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Enlarging fuel flexibility for Frame 5 DLN: Combustor operability and emissions with high C2+ content

Abstract

Fuel flexibility is a key feature of Dry Low NOx (DLN) combustors, which can accept a wide range of fuel compositions to meet increasingly challenging requests for both upstream and downstream applications in the oil and gas industry. However, high concentrations of non-methane hydrocarbons (C2+) are present in a variety of fuel gas streams, which can lead to flashback, overheated hardware, increased combustion dynamics and NOx emissions, and ignition in unexpected locations, possibly damaging the combustor, creating operability issues, and impacting durability. As a result, GE Oil & Gas is making C2+ a primary focus of its efforts to enlarge the fuel flexibility of DLN combustors.

To assess how well GE's Frame 5 DLN1 hardware design can handle high C2+ fuels, a single can full pressure test campaign was conducted on a full-size DLN1 combustor at the Sesta Lab in Italy.

The combustion chamber was tested successfully in premix mode with up to 50 percent ethane by volume, and without any of the aforementioned risks occurring. Special tests carried out in both premix and lean-lean operating modes verified the ability of the combustor to maintain a stable and harmless flame and assessed the operability margins in the different operating conditions of the combustor. Tests demonstrated that the current design already provided a good margin.

The expected performances for NOx and CO emissions and combustion dynamics were achieved in the investigated ethane content range. These test outcomes demonstrated that the Frame 5 DLN1 combustor was capable of accepting a greatly increased C2+ concentration in fuel gas.

Introduction

Traditionally, gas turbines have operated on either natural gas (NG) or light #2 distillate fuels (also known as diesel fuel or DF#2). In recent years, however, a wider set of fuels are being employed for power production, cogeneration and mechanical drive applications. Different fuels include associated gas, which is extracted from natural gas and oil fields, or combustible gas streams obtained as a byproduct of many industrial activities, such as those involving coal, oil and gas, refining, petro-chemistry, steel and mining. Agricultural activities are producing fuel sources as well [1]. Both political and economic drivers are making a strong push to enlarge gas turbine (GT) fuel flexibility by using cheaper gas and liquid fuel alternatives that don't compromise efficiency or emissions performance.

The case of LNG fields is a clear example; it presents unique challenges in terms of fuels that typically contain higher levels of ethane or nitrogen than traditional pipeline natural gas. In particular, non-methane hydrocarbon content can reach 50 percent, which consequently increases reactivity with respect to natural gas, which is comprised primarily of methane. Such higher reactivity can lead to higher flame speeds and flame temperatures, impacting exhaust emissions production, combustor operability and durability.

When this type of fuel (high C2+ gas) is burned, diffusion flame combustion systems are an effective, proven technology to deploy, since they can handle sudden changes of fuel gas composition, using steam/water or nitrogen to comply with emission requirements.

Nomenclature

BPV	Back-pressure valve
C2+	Hydrocarbons with two or more carbon atoms (in the present study limited to C2, C3 and C4 alkanes)
DLN	Dry Low NOx
FSFL	Full Speed Full Load
ISO	International Standards Organization
LHV	Lower Heating Value
LL	Lean-Lean mode
MWI	Modified Wobbe Index
NB	Nozzle Box
PCD	Compressor Discharge Pressure
PL	Partial Load
T39	Combustor Exit Temperature
TCD	Compressor Discharge Temperature
TP	Transition Piece

Recently, however, emissions regulations, water costs, and the desire to avoid Selective Catalytic Reduction (SCR) systems for NOx abatement have led to increased demand for lean-premixed DLN combustion systems in industrial applications. DLN systems historically have been designed to operate on natural gas fuels and have had characteristically lower fuel flexibility than diffusion combustors. One of the most widely used indicators of the fuel flexibility of a DLN combustion system is the allowed variation of the fuel Modified Wobbe Index (MWI). The acceptable variation of MWI for Frame 5 engines, generally set around +/- 5 percent of the nominal value [2], is sometimes too restrictive with respect to customer needs, and a deeper assessment of the real capabilities of the combustor is required to evaluate possible enlargements of this range.

In the last few years, fuel flexibility has become a key feature for DLN combustors that must meet increasing challenges, and it has gained importance especially in the oil and gas market, where LNG fuel gases, refinery off-gas, syngas and furnace gas are commonly managed.

Considering the above scenario, GE has launched several development projects to extend the fuel flexibility of multi-can combustors equipped with DLN1 and DLN2 systems, with a particular focus on industrial applications [3-6]. One of the most important results of these projects is that the DLN1 combustor exhibited good fuel flexibility with a wide range of fuel compositions, including both low-LHV fuels with high content of inert gases such as N_2 or CO_2 and fuels rich in highly reactive constituents, such as non-methane hydrocarbons and H_2.

