Experimental and numerical results of a non-DLE aeroderivative GT combustion system burning methane-ammonia blends at intermediate pressures

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Abstract

Ammonia is considered as a practical hydrogen carrier, as it can be stored in liquid form at moderate pressures and temperatures and is commonly produced and transported today. Ammonia could be used directly as a Gas Turbine fuel to replace current hydrocarbon-based fuels, but its low reactivity and propensity to produce high NO_x will require major combustor design changes. Alternatively, ammonia can be fully or partially converted back into hydrogen and nitrogen before using it as a fuel with additional equipment and penalty on cycle performance. Another option is to replace only part of the natural gas with ammonia to minimize the changes of combustion properties and hence combustor design. Although this only partially decarbonizes the fuel, it may be a viable intermediate step to reduce the gas turbine footprint in the short term and with minimum hardware changes to the GT. This experimental and numerical study investigates combustion of methane-ammonia blends with a simplified version of the non-DLE Siemens Energy SGT-A35 turbine combustion system (Rich-Quench-Lean system, RQL) at pressures up to 8 [bar] and powers up to 100 [kW]. The effect of ammonia/methane ratios and Primary Zone Equivalence Ratio ($PZ\,ER$) on emissions of NO_x, CO and N_2O has been investigated for different pressures and power. A pressure exponent has been extracted based on this experimental data to provide an order of magnitude of NO_x emissions at engine conditions. To complement these experimental results, a simple Chemical Reactor Network (CRN) has been used to support the experimental results further. The experimental results showed that even small amounts of ammonia in methane

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result in unacceptably high NO_x emissions for all Primary Zone temperatures and pressures investigated. Although increasing pressure reduces NO_x emissions (as previously reported), extrapolation to engine conditions showed that the order of magnitude of NO_x emissions will remain unacceptably high. It is also shown that flame stability becomes insufficient for fuels containing more than 40-50 [% by vol.] of NH_3 as blow out occurred for these fuels. Furthermore, the results showed that N_2O emissions are very low for rich Primary Zone Equivalence Ratios and increase approximately exponentially with decreasing equivalence ratios, but remained below 10 [ppm] for cases at higher pressures. Finally, the CRN results reproduced the experimental trends qualitatively well for $\%NH_3$ variations but PZ ER variations and absolute values could not be matched for all cases simultaneously without re-tuning of the CRN.

Keywords: Combustion, staged combustion, RQL, non-premixed combustion, Ammonia, Ammonia blends, NO_x

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INTRODUCTION

Hydrogen produced from renewables (green H_2) or from Steam Reformed Methane (SMR) with Carbon Capture (referred to as blue H_2) can be used as a fuel to achieve Carbon free power production from land-based gas turbines [1] [2]. However, since liquifying and transporting cryogenic hydrogen is very energy intensive and costly, ammonia is considered a practical hydrogen carrier as it can be stored in liquid form at moderate pressures and temperatures, thus increasing its energy density considerably. Ammonia can be used directly as a fuel to replace natural gas, but its low reactivity and turbulent flame speed (approx. 7 times smaller than methane, [3]) makes combustion stability and combustor size challenging for gas turbine combustors. To circumvent this challenge, ammonia can be fully or partially converted back into hydrogen and nitrogen before using it as a fuel [4], but this approach requires additional equipment and energy. Another option is to replace only part of the natural gas with ammonia to minimize the changes of combustion properties and hence combustor design. Although this only partially decarbonizes the fuel, it may be a viable intermediate step to reduce the gas turbine footprint in the short term and with minimum hardware changes to the GT. This approach has been investigated experimentally in a previous study using a 4th generation DLE burner (SGT-750) [5] where stability, NO_x, NH_3, N_2O

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and other carbon-based pollutant emissions were quantified in both single stage (retrofit) and two stage rich-lean configurations (Premixed). It was established that NO_x emissions are largely dominated by the NH_3 content in the fuel. Therefore, the use of DLE technology, originally developed to target thermal NO_x, is believed to have little positive impact on the emissions performance of the combustor, while potentially causing dynamic stability issues, inherent to that type of technology. Okafor *et al.* [6][7] investigated NO_x emissions from a micro-gas turbine with a similar RQL combustion system at relatively low pressures, but not many other investigations were conducted on RQL system running with ammonia, underlining the utility of the current investigation. Indeed, the present study aims at investigating the potential of using RQL combustor technology with $NH_3 - CH_4$ blends and identify limitations of non-premixed systems in the context of ammonia combustion. This knowledge is of great practical importance since this partial decarbonization approach is particularly relevant for the vast majority of existing power generation assets based on RQL technology.

This experimental and numerical study investigates combustion of methane-ammonia blends with air in a simplified version of the non-DLE Siemens SGT-A35 aeroderivative Gas Turbine combustion system. The effect of primary zone (PZ) equivalence ratio and ammonia/methane ratios on emissions of various pollutants and unburnt fuels has been studied for different pressures and power. To complement these experimental results, a simple Chemical Reactor Network (CRN) has been used in an attempt to support the experimental results further.

