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EXPERIMENTAL INVESTIGATION OF THE 4TH GENERATION DLE BURNER CONCEPT: EMISSIONS AND FUEL FLEXIBILITY PERFORMANCE AT ATMOSPHERIC CONDITIONS

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ABSTRACT

The "4th Generation DLE" (4G-DLE) gas turbine burner has been developed at Siemens Industrial Turbomachinery AB in Finspong, Sweden (SIT).

The present document describes the design concepts of the 4G-DLE burner; emission performance and fuel flexibility capacity. These features were explored at atmospheric conditions at SIT. High concentrations of H_2 and N_2 mixed with natural gas were used in the experiments. Emissions (NOx, Unburned hydrocarbons, CO), combustion dynamics and temperature operation range were evaluated. Moreover, operation characteristics of the burner were investigated through forced flashback, flameouts and unfavorable ignition situations.

The fuel flexibility concerning H_2 stretched up to 90% vol.[1] in a mixture with natural gas. In the case of N_2 it was possible to use over 50% vol. mixed with natural gas. The operation was stable in all cases.

The 4G-DLE burner showed good NOx emission performance that was linearly dependent on the flame temperature, while CO levels were also low. This fact reveals the high mixing level achieved in the burner. Finally; the burner operated over in a wide flame temperature range (approximately 200 K), showing both good stability and good emission levels.

Key words: Gas Turbine, Combustor, Fuel Flexibility, Emission, Hydrogen, Nitrogen.

INTRODUCTION

In the latest decades the interest towards cleaner gas turbine operation has increased sharply. First it was driven by a desire of higher efficiency and later by environmental concerns (reflected in governmental regulations). This trend continues, and the capacity to operate with wide variety of fuels can be seen as a further step to the ever increasing demands on gas turbines.

The first generation of low emission burners used water or steam injection to reduce NOx emissions from diffusion type flames (but in turn worsening CO emissions). Then "dry" techniques for emission control were developed (2nd generation, Dry Low Emissions). These have been used in the DLE system in the SGT-600 (25MW) engines since 1991. The SGT-600 DLE system (see Figure 1) is capable of emission levels below 25 ppm NOx using natural gas. A complete description is given in [1].

In the middle of the 90's the 3rd Generation DLE was developed for SGT-700 (31 MW) and SGT-800 (47 MW). Then the DLE technology was brought one step further by using the gained experience from the 2G-DLE. The NOx emissions decreased further; this time on both natural gas and liquid fuel. The 3rd generation DLE system was successfully tested and verified on the SGT-800 during 1998 and forward. The 3G-DLE,see Figure 2,delivers below 15 ppm NOx emissions on natural gas and 42 ppm NOx on liquid fuel. This burner consists of a split cone forming four air slots where main gas is injected followed by a mixing section with film air holes (not shown). Near the tip of the cone central gas and main liquid is fed and intensively mixed with the combustion air. The pilot fuel injection is positioned at the burner tip. Detailed description of the 3G DLE burner can be found in [2].

[1] %vol. indicates concentration by volumetric percentage

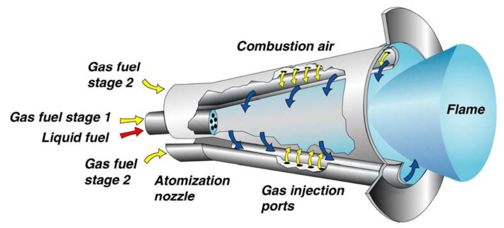

Figure 1. *The 2nd generation, DLE burner used in SGT-600 DLE and SGT-500 DLE types engines*

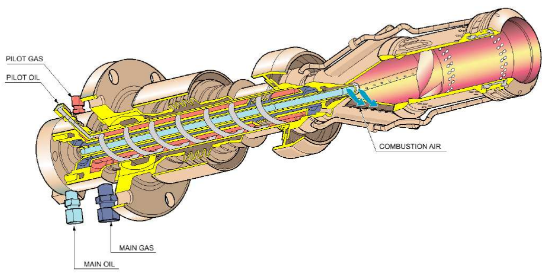

Figure 2. *The 3rd generation, DLE burner for SGT-700 and SGT-800.*

Siemens in Finspong has developed the 4th generation DLE burner [3,4] to achieve greater fuel flexibility, low emissions, (NOx below 15ppm), and a large and stable operating range. All of this as an answer to the current demands on the middle size gas turbines.