Based on that result and to meet customer demands for low emission combustors that can handle fuels increasingly rich in ethane and higher hydrocarbons, GE has conducted a similar study to enlarge the fuel flexibility of the Frame 5 DLN1 combustor.

The experiment used a Frame 5 DLN1 combustor fed with different fuel mixtures of natural gas and C_2H_6. Tests focused on the combustor performances at different ambient and load conditions of the gas turbine; minor design modifications of some components were evaluated to identify the most robust solution for reducing NOx emissions and enhancing system operation.

Combustion system

DLN1 is a well-proven and reliable technology for low- emission premixed combustors and is widely employed on GE E-class heavy duty gas turbines. DLN1 is a hybrid dual stage combustion system; the fuel can be fed to the combustion chamber into the "primary zone" through five primary burners located in the cap's region, and/or to a secondary burner located on the combustor axis in a center body.

The flame can be established in the primary and secondary zones, depending on the combustion mode. A schematic summary of the possible combustion modes is shown in Figure 1. The engine ignites and starts up in a diffusion combustion mode called the primary mode, with flame in the primary zone and no fuel fed to the secondary burner. As load is increased, the secondary burner is fed as well (lean-lean mode) and a diffusion flame is present in the primary and secondary zones. As the load is further increased, the transfer to the premix mode begins. In the premix mode, fuel is fed to both burners, but flame is present in the secondary zone only, so that the primary zone acts as a premixer.

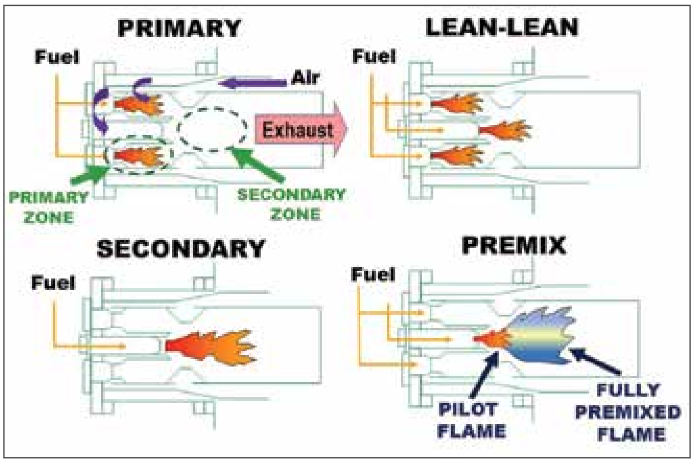

Figure 1 DLN1 operating modes

To reach this condition, the primary flame must be extinguished through the transient secondary mode, in which the fuel is cut off on the primary burners and fed to the secondary burners only.

The fuel split between the primary and the secondary burners can be adjusted during both the lean-lean and premix modes to enhance the combustor behavior. If flame is detected in the primary zone during premix operation, the engine will ignite the primary zone and go back to lean-lean mode even at high load (extended lean-lean). This operating condition results in higher NOx emission levels and higher metal temperatures in the primary region with respect to the premix mode. More details on the design and operation of the DLN1 combustion system can be found in literature [7, 8].

The presence of C2+ in a fuel mixture leads to an increase in flame speed, with a potential impact on the positioning of the premixed flame. Hardware damage can occur to the DLN1 combustor if the flame anchors in the secondary premixer, which is not designed to host the flame. On the contrary, the primary zone normally hosts the flame in primary, lean-lean and extended lean-lean modes. However, if the flame is re-established into the primary zone during the operation in premix mode, there will be an undesired transfer to the extended lean-lean mode.

A single-chamber, full-pressure rig test campaign was conceived to evaluate the combustion system's capability for handling high C2+ content fuels over the desired range of loads and ambient temperatures. In the present study, C2+ mainly refers to the C2/C4 hydrocarbons, which are most commonly found in fuel gases.

The lab test campaign focused on mitigating the following risks:

- **Spontaneous reignition of the primary zone** – If spontaneous reignition of the primary zone occurs, the system will leave the premix mode, with the consequences described above. One cause of spontaneous reignition is the flame back-propagation from the secondary zone. This event is prevented by the presence of the venturi, which increases the main flow velocity in its restricted section and generates local recirculation zones that help stabilize the flame front in the secondary zone. However, the increased flame speed related to the high ethane content might cause the flame to propagate back and ignite the mixture upstream from the venturi. The air pressure and temperature conditions in the primary zone (about 11 bara and 325°C) make the risk of auto-ignition negligible for fuels containing the explored concentrations of C2/C4 hydrocarbons. The risk of spontaneous reignition was assessed by forcing extreme operating conditions under which it could occur.