Experimental Setup

The burner used in this investigation is a simplified version of the Siemens Energy SGT-A35 conventional Dual-Fuel burner (see Fig. 1). Due to the complexity of the original injector, it was modified to fit in the HIPROX facility, while retaining its main features influencing combustion characteristics. Special care was given to maintain its original (engine) air splits between Primary and Secondary Zones, Primary Zone Equivalence Ratio (PZ ER), Fuel injection pattern, Fuel jet injection velocities and central air Swirl number (see Fig. 2). Furthermore, the main air jets, the swirled air and the fuel jets were designed to reproduce the flow field, fuel placement and stoichiometry of the near region of the original injector. Note that Primary Zone cooling air (Primary liner and heat shield cooling air on the engine) was in-

cluded in the main air jets to reproduce the engine Primary and Secondary zone stoichiometries. The experimental facility HIPROX at SINTEF is a
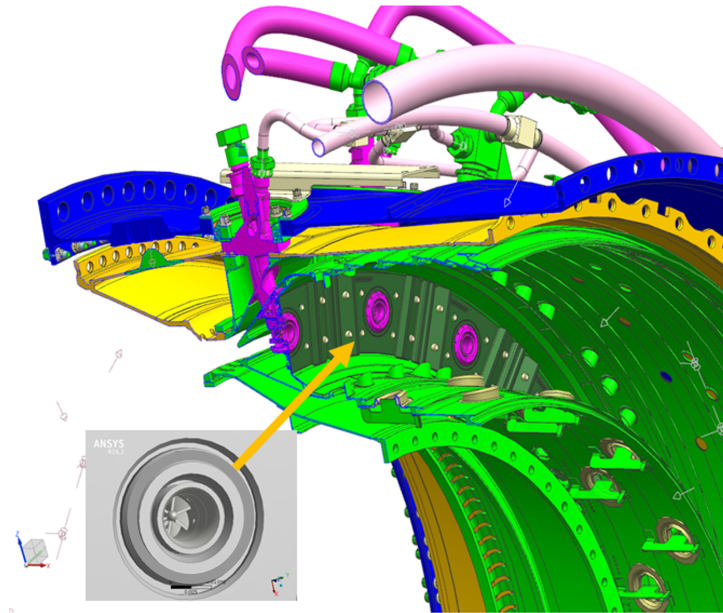

Figure 1: GENERAL VIEW OF THE SGT-A35 NON-DLE COMBUSTION SYSTEM (WITH A ZOOM ON THE INJECTOR).

high-pressure combustion test rig with extensive modularity enabling burner testing with various fuel and oxidizer compositions already described in [4] and [5], but with a different combustor module. 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 this study is made of a double walled metal tube as illustrated in the cross section shown in Figure 3. The Primary Zone (PZ) has a Thermal-Barrier Coating and the secondary air flow is used to cool the PZ wall before being injected at the end of the PZ through multiple holes equally spaced around the tube. Wall temperatures are monitored at 5 different streamwise stations. After passing through the back pressure valve controlling the combustor pressure, the exhaust gas is sampled at a single point in the centre line of the exhaust channel. Mixture uniformity is ensured by the passage through the strong area blockage ratio at the pressure valve and bends before the sampling point. The exhaust gas samples are drawn into a commercial FTIR instrument where the concentra-
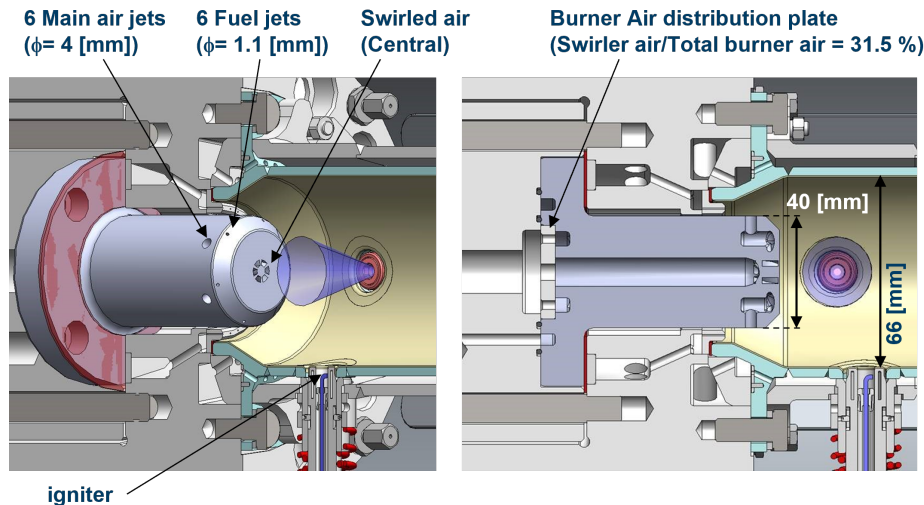
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Figure 2: VIEW OF THE SGT-A35 NON-DLE SCALED GEOMETRY.

