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PARAMETRIC STUDY OF EMISSIONS FROM LOW CALORIFIC VALUE SYN-GAS COMBUSTION, WITH VARIATION OF FUEL DISTRIBUTION, IN A PROTOTYPE THREE SECTOR BURNER

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ABSTRACT

The emission composition is measured for a prototype burner while varying the equivalence ratio in discrete portions of the burner. The burner is a three sector system, consisting of a separate igniter, pilot/stabilizer and main burner. The design allows for discrete control of equivalence ratio in each of the three sectors. The ignition sector, designated RPL (Rich-Pilot-Lean), operates from rich to lean equivalence values, and serves to ignite the pilot sector, which, in turn, stabilizes the main combustion sector. All three burner sections are premixed. The burner is operated at atmospheric pressure with inlet flows heated to 650 K (±8 K). Tests were performed for three gases: methane, a model syngas (10% CH_4, 22.5% CO, 67.5% H_2), and dilute syngas. The dilute gas includes sufficient nitrogen to lower the heating value to 15 MJ/m^3. The model syngas and diluted syngas are representative of fuels produced by gasification process. The burner emissions, specifically, CO, CO_2, O_2 and NO_x, are measured while holding the RPL equivalence value constant and varying the equivalence ratio of the pilot and main sectors. The equivalence ratios for pilot and main sectors are chosen such that the total burner equivalence ratios remain constant during a test sequence. The target total equivalence ratio for each gas is chosen such that all experiments should have the same flame temperature.

INTRODUCTION

Minimization of pollutive emissions is a continuing goal of power source designers, both to meet legislative mandates [1] and for environmental conservation. Anthropogenic CO_2 emissions are currently targeted for reduction, which can practically be minimized in two ways; CO_2 can be stored in physical or chemical sink [2] and fuels that are considered CO_2 neutral can be burnt. CO_2 neutral fuels have various sources and component makeups; burning these non standard fuels necessitates a flexible combustor that can handle a wide range of fuels.

While CO_2 is a primary product of combustion, NO and NO_2 (collectively NO_x) are negative byproducts of combustion. NOx is both a local pollutant, contributing to smog and acid rain, and also a catalyst in the removal of ozone from the stratosphere [3]. There are several combustion reaction pathways that lead to NO_x formation. Two are most prominently associated with NO_x emissions for combustion under gas turbine conditions. One of these is the Fenimore mechanism, which is the reaction of CH radicals with N_2 to form HCN which then further oxidizes to NO [4]. As CH radicals form early in the hydrocarbon combustion process, this mechanism is also known as prompt NO_x. A second is the

Table 1 Compositions of the gases examined

Gases	Gas compositions vol.%				W* [MJ/m^3]	LHV [MJ/kg]	Fuel/Air$_{St}$
	CH_4	H_2	CO	N_2			
Ref.	100	0	0	0	55.30	50.01	0.0584
Syngas	10	67.5	22.5	0	27.70	33.14	0.104
Diluted Syngas	6.9	46.56	15.52	31.02	15.00	14.05	0.245

*Wobbe index based on the higher heating value (HHV).

Zeldovich mechanism, which produces NO from the oxidation of thermally generated nitrogen radicals [5]. This `thermal NO_x' is the main mechanism of NO_x production in high temperature combustion, e.g., gas turbine combustion. Under certain conditions the other pathways can contribute appreciably to NO_x emissions; for instance, the Nitrous oxide pathway, which is significant at lean conditions [6, 7].

When designing a combustor that can be fueled with CO_2 neutral fuels, the NO_x emissions should not be neglected. This investigation is a parametric study of emissions using different fuels and fuel distributions in a scaled 4th generation dry low emission burner. Specifically, the concentrations of CO and NO_x are monitored while running the burner on three types of gaseous fuel, and for each fuel, varying the distribution to specific regions of the burner. While not typically a major pollutant in gas turbines, CO values are used herein as an indication of combustion quality, as its presence can indicate incomplete combustion or impending blowout [8]. CH_4 is used as the reference fuel, as it is the primary component of natural gas, a commonly used fuel in gas turbines. The other fuel examined is a syngas with high H_2 and CO content (Table 1) [9]. This fuel is also examined when diluted to a Wobbe index of 15 MJ/m^3. It can be considered a typical gasification gas [10].

