hydrogen premixed flame is featured by considerably higher flame speed than natural gas, very high air velocity values are required to prevent flash-back phenomena, with obvious negative repercussions on combustor pressure drop. In this context, the characterization of hydrogen lean premixed combustion via experimental and modeling analysis has a special interest for the development of hydrogen low NOx combustors.

This paper describes the experimental and numerical investigations carried-out on a lean premixed burner prototype supplied by methane-hydrogen mixture with an hydrogen content up to 100%. The experimental activities were performed with the aim to collect practical data about the effect of the hydrogen content in the fuel on combustion parameters as: air velocity flash-back limit, heat release distribution, NOx emissions. This preliminary data set represents the starting point for a more ambitious project which foresees the upgrading of the hydrogen gas turbine combustor installed by ENEL in Fusina (Italy). The same data will be used also for

building a computational fluid dynamic (CFD) model usable for assisting the design of the upgraded combustor.

Starting from an existing heavy-duty gas turbine burner, a burner prototype was designed by means of CFD modeling and hot-wire measurements. The geometry of the new premixer was defined in order to control turbulent phenomena that could promote the flame moving-back into the duct, to increase the premixer outlet velocity and to produce a stable central recirculation zone in front of the burner. The burner prototype was then investigated during a test campaign performed at the ENEL's TAO test facility in Livorno (Italy) which allows combustion test at atmospheric pressure with application of optical diagnostic techniques. In-flame temperature profiles, pollutant emissions and OH* chemiluminescence were measured over a wide range of the main operating parameters for three fuels with different hydrogen content (0, 75% and 100% by vol.). Flame control on burner prototype fired by pure hydrogen was achieved by managing both the premixing degree and the air discharge velocity, affecting the NOx emissions and combustor pressure losses respectively.

A CFD model of the above-mentioned combustion test rig was developed with the aim to validate the model prediction capabilities and to help the experimental data analysis. Detailed simulations, performed by a CFD 3-D RANS commercial code, were focused on air/fuel mixing process, temperature field, flame position and NOx emission estimation.

NOMENCLATURE

D	Exit section nurner Diameter [m]		
k	Turbulence kinetic energy $[m^2/s^2]$		
J	Momentum ratio	[-]	
m	Mass flow rate	[kg/s]	
р	Pressure	[Pa]	
Q	Volumetric flow rate $[m^3/s]$		
Sn	Swirl number	[-]	
Т	Temperature [K]		
V	Volume	$[m^3]$	
v	Velocity magnitude	[m/s]	
Х	Axial coordinate	[m]	
y+	y plus	[-]	
Greek			
Φ, φ	Equivalence ratio	[-]	
τ	Residence time	[s]	
ω	Specific dissipation rate	$[s^{-1}]$	
Abbreviation			
CTRZ	Central Toroidal Recirculation	Zone	
EXP	Experimental		
IGCC	Integrated gasification combin	ed cycle	
MGT	Micro Gas Turbine		
NG	Natural Gas		
PAH	Polycyclic aromatic hydrocarb	oon	
DLN	Dry Low NOx		
ID	Identification		
PDF	Probability density function		
P.I.	Premixing Index		
RANS	Reynolds averaged Navier-Sto	okes	
SST	Shear Stress Transport		
STD	Standard		

INTRODUCTION

UHC

The energy demand and the environmental protection ask for the development of new and improved technologies for low emission power plants designed to be fired by fuels derived from coal gasification. This kind of plant will utilize advanced gas turbine based IGCC cycles.

Unburned hydro-carbons

The use of hydrogen as syngas fuel in gas turbine combustors provides environmental benefits with respect to natural gas because negligible quantities of CO, UHC and PAH are released. Moreover, if hydrogen is produced by renewable energy, the net CO_2 production becomes equal to zero. However, the use of hydrogen as fuel is nowadays limited to gas turbines equipped by diffusive-type combustors, where the pure hydrogen supply leads to NOx emissions three times higher than those of the natural gas firing [1]. Methods for reducing pollutant emissions are borrowed from those used in diffusive gas turbine combustion chambers supplied by natural gas.

Advanced options to be explored are represented by catalytic and premixed combustion technologies. Although the

latter represents a mature technology for reducing NOx emission in gas turbine supplied with conventional fuels, its application to hydrogen fired gas turbines is hampered by the higher flame propagation velocity and by the wider air-fuel ignition range which lead to flashback and explosion risks.