- **Flame anchoring in the secondary zone** – The high C2+ content increases the risk of anchoring the flame upstream from the secondary swirler in an undesired location that can result in hardware damage. The mechanism is similar to the one described above for the spontaneous reignition: As fuel reactivity increases, the flame front locates closer and closer to the secondary burner's tip, until the flame can propagate through the swirler blades and potentially anchor upstream on the fuel injectors. Specific tests were carried out to assess the resistance of the hardware at increasing ethane contents.
- **NOx emissions** – The higher flame temperature induced by the high C2+ content can lead to an increase in NOx emissions. Emissions were sampled and continuously analyzed during the test to assess the effect of fuel composition.
- **Combustion dynamics** – No significant flame stability issues are expected with fuels rich in ethane, but the higher flame temperature in some conditions could force "hot tones." Combustion dynamics were thoroughly monitored during the test.
- **Metal parts' temperature** – High fuel reactivity could change flame shape and position, where possible hot zones could arise on the metal liner surface.

Since ethane usually is the main C2+ component in the field gases used to feed the GT, as well as the main contributor to the flame speed increase (more than higher hydrocarbons like propane and butane) [9, 10], the investigated mixtures were a blend between natural gas (>98 percent CH4) and ethane (C_2H_6). Therefore, in the case of C3 and C4, the first two risks above are considered lower than with ethane. With regard to emissions, combustion dynamics and metal temperatures, the expected impact of propane and butanes is comparable with ethane, and minor differences in reactivity can be compensated by a proper tuning of the fuel split and minor dilution air tuning.

Rig test layout

Full-scale pressurized tests were performed on a single combustion chamber using a dedicated full-scale combustor test cell at the Sesta Lab in Italy, represented in Figure 2. The combustor and rig setup, schematically shown in Figure 3, consists of the following components:

- The combustor liner, which is arranged in a reverse-flow configuration replicating the actual positioning into the engine
- The hot gas distributor, called the transition piece [TP], located at the liner exit
- A nozzle box, including temperature rakes for exhaust gas measure and nozzle bars that simulate the effective area of the turbine's first stage nozzle
- A specially shaped confinement case, which can better simulate the fluid-dynamic conditions at the combustion chamber inlet
- A combustor casing modified to couple with the cell's vessel

Figure 2 Combustor test cell

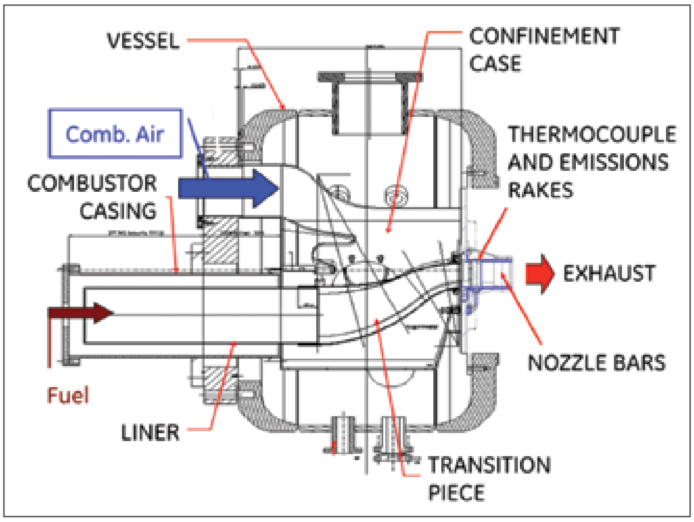

Figure 3 Test rig description

The combustion air, pressurized and heated to the desired values, is distributed in the confinement case after entering the cell, and then it flows into the combustion chamber. After the combustion process, hot gas exiting the liner goes through the nozzle box and finally flows to the exhaust-duct, where it is chilled by cold air.

The fuel nozzles located on the combustor's end cover are fed by two independent fuel gas lines equipped with shutoff valves for the system's protection.

Sesta Lab can provide the full-scale conditions of a single chamber of Frame 51PA and Frame 52D engines.

The combustor test cell is equipped with two sets of instruments:

- Those generally called "standard," which are necessary to properly control the combustion system and all facility devices. Owned by Sesta Lab, these include fuel and air mass flows, pressure, temperatures and fuel gas composition.
- "Special" instrumentation, strictly related to the combustion system for the execution of this specific test campaign and devoted mainly to monitoring. This additional instrumentation consists of static and dynamic pressure probes, and thermocouples to measure metal and gas temperatures.

