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EXPERIMENTAL STUDY ON HIGH PRESSURE COMBUSTION OF DECOMPOSED AMMONIA: HOW CAN AMMONIA BE BEST USED IN A GAS TURBINE?

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ABSTRACT

Hydrogen, a carbon-free fuel, is a challenging gas to transport and store, but that can be solved by producing ammonia, a worldwide commonly distributed chemical. Ideally, ammonia should be used directly on site as a fuel, but it has many combustion shortcomings, with a very low reactivity and a high propensity to generate NOx. Alternatively, ammonia could be decomposed back to a mixture of hydrogen and nitrogen which has better combustion properties, but at the expense of an endothermal reaction. Between these two options, a trade off could be a partial decomposition where the end use fuel is a mixture of ammonia, hydrogen, and nitrogen. We present an experimental study aiming at finding optimal NH_3-H_2-$N2$ fuel blends to be used in gas turbines and provide manufacturers with guidelines for their use in retrofit and new combustion applications. The industrial burner considered in this study is a small-scale Siemens burner used in the SGT-750 gas turbine, tested in the SINTEF high pressure combustion facility. The overall behaviour of the burner in terms of stability and emissions is characterized as a function of fuel mixtures corresponding to partial and full decomposition of ammonia. It is found that when ammonia is present in the fuel, the NOx emissions although high can be limited if the primary flame zone is operated fuel rich. Increasing pressure has shown to have a strong and favourable effect on NOx formation. When ammonia is fully decomposed to 75% H_2 and 25% $N2$, the opposite behaviour is observed. In conclusion, either low rate or full decomposition are found to be the better options.

Keywords: Combustion, Ammonia, Hydrogen, NOx

NOMENCLATURE

DCR	(Ammonia) Decomposition rate
Main	Main fuel section of the burner
R+P	RPL and Pilot fuel sections of the burner
PZ	Combustor primary zone
ER	Equivalence ratio

1. INTRODUCTION

Hydrogen is a carbon free fuel that has long been recognized as the fuel of the future. Unfortunately, that future has struggled to materialize due to several factors. One of them being that hydrogen is not naturally found on Earth and must be produced by a chemical or electrochemical process at an energetical cost considerably higher than that of natural gas extraction and production. The other issues are related to its physical properties. Hydrogen has a very low density, responsible for a low volumetric calorific value, which causes a problem for transport and storage requiring either very high pressure or large volume. This point is further aggravated by its high diffusivity and therefore potential for leakage. And leakages of hydrogen must be avoided at all costs because it is highly reactive with a wide flammability range in air. Transport and storage in liquid phase is therefore an interesting option, but it is also expensive as the vaporization point of hydrogen is at very low temperature. One solution is to transform hydrogen to ammonia [1] and transport it as a liquid, which is already distributed worldwide at very large scale by pipeline, rail, road, or ship. Some of the largest pipelines transport up to several million tonnes ammonia per year. The conventional Haber-Bosch process for producing ammonia is a

well-known technology, although it results in an added cost to the already expensive hydrogen production.

Ideally, ammonia could be used directly on site as a fuel, but it has many combustion shortcomings, such as a very low reactivity, making flame stability challenging and a high propensity to generate NOx far beyond current regulation limits. Alternatively, ammonia can be decomposed back to its original reactants, hydrogen and nitrogen (3:1 by volume), a mixture which has better combustion properties, but at the expense of an endothermal reaction costing at least 2.7 kJ/g_NH3 [2]. Between these two options, a trade off could be a partial decomposition where the fuel is a mixture of ammonia, hydrogen, and nitrogen.

Although CO_2 free, both hydrogen and ammonia offer challenges from a pollutant emission point of view. The former generates high temperature and subsequent high NOx and has very high flame propagation velocity. Oppositely, ammonia flames are difficult to stabilize and nonetheless are prone to NOx formation at all temperature. Furthermore, unburned ammonia slip is also strongly regulated. Okafor et al. [3] and Kurata et al. [4] studied pure ammonia combustion with a swirl burner in a micro turbine for operation. They found that low NOx emissions without ammonia slip could be obtained with 2-stage combustion with a slightly rich 1st stage. The optimum 1st stage ER was found to be about 1.1 and the ER in the 2nd stage was not found to influence the NOx formation strongly. Valera Medina et al. [5] studied combustion of ammonia and hydrogen mixture (70%-30% respectively) with the focus on the NH_3 combustion chemistry, NOx formation and stability. They experimental work was performed with a swirl stabilized burner at atmospheric pressure and also found that low NOx is possible at fuel rich conditions.