Several experiences/studies on premixed hydrogen combustion for gas turbine combustors have been carried out during the last decade. Test laboratory on a radial swirler burner prototype [2] showed the possibility, by proper vortex breakdown, to obtain stable flame anchored close to the exit of the nozzle. In this case the burner exhibited remarkable fuel flexibility and the flashback phenomena were reasonably controlled.

Therkelsen et al. [3] implemented multiple modifications to the fuel injectors of a commercial DLN, natural gas fired MGT allowing the engine operation with pure hydrogen. These modifications were focused to achieve three different fuel/air mixing profiles while maintained similar equivalence ratio operational ranges. Compared to natural gas, the engine operation with hydrogen produced larger volumes of NO.

Micro-mixing fuel injectors for hydrogen ultra low emission combustion [4] are also described in literature. The design avoids flashback for the tested conditions. The obtained NOx emission performances were below 3 ppm values with hydrogen over a range of adiabatic flame temperatures.

The objective of the work described below was to explore the potential of reducing NOx emission from hydrogen combustion by means of air-fuel premixing. The activity aimed to identify some practical data/correlation to be used for the development of Low-NOx hydrogen combustor for heavy-duty gas turbine application. In this contest, an experimental campaign was carried out to investigate lean hydrogen combustion in a premixed burner prototype. First the premixer was designed, built and tested at atmospheric pressure with air preheating at ENEL's TAO test facility in Livorno-Italy. Test were performed for natural gas, methane/hydrogen mixture (25%/75% by volume) and pure hydrogen too. At the same time a CFD 3D RANS models of the combustion system were developed to support: first the design activity and then to integrate the experimental data analysis. Initial comparison between numerical and experimental data are described. Once the CFD model tuning will be accomplished, it will be applied to estimate the effect of working pressure and combustor heat losses on the main combustion parameters like NOx emission and flame front position.

THE BURNER PROTOTYPE

The premixer prototype under investigation derives from a DLN combustor, designed for natural gas, installed on a 120 MW FIAT heavy duty gas turbine. The original premixer was featured by an axial swirler and cross-flow fuel injection system. The swirler was composed by eight blades with a mean outlet angle of 24° degree with respect to the axial direction. This kind of swirler (swirl number 0.24) was not able to produce a stable toroidal recirculation zone at premixer's outlet.

The fuel was injected through four holes made on a central lance and located on a plane close to the swirler outlet section; their distance from the burner exit was approximately equal to one premixer diameter. A first RANS CFD model was built to support the premixer redesign. The model prediction capability was validated in isothermal condition by comparing numerical data and experimental measurements performed by Hot-Wire probe (Figure 1).



Figure 1: Axial velocity profile of the original premixercomparison between hot wire measurement and CFD

In order to obtain a stable flame, a new swirler characterized by a wider mean outlet angle (43°, Sn=0.7) was designed and built [2], [5]. The new geometry was verified through RANS numerical simulations in order to check the formation of a recirculation zone at the premixer outlet and to verify the flow/turbulence inside the premixer duct generated by the new swirler blades. A new co-flow injection system [6] was designed to prevent the formation of high turbulence regions typical of the cross-flow interaction. The new injection system was composed by eight lances which pierce the swirler blades, Figure 2. The fuel lances were movable along the axial direction, to change the fuel delivery point and consequently the mixing level. Moreover, a demountable ogive at the burner exit was designed and built to increase the premixer outlet velocity and limiting flash back phenomena.



Figure 2 : A picture of the burner prototype

The new injection system was investigated by means of detailed CFD simulations focused on the air/fuel mixing process. Figure 3 shows as the new premixer duct was able to guarantee a proper air/fuel mixing at its exit section.



Figure 3: Equivalence ratio maps on several crossingsections of the burner prototype

To extend the operating range of the premixer, a commercial pilot burner was installed on the premixer axis instead of the original premixer injection lance. The schematic drawing in Figure 4 shows the main components of the developed burner prototype.



Figure 4: Schematic drawing of the burner prototype

The nominal/reference operative condition of the burner prototype (Table 1) was defined maintaining unchanged premixer equivalent ratio, air temperature, burner discharge velocity of the original TG50 DLN premixing system operated at full-load with natural gas.