With regard to the doped gas production and control, C_2H_6 and natural gas flows were measured separately by Coriolis devices and then the C_2H_6 concentration was calculated. Moreover, an additional C_2H_6 concentration measurement was performed by an online gas-chromatographic analysis for monitoring purpose only.

To investigate how the fuel characteristics affect the flame shape and position and, in turn, the hardware temperatures, the liner and the TP were instrumented with several thermocouples, providing a discrete map of the metal temperature profile. Specifically, 44 thermocouples were placed along the liner body surface and distributed on 11 axial locations and four radial locations, while the center body was equipped with 16 thermocouples and placed on a grid of four axial and four radial positions. Similarly, the transition piece was instrumented with 23 thermocouples in five axial locations.

Combustion dynamics were measured by two kinds of piezoelectric pressure probes, suitable for installation in either high temperature or low temperature environments, and located in five different hardware zones, as follows:

- 'High temperature' probe, in the casing plenum, sensing the primary zone
- 'High temperature' probe, at mid length of the casing plenum
- 'High temperature' probe, on the dummy cross-fire
- 'Low temperature' probe, in the standard DLN1 tuning kit location, sensing the primary zone
- 'Low temperature' probe, sensing into the liner fat zone

The location of these five probes is sketched in Figure 4.

To verify the combustion dynamic behavior in terms of frequencies and amplitudes, each probe signal, after passing through a conditioning system, was acquired in streaming and elaborated in real time through Fast Fourier Transform (FFT) to describe combustion pressure pulsations in the frequency domain.

Exhaust gas emissions were measured and recorded continuously during test operation.

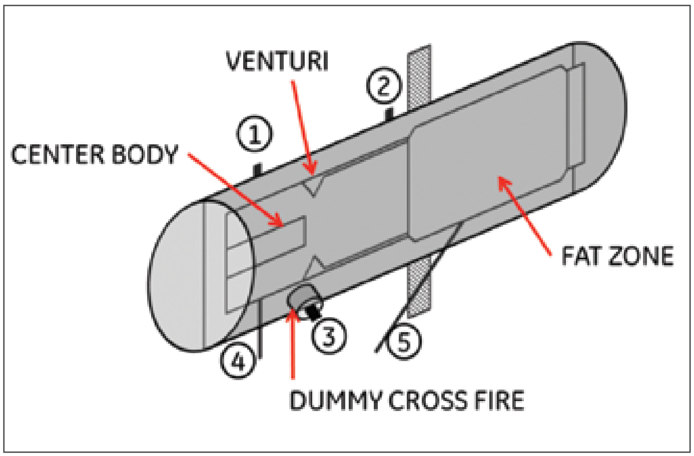

Figure 4 Location of probes for combustion dynamics monitoring

Four independent emission analyzers were used to sample the flue gas in four different points (see Figure 5):

- Rakes located upstream the TP exit
- Rakes located in the nozzle box (NB)
- A dilution section of the exhaust duct, upstream from the back-pressure valve
- A section downstream from the back-pressure valve

Chemiluminescence analyzers for NOx concentration, non-dispersive infrared analyzers for CO, paramagnetic O2 analyzers and UHC analyzers were used.

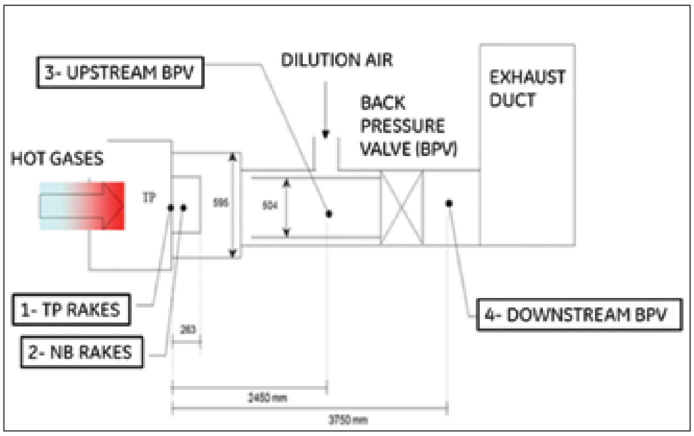

Figure 5 Location of probes for exhaust gas sampling and emission monitoring

Test Description

Combustion mapping at load

Sesta Lab can operate the combustor in the entire range of Frame 5 ambient and load conditions by adjusting combustion air pressure (PCD) and temperature (TCD), and air and fuel mass flow rates (fuel split). The test campaign was structured into a sequence of steady-state test points representing the different operating conditions and combustion modes. While the behavior was well explored at ISO day conditions (T=15°C), particular focus was put on the hot day conditions (T=+55°C), which are more critical as far as flashback is concerned. The tests were intended to completely assess emissions, combustion dynamics and metal temperatures.