Although some experimental results from combustion of NH_3 and mixtures with either CH_4 or H_2 exist in the literature (see review in Kobayashi et al. [6]), but none (known to the authors) in mixtures which are relevant to decomposed ammonia. There are also studies under in standard laboratory flames for the study of kinetics and flame speed (eg. Mei et al. [7]), but a lack of pressurized studies with practical gas turbine burners. The main objective of this study is to assess the different pathways for the use of ammonia in power applications to highlight the pros and cons of the various rates of partial decomposition of ammonia as a fuel for gas turbines. The secondary goals are to provide quantitative evaluation of NOx emissions, specific to a commercial dry low NOx burner, stability behaviour, combustion efficiency, the effect of pressure up to 5 bar, and spontaneous spectral emission of ammonia-hydrogen-nitrogen fuel mixtures. The study is based on the latest generation burner of the Siemens industrial gas turbine SGT-750.

2. EXPERIMENTAL METHODOLOGY
2.1 Burner and combustor

The experimental facility HIPROX is a high-pressure combustion test rig with extensive modularity allowing burner testing with various fuel and oxidizer compositions. The facility is composed of a pressure vessel containing the combustor and the burner and a gas control and distribution unit. The combustor

module used is made of a pair of concentric quartz flame tubes as described elsewhere [8]. A cross section view of the burner placed in HIPROX with the flame tube is shown in Figure 1.
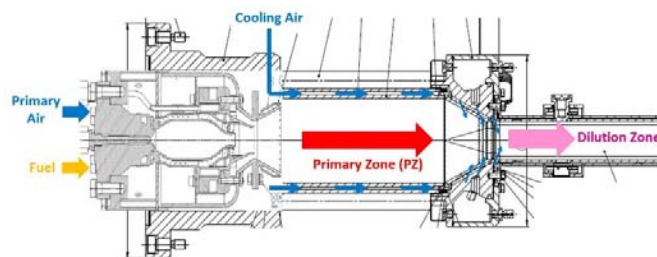

FIGURE 1: BURNER – COMBUSTOR ARRANGEMENT IN THE HIPROX HIGH PRESSURE FACILITY

The burner is a down-scaled version of Siemens swirl stabilized burner used in the SGT-750 gas turbine engine [9]. The main fuel path is injected through holes located on the swirler of outer annular channel, referred to as "Main". The second annular channel with swirler is termed the "Pilot" where fuel is injected through holes in the double-wall vanes of the axial swirler. Depending on the operating mode of the burner the fuel split Main/Pilot controls flame stability, in particular at lower overall adiabatic flame temperatures. The innermost chamber is called the RPL where fuel and air are injected and uncomplete combustion takes place. This section has an important role for the stabilization of the flame when fueled with ammonia. The primary air flowing into the burner through all three streams is pre-heated in the range 250 C - 320 C. The air/fuel mixtures from the three stages of the burner discharge into a 173 mm long flame tube of 90 mm inner diameter called the Primary Zone (PZ). Cooling air (at room temperature) flows between the concentric quartz tubes before being bled into the flame hot gases at the transition between the flame tube and dilution section as shown in Figure 1. The dilution section role is to mix homogeneously and cool the total exhaust gas before the pressure controlling valve, but also acts as a secondary combustion zone when the PZ is operated rich.

The burner used is scaled from the original SGT-750 burner designed for natural gas operation. Prior to operation with ammonia mixtures, the burner has been validated with methane and it performed as stated in the supplier datasheet of the SGT-750 gas turbine, with NOx emissions values below 15 ppm @ 15% O_2 dry. It has been tested in our experimental No design changes have been made and therefore the study therefore represents the case of a retrofit application. Since there is a variation of fuel LHV and adiabatic flame temperature when the fuel $NH_3/H_2/N_2$ mixture varies the air and fuel distribution through the burner will not be the same as with natural gas. The burner operational map at a given load and pressure has been adapted such as the mass flow rate of air is kept constant and the flow rate of a given fuel mixture is adjusted to reach the same overall adiabatic flame temperature. With this strategy, when nitrogen is used in the mixture, the total flow rate increases and the relative hydrogen and ammonia must increase too in order to compensate for the temperature. As a result, throat velocities are

not conserved with a change of fuel. The configuration depicted in Figure 1 is close to that of gas turbine combustor, however due to the need to cool the exhaust before the back pressure valve and the presence of instrumentation, the dilution zone is much longer than in a real engine, therefore residence times are longer in our experiments.

2.2 Instrumentation, measurements and accuracy

All gas flow streams, temperature, and pressure are monitored. Wall temperatures are measured along the length of the dilution section and inside the burner at several locations. The burner is also equipped with several pressure taps for measurements of static and differential pressures. The exhaust gas temperature and pressure are monitored before the pressure regulating valve. Although all species concentration data were measured at steady state conditions, some wall temperatures having a tendency to have longer response time, may not have reached steady state.