Premixer air flow rate	g/s	109
Premixer air temperature	°C	380
Premixer fuel	-	NG
Premixer fuel flow rate	g/s	2,8
Premixer thermal load	kW	132
P/T	%	6
Pilot air flow rate	g/s	2,5
Pilot fuel	-	NG
Premixer discharge velocity	m/s	67
Premixer equivalence ratio	-	0,44

 Table 1: Nominal operative parameters of the burner

 prototype

Test rig

The combustion test rig - named TAO (Turbogas Accesso Ottico - Turbogas Optical Entry) - is installed in the ENEL's experimental area located in Livorno (Tuscany, Italy). This facility was built in 2004 with the aim to perform experimental investigations on gas turbine burners by means of advanced optical diagnostic techniques. Among several experimental campaigns performed up to now on the TAO facility, one of the most remarkable is the numerical-experimental study about thermoacoustic combustion instabilities in lean premixed burner carried-out in the frame of PRECCINSTA European Program [7]. The rig consists of a vertical combustion chamber suitable for atmospheric pressure test of burners with a maximum thermal power input of 800 kW. Figure 5 shows a sectional view of the tested burner installed on the rig. Flat quartz windows used for optical access are installed on four walls of the octagonal chamber. The chamber, made in stainless steel, is 85 cm long with a 31 cm equivalent inner diameter $(2 \cdot r_c)$, see Figure 5). At its end a conical shaped restriction leads to a downstream smaller chamber used for gas sampling and separates the combustion chamber from the exhaust discharge piping.



Figure 5: Combustion chamber section view

The combustion chamber cooling is done by means of ambient temperature air for the quartz windows and water for the metal walls. With regards for the experimental campaign here described, it was estimated that the average thermal power subtracted to the chamber by the overall cooling system was approximately equal to the 45% of the fuel power input.

The rig fuel system allows for supplying both gaseous and liquid fuels through three different lines. With regard to the test described here, premixed and pilot gas lines were used to supply the main and the pilot burner respectively. Apart from the case of the natural gas operation, pressurized bottles were used for supplying pure hydrogen and hydrogen/methane mixture fuels.

Air is supplied to the combustion chamber by means of two different lines. The first one is connected to the main fan and carries heated air to the plenum upstream of the main burner. The other supplies the pilot burner with air at ambient temperature.

Hardware and rig instrumentation

The combustion test rig is equipped with resident instrumentation, dedicated to air and fuel systems' control and necessary to ensure proper test rig operation. For test execution, the most important instruments are those providing mass flow measurements. Fuel mass flows have been measured by means of both standard orifices and flowmeters. Pressure and temperature transmitters provide continuous monitoring of air and fuel supply conditions. The test hardware has been equipped with dedicated instrumentation in order to provide a detailed and comprehensive screening of the combustion system performances.

Flue gas temperature inside the combustion chamber was measured by means of twelve thermocouples Pt-Rd type, installed along the chamber at a radial distance of 51 mm from the burner axis (see " r_t " in Figure 5 for details). Data collected by thermocouples were corrected by using correlation [9] in order to take into account of their energy radiation losses.

Two 180 degree-shifted thermocouples were installed at the burner exit in order to monitor its metal temperature and to identify the flame flash-back onset.

Two sampling probe and a thermocouple were installed at the combustion chamber exit for measuring main species and flue gas temperature. NOx emissions were measured by means of both chemiluminescence and infrared analyzers. Nondispersive infrared analyzers are available for CO emission measurement, while oxygen content is measured by means of paramagnetic O_2 analyzers.

In order to evaluate the burner operability with regard to combustion instability, a Kistler type dynamic pressure transducer was installed at the bottom of the combustion chamber and its signal has been processed by means of a realtime spectrum analyzer, providing the characterization of pressure pulsations in the frequency domain. Since no significant differences were found between the pressure spectra of natural gas operation and those of the two hydrogencontaining fuels, results of pressure oscillations are not here described.

The flame pattern has been obtained using the OH* chemiluminescence imaging. The OH* emission imaging highlights specific zones where heat release rates are supposed to be highest and carries out morphological and dynamic information of the flame. Many references of chemilumenescence imaging application in practical flames can be found in the recent review by J. Ballester and T. Garcia-Armingol [8].