tions of species of interest ($H_2O, CO_2, CO, NO, NO_2, N_2O, HCN, NH_3$) are measured. The uncertainty on the actual measured species concentrations is given as 2% by the manufacturer, however the total uncertainty depends also on the mass flow controllers of all streams (between 5 and 7 were used). The measured concentrations of the major species ((H_2O, CO_2, O_2) were always compared to those calculated from mass balance based on inputs of all mass flow rates and the agreement was always within 5%. The main air stream can be split and distributed to suit typical Dry Low Emissions burner as well as conventional injectors in a RQL configuration by-passing air from the injector to mimic dilution ports (Secondary Air in Fig. 3). The split ratio is not fixed, but set by mass flow controllers for each streams, and has been adapted depending on whether adiabatic temperatures or equivalence ratios in the primary zone were targeted when the fuel composition was varied. The pressure to thermal power load ratio is kept at 1 bar/kW, except at atmospheric pressure where 15 kW was used.

Chemical Reactor Network

A simple Chemical Reactor Network (CRN) was used in an attempt to support the analysis. The Primary zone is composed of a first Perfectly
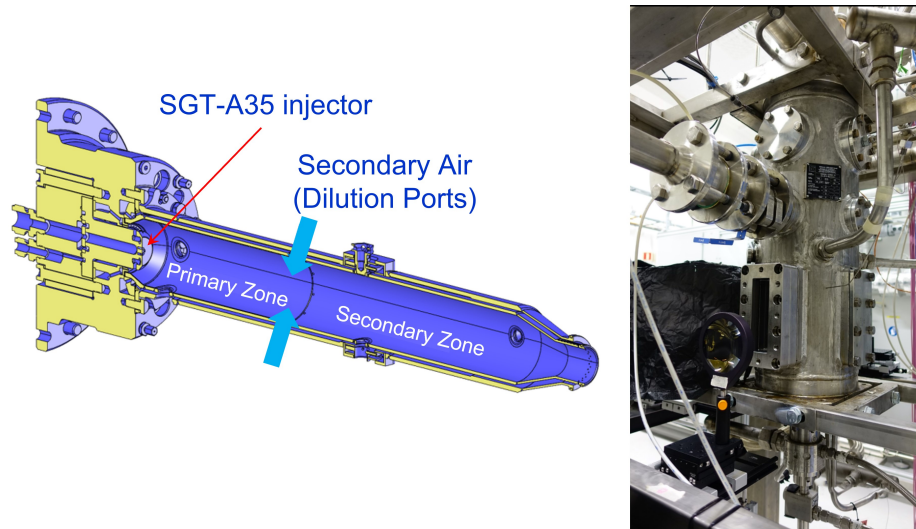
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Figure 3: EXPERIMENTAL SETUP AT SINTEF.

Stirred Reactor (PSR1) followed by a Plug Flow Reactor (PFR1 in Fig. 4) simulating the flame front and post-flame zones respectively. Secondary Air is introduced at the end of PFR1, diluting or reacting with the combustion products from the PZ in a second PFR reactor (PFR2). Inputs for the CRN model are the fuel composition ($\%NH_3$), mass flows of CH_4, NH_3, air entering PSR1 and secondary air. Dry emissions corrected to $15\%O_2$ are taken at the end of PFR2. This network is a simplified first version of the combustor, which is obviously not designed to capture all the complexity of the actual mixing of fuel and air, as well as flow field features (recirculation zone for instance), but aims at capturing the main qualitative trends of experimental results. For this reason, the *effective* chemcial residence times imposed on the different reactors are not derived from the bulk flow velocities and dimensions of the combustor parts they represent. The distribution of the residence time between PSR1 and PFR1 representing the PZ has been adjusted to $20\% - 80\%$ on the grounds that 1. the flame front is thin and PSR1 should reflect the chemical time through the flame and not the entire PZ region and 2. this combination reproduced experimental NO_x emissions best for the lean case at 5 [bar]. The ratio of residence times between the Primary and Secondary zones has been set equal to that of the experimental combustor. Additionally, a sensitivity analysis on the CRN total residence

time was conducted to make sure the selected total residence time was far enough from equilibrium as similar experiments were conducted on the rig, varying the bulk residence time and measuring NO_x emissions, which showed that the rig operating conditions were indeed not reaching equilibrium.
The mechanism used for the simulations is from Okafor et al. [8], a detailed reaction mechanism based on GRI Mech 3.0. The reactor network is built with the open-source chemical kinetics software CANTERA [9] under the Python programming language.
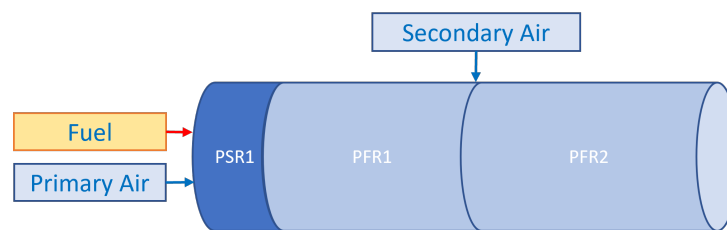