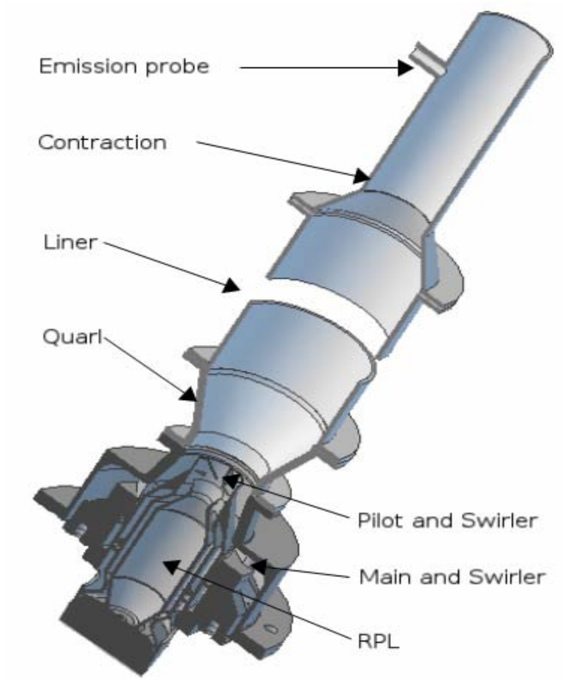

Figure 1: Burner Assembly

EXPERIMENTAL SETUP

Burner

The burner under investigation is a prototype of a 4th generation DLE syngas burner designed by Siemens Industrial Turbomachinery (Figure 1). The burner is a three sector design with separate ignition, stabilization and bulk combustion sectors. Fuel flow to each of these sectors is individually controlled.[1] The ignition sector, RPL (Rich-Pilot-Lean), houses the spark ignition source and has isolated fuel and air feeds. Swirl is introduced in the base of the RPL by using angled inlet ports. The stabilization sector, Pilot is positioned between the RPL and bulk combustion sector. The Pilot air flow shrouds the RPL, with fuel being added just below the swirl vanes at the burner throat. The short distance between fuel injection and the combustion zone results in the Pilot probably not being fully premixed. The bulk combustion sector, Main, is the outermost of the three sectors. Fuel is added sufficiently upstream of the burner throat that the Main can be considered fully premixed. The prototype burner has a conical dump extension (quarl) that is coupled to a steel cylindrical liner, which contracts to ~50% of liner cross sectional area at the exit. The cylindrical liner, (size 85 mm x 700 mm) was constructed so that an adequate residence time (~15 ms) and a combustor loading [11] below 10 kg/s atm$^{1.8}$m^3 was obtained [8].

Air and Fuel system

The high volume air supply from two Rietschle SAP 300 blowers is divided between the Pilot and Main burner sectors, with 21% going to the Pilot and 79% to the Main [8]. Blower output is varied by controlling the line frequency with a Vacon OYJ variable AC driver. The AC driver is interfaced using a Velleman 8055 A/D convertor, allowing control of the bulk air flow. A precise flow rate for the bulk air flow is measured by two Eldridge MPNH-8000 thermal mass flow meters mounted just downstream of the blowers. The mass flow range for the blower system is from 0 to 110 g/s when combustion is absent. A separate air feed is supplied to the RPL sector from a compressed air source, controlled using an Alicat Scientific mass flow controller. All air supplies are heated to a temperature of 650 K (± 8 K) before entering the burner. Fuel supplies are controlled individually for each of the three sectors; the flows are controlled using Alicat Scientific mass flow controllers. Equivalence ratios computed from the measured O_2 and CO_2 values (assuming complete combustion) were within 5% of the equivalence ratios indicated by the measured mass flow rates. The three fuels tested were purchased preblended in 50 liter gas cylinders. The fuel compositions and selected properties are found in table 1.

Emissions Tracking

Samples are collected 5 cm upstream from the dump plane of the liner, after the contraction. The sampling rake is a 6 mm diameter, closed end, steel tube that lays perpendicular to the effluent flow, across the center of the liner outlet. There are eight 1.0 mm holes drilled at equally spaced intervals along the tube, which collect an averaged sample across the entire exhaust stream. The sample gas travels along a 50 cm length of steel tubing, and then ~3 m of unheated polymer tubing to the measurement rack. Directly on entry to the emissions rack, the sample is passed through a cooled condenser, to remove water from the sample. The response time for measurements is 25 seconds for NO_x measurements and 6

[1] Since equivalence ratio can be set in each of the three burner sectors, the respective values are referred to by the sector name, e.g., "Pilot equivalence ratio". The net equivalence ratio is referred to with, "total equivalence ratio".