NOMENCLATURE

ACR		Atmospheric Combustion Rig
AGA		Aktiebolaget Gasaccumulator
CO	ppm	CO emissions corrected to 15% O_2
DLE		Dry Low Emissions
DPtot	%	Pressure drop over the burner
ER		Equivalence ratio
LHV	MJ/kg	Lower Heating Value
M1	g/s	Main fuel injection 1 mass flow
M2	g/s	Main fuel injection 2 mass flow
M3	g/s	Pilot fuel mass flow
NOx	ppm	NOx emissions corrected to 15% O_2
PFR	%	Fuel mass flow ratio Pilot/Total Flow
PuFR	mbar	Combustion dynamics (Pulsations)
RPL		Rich Pilot Lean (RPL)
SIT		Siemens Industrial Turbomachinery AB
T_{flame}	K	Calculated Flame Temperature
T_{in}	K	Combustion air temperature inlet
T_3	ºC	Combustion air temperature inlet
WI	MJ/Nm^3	Wobbe Index

BURNER DESCRIPTION

The 4G-DLE (Figure 3) burner could be described as a burner with three fuel injection systems nested into one. The Rich Pilot Lean (RPL) unit is located at the core of the burner and its main function is to provide radicals or high temperature oxygen rich flue gases to the symmetry axis of the burner (depending on the operational mode). The RPL has its own air and fuel supply. The pilot burner (M3) is built around the RPL. It uses air that flows between the RPL body and the main tangential swirl generator. This air, flowing downstream, cools externally the walls of the RPL. The pilot fuel is injected before reaching a swirl that is coaxial and placed downstream of the exit of the RPL.

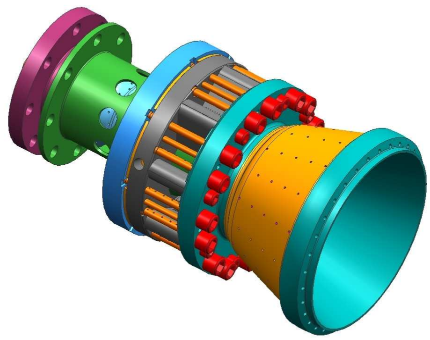

Figure 3. *Isometric view of the 4G-DLE burner prototype*

The main fuel injection (M1/M2) is done by two separated manifolds. Each manifold delivers fuel to a separated set of injection rods that are located around the radial swirlers (each one in between the guide vanes of the radial swirlers) in such way that each “slot” between swirler guide vanes has two fuel gas injection rods.

The fuel feedings are controlled independently. Air, on the other hand, is determined by the effective area of the respective “air path”. For the present test it was important to control the equivalence ratio of the RPL and an independent air supply was administered. The flow description of the 4G-DLE burner is depicted in Figure 4

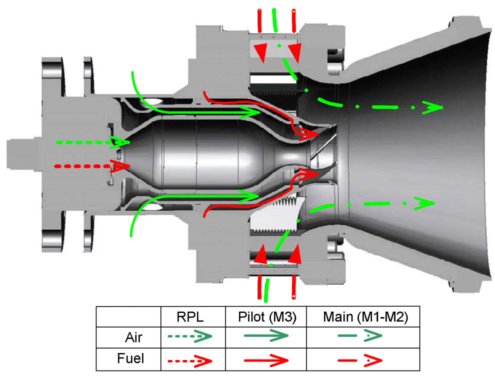

Figure 4. *Section view of the 4 G-DLE burner prototype.*

EXPERIMENTAL SET UP

At SIT an atmospheric combustion rig (ACR) is used for initial combustion investigations. This test facility allows simulating the prevailing conditions (flow velocity and temperature) for single burner test of SGT-600, SGT-700 and SGT-800. Previous experiences indicate that the similarity conditions to transport engine conditions to atmospheric test conditions based on Mach number and T_{flame} give good results to investigate burner behavior. It was also found that NOx emissions obey the "square root of pressure ratio" rule to relate NOx emissions at different pressures. On the other hand combustion dynamics are particularly dependent on the geometry of the set up; therefore, this parameter is more difficult to transport to engine conditions.

The new 4G-DLE burner prototype was tested at combustion conditions resembling SGT-700. The M1/M2 split chosen was 50/50 for all experiments, T_{in}/T_3 , RPL equivalence ration (ER), PFR and T_{flame} are indicated in the Figures legends when possible.