The combustor characterization was carried out first with natural gas to establish a reference for the subsequent mapping with doped fuel. The chemical composition of the natural gas supply was provided on every test day, certified by the contractor and checked by Sesta Lab. Once the reference characterization was built with natural gas, the combustion mapping was performed with increasing ethane content, up to 40 percent by volume.

Flashback risk assessment

The resistance to flame propagation in primary and secondary zones can be assessed by forcing the combustor to operate in off-design conditions that will promote the flashback mechanism. Increased air temperature and thermal load, reduced flow velocity and a fuel-to-air ratio closer to stoichiometric make it more likely that a flashback event will be detected.

Specific tests also can be designed to assess the combustor's capability to operate without harm in case the flame propagates into the premixer. The scope of the test is to verify whether a flame, ignited in the premixer by a special torch, is cleared as soon as the ignition source is removed (torch switched off) or if it is sustained afterward. In the first case, the combustor can be operated safely in the test conditions with the investigated fuel composition. The test is carried out at reduced flow velocity in the premixer by increasing the air pressure to boost air density so that some margin can be taken with respect to the nominal operation. Tests were performed with up to 50 percent ethane by volume.

Results and Discussion

Spontaneous reignition in the primary zone

Although the combustor was operated in significantly off-design operating conditions (air temperature and firing temperature increased by maximum 100°C, pressure increased by maximum 25 percent, primary fuel split increased 5 percent above the desired level), no spontaneous reignition events were detected in the primary zone with the whole range of tested ethane concentration.

Flame anchoring in the secondary zone

Tests to assess the risk of flame anchoring in the secondary zone were carried out with both natural gas and fuel mixtures containing between 25 percent ethane by volume and 50 percent ethane by volume. Tests were performed both in premix and lean-lean modes, focusing on the most critical condition (full load at hot day, +55°C ambient temperature). The lean-lean condition was preferred, since it's the most critical in terms of flame propagation and stabilization into the secondary premixer, due to the higher equivalence ratio of the mixture in that zone.

The flame was never stabilized into the secondary premixer during tests in premix or lean-lean modes over the whole explored ethane concentration range.

Emissions

Emissions were measured continuously throughout the tests, and the emission behavior was explored in detail for both natural gas and blends containing 25 percent ethane by volume and 40 percent ethane by volume. The emissions from natural gas confirmed the expected behavior of the combustor, based on current fleet experience and relevant predictive modeling. The tests with ethane-blended fuel clarified the effect of the fuel composition on emissions, confirming the expected trend. Plots for NOx and CO emissions at ISO BL are reported in Figures 6 and 7 and show a comparison of the performances with natural gas and doped fuel mixtures.