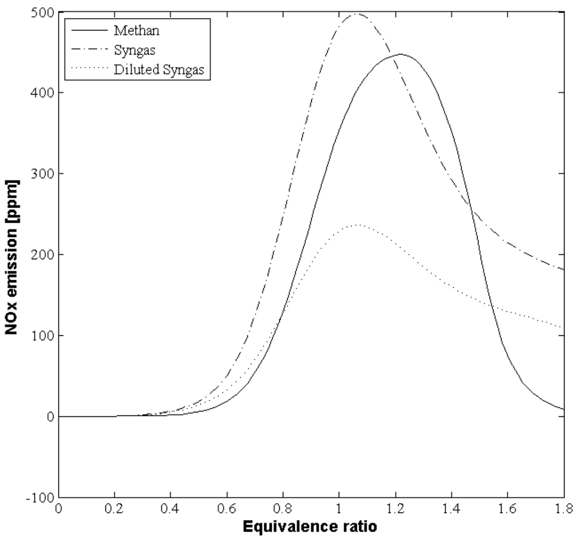

Figure 2: NOx emissions from PSR, 1.5 ms residence time

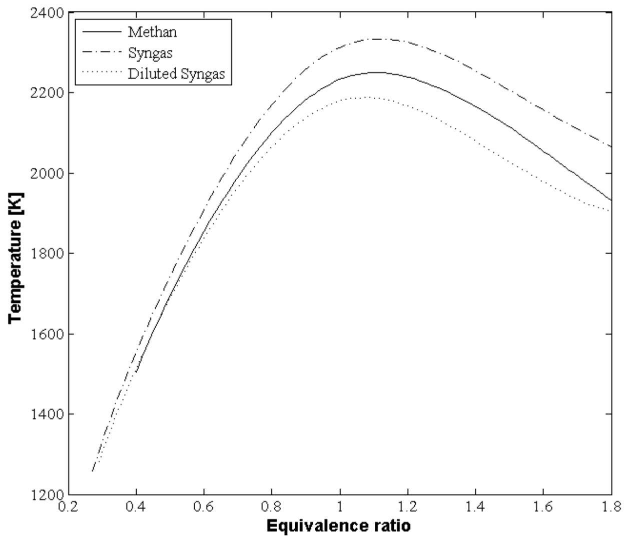

Figure 3: Temperature from PSR, 1.5 ms residence time

seconds for all other species. Values from each analytical instrument are recorded at 1 second intervals.

CO and CO_2 are measured using a Rosemount Analytical Binos 100 gas analyzer. The measurement range is 0-1000 ppm and 0-20% for CO and CO_2 respectively. The stated uncertainty, from measurement of calibration gas, is <1% full scale reading for both CO and CO_2. The instrument was calibrated daily with 0 and 103 ppm CO, and 0 and 8% CO_2.

NOx measurements were made using an Eco Physics model 700 EL-ht nitric oxide measurement instrument, with a range of 0.1-100 ppm NO_x. The error in measurements for all nitrogen oxides measured was found to be ~ 0.1% full scale. The NO_x meter was calibrated daily with 30 ppm NO_x.

Oxygen is measured with a Rosemount Analytical Oxynos 100. The instrument measurement span was set to 0 to 25% dry oxygen. The O_2 meter was calibrated daily with 0 and 21% O_2 (nitrogen and air).

EXPERIMENTAL PROCEDURE

In order to evaluate the contribution of different burner sectors to total emission levels, it was necessary to isolate each sector while maintaining a reasonable total adiabatic flame temperature. Investigation of the lean blowout limit effectively isolated the RPL component of emissions, while a second experiment focused on the Pilot and Main sectors by varying only the fuel splitting between the Pilot and Main sectors, all other variables held constant. For all tests, the flow through the RPL was the same, i.e. ~2.4% of the total flow in the methane test. The flow rates of the unburnt gas in the experiments were 0.12 m^3/s for methane; 0.09 m^3/s for syngas and 0.13 m^3/s for diluted syngas.