Figure 4: SCHEMATIC OF THE CRN USED. PRIMARY AIR INCLUDES MAIN AIR JETS AND SWIRLER AIR FROM FIG. 2.

Results

This section first presents the impact of blending NH_3 into CH_4 fuel on NO_x, N_2O and CO_2 emissions for 2 different intermediate pressures and Primary Zone Equivalence Ratio, followed by a more detailed investigation of the impact of pressure on NO_x and N_2O emissions for a $40\%NH_3 - 60\%CH_4$ blend as a function of $PZ\ ER$.

Impact of blending NH_3 into CH_4 on emissions

This section presents emissions results obtained as the molar fraction of NH_3 in CH_4 is increased. For the lean case, the total mass flow rate of air in the combustor were kept constant and the fuel flow rates were adapted to maintain a constant Primary Zone adiabatic temperature (within $10\ [C]$) as the fuel composition was changed. As a result, the variations of power and equivalence ratio across the investigated fuel composition range were kept small with a maximum of 8% and 6% respectively. For the rich cases at 5 [bar] and 8 [bar], the thermal power and equivalence ratios were kept constant and the air flow rate was adjusted to the fuel composition resulting

in a maximum variation of 2% mass flow rate from pure methane to $60\%\,NH_3$ in CH_4. A lean ($PZ\,ER = 0.7$) and a rich ($PZ\,ER = 1.5$) case with similar PZ temperatures ($\approx 1570\,[C]$) have been investigated at a pressure of $5\,[\mathrm{bar}]$ to highlight the impact of stoichiometry (and hence heat release distribution in the combustor), as well as a case at $8\,[\mathrm{bar}]$ to illustrate the effect of pressure (see Fig. 5). It is important to note that, although the overall zone equivalence ratio is lean for the first case, the *effective* equivalence ratio in the flame remains close to stoichiometric conditions given the non-premixed nature of the burner. Hence, high temperature regions do exist in the flame and all the fuel is consumed in the PZ, whereas for the rich cases some fuel is left over and will burn with secondary air downstream of the dilution ports, resulting in longer residence times in a hot environment for rich conditions. For smaller molar fractions of NH_3 in CH_4 ($< 20[\%]$),
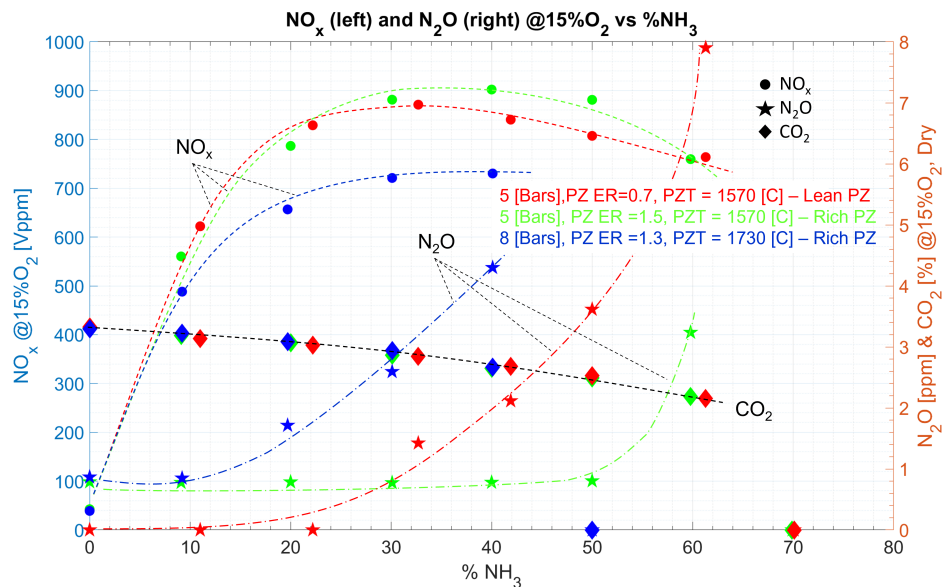

Figure 5: DRY CORRECTED NO_x (LEFT AXIS) AND CO_2 AND N_2O (RIGHT AXIS) VS $\%NH_3$ IN CH_4 FOR 5 [bar] (WITH LEAN AND RICH PZ CASES HAVING THE SAME PZT) AND 8 [bar] AT RICH PZ.