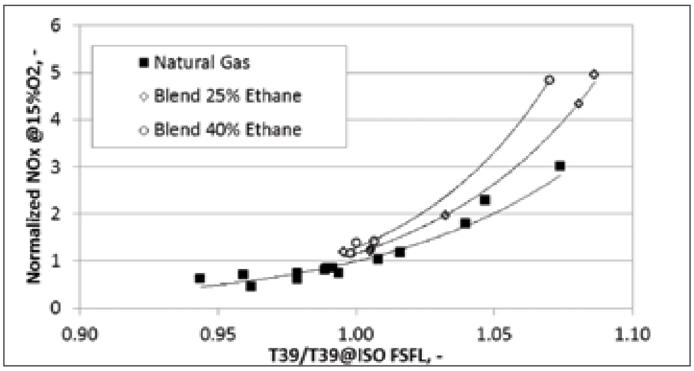

Figure 6 NOx emissions at ISO full speed full load

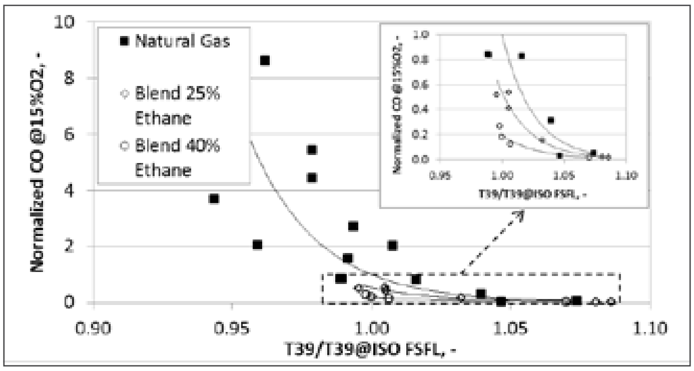

Figure 7 CO emissions at ISO full speed full load

The emission levels are reported for constant fuel split as a function of the ratio between the combustor exit temperature (T39) in the specific test point and the nominal one at ISO FSFL. The emissions values for both NOx and CO are normalized with respect to the baseline measured value at ISO nominal T39.

Figure 6 clearly shows that the increase of ethane content in the fuel leads to a corresponding increase in the NOx levels. The higher NOx levels induced by the presence of higher hydrocarbons in the fuel can be related to different mechanisms:

- A higher temperature of the diffusive pilot flame, which is responsible for a significant fraction of the thermal NOx produced in the premix mode
- A higher local temperature of the premixed flame caused by imperfect mixing and a higher heat release rate
- An increase in the relative importance of NOx formation mechanisms – especially the N_2O pathway [11, 12] – other than the thermal one

As expected, the effect is more important in the case of over-firing (T39 higher than the nominal value), since the equivalence ratio increases toward the stoichiometric ratio, while the impact on emissions at the nominal temperature is not dramatic and doesn't appear to compromise the current combustor's NOx emissions capability.

The complex concurrence of the different mechanism is still well reproduced, considering the effect of the increased stoichiometric flame temperature on the thermal NOx according to the Zeldovich mechanism. The NOx factor, defined as the ratio between the NOx emissions with a given fuel and the NOx emissions with pure methane [13], is predicted to be approximately 1.2 for a blend of 25 percent C_2H_6/75 percent CH_4, which is consistent with the results of this test campaign.

As expected, the effect of the presence of C_2H_6 on CO emissions was beneficial, as shown in Figure 7. While the CO levels with natural gas were quite high at T39 lower than the nominal value and presented a significant data dispersion, CO emissions with ethane-doped blends were significantly reduced (to about 50 percent with 25 percent ethane by volume, and to about 25 percent with 40 percent ethane by volume).

Combustion dynamics

Combustion dynamics were recorded during the test to verify how reactive fuel blends affected dynamics pressure magnitude increase and frequency shift. Mainly cold tones and hot tones were considered. Cold tones are generated when the lean premixed flame strength becomes too weak to provide a stable flame (namely, when the flame temperature is reduced), while hot tone amplitude increases as flame temperature increases.

Figure 8 shows experimental data taken during the test, where the combustor operating conditions, including inlet air temperature, pressure and flow, and the exit temperature were maintained while the concentration of reactive fuel in the fuel blend was augmented. There was an increase in hot tone dynamic pressure amplitudes versus gas composition variation, while the RMS value remained the same due to corresponding cold tone amplitude decrease. No significant shift in frequency occurred and the increased value of hot tone amplitude was well below the upper design limits. Therefore, inside the investigated fuel gas window, combustion dynamics is not considered to be a limiting factor in defining the acceptable dopant value.

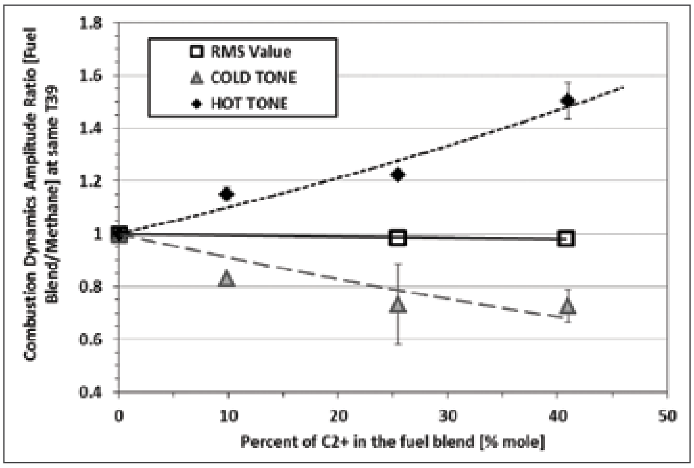

Figure 8 Hot/cold tone and RMS combustion peak dynamics amplitudes as function of C2+ in the fuel mixture

Metal temperature

Due to the higher fuel reactivity resulting from increasing the C2+ content in the fuel mixture, some modifications on flame shape and location were expected.