Lean Stability Sweep

Emissions levels were recorded in conjunction with an investigation of the burner lean blowout limit [8]. Tests were performed by igniting the burner at a specific RPL equivalence ratio and an arbitrary total equivalence ratio that gave stable combustion. During the test, the Pilot and Main equivalence ratios were kept equal to one another at all times, while the RPL equivalence ratio was kept static. The Pilot and Main equivalence ratios were reduced in equal measure until the burner was unable to sustain combustion***:*** indicated when two consecutive tests gave an off-scale CO value or the flame extinguished. Measurements were recorded for each equivalence ratio, and this process was repeated for each of the fuels, and for several RPL equivalence ratios.

Fuel Partitioning

Emissions were measured while varying the relative fuel flow to the Pilot and Main burner sectors. The total equivalence ratio, corresponding to an adiabatic flame temperature of 1700 K, was held constant for each test. The respective total equivalence ratios were: methane 0.47, syngas 0.40 and dilute syngas 0.41. For all tests, the RPL equivalence ratio of 0.80 was maintained, and the remaining fuel necessary to reach the desired total equivalence ratio was supplied to the Pilot and Main sectors. The test began by setting the Pilot fuel flow controller to the highest achievable flow (mass flow controller limited), with the balance of fuel going to the Main burner region. The test proceeded by reducing the Pilot fuel flow in 0.1 g/s increments, and adding that same amount of fuel to the Main sector. Measurements were recorded at each increment until either blowout or zero flow in the Pilot Sector.

Table 2 NOx Reaction flow analysis

Gases	Equivalence ratio	Reaction flow%			
		Nitrous Oxide	NNH	Prompt NO_x	Thermal NO_x
Ref.	0.47	53.7%	29%	7.2%	10.1%
	1.21	-1.3%	3.3%	54.8%	43.2%
	1.40	0%	-1.0%	67.4%	38.66%
Syngas	0.45	39.5%	52.5%	1.3%	6.7%
	1.05	5.3%	14.1%	6.4%	74.2%
	1.40	0.0%	17.3%	32.4%	50.3%
Diluted	0.48	36.2%	55.5%	1.6%	6.7%
Syngas	1.05	4.7%	25.6%	10.4%	59.3%
	1.40	9.9%	20.9%	30.2%	39.0%

MODELLING

The RPL NO_x emission was modeled by an adiabatic, non-isothermal perfectly stirred reactor (PSR) [12] , which should accurately model the behavior of the RPL primary recirculation zone[13]. For this analysis, GRI 3.0 [14] was used as the chemical kinetic model for each fuel, with DARS software [15]. The residence time was set to 1.5 ms to get a similar NO_x response as in figure 7. It can be seen that there is a difference in where the modeled and measured NO_x emissions peak, this was allowed because there is expected to be a diffusive combustion of the unburnt fuel in rich equivalence ratios giving rise to a higher NO_x production. It should be noted that the PSR reactor can only be considered applicable in the strongly recirculated primary zone. The secondary zone is not modeled in this investigation. The predicted NO_x level for each gas as a function of RPL equivalence ratio is shown in figure 2, while the predicted temperatures relation is shown in figure 3. The PSR model was repeated using DARS. The DARS software was used to estimate the contribution to total NO_x (reaction flow%) of the various NO_x pathways included in the GRI 3.0 mechanism (Table 2). The three mentioned NO production pathways, prompt, thermal and nitrous oxide, are shown. Also included is a fourth pathway, NNH, which is found to be important in high H_2 fuel combustion [16]. The reaction flow% is reported at three equivalence ratios for each fuel. The first, lowest equivalence ratio is at 1650 K adiabatic flame temperature, the middle equivalence ratio is the peak modeled flame temperature, and the last equivalence ratio is common between all three fuels.

RESULTS

Lean Stability Sweep

The CO emissions resulting from the combustion of dilute syngas are shown in Figure 4. The result is characteristic of all the gases tested, with the only variation being the equivalence ratio of blow out. At the lean blowout limit, CO emission is high, but it quickly reaches a low plateau when operating in stable, lean combustion.