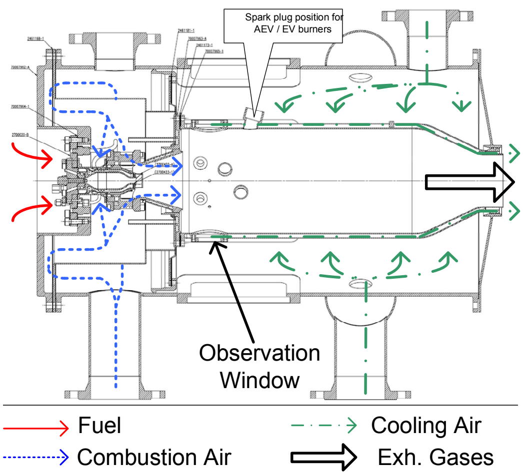

Figure 5. *4G-DLE prototype in the ACR. Spark plug is located in the same position as for 2G-DLE and 3G-DLE burners.*

The ACR encompasses a hot air supply (up to 500 ºC, and a maximum combustion air mass flow of 350 g/s), water cooled exhaust; two observations windows, one located at the side of the liner and the other covering the plane perpendicular to the burner axis. The liner is air cooled independently to the exhaust. The liner itself has "circular" observation windows mounted on the side. A split view of the 4G-DLE burner prototype in the ACR is shown in Figure 5.

The burner itself is instrumented with thermocouples, and pressure taps as it is shown in Figure 6. Burner's combustion dynamics over the burner are measured in the liner/burner interface.

Fuel flow and air flow to the RPL were measured with coriolis mass flow meters. The maximum error is in the order of 1,00%. Details about the ACR can be found in [5].

The emissions measurements were performed using instruments according to Table 1. The instruments were calibrated before each experimental day.

The fuel utilized was natural gas (main components: CH_4 98%vol., C_2H_6 0,7%vol., C_3H_8 0,2%vol., N_2 0,95%vol.), nitrogen (N_2 > 99,95%vol.), and hydrogen (H_2>99,5%vol.) all supplied by AGA-Linde.

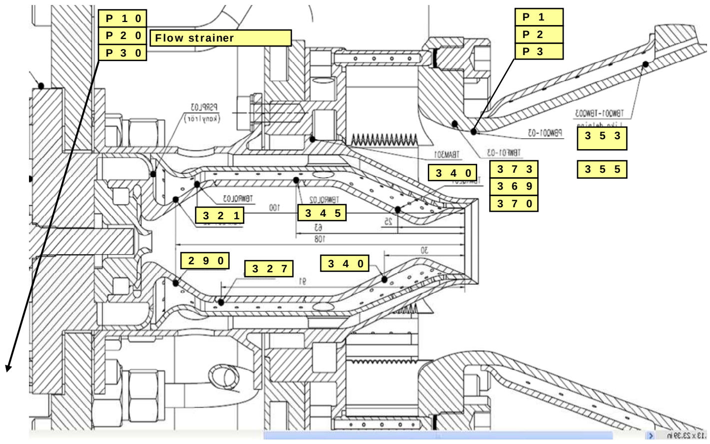

Figure 6. *Instantaneous view of the temperature readings Temperature readings in ºC*

Table 1. *Used emissions measurement instruments, measurement principle and absolute accuracy.*

	Unit	Instrument	Method	Range	Absolute accuracy (%)
O_2	%vol.	Maihak S710-3	Paramagnetic	25	1,8
CO_2	%vol.	Maihak S710-3	IR	5	0,4
CO	ppmv	Maihak S710-3	IR	100	5,9
NO	ppmv	CLD700-3	Chemilum.	10	0,7
NO_X	ppmv	CLD700-3	Chemilum.	10	0,8
TOC	ppmv	BA M3006-4	FID	100	9,0

EXPERIMENTAL RESULTS

The experimental campaign can be divided in a fuel flexibility test (with N_2 and H_2 variation), a flame temperature variation test, a start up and engine operation test, and finally a forced instability test.

Fuel Flexibility tests

In these tests N_2 and H_2 were used as agents to modify the combustion characteristics of the natural gas. The natural gas was diluted up to 50%vol. of N_2 and up to 70%vol. of H_2. Both mixtures were tested for similar burner settings obtaining stable burning conditions (normal settings in Table 2). In the case of N_2 it was possible to operate up to 55% dilution with slightly higher pulsation levels. In the case of higher H_2 it was necessary to modify the settings to reach 90%vol. of H_2 operation. The characteristics of the mixtures (fuel) used are shown in Table 2.

Table 2. *Variation of fuel characteristics by dilution of H_2 and N_2 on natural gas (% vol.)*

	Ref.	Normal Settings		Modified Settings	
	NG	N_2	H_2	N_2	H_2
	100%	50%	70%	55%	90%
Lower Heating Value [MJ/kg]	48,4	19,1	63,0	16,9	84,0
Wobbe Index [MJ/m^{3}n]	49,7	22,1	39,7	19,7	38,5

Nitrogen

The objective of this experiment was to test how lean fuel the 4G-DLE is capable to operate with. In order to do this natural gas was mixed with N_2 (dilution agent). The burner kept the same parameters (PFR, M1/M2 ratio, RPL conditions, T_{flame}). The results are shown in Figure 7.