The influence of C2+ fuel content on the combustor metal temperature is shown in Figures 9-12. In each graph, the axial temperature profiles for the liner and the center body are represented at four circumferential locations and identified by the letters A, B, C and D. The values recorded by each thermocouple when running with ethane-doped fuel are normalized with respect to the value read by the same thermocouple, when the rig was operated with pure natural gas in the same testing condition (i.e , at the same PCD, TCD, T39 and combustion mode).

Figure 9 refers to premixed combustion, in ISO FSFL conditions, with 25 percent C2 fuel. In this case no significant variations in metal temperature distribution were detected between the two cases of pure natural gas and 25 percent C2 fuel. Similar conclusions about 40 percent C2 fuel can be drawn from Figure 10: Further increasing C2+ content in the mixture still doesn't significantly affect the metal temperature distribution in premix mode.

In the subsequent graphs, analogous plots were reported for lean-lean conditions at partial load, before the transfer to the premix mode. With all fuel gas compositions – natural gas, 25 percent C2 (Figure 11) and 40 percent C2 (Figure 12) – the center body outer surface close to the venturi throat is the hottest section (see also Figure 13).

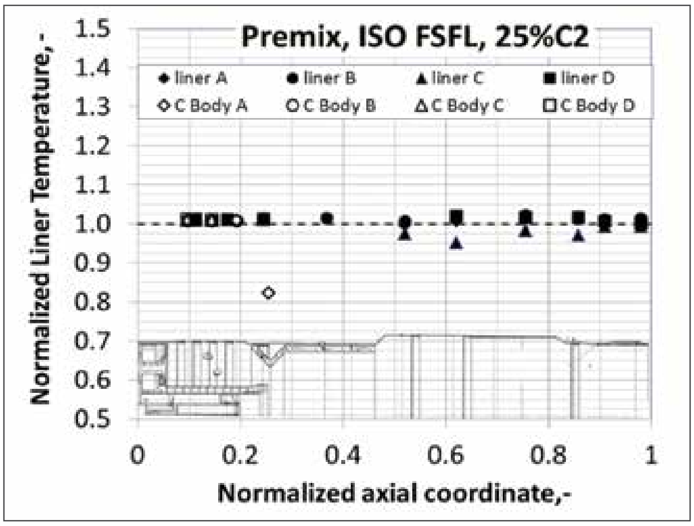

Figure 9 Cap and liner metal temperature, premix ISO FSFL condition, 25 percent C2 normalized with respect to pure natural gas

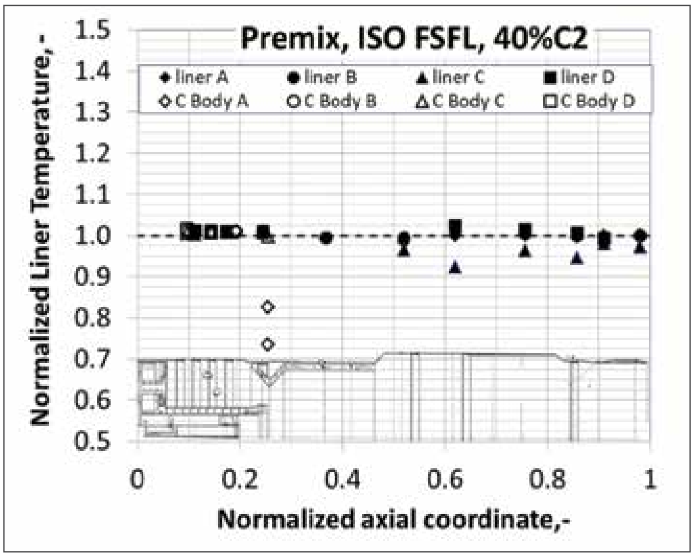

Figure 10 Cap and liner metal temperature, premix ISO FSFL condition, 40 percent C2 normalized with respect to pure natural gas

When C2 is added, there is an increase in the primary zone temperature, and especially in the center body; this effect is related to a change in the flame shape in the primary zone resulting from the increased flame speed. Although significant, this rise in metal temperature does not have a relevant impact on the hardware durability because the absolute temperature levels still are within the acceptable limit. Moreover, since the DLN1 unit is a dual stage combustor, the fuel split can be optimized in lean-lean mode to reduce the metal temperature when running with high C2+ fuels.