Figure 6 shows the experimental set-up used for the OH* chemiluminescence imaging acquisition. The OH*-spontaneous emission, selected by the interferential filter at 310 ± 5 nm, was collected by a lens (UV Nikkor 105mm f/4.5) and focused on a imagine intensifier. The intensified imagine was carried to the CCD surface by a fiber bundle. The processed signal is sent to a PC to acquire the flame image. The system allows for a variable acquisition frequency up to 100 frames/s.



Figure 6 : OH imaging experimental setup

TEST RESULTS AND DISCUSSION

Test campaign structure

The main variables investigated during the campaign are listed below:

- conventional pollutant emissions (NOx, CO);
- flame pattern (via OH and gas temperature);
- burner operability (flash-back speed limit detection);
- burner pressure drop.

The above mentioned variables were assessed against the variation of operation parameters reported below:

- fuel type: natural gas, methane/hydrogen mixture (25%/75% in volume), pure hydrogen;
- premixer equivalence ratio;
- air velocity at burner exit;
- burner thermal load;
- pilot-to-total thermal input ratio;
- air/fuel premixing degree.

These parameters were varied with respect to those of the nominal burner operative setting reported in Table 1.

Test rig set-up

Preliminary test of the proper rig operation was done by comparing the oxygen concentration at the rig outlet with the value calculated through a mass balance based on operative conditions acquired by the facility control system. The same operation data were used as input of an energy balance for estimating the theoretical adiabatic temperature at combustion chamber outlet. The thermal power subtracted to the chamber by the cooling systems was then estimated comparing the measured temperature at rig outlet with the value calculated from the energy balance. Data regarding the thermal power transferred to the cooling flows were used as boundary condition for the CFD model. Table 2 gives, for the tested fuels, the comparisons between oxygen and temperature values measured at the rig outlet with the calculated ones.

Fuel type	Oxygen		Temperature	
	[% vol. dry conc]		[°C]	
	Calculated	Measured	Calculated	Measured
NG	12,8	12,7	1302	910
CH4/H2	13,4	13,5	1326	880
H2	14,8	15,1	1356	900

Table 2: Rig mass and energy balance verification

In case of CH₄/H₂ mixture and pure H₂ fuels, whose chemical composition was certified by the bottle supplier, measured oxygen concentrations at combustor outlet were slightly higher than the calculated ones. This can be explained taking into account some air leakages into the chamber due to the window cooling. In the case of natural gas operation, the facility is directly connected to the gas national distribution pipeline. Due to large variation of the natural gas composition during the day, oxygen value calculated through the mass balance is affected by some uncertainty which can definitely explains the fact that the calculated oxygen is higher than the measured one. The comparison between the computed discharge temperature values and the measured ones allowed to estimated that the thermal power subtracted from the combustion chamber by the cooling systems was approximately equal to the 45% of the fuel thermal input.

NOx and CO emissions

The first investigation concerned a sensitivity analysis of NOx and CO emissions in natural gas operation with respect to equivalent ratio variations (Figure 7, NOx on left ordinate axis and CO on right ordinate axis). Two different procedures were considered to vary the equivalent ratio: the modulation of the fuel flow with constant air flow and the opposite (variations were done with respect to parameters given in Table 1.



Figure 7 : Effect of equivalent ratio variation on NOx and CO emissions (NG operation)

Figure 7 shows as measured NOx and CO emissions at the design point were about 15 and 1 ppm@15%O₂ respectively. These values are similar to those of typical DLN gas turbine combustors natural gas fired, ensuring that the burner was correctly designed especially in terms of air-fuel mixing. For leaner equivalent ratio, the CO emission trend highlights a sudden increase due to the flame temperature decrease, in agreement again with the typical feature of DLN combustors. Moreover, slightly different emission trends were found depending on whether air or fuel were modulated. These differences are mainly explainable considering that, for a certain equivalent ratio, the NOx and CO emissions are affected by the mixing degree at the flame front, whose position depends on air flow rate mainly. Concerning the investigation about the effect of the air-fuel mixing quality on pollutant emissions, the gas lance position was varied by moving the main injector toward the burner exit, i.e, realizing different premixing degrees. Each position was identified in terms of the ratio between the distance of the gas nozzle from the burner exit and the burner diameter (in the following, we will use "R" to refer to this ratio). The graph in Figure 8, showing the NOx emissions for three values of R (0.5, 0.9 and 1.2), highlights that the 60% decrease of the dimensionless distance R leads to a 35% raise of the NOx emissions with respect to the nominal configuration.