NO_x emissions drastically increase with the addition of NH_3, even for very small amounts, and this for the 3 cases. They are approximately 20 and 15 times larger for a mixture of $20\%NH_3 - 80\%CH_4$ than for pure methane

for 5 and 8 $[bar]$ respectively. NO_x emissions reach a maximum between $NH_3 = 30\%$ and 40% and slightly decrease for higher NH_3 content for the cases at 5 [bar], while NO_x emissions plateau for the 8 [bar] case and blow out is reached before a decrease is observed. The $PZ\,ER$ (hence axial distribution of heat release throughout the combustor) doesn't seem to have a significant influence on NO_x emissions, at least for these two 5 [bar] cases (see the red and green curves in Fig. 5). This is a significant difference with the trends observed with a two stage DLE (premixed) burner in Ditaranto et al[5], where up to 85% reduction could be achieved by operating the PZ rich. One possible explanation is that in non-premixed mode, the *zone* equivalence ratio is not representative of the actual fuel-air ratio at which combustion occurs in the flame. For non-premixed systems, even if the $PZER$ is lean, the fuel locally starts burning in conditions close to stoichiometric and preferably on the rich side, i.e. with less oxygen available than the overall conditions implies, thereby limiting the conversion of NH_3 to NO. In parallel, while mixing of fresh and burnt gases progresses in the post-flame region as the gases are convected towards the secondary leaner zone (as well as combustion reactions), NH_3 thermally decomposes thereby further limiting the amount of NH_3 available to react directly with oxygen to form NO downstream of the dilution ports. These reasons could explain the lower propensity of lean non-premixed flames to form NO than in premixed ones, but more work is required to support this statement.

Although NO_x emissions don't exhibit a strong dependence on $PZ\,ER$, N_2O emissions exhibit different behaviors for the lean and rich $PZ\,ER$ cases (at 5 [bar]). The rapid increase of N_2O as the molar fraction of NH_3 is increased (associated with a loss of combustion efficiency), occurs for lower concentrations of NH_3 for the lean case (red curve in Fig. 5). This might be due to the fact that the heat release for the richer case is distributed more evenly throughout the combustor (since some fuel is left over and burns in the secondary zone) resulting in a longer *effective* residence time at higher temperatures. Finally, although pressure effects will be discussed in the next section, it can be seen on Fig. 5 that increasing pressure results in lower NO_x as expected from previous work [6] (blue curve), particularly for NH_3 concentration larger than 20%.

In summary, the general shape of NO_x curves as the amount of NH_3 in the fuel is increased follows a) a steep positive slope, b) a plateau of maximum values, c) a negative slope, and d) flame blow off before reaching $100\% NH_3$. This trend can be linked to the lower reactivity of NH_3 mixtures

(compared to CH_4 at same flame temperature) and the consequent change in axial distribution of heat release within the combustor. Indeed, as $NH_3\%$ molar fractions increase beyond 30-40%, the fuel mixture reactivity becomes lower and the heat release distribution slightly moves downstream in the combustor and extends well into the Secondary Zone. All these factors limit the formation of NO_x and eventually lead to flame blow off. This explanation is also supported by the levels of N_2O, which rise when the NH_3 content in the fuel exceeds 30% , highlighting the loss of combustion efficiency beyond $NH_3 = 30\%$.

Primary Zone Equivalence Ratio variations for a $40\%NH_3 - 60\%CH_4$ mixture and influence of Pressure

NO_x emissions for a $40\%NH_3$–$60\%CH_4$ mixture at 1, 2 and 5 [bar] as a function of $PZ\ ER$ are shown in Fig. 6 (note that the flame temperature is changing). The general shape of NO_x vs $PZ\ ER$ is typical of RQL systems with lower reactivity fuels (see [10]). Starting from leaner conditions, NO_x emissions are roughly constant (all the fuel is burnt in the PZ and burnt gases are quenched by dilution air), then increase with increasing $PZ\ ER$ at about $PZER = 0.9-1$, when some fuel is left over and burns with secondary air (increased thermal NO_x production). As $PZ\ ER$ is increased further, the average heat release moves further downstream, while the PZ temperature decreases leading to a decrease of total NO_x as discussed previously. The impact of $PZ\ ER$ on CO and N_2O emissions for the 3 pressures is shown in Fig. 7 (note the logarithmic scale for N_2O on the right axis). Similarly to previous observations on RQL systems from Okafor *et al.* [6], N_2O emissions increase, approximately exponentially, for decreasing $PZ\ ER$ and for all pressures investigated, as the reactivity and hence combustion efficiency decrease. CO follows a similar exponential increase with decreasing $PZ\ ER$ for the 1 [bar] case while CO emissions are effectively zero for all $PZ\ ER$ for the 2 and 5 [bar] cases.