Exhaust gas was sampled downstream of the back-pressure valve and analysed with a FTIR analyser (Gasmet DX 4000) for: NO, NO_2, N_2O, NH_3, and H_2O. Oxygen concentration is also measured with a Zirconia cell built in the analyser. The spectral library used and the setup for spectra range selection for each species and the correction of species overlapping has been prepared specifically for these mixtures and the expected concentration ranges. Nevertheless, the available calibration spectra for the minor species were often at too low concentrations. Additional calibration spectra obtained with other instrument, but same model, have been added to extend the range. Therefore, it must be kept in mind that the higher the values for NOx and NH_3, the less accurate they are. The uncertainty of measurement of species concentrations is not only dependent on the instrument, but also on the uncertainty on all controlled flows into combustor. Because of the complex burner configuration with three fuel inlets and extensive mixture space studied, there are around 10 flow controllers in operation at each measurement point. Nevertheless, the mass balance based on the gas inlets is good, as measured concentrations of H_2O and O_2 are always within 1% and 3% deviation of the expected calculated values respectively.

Since the molar production of water depends on the fuel mixtures, correcting concentration to dry basis as is often done in emission reporting, would make the comparison of results inconvenient. Therefore, all species concentrations when given in ppm are corrected to 15% O_2 concentration on a wet basis unless stated otherwise.

2.3 Models

The kinetic calculations have been made using the CANTERA [10] run under Python 3.5 and using the NH_3 recently updated nitrogen chemistry (N/H/O) subset of the San Diego mechanism [11]. Flame speeds were calculated in a 1D laminar flame case. Because of the complexity of the burner (three swirling streams of different equivalence ratios interacting at their regions of highest strain rates), it was not attempted to reproduce the flame by setting up a reactor network as the

number of single reactors, their type, their composition, and their residence time or length would need to be carefully adjusted to properly represent the mixing. This is beyond the scope of the present work and instead NOx formation has been calculated in a single continuously stirred tank reactor (CSTR) with a residence time arbitrarily set at 10 ms with the mere ambition to draw a parallel with the overall kinetics and possible trends observable with these new fuel mixtures.

3. RESULTS AND DISCUSSION

The main parameter of this experimental study is the decomposition rate of ammonia (DCR) defining the fuel mixture composition as shown in Figure 2, where it can be noted that the ratio H2/N2 in any mixture is always 3. The burner described in section §2 has three fuel feed lines which can be operated independently both in mass flow rates and in fuel composition, making the possible experimental matrix very large. The results presented herein is a representative subset of the main findings. The RPL and Pilot fuel sections are always fed with the same fuel composition and will be here considered as one section denoted R+P, although the fuel flow rate (i.e. power input) distribution between RPL and Pilot can vary.

The investigation of the burner over the whole composition range at atmospheric conditions exhibit a strong flame stability even for mixtures with high ammonia content (low DCR). The only cases that could not be stabilized are with ammonia levels higher than 90 % at all fuel inlets. Note that lower limits have been reported in other studies [12] and it is a direct result of SGT-750 burner design which provides strong stability thanks to its fuel staging strategy.

The results from experiments are presented below divided into low, medium/high and full decomposition rate (DCR) of the ammonia. Kinetic modelling is included for comparison and validation of the kinetics.
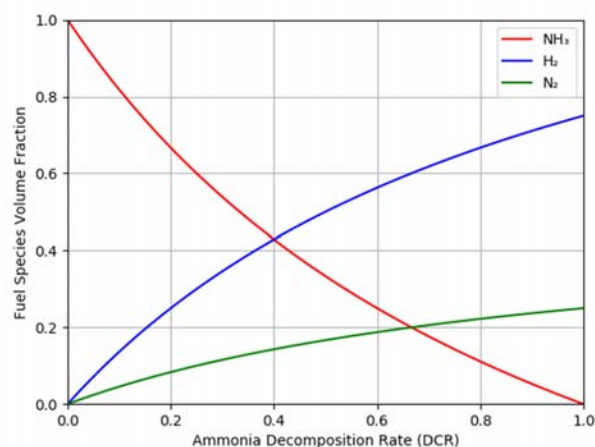

FIGURE 2: FUEL COMPOSITION AS A FUNCTION OF DCR

3.1 Modelled impact of decomposed ammonia as fuel

When shifting fuel in a gas turbine it is important to maintain turbine inlet temperature (TIT) in order to conserve the original specifications and efficiency of the engine. As a result of

decomposing ammonia, the equivalence ratio needs to be decreased from 0.6 to 0.5 from pure to fully decomposed ammonia respectively for keeping a constant TIT of 1450 C.