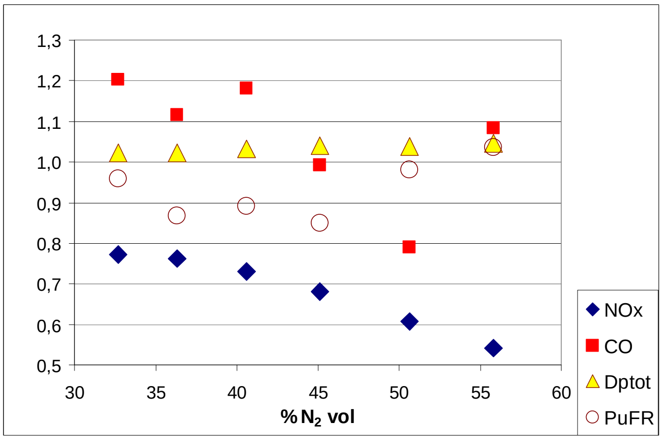

Figure 7. *N_2 dilution. M1/M2 split was set to 50/50. 20% pilot, 1% air in RPL, ER 1,4 in RPL,. High combustion dynamics (pulsations) levels appear after 56% dilution. Data normalized to 0%N_2vol. dilution.*

It was possible to dilute up to 50%vol. with N_2 with stable operation, at 55%vol. N_2 dilution combustion dynamics start to rise (low frequency band <100 Hz, not showed in the Figure 7) and this is considered the last stable point before flame blow out. It could be mentioned that the dilution of 45-50%vol. would have a reasonable safety margin to instability. NOx emission diminishes roughly 40% compared to the undiluted case while CO shows much lower variation.

Hydrogen

The natural gas stream was doped with H_2. Figure 8 shows emissions and pulsations as function of the H_2 concentration in the fuel. The burner parameters (ER in the RPL, T_{flame}, M1/M2 ratio, Tin, and PFR) were kept constant and similar to Figure 7. NOx emissions increase while the combustion is kept stable up to 70% H_2. All the other combustion parameters are stable except CO that registers a slight decrease. It was possible to operate a higher H_2 concentration (up to 90%) but RPL operation, pilot and flame temperature had to be controlled carefully to overheating and eventually flashback.

NOx increases approximately 50% at 70%vol. H_2 related to the undiluted case. Two T_{flame} conditions were tested (temperature difference between them was approx. 90K). They are shown with solid and dashed lines in Figure 8. CO on the other hand reduces by half for the same increase of H_2. At higher H_2 concentrations flash back and flame attachment occur (this is discussed later in the text). Then burner parameters were modified (ER and air flow in the RPL, PFR) and it was possible to reach 90%vol. H_2 dilution at the lower T_{flame} tested, with lower pilot and without RPL operation (only air in RPL).

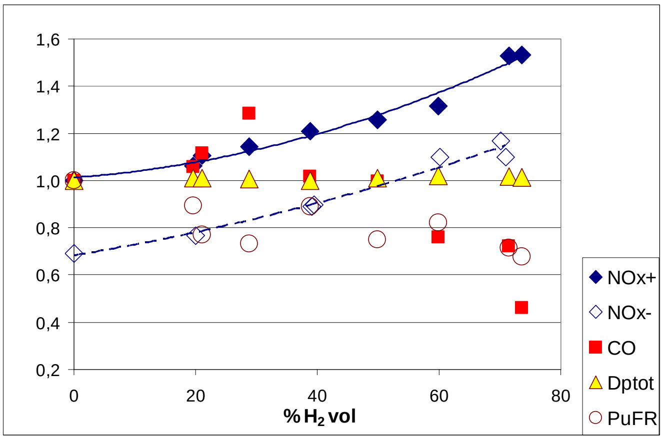

Figure 8. *H_2 variation, high T_{flame} (same temperature as Figure 7-solid line) and low T_{flame} (dashed line), 20% pilot, 1% air mass flow and ER 1,4 in RPL. Data normalized to 0%H_2vol. dilution*

Flame temperature variation test

Figure 9 shows the variation of NOx, CO, pulsation and pressure drop, when the flame temperature reduces 180K (from reference point). In this test pilot flow (M3) was fixed at 20% of total fuel flow.

Pulsation and pressure drop are relatively insensitive to the variation of flame temperature. CO increases as expected when flame temperature decreases.