As shown in Fig. 6, NO_x emissions decrease with pressure as reported in literature. Given that experimental data are available for 1, 2 and 5 [bar], a pressure dependency of NO_x (with this particular fuel composition) can be extracted to estimate an order of magnitude of NO_x emissions at 20 [bar]. This was done in 2 steps: Firstly the experimental data were fitted with a polynomial function to obtain continuous NO_x values for all (and same) equivalence ratios, and secondly for each equivalence ratios (bin size was 0.05), the 3 NO_x data points were fitted with a power fit of the form
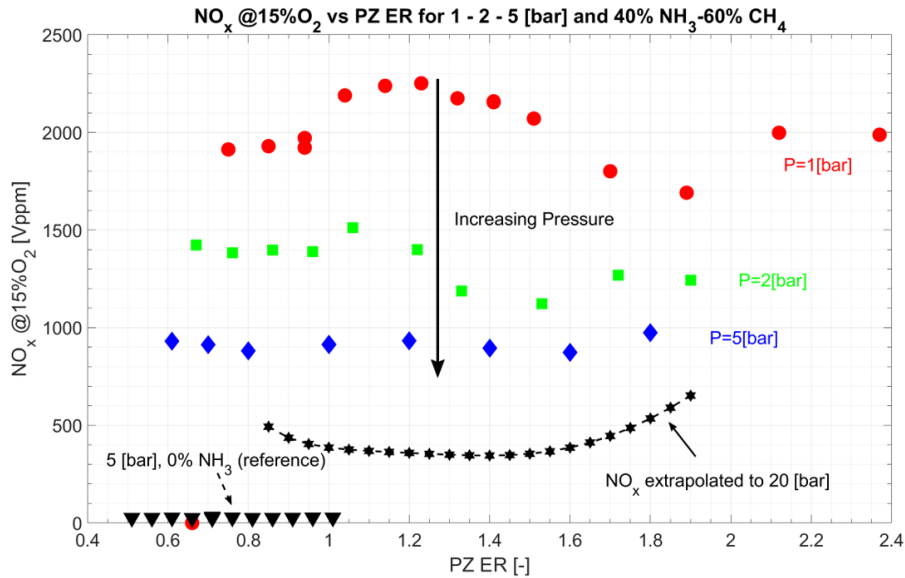
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Figure 6: NO_x EMISSIONS VS $PZ\,ER$ FOR A MIXTURE OF $40\%NH_3 - 60\%CH_4$ FOR 1, 2 AND 5 [BAR]. THE BLACK CURVE ARE NO_X EMISSIONS EXTRAPOLATED TO 20 [BAR], SEE FIG. 8.

$NO_x(p) = Ap^\alpha$ with α being the pressure exponent (negative values for NH_3 mixtures). An example for $PZ\ ER = 0.95$ is given in Fig. 8 (top). The obtained pressure exponents as a function of $PZ\ ER$ are given in Fig. 8 (bottom, black diamonds), together with the extrapolated NO_x at 20 [bar] (red circles), which is also shown in Fig. 6 for comparison with lower pressures (black curve). The mean relative error between the exponential fit and the experimental data is also provided in Fig. 8 (grey circles). Note that these extrapolated values are to be taken with care since only 3 pressures were available from the experiment and this at fairly low pressures. However, they still provide a good estimate of the expected range of NO_x emissions at 20 [bar]. The data indicates a minimum of NO_x of 350 [ppm] at 20 [bar] and at a $PZ\ ER$ of 1.4 (in good agreement with [6]), while NO_x emissions increase steeply for leaner and richer mixtures.

CRN Results

The results from the Combustion Reactor Network for the three cases in Fig. 5 are shown in Fig. 9 (diamonds) together with experimental data
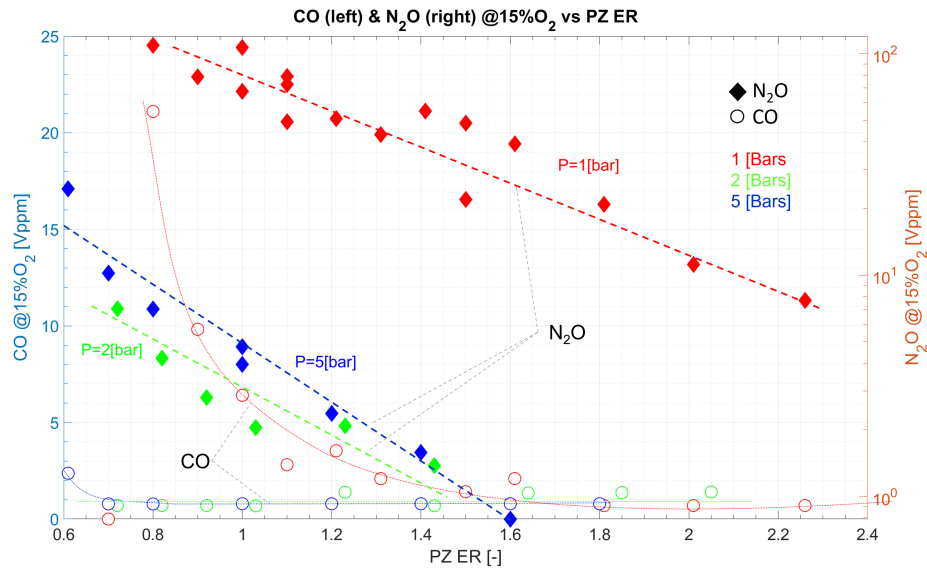
Figure 7: CO (LEFT) and N_2O (RIGHT) EMISSIONS VS PZ ER FOR A MIXTURE OF $40\%NH_3 - 60\%CH_4$ FOR 1, 2 AND 5 [BAR].

