Preliminary Study of NO_x, CO, and Lean Blowoff in a Piloted-Lean Premixed Combustor -- Part I: Experimental

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Preliminary Study of NO_x, CO, and Lean Blowoff in a Piloted-Lean Premixed Combustor Part I: Experimental

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In order to validate the models for NO_x, CO, and lean blowoff discussed in part II of this paper, the development of an experimental datum base was initiated. Experimental data were collected from an industrial, piloted-lean premixed, natural gas fired, can combustor rig. The experiments were designed in order to minimize testing cost and time. Independent variations of inlet pressure (8 to 14 atm), inlet temperature (550 to 750 K), and residence time (13 and 23 ms) were performed in order to gain insight into the sensitivity of the emissions levels to changes in combustor operating conditions.

INTRODUCTION

Lean premixed (LP) combustion is a technique for pollutant emissions control which is seeing increased application in gas turbines as an alternative to conventional, diffusion flame combustion. Currently, several manufacturers offer natural gas fired LP designs which can meet emissions standards (corrected to 15%O₂, dry) of less than 25 ppm nitrogen oxide (NO_x) and 50 ppm carbon monoxide (CO) under full load combustion conditions. However, continuing LP combustor research and development is necessary for the consistent realization of NO_x emissions below 10 ppmvd and CO emissions on the order of equilibrium levels. Conclusions from the LP combustor research can then be applied to advance the development of the more complex lean prevaporizing/premixing (LPP) combustor designs.

For the purposes of validating the LP and staged CO and NO_x emissions models discussed in part II of this paper, tests were performed with a premixing fuel injector and combustor liner representative of a natural gas fired, dry low emissions gas turbine combustor. This combustor is referred to here as Combustor A. The design of the experiments is discussed first followed by a description of the combustor rig and the instrumentation. Finally, the trends in the raw combustor emissions data are discussed with respect to other LP emissions data found in the literature.

TEST MATRIX DESIGN

For a given LP combustor operating without pilot fuel injection, there are four independent test variables: inlet temperature, inlet pressure, air flow rate, and equivalence ratio. The use of the pilot injector introduces an additional

independent variable. Baselines are defined with the mid-range value of each variable, and the test matrix consists of up and down changes in each variable, one at a time, from its baseline value. For the tests of Combustor A two baselines are used, one corresponding to zero load and the other to full load. Additional test cases in which the pilot fuel flow split is varied at ten percent increments between zero and 100% are also conducted to yield insight into possible coupling between the pilot and LP flames.

COMBUSTOR RIG CONFIGURATION AND INSTRUMENTATION

Combustor A is can-type. Natural gas is delivered through a premixing fuel injector that includes pilot fuel injection capabilities. A fraction of the total mass flow of air enters through film cooling slots in the liner and the balance through the premixer. Combustor A operates in a stable, low-emissions mode at full power, but the pilot (diffusion) flame is needed to maintain combustion at low load conditions. Use of the pilot flame tends to decrease the mixedness of the primary zone thereby creating a significant tradeoff between emissions of NO_x and flame stabilization.

The Combustor A tests were performed in-house by the gas turbine engine manufacturer. Exhaust gas samples were collected with an area-averaging rake which was fixed downstream of the combustor exit plane. Emissions were measured on a dry basis. NO_x was measured using a chemiluminescence analyzer, UHC was measured with a flame ionization detector, CO and CO₂ were measured with non-dispersive infrared analyzers, and O₂ was measured with a paramagnetic analyzer. NO_x and UHC measurements are

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estimated to be accurate to ± 2 ppmvd, and CO measurements are estimated to be accurate to ± 4 ppmvd. NO_x , CO, and UHC measurements in ppmvd were corrected to 15% oxygen following the Code of Federal Regulations [1] and converted into units of emissions index (grams of pollutant per kilogram of fuel) following Wade and Cornelius [2]. Note that 1 EI of NO_x typically corresponds to approximately 12 ppmvd NO_x at 15% O_2 , dry. The corresponding equivalence for CO is 1 g/kg ≈ 19 ppmvd at 15% O_2 . Visual access to the flame was provided via a video camera mounted downstream of the combustor test section. Blowoff points were measured by backing off the combustor fuel flow at a slow rate until the flame extinguished (i.e., was no longer visible on the video monitor). Combustor equivalence ratios were measured using oxygen balance and the fuel and air flowmeter readings. Equivalence ratios measured with the flowmeters agree to within $\pm 5\%$ of those calculated from the O_2 measurements.