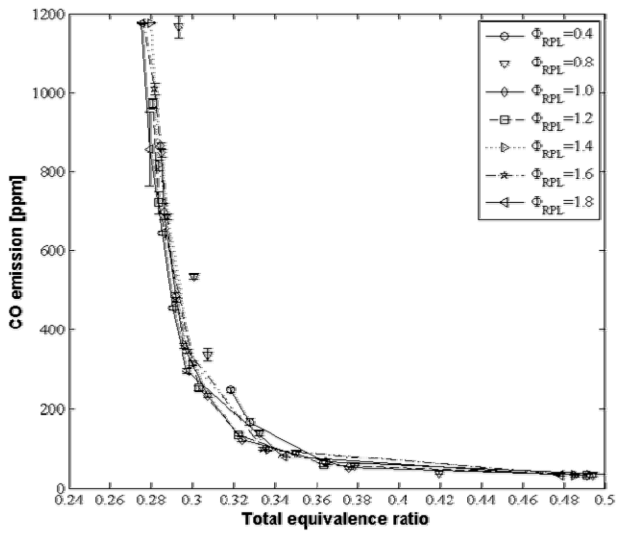

Figure 4: Dilute syngas, CO emission with total equivalence ratio for relevant RPL equivalence ratios.

NOx values from the same series of tests are shown in figures 5, 6 and 7; for methane, syngas and dilute syngas, respectively. Each figure shows an increase of NOx as total equivalence ratio increases; methane having the steepest response, syngas and diluted syngas approximately equal (note axis values).

The RPL has different response depending on the fuel used. Syngas and diluted syngas both have their peak NO_x emission at equivalence ratios slightly below 1.2. The NO_x response for Methane is increasing until an equivalence ratio of 1.7. The trend is seen more clearly when looking at measurements with adiabatic flame temperature of 1650 K shown relative to specific RPL equivalence ratios (Figure 8).

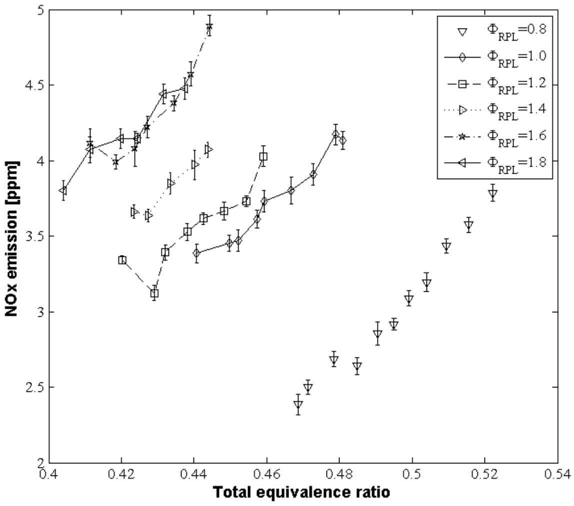

Figure 5: Methane, NO_x emission with total equivalence ratio for relevant RPL equivalence ratios.

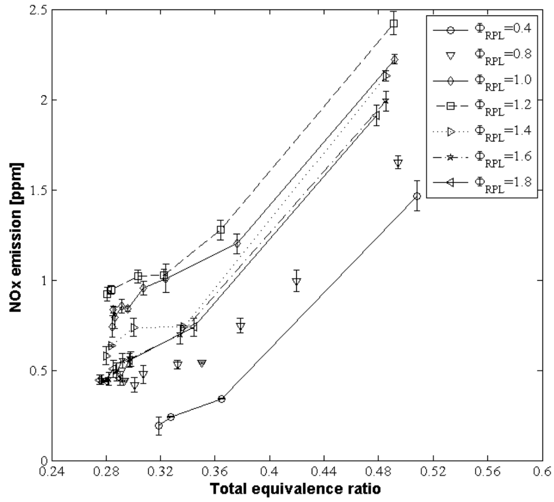

Figure 7: Dilute syngas, NO_x emission with total equivalence ratio for relevant RPL equivalence ratios.

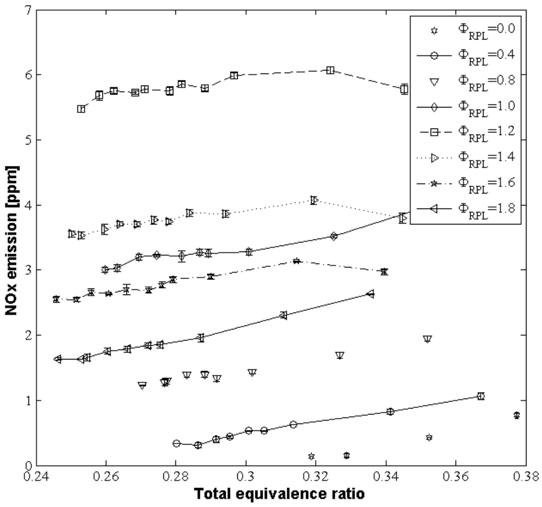

Figure 6: Syngas, NO_x emission with total equivalence ratio for relevant RPL equivalence ratios.