Figure 8 : Effect of the premixing degree on NOx emissions (NG operation)

The effect of the pilot-to-total thermal ratio on NOx emissions was evaluated by varying the pilot fuel and its air flows, keeping the main premixer at nominal operative condition (Figure 9). It was found that the premixed flame accounts for the 75% of total NOx emissions produced by the burner.



Figure 9 : Effect of the pilot-to-total thermal ratio on NOx emissions (NG operation)

The effect of the hydrogen content in the fuel was evaluated by supplying the burner with the NG/H2 mixture (25%/75% volume split, equivalent to 50%/50% in terms of energy). It was found that the switch from natural gas to the NG/H2 mixture leaded to flash-back phenomena onset if the burner was operated with nominal air flow rate. To restore the burner operability at nominal condition, the fuel lances were moved forward; it was found that the maximum R allowing the stabilization of the flame outside the burner was 30% lower than the nominal value in natural gas configuration.

In order to evaluate the possibility to supply the burner with CH_4/H_2 mixture without change the fuel lance position, test were repeated on the burner equipped with an ogive which allowed the 22% increase of the air velocity at the premixer outlet. This geometry configuration was initially tested in natural gas operation, too. Figure 10 shows the effect of the ogive installation on NOx emissions in the case of natural gas operation. In the following we will refer to burner equipped with the ogive as "high-speed configuration".



Figure 10: Effect of the ogive installation on NOx emissions (NG operation)

Figure 10 highlights that the high-speed configuration exhibited lower NOx emissions with respect to the nominal ones. This result can be explained assuming that the presence of the ogive forced the flame front to move forward, leading after

all to an increase of the premixing time. The high-speed configuration was used also for the pure hydrogen operation. In this case, despite the ogive installation, flash-back phenomena were detected for nominal air flow rate and nominal premixing degree. The operability of the burner at the nominal air flow was restored by moving forward the fuel lances (until R reached a value of 0.5, i.e 60% lower than the nominal premixing with natural gas operation). Conversely, operating the burner at higher air flow (maintaining an equivalent ratio equal to the nominal one, i.e varying simultaneously air and fuel flows), it was possible to stabilize the flame outside the burner even with the fuel lances in their nominal position. In particular, the minimum air flow value allowing the flame stabilization was about 60% higher than the nominal value (the latter referring again to the natural gas operation). Figure 11 shows the NOx emissions measured for the three different fuels with the burner operated at both nominal and low-premixing configurations.

In both investigated configurations (nominal flow/low premixing and increased flow/nominal premixing), NOx emissions in case of pure hydrogen firing were about 3 times higher with respect to the natural gas ones. Similar results were found in the previous test performed on GE Oil&Gas PGT10 diffusive type combustor in full-scale/full-pressure conditions [10]. Such a large variation of NOx emissions between hydrogen and natural gas was not expected. It is the author's opinion that the flame front moving back due to the hydrogen content increase leads to a significant decay of fuel-air premixing.



Figure 11: NOx emissions for different CH_4/H_2 fuel blending and different premixing level

Operability (flash-back speed limit)

The flash-back limit was investigated by changing step-bystep both the air and the fuel flow rate (keeping the equivalent ratio unchanged) until the flash-back was detected. Premixer fuel lances were positioned at the nominal premixing degree. Flashback onset was detected via UV camera signal which slightly anticipated the facility shut-down driven by the burner overheating protection, the latter being activated when the difference between the burner metal temperature and the combustion air temperature was larger than 15° C. The above mentioned investigations were performed for each fuel type and the results are shown in Figure 12. With regard to the natural gas operation, the minimum velocity allowing the stabilization of the flame outside the burner was 29 m/s. It was found that the hydrogen content in the fuel strongly affected the flame flash-back speed limit. In facts, to guarantee a stable burner operation, the discharge velocity had to be increased up to 53 m/s and 127 m/s for fuel having 75% and 100% hydrogen content (vol%) respectively. The higher burner exit velocity necessary to prevent flashback phenomena leaded to a significant increase of the pressure drop across the burner (see the right axis on Figure 12).