Flame speed as a function of DCR (Figure 3) shows the large span of expected stability while Figure 4 highlights that the NOx propensity is a trade-off between NH_3 concentration in the fuel and adiabatic flame temperature which increase opposite ways with varying DCR. The same calculations at a pressure of 15 bar shows that while for the hydrogen case at fully decomposed ammonia NO has increased, all the other cases where ammonia is present in the fuel have seen their NO formation considerably decrease. These general effects have already been reported in eg. Kobayashi et al. [6]. As a function of DCR we observe that the peak NOx are obtained at DCR of 0.6 at atmospheric pressure and at a higher DCR of 0.7 at 15 bar. In the following sections we will see how the kinetics basics transfer to the case of a complex industrial burner.

3.2 Spontaneous spectral emission

In hydrogen fuels without hydrocarbon or ammonia, the visible spontaneous emission of the flame is very weak as no soot is formed nor radicals giving rise to chemiluminescence in the visible region. In some flame conditions a faint red emission can be observed and attributed to water bands in the near IR - visible region, but it is not representative of the flame structure. Such a flame developing in the present burner investigated is shown in Figure 5, where in fact the only observed emission is that of the quartz tube being red hot. The following flames all have a R+P section with a fully decomposed fuel, while the ammonia content in the Main section increases. A typical orange-like colouring of the flame appears and increases in intensity as ammonia increases.

A spectral analysis of the spontaneous flame emission is shown in Figure 6 corresponding to the last flame of Figure 5 with pure ammonia in the Main section. The dominant feature of the spectrum which extend into the near IR is the water structure from ca. 700 nm to 1100 nm. In the UV, NH* chemiluminescence is visible around 330 nm, while the largest band around 300-320 nm is truly OH* chemiluminescence. The wide visible broadband starting to rise above 500 nm constitutes the orange colouring visible to the eye, where some peaks related to ammonia combustion are discernable: ca. 565 nm (Schuster bands) and ca. 630, ca. 660 nm (both NH_3 alpha bands).
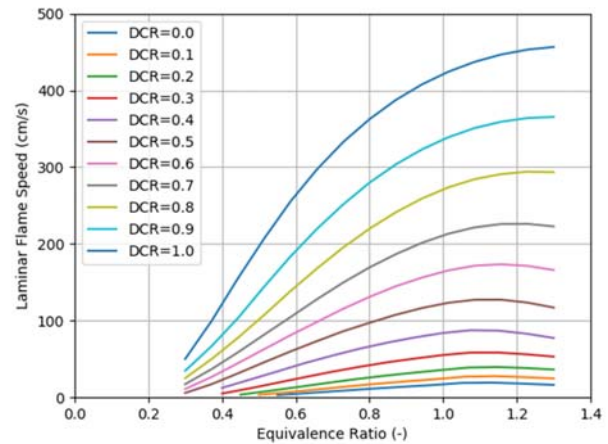

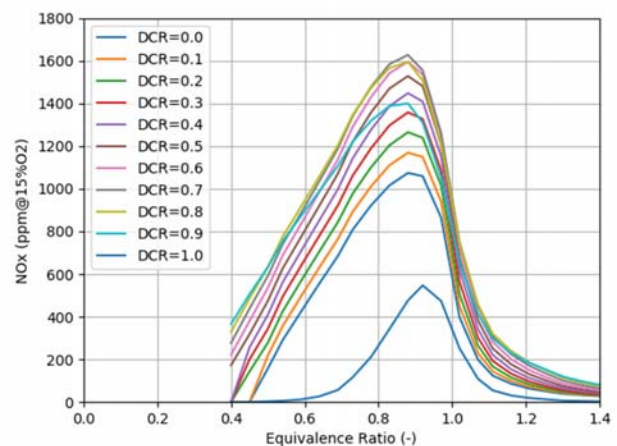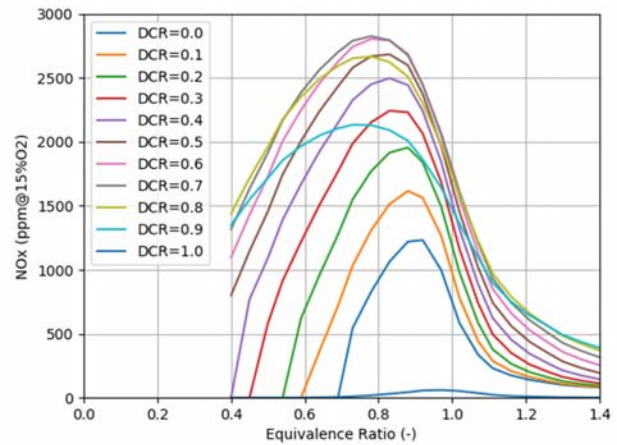**FIGURE 3:** FUEL COMPOSITION AS A FUNCTION OF DCR