Note that the exponential and linear regression curves on the NOx emissions have correlation coefficients (R^2) practically similar. NOx linearity indicates that there is an "overall" good mixing and NOx emissions are not highly coupled to the thermal NOx formation mechanism [6]. The later effect would predict a clear exponential behavior of NOx to flame temperature increment. This also might imply decoupling of NOx from pressure influence. Another important fact is that the range of temperature variation at "one" fixed burner setting reaches 180K. It is possible to change the burner setting to further increase this temperature range on both high and low temperature limits. The higher limit might consider limiting material temperature, while the lower temperature limit might be governed partially by the pilot stabilization effect. It has been experienced that for lower flame temperatures a higher pilot is required. Hence, a pilot flow higher than 20% would be required. 200K temperature range is achievable by modifying the burner settings.

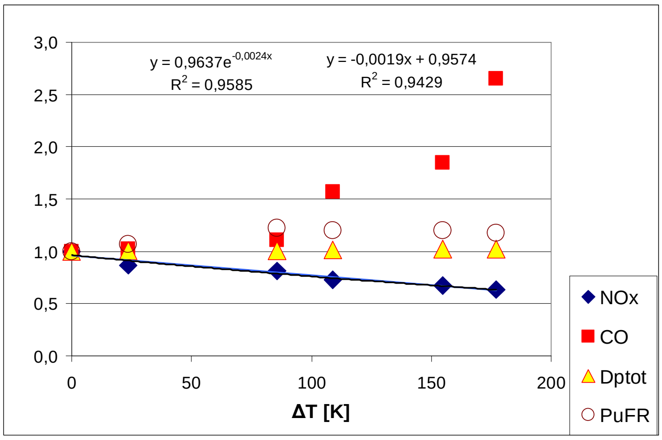

Figure 9. *T flame variation with PFR at 20%, 1% air mass flow in RPL at 1,4 ER. Data normalized to full load conditions*

Operation simulation test

Start up and Ramp Up

A start up simulation was performed by igniting the burner by the standard plug used for the 2G-DLE and 3G-DLE burners in the ACR. The ignition was achieved by igniting main fuel flows (M1/M2) then pilot (M3) and finally the RPL (M3). After controlling flame interaction (by reducing main) it was possible to ramp up the flame temperature. RPL was set only in fuel rich conditions (ER 1,4). It was possible to increase the fuel in the pilot until a flame temperature of 1600K was reached.

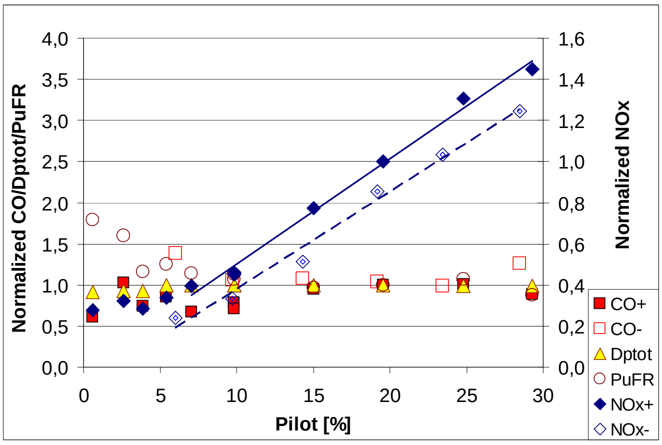

Figure 10. *Pilot Variation with 1% air flow in RPL at ER 1,4. High T_{flame} (solid line) and low T_{flame}(dashed line). The three last points at lower PFR run at ER 1,28 in the RPL. Data normalized to 20%PFR*

Pilot Variation

Pilot (M3) flow amount traditionally helps to govern flame stability but increases NOx emissions. In case of using a diffusion pilot, as is the case of the 2G-DLE, NOx emissions respond exponentially to the pilot fuel percentage (PFR). This is not the case for 4G-DLE burner, as can be seen in Figure 10.

The RPL operating under rich conditions (ER 1,4) would affect the NOx linear dependence if mixedness in the RPL is low; however, this is not the case as the linearity is kept. Moreover, The NOx linearity dependence on PFR can be taken as an indication of high degree of mixing that pilot flow undergoes in the pilot influencing zone. Note that NOx decreases linearly down to a PFR value of 5% for the both flame temperatures tested (solid and dashed line in Figure 10). Thereafter, ER in the RPL needed to be increased to keep stability (ER 1,28). By doing this it is possible to reach a PFR lower than 1%. The temperature difference between both T_{flame} lines is 90K same as in Figure 8. The other parameters show little variation.

RPL operation

The function of the RPL flow is to stabilize the flame by providing radicals (in case of running at rich conditions) or a high temperature flue gases stream rich in oxygen (in case of running in lean conditions). Figure 11 shows a comparison of the two RPL running strategies equalized on the fuel flow into the RPL. CO, pulsations and pressure drop are similar for both running cases (rich and lean RPL). In general terms there is a penalty in NOx emission when running in rich RPL instead of lean RPL for the same fuel flow in the RPL. The RPL rich line is obtained using a constant air flow and increasing fuel flow while the RPL lean is obtained by keeping a constant ER.