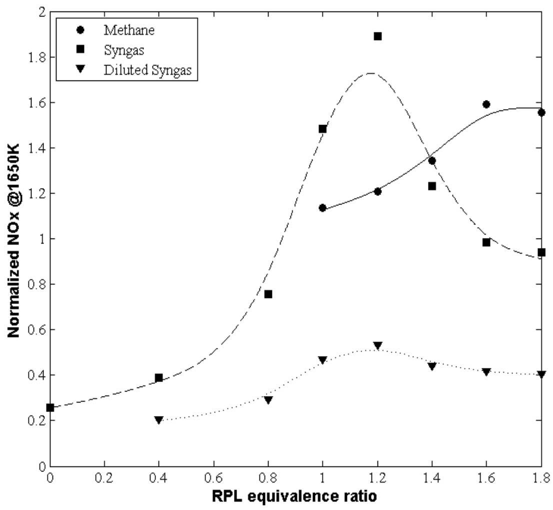

Figure 8: NO_x emission for relevant RPL equivalence ratios, total flame temperature 1650 K.

Fuel Partitioning

Measurements of CO during fuel partitioning experiments did not show any appreciable variance over the range of tested parameters. It was possible to run the burner with no fuel supplied to the Pilot when using diluted syngas, and for syngas, combustion persisted with both the RPL and Pilot extinguished. Even in these extreme cases, there was no change in CO emission that could be distinguished from measurement uncertainty.

The measured NOx emissions showed a dependence on the fuel distribution between the Pilot and Main burner regions (Figure 9). The x axis values are the ratio of the Pilot equivalence ratio to the total equivalence ratio. To the right of the x value: 1, the Pilot equivalence ratio is higher than the Main. Maximum measured Pilot equivalence ratios, limited by the range of the mass flow controller, were approximately 1.75, 0.62 and 0.90 for methane, syngas and diluted syngas, respectively. For x values less than 1 the Main equivalence ratio is higher than the Pilot. For the two syngas fuels it was possible to run the burner without the Pilot. A magnification showing values less than one is seen in Figure 10.

DISCUSSION

Relating the response of emissions to variations in burner operation sheds light on individual sector contribution to total emissions production. However, interactions of the three combustor sectors occlude direct cause effect relationships.

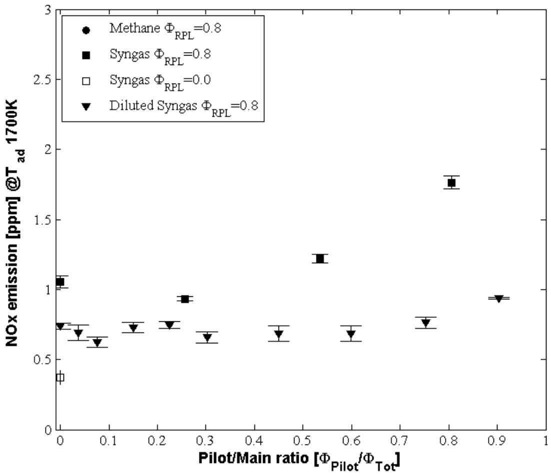

Figure 9: NO_x emission, fuel partition weighted to Main burner sector.

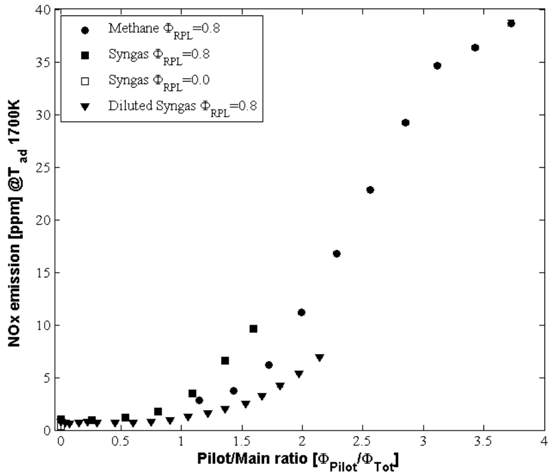

Figure 10: NO_x with fuel partitioning, Pilot divided by total equivalence ratio.