FIGURE 4: CALCULATED NOX AS A FUNCTION OF DCR AT 20 C AIR - 1 BAR (TOP) AND 300 C AIR - 15 BAR (BOTTOM)

3.3 Combustion at low decomposition rate

A strategy of using ammonia with as low decomposition as possible would be preferred for an operator desiring to minimize infrastructure need, as for example on an offshore rig, and operating costs related to the fuel. Under atmospheric conditions, pure ammonia can however not be safely stabilized and would be an issue for starting and idling of the gas turbine. Thanks to the fuel staging design strategy of the burner, a stable flame can however be achieved by partially decomposing only the ammonia in the R+P or in the Main section. An overall decomposition rate of ca. 10 % (ie. ca. 15 % H_2) or more is necessary to sustain the flame. A small concentration of hydrogen of approximately 25% in the mixture of one of the two fuel streams (either R+P or Main) is sufficient to initiate and stabilize combustion, even if the other fuel stream is pure ammonia. A precise value is difficult to give without an extensive experimental matrix as it also depends on the fuel split between these streams. At these low DCR no combustion occurs inside the RPL section, the flame being stabilized inside the quarl aerodynamically.
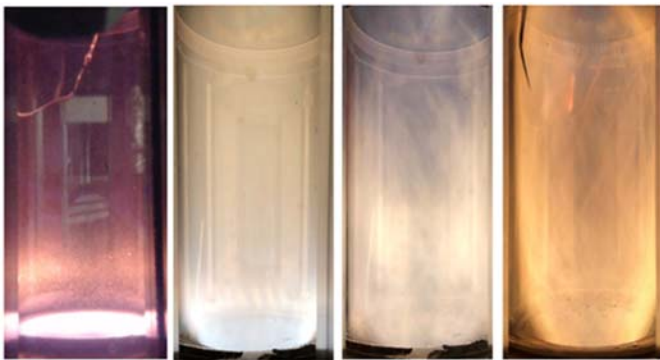

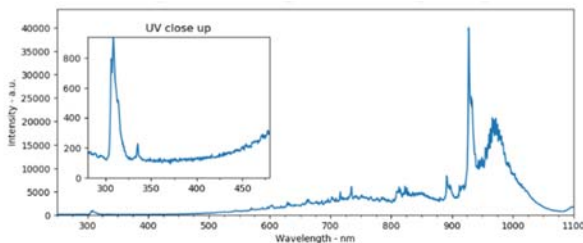**FIGURE 5:** PHOTOGRAPHS OF FLAMES AT DECREASING DCR FROM LEFT DCR R+P/MAIN: 100/100; 100/30; 100/18;100/0

FIGURE 6: SPONTANEOUS FLAME EMISSION SPECTRA OF NH_3 CONTAINING FUEL MIXTURES (DCR R+P/MAIN=100/0)

NOx emission characteristics typical of some low DCR cases are shown in Figure 7 at various fuel distribution and DCR (various symbol colors) as a function of PZ equivalence ratio. We first note that the emissions are high compared to conventional NG fired gas turbine, with the point of minimum being around 500 ppm. The position of the minimum NOx formation is obtained when the PZ is operated rich and above an equivalence ratio of 1.2. For all these cases the overall fuel to air

ratio is identical and all unburned from the PZ are consumed in the secondary zone with no measured NH_3 slip. At lean conditions NOx start to increase due the R+P mixture equivalence ratio becoming leaner, creating pockets of readily available O_2 for the NH_3. In the low DCR cases, there is no combustion initiated in the RPL and thus it operates as a mixer and provider of a rich fuel mixture jet on the axis of the flame. All the cases around the minimum NOx point, whatever the power distribution and DCR are, have in common that none of the three fuel sections have a mixture ER lower than unity. Therefore, it is important with NH_3 that no regions near the burner exit have unmixed O_2 available that could generate locally lean condition favourable to NO formation. These results compare well with the case of pure NH_3 combustion achieved in the study of Okafor et al. [3], where the minimum NOx formation was obtained at ER = 1.1.
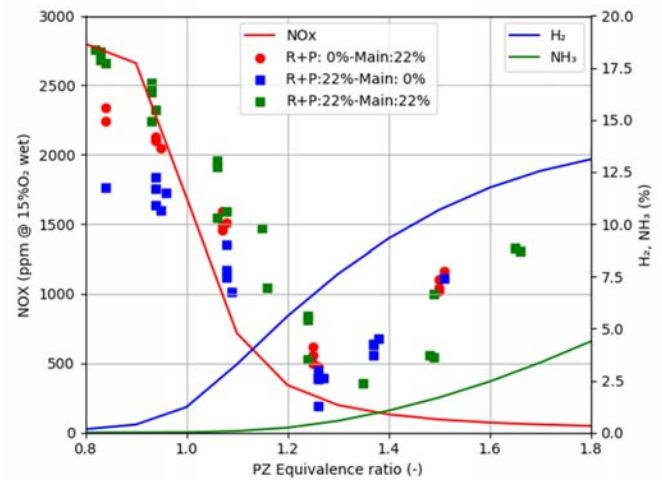