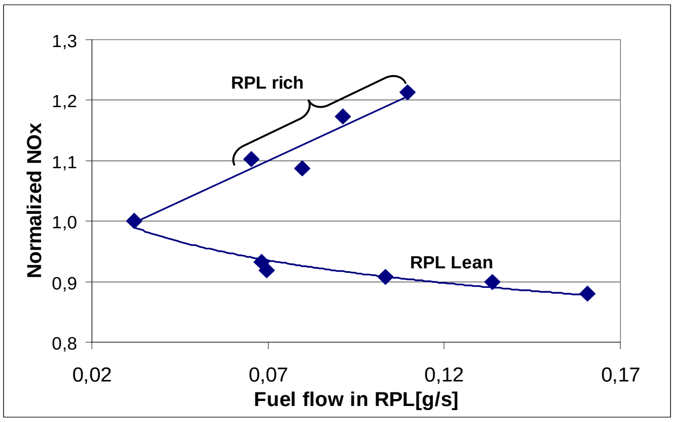

Figure 11. *Stabilization fuel power (Rich/Lean RPL)*

Rich RPL running offers better combustion "resilience", as it can absorb better transients than the lean RPL operation (observe the linearity in the rich case). Interestingly at ER > 1 (that occurs at approx. 0,05g/s fuel on the rich curve) unburned fuel and radicals flow into the pilot region and consume O_2, which is abundant in the overall combustion balance (approx

ER=0,5). The linear relation NOx – RPL fuel indicates high mixing velocities and/or slow chemical kinetics. In case of RPL slightly leaner than 1, it is the excess of O_2 from the RPL stream that reaches the pilot combustion region, competes for fuel (injected in the pilot) and reduces the flame temperature. This effect explains the reduction of NOx in comparison with the rich RPL case. The draw back in this operation mode is that the "resilience" of the combustion is lower. Both operation modes have advantages and disadvantages.

Lean RPL it is advantageous at medium to high PFR (probably part load) or if the engine will operate at stable load. Low PFR (<5%) and lean RPL can be associated with lower combustion "resilience" but it can reach a lower level of NOx emissions. On the other hand, lower PFR regimes work well with rich RPL regimens (probably full load) or at variable load operation, as it has higher combustion "resilience". There is a NOx penalty in this case. According to the experiments performed both RPL operation modes are feasible.

Forced Instability test

Flash back

Figure 12 shows operation at 90% H_2, when increasing the T_{flame} (solid line) two flash back situations could be observed (frames 3, 4 , and 6 in Figure 12) . The flash back starts at a region in the main annulus and extended to the whole burner.

Figure 13 shows a similar phenomenon; however, this is triggered by increase of the H_2 content in the fuel, but in this case the flash back occurs locally at the swirl's pilot and then a flame attachment can be seen in the frame sequence 2 to 5. In this case it is necessary to reduce the pilot flow from 20% to below 5%. Thereafter, it is possible to increase the H_2 content up to 90%vol. Another flash back occurred at 93% H_2 which is considered the operation limit on H_2 dilution at a T_{flame} slightly higher than reference temperature.

Flame out

Figure 14 shows an experiment were the burner is forced to flame out, in order to do this the fuel is diluted with 45% vol. N_2 and the PFR is reduced slowly. As expected pulsations (combustion dynamics) start to rise reaching 9 times the initial reference value. Then, when reducing the pilot fuel flow further, the combustion dynamics reduce sharply.

It was also observed that the pilot flame is assimilated into the main flame at very low PFR. The "weakened" pilot seems to move into the main flame as the anchoring position of the flame moves downstream. This should produce an increase in the effective area that would explain the slight reduction in the pressure drop across the burner. This quasi-equilibrium stage is close to the blow out limit of the burner.