ACTUAL TESTING RESULTS VERSUS TESTING GOALS

Consistent with the testing goals discussed above, the combustor datum set includes cases in which the inlet pressure (p_{in}), inlet temperature (T_{in}), equivalence ratio (ϕ), mass fraction of fuel to the main injector (y_{fm}), and the cold-flow combustor residence time (τ_{res}) were independently varied. In

Table 1, the tests in which the mass fraction of the fuel flow to the main injector was varied ($0.0 \leq y_{fm} \leq 1.0$) are referred to as piloted-LP tests, and those in which the combustor was operated strictly in the LP mode ($y_{fm} = 1.0$) are referred to as LP tests.

One hundred ninety-nine piloted-LP tests were performed, and as is shown in Table 1, the range of each combustor operating parameter except ϕ approximately met or exceeded the respective goal (facility temperature limitations and blowoff compromised the desired ϕ range). This is deemed important because a wide range in the combustor operating conditions allows for an extensive validation of the models. As noted above, in addition to the piloted-LP tests, 138 LP test points were collected from Combustor A. The latter measurements are similar to those reported by various combustor manufacturers in the literature (see Fig. 5 below) in which the combustor is operated at a fixed inlet pressure, inlet temperature, and residence time, and the equivalence ratio is varied. As shown in Table 2, for a given LP test case, the inlet conditions were held essentially constant while the equivalence ratio was varied. Consistent with the experimental goals noted in Table 1, all of the Combustor A tests were performed twice on two different days. The day two tests were performed in the reverse chronological order of the day one tests.

Table 1. Summary of the Combustor A test data in terms of testing goals.

Parameter	Goal	LP Tests	Piloted-LP Tests
ϕ_{max}/ϕ_{min}	3.5	1.84	1.79
$p_{in,max}/p_{in,min}$	1.8	1.75	1.75
$T_{in,max}/T_{in,min}$	1.19	1.35	1.36
$\dot{m}_{a,max}/\dot{m}_{a,min}$	2.00	1.96	1.9
$y_{fm,min}$	0.0	1.0	0.0
$y_{fm,max}$	1.0	1.0	1.0
Number of test points	28	138	199
Repeatability	Perform each group of tests twice on two separate days	Consistent with the goal	Consistent with the goal

Table 2. Nominal conditions for Combustor A LP tests. The characteristic time $\tau_{sl,co}$ based on combustor length and diameter (see Connors et al. [3]) is used to indicate the magnitude of the cold-flow combustor residence time. Standard deviations (σ) are shown as percentages of mean values for differing equivalence ratios tested.

Case	Statistics	$\dot{m}_a$	p_{in}	T_{in}	$\tau_{sl,co}$
LP Base 1	$\sigma/\text{mean} (\%)$	1.11	1.0	0	1.37
LP T_{in} 1	$\sigma/\text{mean} (\%)$	1.63	0.7	0	1.73
LP p_{in} 1	$\sigma/\text{mean} (\%)$	3.14	0.6	0	3.12
LP p_{in} 2	$\sigma/\text{mean} (\%)$	0.45	0.2	0	1.14
LP Base 2	$\sigma/\text{mean} (\%)$	0.37	0.5	0	0.85
LP τ_{res} 1	$\sigma/\text{mean} (\%)$	0.26	0.3	0	1.06

TRENDS IN THE COMBUSTOR A RAW DATA

LP NO_x and CO

All of the Combustor A LP NO_x data are graphed versus overall flame temperature (T_f) in Figure 1. These burner exit temperatures were computed with the chemical equilibrium code STANJAN [4] using the natural gas composition provided by the Combustor A manufacturer and the overall air and fuel flow rates. In order to focus on subsets of the Combustor A LP NO_x data in which only one combustor operating parameter is independently varied, Figs. 2 through 4 are shown. In general, the Combustor A trends shown in the figures indicate: 1) NO_x increases exponentially with burner exit temperature, 2) NO_x increases with increasing inlet temperature, 3) NO_x increases with increasing residence time, and 4) NO_x has a neutral to slightly negative sensitivity to increasing inlet pressure.

The raw LP NO_x data are compared to those from other lean premixed combustor rig/flameholder tests in Fig. 5. The data of Joshi et al. [5] are from a rig configured with a single premixer module, and the data of Leonard and Stegmaier [6] are from tests with various flameholder geometries. The Leonard and Stegmaier data are often referred to as being perfectly premixed because of the long fuel/air premixing length (~several hundred premixing duct diameters) used in their experiments. In general, the Combustor A data are higher than most of the other reported LP NO_x data, in part a result of testing here over a wider ϕ range. Leonard and Stegmaier and Joshi et al. suggest one possible explanation of the vertical displacement between NO_x emissions data for a given LP combustor rig and the Leonard and Stegmaier data at lower T_{fz} is fuel/air unmixedness. Additional comparisons between the data shown in Fig. 5 (and other data found in the literature) with respect to the sensitivity of LP NO_x to variations in combustor operating conditions are summarized in Table 3 and discussed further in part II of this paper with alternative explanations.