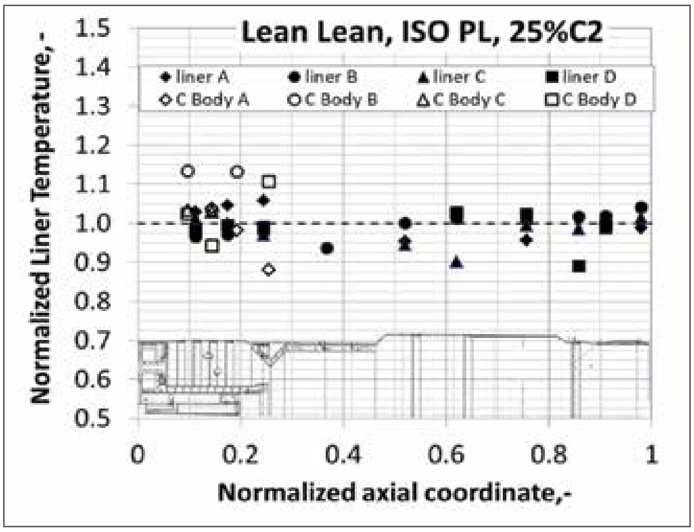

Figure 11 Cap and liner metal temperature, lean-lean ISO PL condition, 25 percent C2 normalized with respect to pure natural gas

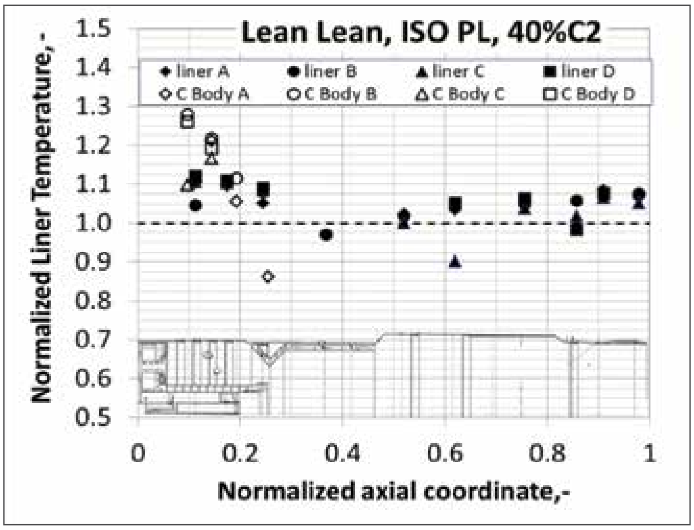

Figure 12 Cap and liner metal temperature, lean-lean ISO PL condition, 40 percent C2 normalized with respect to pure natural gas

The effect of the fuel split on the center body metal temperature is shown in Figure 13, where the temperature, normalized with respect to the maximum measured value, is reported as a function of the fuel split, which in turn is normalized with respect to the one corresponding to the maximum temperature. The profiles are reported in four axial locations along the length of the center body. The graph shows that a reduction of the primary fuel split in lean-lean mode can help produce up to a 10 percent reduction in the maximum absolute metal temperature on the center body, thus mitigating the effect of the increase in C2+ content.

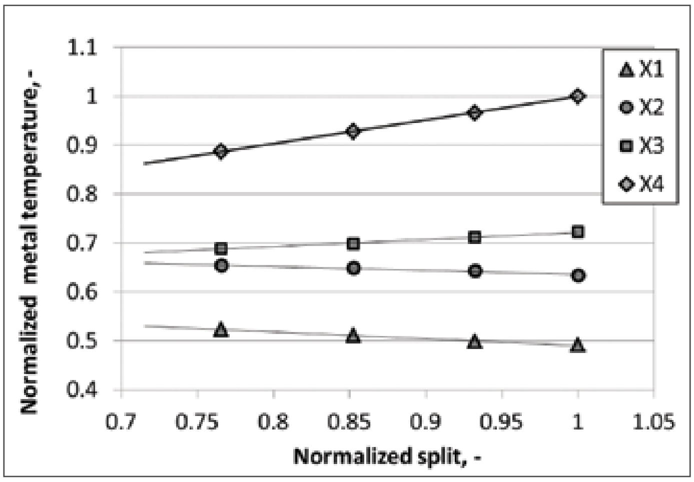

Figure 13 Center body metal temperature in lean-lean mode: Effect of fuel split

Conclusions

The analysis of test results shows that the standard hardware currently installed on Frame 5 units can burn fuel gases with up to 40 percent C2+ without damaging the combustor's operability and integrity.

Again, the DLN1 combustion system demonstrated a wide robustness in increasingly heavy operating conditions, keeping it competitive among E-class machines.

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Imagination at work

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Enlarging fuel flexibility for Frame 5 DLN:
Combustor operability and emissions with high C2+ content

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