Figure 12: Effect of H₂ fuel content on flame flash-back speed limit and burner pressure drop

Gas temperature distribution

The effect of the hydrogen content in the fuel on the gas temperature distribution along the combustion chamber was estimated by means of in-flame thermocouple measurement. Twelve thermocouples were positioned at increasing distance from the burner exit, their sensor being located at a radial distance of 51 mm (equivalent to 0.75 D) from the burner axis. Three "high-speed" configurations featured by different hydrogen content in the fuel but the same thermal power input were chosen for the comparison in terms of temperature flowfield:

- NG fuel, high-speed config., nominal premixing, nominal air and fuel flow rates;
- H2 75%/CH4 25% fuel, high-speed config., nominal premixing, nominal air and fuel flow rates;
- H2 100% fuel, high-speed config., nominal premixing, air and fuel flow rates increased of 60% with respect to nominal ones.

It can be noticed from Figure 13 that the hydrogen adding in the fuel leads to a heat release moving back toward the burner and a larger flame opening angle (see zone at x/D equal to 1.5).



Figure 13 : Effect of hydrogen content in the fuel on gas temperature distribution

Heat release distribution

The heat release distribution of the first part of the flame was investigated by means of OH* chemiluminescence imaging technique. The OH* maps of the most meaningful configurations are given in Figure 14, each of them identified by a letter which defines the main operating parameters according to data reported in Table 3.

Config.	Fuel	Burner	Air flow	Fuel flow	Premixing - R
А	NG	STD	NOMIN.	NOMIN.	NOMIN 1.2
В	NG	OGIVE	NOMIN.	NOMIN.	NOMIN 1.2
С	NG	OGIVE	+60%	+60%	NOMIN 1.2
D	MIX	OGIVE	NOMIN.	NOMIN.	NOMIN 1.2
E	H2	OGIVE	+60%	+60%	NOMIN 1.2
F	H2	OGIVE	NOMIN.	NOMIN.	LOW - 0.5

Table 3: Configurations investigated through UV imaging

In order to help the result analysis, a sketch showing the main combustion system components is reported at bottom of Figure 14 with a generic OH frame. Moreover, a schematic streamline path (according to the flow field calculated by the CFD model) has been included.

The analysis of images reported in Figure 14 suggests the following remarks:

- the maximum reaction rate zone is located, for all configurations, on the interface between the premixer jet and the central recirculation zone;
- the pilot flame jet, visible on the burner axis zone, completely penetrates the internal recirculation zone;
- the heat release occurs mostly before the end of the observed window, i.e at a distance equal to two burner diameters;
- the increase of the air flow (keeping the equivalent ratio constant) does not change significantly the heat release distribution;
- in the three cases of hydrogen containing fuels, considerable flame moving back and shortening can be observed with respect to NG operation;
- the higher the hydrogen content in the fuel, the higher the maximum value of OH signal and the opening angle of the flame;

- in the case of pure hydrogen supply, the lowering of the premixing degree leads to a more extended OH emission zone.



Figure 14 : OH distribution measured for configurations reported in Table 3

CFD SIMULATION

Gas turbine combustion simulation requires to take into account the interaction between chemistry and turbulence. The thermal radiation too, plays an important role in the heat transfer mechanism. So, a radiative heat transfer model is also required for accurate temperature field prediction. The following numerical results were obtained with CFD simulations carried out with ANSYS FLUENT code (ver 12.0) [12]. For the test-case under investigation, the air/fuel mixture produced by the interaction between the air from the swirler and the fuel from the adduction nozzles is not homogeneous at the combustion chamber inlet. Appropriate models for simulating a partially premixed system are both the EDC model and the partially premixed approach as well. The partially premixed model was preferred with respect to the EDC because two main reasons: 1) the EDC is featured by high computational cost if used in conjunction with semi-detailed kinetic scheme (necessary for an accurate prediction of NO_x; 2) the EDC model tends to produce mean temperature's spurious peaks in the reaction zone [13] that can prevent an accurate NO_x prediction.

In particular, the Zimont approach [14] in conjunction with the Steady Laminar Flamelet model with Non-equilibrium and Non-adiabatic PDF tables was selected. The effect of preferential diffusion was taken into account by estimating the laminar flame speed through the fitted curves obtained from numerical simulations proposed by Gottgens et al. [15].

The tuning of the characteristic parameters responsible of both energy and mass turbulent diffusion and turbulent flame velocity near the walls was performed in order to improve the CFD results accuracy compared to the experimental data.