(circles). The *general* trend of NO_x emissions as a function of NH_3 content in the fuel is captured reasonably well, i.e. the steep increase for low $\%NH_3$, the $\%NH_3$ values maximizing NO_x emissions (lean case at 5 [bar]), as well as the "blow off" behaviour observed for the same $\%NH_3$ as experimentally (for which the CRN doesn't ignite). However, although the trend of decreasing NO_x emissions with increasing pressure is in-line with the experimental data (green and blue curves), this reduction is over-predicted with the CRN model. The impact of PZ ER is over predicted by the CRN as well: while the experimental data shows hardly any difference of NO_X emissions for the two cases at 5 [bar] (red and green curves), the CRN model predicts much lower emissions for the richer case. Given the results form Okafor *et al.* [7] for non-premixed systems, showing that increasing pressure reduces NO_x emissions more for leaner mixtures, both discrepancies (with pressure and PZ ER) seems to indicate that the residence time of the leaner secondary zone is over-estimated in the CRN relatively to the PZ reactors. This could be due to the recirculation zone in the PZ, which exists in the experiment but is not modeled in the CRN. This being said, these are only assumptions at this

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stage and more work is needed to verify them.

Conclusions

This experimental and numerical study presented emission results for a simplified version of the non-DLE Dual-Fuel Siemens Energy SGT-A35 turbine combustion system burning methane-ammonia blends at pressures up to 8 [bar]. The effect of ammonia concentration in the fuel and Primary Zone Equivalence Ratio on emissions of NO_x, CO and N_2O has been studied for these different pressures. A pressure exponent has been calculated based on this experimental data to provide an estimate of NO_x emissions at engine pressures. The experimental results have shown that even small amounts of ammonia in methane leads to unacceptably high NO_x emissions for all Primary Zone equivalence ratios and pressures investigated. Although increasing pressure reduces NO_x emissions (as previously reported), extrapolation to engine conditions showed that NO_x emissions will remain unacceptably high without combustor design changes. It is also shown that flame stability becomes insufficient for fuels containing more than 40-50 [% by vol.] of NH_3 as blow out occurred for these fuels. The results also showed that N_2O emissions are very low for rich Primary Zone Equivalence Ratios and increase approximately exponentially with decreasing equivalence ratios, but remained below 10 [ppm] for cases at higher pressures. Finally, the simple CRN results captured the qualitative trends of NO_x emissions with increasing NH_3 concentrations reasonably well, but failed to capture absolute values as well as the effect of Primary Zone equivalence ratios (at constant pressure). However, as mentioned, this CRN model is a first attempt and is lacking fundamental features such as fuel stratification (distribution of equivalence ratios to capture the non-premixed nature of the injector), recirculation flows in the PZ and potentially heat losses, which will be included in future work.