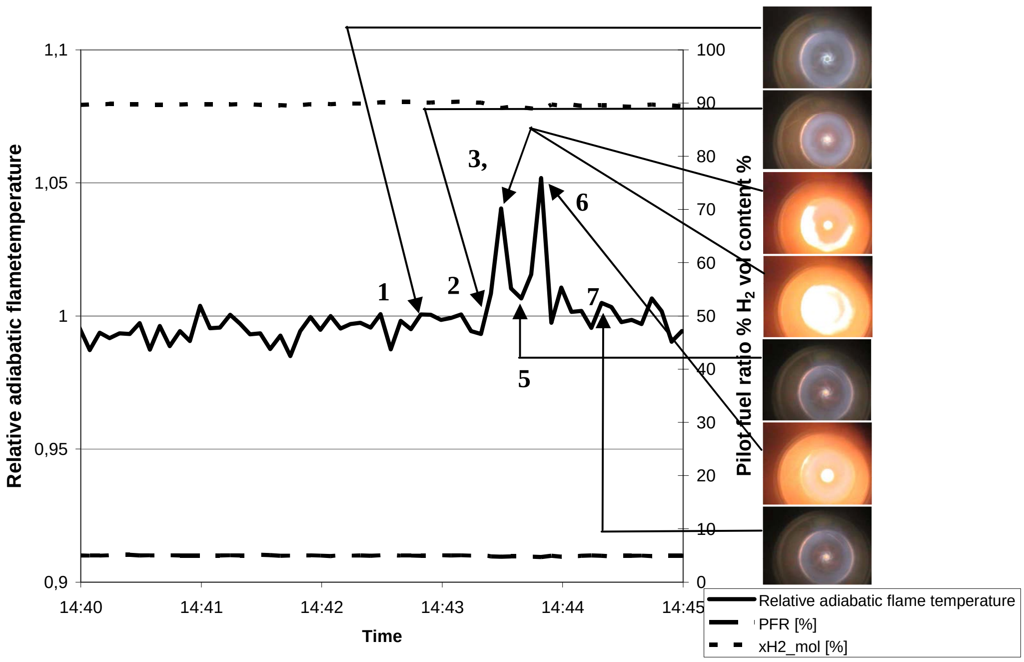

Figure 12. *Flashback at H_2 rich fuel (90%). Flash back forced by T_{flame} increase(solid line)*

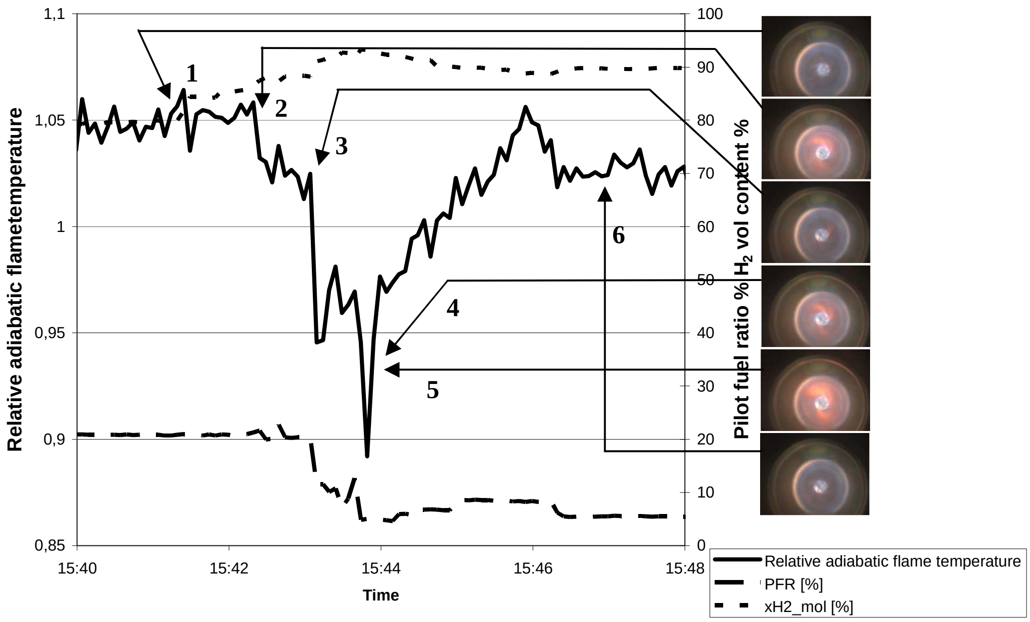

Figure 13. *Flashback at H_2 rich fuel (90%). Flash back forced by increase of H_2 content in the fuel*

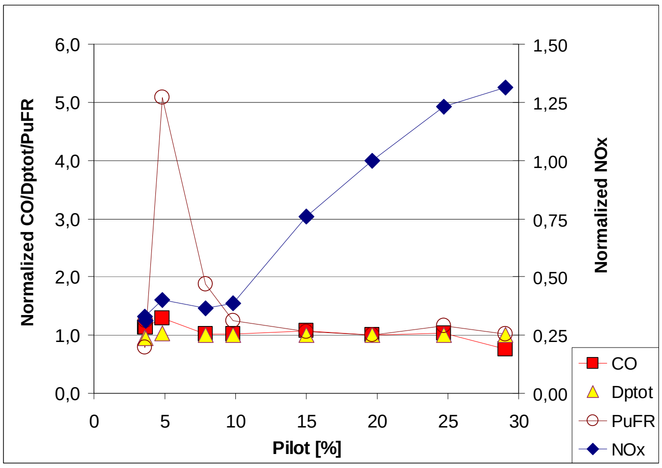

Figure 14. *Pilot variation (M1/M2=50/50) and 45%vol. N_2 dilution, 1% air mass flow and ER 1,4 in RPL, T_{flame} and Tin of SGT 700.. Data normalized to 20%PFR*