A RANS approach was used for turbulence modelling and the k- ω SST model was selected. Only results of pure hydrogen combustion simulations are shown in this paper. The laminar flamelet tables were generated by using the "Hydrogen37" kinetic mechanism proposed by Peters and Rogg [16]. This mechanism contains 13 species and 37 reactions.

Radiation was taken into account using the Discrete Ordinates (DO) radiation model, which solves the radiative transfer equation (RTE) for a finite number of discrete solid angle. The optical thickness for the system under investigation is less than 1, so the use of simpler and cheaper approaches as P-1 or Rosseland models was not appropriate [12]. The grey radiation formulation was selected and the absorption coefficient of the participating media was evaluated through the WSSG model. The internal emissivity of the liner walls was defined through the correlation proposed by Cao and Xu [17], valid for a high quality stainless steel.

The NOx formation modelling tool was finally used. The tool applied in this work took into consideration the Zeldovich mechanism only. The O and OH concentration values included in the NOx formation scheme were determined through the Laminar Flamelet model. The effect of turbulence on NO formation was modelled through an assumed shape PDF distribution approach applied to temperature local values.

Geometric model and computational grid

Figure 15 shows a view of the premixer and test rig geometric model with details about the air and fuel inlet. The axial swirler, featured by eight blades and eight fuel lances, defines a 45° rotational periodicity of the model.



Figure 15: Geometric model views

The computational mesh, hybrid non-structured type, was generated by means of the commercial code CentaurTM. The grid is composed by 2.2 million of elements with prismatic layers used for near-wall treatment and tetrahedral cells elsewhere (Figure 16). The mesh quality near the walls was controlled by the analysis of y+ values [12].



(b) Detailed View

Figure 16: Computational grid

CFD Simulation Results and Discussion

The burner prototype was investigated through the above mentioned CFD model and the numerical results were compared with experimental data.

The TAO ENEL test rig CFD model was built for both supporting the design of the premixed burner prototype and integrating the collected experimental data. Once the CFD model will be validate it will be then used to estimate the effect of higher pressure level, typical for gas turbine, and the effect of reduced cooling of the test-rig combustor walls. The definition of a RANS CFD reactive procedure for the complete characterization of the TAO test rig is currently ongoing.

In this paper the results of the CFD simulation focused on the aerodynamics flow field, air/fuel mixing and flame front position characterization are given in case of pure hydrogen operation of the burner. The CFD simulation are related to the experimental configuration named "E" in Table 4.

Operating Condition ID		E
Working pressure, p	[ata]	1
Air temperature, T	[°C]	375
Air mass flow rate	[g/s]	175
Hydrogen mass flow rate	[g/s]	1.724
Equivalence Ratio "Φ"		0.338

 Table 4: Combustor operating condition used by the CFD model

Aerodynamics

Aerodynamic flow field for both for the premixer duct and the combustion region as well, shows a proper pattern as expected from the design activity. Figure 17 shows the axial velocity map plotted on a longitudinal plane containing the burner axis. Inside the premixer duct the flow is well aligned and free of recirculation. At the premixer outlet the new swirler geometry is able to promote the formation of a typical recirculation zone (CTRZ) [5]. Iso-lines were reported in the region featured by negative values of the axial velocity at the premixer outlet.



Figure 17: Axial velocity map calculated on a longitudinal plane with negative velocity iso-lines of CTRZ

<u>Mixing</u>

The CFD model was used also to estimate the air-fuel mixing with particular concern to the premixing degree at the premixer outlet section. Figure 18 reports several maps of the equivalent ratio computed on crossing-sections at rising distance from the premixer fuel nozzles. The simulation showed a fairly homogeneous distribution of the equivalence ratio at the premixer outlet and confirms the proper design of the injection system with regard to the air-H₂ mixing.



Figure 18 : Equivalence ratio maps calculated on several cross-sections inside the premixer duct

Flame Position

The CFD model predicted a typical "V" shape flame pattern for the simulated case. Quantitative information about the flame position can be outlined by means of the Progress Variable [12] and its production rate analysis, which are the specific variables of the Zimont model [14].



Figure 19 : Progress variable production rate on a longitudinal section with a 0,9 value iso-line of the Progress Variable

Figure 19 confirms the information about the heat release distribution coming from the experimental OH measurements, i.e the maximum reaction rate is located at the shear layer between the premixer outflow and the internal recirculation zone. With regard to the OH distribution estimation, it has to be noticed that measured (OH*) and numerical values cannot be directly compared. Despite this, a first preliminary analysis is here given comparing Figure 20 and Figure 21. In order to make the interpretation easier, the Figure 21 was reconstructed by coupling the OH* experimental map with the burner geometry, taken from the CFD geometric model.