At all practical operating points, no difference in CO was found, within the limit of instrumental accuracy. This indicates that for the conditions tested, combustion had reached approximately the same degree of completion in the time it took to reach the liner exit. Also, all tests showed a remnant of CO in the exhaust. While this is not common in gas turbine combustion, it most likely arises in these experiments from wall cooling in the uninsulated liner. NO_x showed a strong dependence on the tested parameters, whether type of fuel, equivalence ratio or distribution.

RPL NOx emission

The RPL is the least significant of the three burner sectors when considering the volume of fuel and air that pass through it, in this investigation ~2.4% of the total flow. It is remarkable that the RPL has such a large effect on total NO_x. By isolating the total equivalence ratios for an adiabatic flame temperature of 1650 K, NO_x is seen essentially as a function of the RPL equivalence ratio (Figure 8). Variation in the RPL equivalence ratio gave a large relative change in NO_x, especially for syngas, where levels increased almost six fold. This is also observed in the modeled PSR (Figure 2). This indicates a dominance of the thermal NO_x pathway in NO_x formation for syngas; for methane, thermal NO_x and prompt NO_x have similar contributions (table 2). This is due to low residence time and subsequently incomplete combusting. Increasing the PSR residence time move the peak NO_x towards equivalence ratio 1 and the thermal NO_x becomes the prominent path. Low total equivalence ratios for the burner mean that the bulk of fuel is combusted in an environment where the Nitrous oxide and NNH pathway are most important (table 2).

The RPL related NO_x was found to vary for each of the three fuels investigated. For syngas and diluted syngas, the highest NOx measurements were found near the RPL equivalence ratio 1.2 (Figure 8). This is in vicinity of the highest combustion temperatures predicted by the PSR model (Figure 3). The difference in NO_x emission between the two syngas fuels is again linked to the thermal NO_x pathway. The low flame temperature of diluted syngas greatly reduces the amount of NO_x production. For methane, NO_x emission levels were similar to syngas; however, methane NO_x emissions did not fall off at high equivalence ratios. Instead, NO_x emission increased steadily until leveling off at an equivalence ratio of 1.60. The PSR model shows that with short residence times, the NO_x peak for methane is expected at higher equivalence ratios than for syngas (figure 2). Essentially, methane does not react quickly enough to reach complete combustion during the RPL residence time. As a result, at high RPL equivalence ratios the RPL flame moves outside the RPL volume and combusts as a partial diffusion flame in the lean environment of the burner [8].

Pilot NOx Emission

Due to the strong interaction of the Pilot and Main sectors, it is impractical to consider them as completely separate. However, the fuel splitting experiment emphasizes the contribution of the Pilot sector to the total NO_x level, as any change in the Pilot equivalence ratio has 1/4 the effect on Main equivalence ratio. All fuels showed a quick increase in the NO_x emission as the Pilot equivalence ratio increased, which is reasonable given the dominance of the thermal NO_x pathway in total NO_x production, when moving towards higher flame temperatures. Although it was not determined for the syngas fuels, methane NO_x emission is increasing with equivalence ratio until approximately 1.60 where it begins to level off. This might be attributed to the mixing layer between the rich Pilot and lean Main flows, which should feature intermediate equivalence ratios, i.e., high combustion temperature. As mentioned, the Pilot is not expected to have complete mixedness, meaning that the equivalence ratio is not uniform, but rather a distribution of local equivalence ratios around a mean value [17, 18]. This effect can be seen by examining the syngas NO_x emissions values shown in figure 10. Ignoring effects of interaction between the burner sectors, the NO_x contribution from the Main should be less than 0.5 ppm ("open square") the NO_x value with the RPL equivalence ratio of 0.80 is about 1.1 ppm (closed square x=0), the NO_x value when the Main and Pilot are equal and the RPL is 0.80 is about 2.5 ppm (estimation). The result is that the Pilot, which flows 1/4 as much as the Main sector, with the same lean equivalence ratio, produces almost 3 times the NO_x.

CONCLUSIONS

CO emissions indicate that the combustion is complete when operating sufficient distance from the blow out limit.

The RPL is a large contributor to NO_x, in spite of having a relatively low flow.

For the syngas fuels there is a peak NOx production where the RPL equivalence ratio show the highest combustion temperature.

Methane does not show highest NO_x at the calculated highest combustion temperature, this is because the combustion is not complete inside the RPL for this RPL flow.

The Pilot is found to give slightly higher than expected NO_x emissions.

The Dilute Syngas gave the lowest NO_x emissions indicating that the high concentration of N_2 and subsequently lower flame temperature inhibits the formation of NO_x.

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