The Combustor A LP CO data are graphed versus the overall combustor flame temperature (T_f) in Figure 6. Note that the CO levels increase sharply with decreasing equivalence ratio (i.e., T_f) as the combustor approaches the lean blowoff limit (this limit corresponds approximately to the lowest flame temperatures shown for each data series). Figures 7 through 9 indicate the sensitivity of the LP CO to changing combustor inlet conditions. In general, the Combustor A trends shown in Figs. 6 through 9 reveal: 1) CO decreases with increasing burner exit temperature, 2) CO decreases slightly with increasing inlet temperature, 3) CO decreases with increasing residence time, and 4) CO is independent of inlet pressure.

Piloted-Lean Premixed NO_x

All of the Combustor A piloted-LP NO_x data are presented versus the mass fraction of fuel to the pilot flame ($1-y_{fm}$) in Fig. 10. The fuel flow to the pilot increases along the x-axis from left to right. It is noteworthy that in all cases the NO_x emissions increase linearly with pilot fuel flow for values of y_{fm} less than approximately 0.70. Furthermore, a significant mass fraction of the total fuel flow (approximately 0.25) is burned in the pilot flame without increasing NO_x or CO (although not shown, piloted-LP CO data were also collected, but due to space limitations, they are not discussed here). Coupled with the fact that the use of a pilot is known to help damp combustor pressure oscillations [10,11] and ensure stable combustion near the lean blowoff limit, this could be an important result with respect to optimization of the combustor operating cycle. This trend is apparent in the data set by virtue of the fact that independent variations of the fuel split to the main over a range between zero and one were included in the design of the test matrices. Preliminary models for all of the data discussed above are developed and applied in part II of this paper.

Table 3. Comparison of trends in LP NO_x observed in flameholder and combustor experiments at average primary zone flame temperatures between approximately 1700-1900 K where the majority of NO is thought to form primarily via the free radical mechanisms (i.e. Zeldovich, nitrous oxide, and prompt mechanisms) if fuel and air are perfectly premixed.

Study Sensitivity	Leonard & Stegmaier [6]	Snyder et al. [7]	Joshi et al. [5]	Aigner et al. [8] & Sattelmayer et al. [9]	Combustor A
$\partial \text{NO}_x / \partial T_{in}$	neutral	neutral	not established	positive	positive
$\partial \text{NO}_x / \partial \tau_{res}$	neutral	neutral / positive	not established	positive	positive
$\partial \text{NO}_x / \partial p_{in}$	neutral	positive	neutral / negative	positive	neutral / negative

Figure 1. Raw LP NO_x data.

Figure 2. Sensitivity of LP NO_x to inlet temperature. The open diamonds and squares represent data obtained at higher inlet temperatures than their closed counterparts. Residence time and inlet pressure are constant for each pair of like symbols.

Figure 3. Sensitivity of LP NO_x to residence time. The open diamonds represent data obtained at a longer residence time than the closed squares. Inlet temperature and pressure are constant.

Figure 4. Sensitivity of LP NO_x to inlet pressure. The filled circles were obtained at the highest inlet pressure, and the open circles were obtained at the lowest inlet pressure. Inlet temperature and residence time are constant.

Figure 5. Comparison of Combustor A LP NO_x data to other selected data. $\tau_{res, \phi}$ is the combustor residence time based on burned gas velocity and combustor length.

Figure 6. Raw LP CO data.

Figure 7. Sensitivity of LP CO to inlet temperature. The open diamonds and squares represent data obtained at higher inlet temperatures than their closed counterparts. Residence time and inlet pressure are constant for each pair of like symbols.

Figure 8. Sensitivity of LP CO to residence time. The open diamonds represent data obtained at a longer residence time than the closed squares. Inlet temperature and pressure are constant.

Figure 9. Sensitivity of LP CO to inlet pressure. The filled circles were obtained at the highest inlet pressure, and the open circles were obtained at the lowest inlet pressure. Inlet temperature and residence time are constant.

Figure 10. Raw piloted-LP NO_x data at various residence times, inlet pressures, and overall equivalence ratios.

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