OH Mass Fraction: 1.0E-05 2.1E-05 3.2E-05 4.2E-05 5.3E-05 6.4E-05 7.5E-05 8.6E-05 9.7E-05 1.1E-04 1.2E-04 1.3E-04 1.4E-04

Figure 20 : Computed OH distribution with a 0,9 value isoline of Progress Variable (Case "E" in Table 4)



Figure 21 : Experimental OH* distribution (Case "E" in Table 4)

Both the model and the measurements highlight as the anchoring points of the flame are located over the ogive for the inner side and at the premixer external edge for the external one. Moreover, the CFD model predicts a flame shape wider in axial extension and shifted downstream with respect to that highlighted by the experimental results.

Temperature

Figure 22 reports the temperature map calculated on a longitudinal plane; cells with temperature values higher than 1600K are highlighted. It can be observed that only a very small region has temperature values higher than that value, with a maximum value estimated around 1630K.

It is the author's opinion that the CFD model slightly underestimated the flame temperature. Possible reasons could be the overestimation of both the air-fuel mixing and the distance of the flame front from the burner outlet section. Moreover the model shows a wider flame front than the experimental one. This observation seems coherent with the numerical prediction of the NOx emissions which showed concentration values considerably lower than the measured ones (1 ppm@15%O2 against 18 ppm@15%O2).



Figure 22 : Temperature map on a longitudinal plane and cell region with temperature higher than 1600 K

CONCLUSIONS

A lean premixed burner prototype was developed and tested on an atmospheric combustion test facility with the aim to identify some practical data to be used for the development of Low-NOx hydrogen burner suitable for heavy-duty gas turbine. The development of the burner prototype started from an existing DLN industrial unit, whose internal recirculation zone was reinforced by means of a new swirler. Moreover, it was equipped with a new movable fuel injection system and a removable ogive at the exit, both allowing to control the flame flash-back phenomena.

The experimental campaign was addressed to evaluate the effect of the hydrogen content on burner performances, comparing results obtained with three different fuels: natural gas, hydrogen-methane blend (75%/25% by volume) and pure hydrogen. It was found that, for air speed values typical of natural gas burners, the use of the hydrogen/methane mixture strongly compromises the operability of the burner because of flash-back phenomena. The heat release distribution analysis, performed through the OH radical emission acquisition, highlighted that the increase of the hydrogen content in the fuel leads to a significant flame moving-back and shortening.

Two strategies were successfully tested to restore the burner operability with hydrogen containing fuels at the nominal air mass flow rate: decreasing the premixing degree and installing an ogive at the premixer outlet to increase of 22% the flow discharge velocity. In the case of 75% hydrogen mixture, the results showed that the ogive allowed to stabilize the flame outside the burner without any changes to the premixer fuel lance position (with respect to the natural gas operation). In case of pure hydrogen supply and burner equipped with the ogive, the fuel lances were moved forward searching for the position preventing the flash-back onset. The configuration featured by the maximum allowable premixing degree exhibited NOx emissions which were three times higher than those of the nominal operation with natural gas.

A CFD reactive methodology for the analysis of aerodynamic/mixing, reactive field and flame shape was explored. The CFD model was used first to support the design of the burner prototype, then to help the experimental data analysis.The numerical simulations confirmed the proper design of the premixer in terms of flow field and equivalent ratio distribution at the burner outlet. Consistently, the temperature analysis at the flame front highlighted a quite uniform distribution and the presence of small regions featured by values higher than the premixer mean adiabatic flame temperature. Moreover, the model indicates that the maximum local heat release is located at the shear layer between the premixer jet and internal recirculation zone.

Next developments of the modelling activity will concern the validation of the CFD code by means of detailed comparison between numerical and experimental data. Once validated and calibrated, the selected numerical procedure will be applied to extend the investigation to those parameters not taken into account by the experimental activity (among them: working pressure, heat losses, etc..). Information collected through numerical and experimental activities will be then used as preliminary data set for the development of the upgraded Low NOx combustor installed on the Fusina hydrogen combined cycle.

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