ANALYSIS

The 4G-DLE combustion strategy is based on the management of three combustion zones. These combustion zones correspond to each fuel injection point: RPL, pilot (M3) and main (M1/M2) (see Figure 15).

The linear dependence of NOx on: a) the flame temperature variation, b) the PFR variation and, c) the flow variation in the RPL support the idea that the mixing levels in pilot, main and RPL zones are good. It has been observed as well that instabilities occur every time there is a conflict between different combustion zones. For instance when the PFR is higher than 35% it starts to produce instabilities as the flame anchoring position moves from one stable point favored by the main fuel flows (M1/M2) and the other favored by the pilot fuel. If one of the fuel streams diminishes enough to become subordinate the instabilities (pulsations) reduce sharply. In general terms these instabilities are easy to control by managing the fuel distribution in the burner.

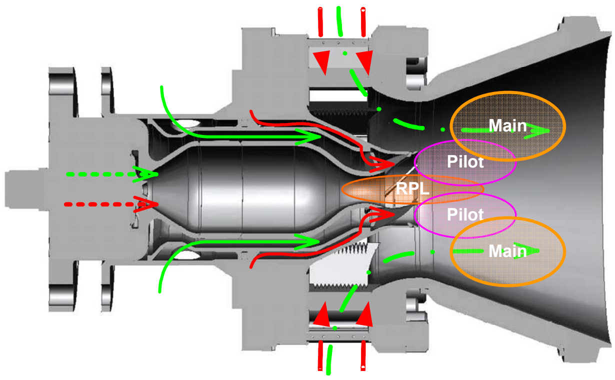

Figure 15. *Associated burning zones for RPL, Pilot (M3) and Main (M1/M2)in the prototype burner.*

In some operation points the disappearance of pilot or RPL flow is accompanied with a reduction of pulsations. This operation point could be defined as quasi-stable. It is also interesting to confirm that these quasi-stable points occur also when burning diluted fuel. In case of N_2 dilution the pilot flow might disappear and the combustion stabilizes only with RPL and main fuels. On the other hand running without RPL was achievable when running on H_2 diluted fuel.

As mentioned previously the function of the RPL is to provide either radicals (rich RPL) or hot flue gases stream (lean RPL) to the centre line of the burner. Lean RPL might be recommended when operating at high PFR regimes (i.e. part load or/and stable load operation) while Rich RPL might be used at low PFR regimes. (i.e high loads or variable load operation). Both strategies influence NOx performance.

Fuel flexibility has been the major focus of this experimental study, the range of fuel tested extended from 19 MJ/kg to 63 MJ/kg in LHV and from 22MJ/Nm^3 to 49,7 MJ/Nm^3 WI. NOx increases with the amount of the H_2 content and it reduces with the amount of N_2. This finding has also been reported in [7]. One of the reasons for the high fuel flexibility is the expansion section of the burner (quarl) where the flame establishes. This expansion offers a variable velocity field; hence, the flame would find an equilibrium position regardless its characteristic size or residence time. Highly reactive fuels would position upstream while less reactive fuels would position downstream. This explanation might be applicable also to the wide range of possible T_{flame} observed. Flash back and blow out limits would be determined by the physical features of the expansion section of the burner.

The experiments were performed on a single burner set and at atmospheric conditions with interesting results. The results encourage us to continue with the experimental trial. The continuation of this investigation would involve pressurized tests.

CONCLUSIONS

The fuel flexibility on H_2 stretched up to 90% vol. in a mixture with natural gas. In the case of N_2 it was possible to use over 50% vol. mixed with natural gas. The operation was stable in both cases.

The 4G-DLE burner showed a NOx emission performance that was linearly dependent on the flame temperature, while CO levels were also low. This fact reveals the high mixing level achieved in the burner.

The burner could operated over a wide flame temperature range (approximately 180K range), showing both good stability and good emission levels. The flame temperature range can be extended to 200K by modifying the combustion settings.

The construction of the burner favors the flame finding an equilibrium anchoring position. This is reflected by the stable pressure drop over the burner in the experiments performed and wide operational range in T_{flame} and fuel flexibility.

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