Acknowledgments

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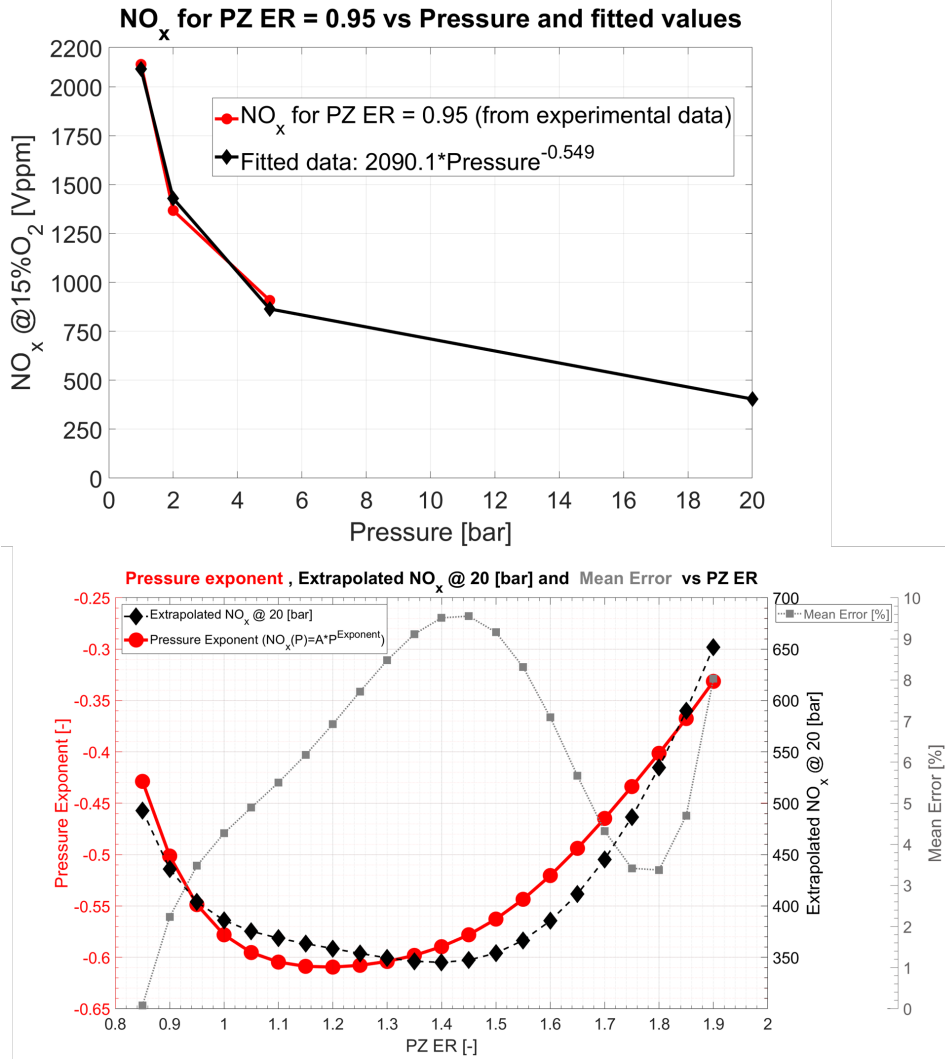URL https://www.sciencedirect.com/science/article/pii/S0378382012002408

Figure 8: LEFT: NO_x EMISSIONS FOR $PZ\,ER = 0.95$ [-] VS PRESSURE FOR A MIX-
TURE OF $40\%NH_3 - 60\%CH_4$ (FROM FIG. 6) WITH EXPONENTIAL FIT. RIGHT:
PRESSURE EXPONENT (LEFT AXIS) AND NO_x EXTRAPOLATED TO 20 [BAR]
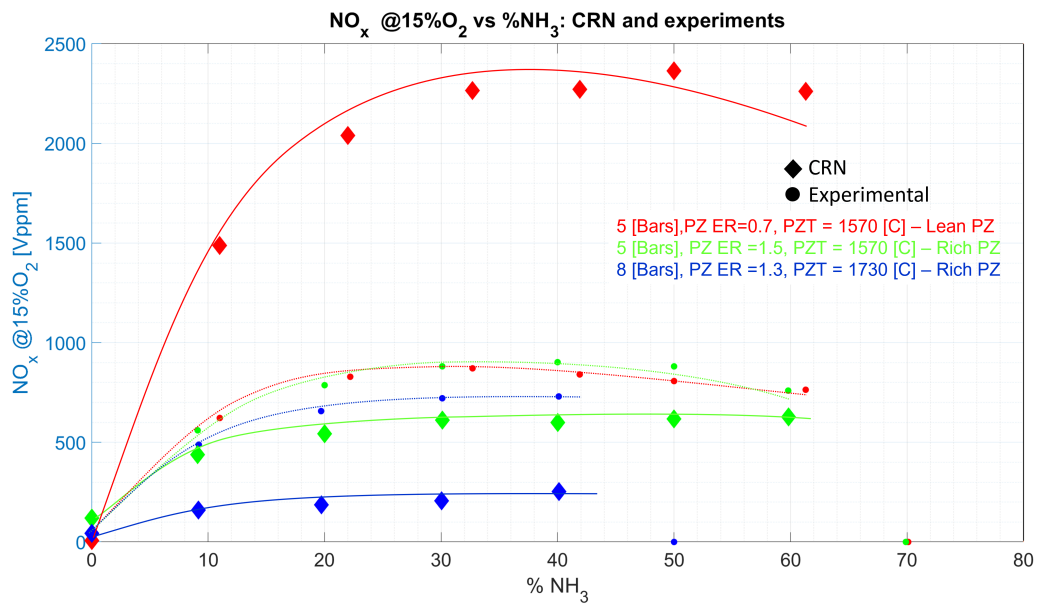(RIGHT AXIS) VS $PZ\,ER$ FOR THE SAME MIXTURE.

Figure 9: NO_x EMISSIONS CALCULATED WITH THE CRN VS $\%NH_3$ FOR THE 3 CASES SHOWN IN FIG. 5.