FIGURE 7: SYMBOLS ALL COLORS: NOx EMISSION MEASURED AT LOW DCR WITH COMBINED PURE NH_3 AND DCR=22% IN EITHER R+P OR MAIN. LINES: CSTR (10 ms) SPECIES CONCENTRATION FOR AN IDENTICAL OVERALL LOW DCR (11%) FUEL

The mixtures with highest decomposed NH_3 (green data points in Figure 7), hence highest adiabatic flame temperature, have understandably higher NOx emissions in the lean region. The other two sets of data are both pure NH_3 in one fuel section and 22 % decomposed mixture in the other. However, when pure NH_3 is in the R+P fuel section, NOx are clearly higher than when in the Main. It has been observed that for the flame to be stabilized, some H_2 must be present in the mixture, therefore the flame stabilizes in the quarl close to the section with the 22 % DCR mixture, which is either upstream (R+P) or downstream (Main). The results indicate that a higher conversion to NO is obtained when the flame stabilizes at the Main and ignites the upstream incoming NH_3/air mixtures (red data points). Even though the result is of practical importance for the operation of this industrial burner, a deeper analysis taking into account how the streams are mixing together in the quarl is required to really

understand the phenomenon. The three data sets of Figure 7 have been obtained at various fuel power distribution, with power in the Main in the range 50 % to 90 %, without having a noticeable effect on the NOx emissions.

The increase in NOx at higher ER than for minimum NOx is believed to be due to an increase in NH$_3$ slipping the PZ and being converted to NO in the air rich secondary zone. Indeed, the CSTR calculations for the corresponding total fuel composition (cf. lines in Figure 7) shows that although H$_2$ is still present at ER = 1, NH$_3$ only starts to escape the flame front in rich conditions, in agreement with the experimental observation of increasing NO. The chemical equilibrium (nearly attained for the main species after 10 ms) results in a fully consumption of NH$_3$ through the in-flame thermal decomposition and some levels of H$_2$ even at slightly lean conditions. This effect is naturally exacerbated as ER increases due to the increasing shortage of O$_2$ which affects H$_2$ consumption while temperature is still high enough for thermal decomposition.

3.4 Combustion at medium - high decomposition rate

At medium – high DCR, say greater than overall value of 30%, one of the fuel streams has always a hydrogen concentration of 50 % or more, ensuring a very stable combustion. When it is the R+P which is mostly decomposed, combustion starts inside the RPL section, further strengthening the flame stability, but also limiting the amount of power that can be injected in that section due to excessive temperature.

When the overall DCR increases beyond ca. 35%, the V-shaped NOx emission signature characteristic of Figure 7 is not to be observed and NOx values are in the 1000s range. The main reason is that due to the higher concentration of H$_2$, the heat release rate increases in the R+P part of the burner which cannot be operated in a low temperature rich zone anymore. It can be seen as a type of flashback behaviour, even though the temperatures are still within the material limits, but the major issue is that combustion is initiated well enough by the local larger H$_2$ concentration present and thus higher temperature improves the conversion of unreacted and undecomposed NH$_3$ to NO, instead of decomposing to NH$_i$ radicals and in turns H$_2$. It could in a manner be referred to as a kinetic flashback. Combination of medium/high DCR and low DCR and fuel distribution in the different parts of the burner can still be found, allowing to operate near the minimum NOx point highlighted in the previous section, however a general observation is that when a local region with high H$_2$ content is present (local medium to high DCR), temperature control and NH$_3$ slip become increasingly difficult. Figure 8 shows the calculated end of flame concentrations of fuel species and NOx which compared to Figure 7 highlights the better NH$_3$ consumption, hence higher NO, that an overall medium to high DCR configuration generates. The measured NOx decreases with ER, but do not reach as low values as in low DCR fuels.
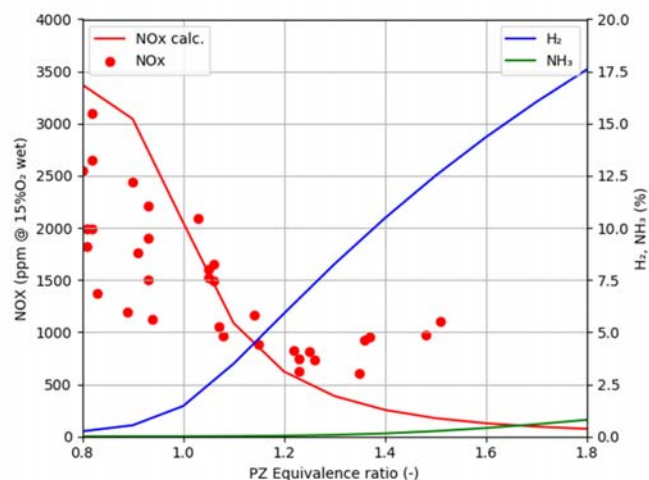

FIGURE 8: SYMBOLS: NOx EMISSION MEASURED AT MEDIUM/HIGH DCR. LINES: CSTR (10 ms) SPECIES CONCENTRATION FOR AN OVERALL MEDIUM DCR (47%) FUEL

In Figure 9 are gathered a set of measurements obtained at various DCR and fuel distribution, sorted by the PZ overall equivalence ratio and plotted against the overall DCR. It illustrates clearly that the primary factor influencing the trend is the PZ equivalence ratio, all other many burner operating conditions (e.g. fuel distribution, ER at each injection zone) having also an impact, but rather second order. In the collection of data of Figure 9, all the measured conditions presenting the slightest NH$_3$ slip have been withdrawn, such as these data are relevant to full combustion efficiency gas turbine operating conditions, although with a NOx issue for many of them.

It must be stressed that even though the behaviour described is in harmony with the 1D laminar flame calculations, the threshold overall DCR value given here of 35 % is burner specific and depends on the staging and mixing strategies.

3.5 Combustion at full decomposition rate

At DCR = 100 % the mixture is only composed of 75% H$_2$ and 25% N2 which corresponds to a stoichiometric laminar flame speed in excess of 400 cm/s (cf. Figure 3). It is therefore difficult for such a mixture to operate in a rich PZ mode similar to the partially decomposed mixtures as the central part of the burner is in combustion. It however allows the burner to operate with maximum air through the PZ and achieve low equivalence ratio without signs of instability. The emissions are consequently very low as indicated by Figure 10 showing measurements with various fuel distribution in the three injection sections. In fact the data are so low that they are around the detection limit of the instrument used which is calibrated for higher typical values, thus be aware of the high uncertainties. As a general behaviour, the more fuel in the R+P, the higher the NOx.
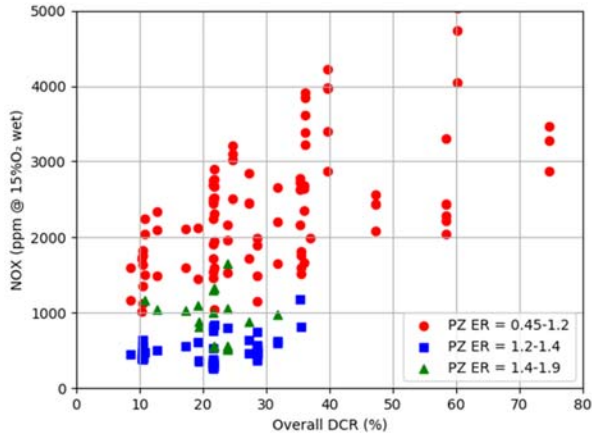
FIGURE 9: MEASURED NOX EMISSIONS VS. OVERALL DCR, SORTED BY PZ EQUIVALENCE RATIO

Note that in practical industrial conditions, perfect full DCR is unlikely to occur as NH_3 impurity would be present or costly to remove. The minimum impurity levels that have been possible to inject in our study was of 1% NH_3, which immediately made the NOx levels jump to the same levels as those obtained in low DCR conditions.

3.6 Effect of pressure

Pressure has been reported by Mei et al. [7] to have a larger negative effect on the laminar flame speed, hence stability, when hydrogen is present as compared to pure NH_3 or NH_3-H_2 mixtures and is attributed to increasing presence of pressure dependent H radical based reaction. The effect of pressure has been analysed on the cases that showed promising results at atmospheric conditions, namely the low and 100% DCR cases. Two sets of results are plotted in Figure 11 at low DCR, where one was obtained by increasing pressure proportionally with the power input and the other by keeping all flows (hence power and equivalence ratio) constant. The former corresponds to normal operation of an engine where pressure in the combustor follows approximately the load, hence keeping residence time constant. In both cases pressure increase has a noticeable reducing effect on NOx formation. Since longer residence time does not increase NOx, it is pressure that has a dominant effect on NO formation with NH_3 rich fuels. The magnitude of the reducing effect on NOx is quite important given the modest pressure increase experimented with roughly a halving of corrected emissions from atmospheric to 2 bar pressure. However, the slope quickly softens as pressure further increases. The calculated cases follow the same trend, but with more moderate slopes. The reduction in NO formation with pressure has been attributed to the promotion of three-body reactions involving H/O radicals, resulting in a reduction of their concentrations, and in turns the production of NO [6]. From a practical point of view, it is a promising behaviour since medium and large scale gas turbines operate

generally at pressures above 15 bars. Worth noting, the negative dependency was only observed with rich primary zone flames.
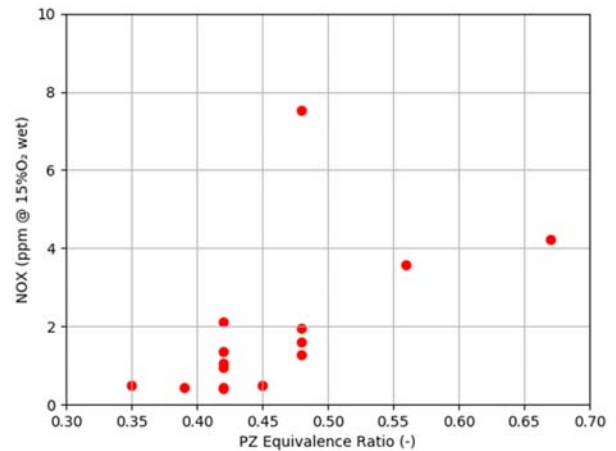

FIGURE 10: MEASURED NOX EMISSIONS AT 100% DCR (75%H_2/25%$N2$) OBTAINED AT VARIOUS FUEL DISTRIBUTION

For the fully decomposed fuel mixture case shown in Figure 12, the opposite behaviour is observed. Only the experimental case at constant power (increasing residence time) is shown, but the calculated cases clearly indicate that pressure increases formation of NOx, and so does to a larger extend residence time, which is expected since NOx is here controlled by the thermal NO mechanism. Kinetic calculations for the full decomposition are given for an ER of 0.8 even though the experimental data of figure 12 are at ER=0.28. However, the latter is the overall value; the actual value at the flame front is mixing controlled therefore richer and over a wider range than a single value. Since the fuel in the case of Figure 12 comes from the R+P section at an ER of 0.8, this value considered as representative is taken.
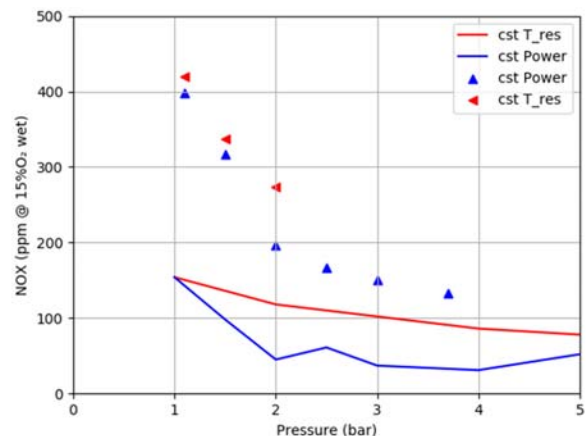

FIGURE 11: MEASURED AND CALCULATED NOX EMISSIONS AT LOW DCR (OVERALL 11%) UNDER PRESSURE AT ER = 1.3 AND 50 KW FOR THE CASE OF CONSTANT POWER
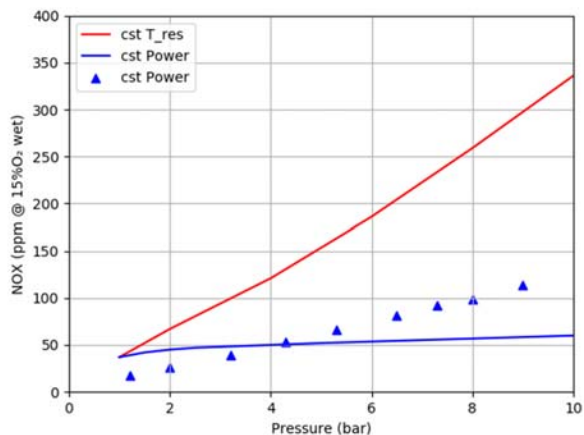
FIGURE 12: NOX EMISSIONS FOR 100% DCR (75%H_2/25%N2) FUEL MEASURED AT P=41 KW / ER = 0.28 AND CALCULATED

4. CONCLUSION

The experimental combustion study performed on an industrial burner fueled with decomposed ammonia mixtures showed that NOx emissions is strongly increasing with the rate of decomposition until full decomposition is achieved (H_2/N2-75/25) where the emissions become very low. Pressure affects oppositely the NOx trend if there is or not NH_3 present in the fuel. With NH_3 mixture it is however necessary to operate with a rich primary zone to minimize NOx.

ACKNOWLEDGEMENTS

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