Emission Characteristics of an Axially Staged Sector Combustor for a Small Core High OPR Subsonic Aircraft Engine

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This paper presents the nitrogen oxides, carbon monoxide, and particulate matter emissions of a single sector axially staged sector combustor designed and fabricated by United Technologies Research Center (UTRC) in partnership with NASA under a compact low-emissions combustor contract supported by the NASA Advanced Air Transport Technology (AATT) N+3 project. The test was conducted at NASA Glenn Research Center's CE-5 combustion test facility. The facility provided inlet air temperatures up to 922 K and pressures up to 19.0 bar. The combustor design concept, called Axially Controlled Stoichiometry (ACS), was developed by Pratt & Whitney (P&W) under NASA's Environmentally Responsible Aviation (ERA) program for an N+2 combustor in twin-aisle subsonic aircraft engine. Under the N+3 project the combustor was scaled-down for application to small-core N+3 engines for single-aisle aircraft. The results show that the NO_x and CO emissions characteristics are similar in both the N+2 and N+3 applications. The N+3 PM emissions (number EI) trends are similar to CO emissions with an exception at high fuel air ratio, as inlet air temperature and pressure conditions change from taxi to approach. Three NO_x correlation equations are generated to describe the NO_x emissions of this combustor. The percentage landing and takeoff (LTO) NO_x reduction of the N+3 ACS combustor is between 82% and 89% relative to the ICAO CAEP/6 standard, which meets the NASA N+3 goal of exceeding 80% LTO NOx reduction.

I. Introduction

NASA's Advanced Air Transport Technology (AATT) project focuses on developing a small-core high compression ratio commercial aircraft engine to enter service in the 2030 to 2040 timeframe. The engine combustor is targeted to have 80% Landing and TakeOff (LTO) NO_x emissions reduction relative to the ICAO CAEP/6 standard, with combustion efficiency greater than 99% at all LTO conditions. To reach this NASA N+3 emissions goal, NASA worked with United Technologies Research Center (UTRC) and Woodward, FST to develop new combustor concepts. The design by UTRC is called the Axially Controlled Stoichiometry (ACS) combustor. Multiple injection points and fuel staging strategies are used in this combustor design. As shown in Figure 1, pilot-stage injectors are located on the front dome plate of the combustor, and main-stage injectors are positioned downstream on the outer diameter of the combustor. Low-power operation uses only pilot-stage injectors. Main-stage injectors are used during high-power operation to help distribute fuel more evenly and achieve overall lean burn, yielding very low nitrogen oxides (NO_x) emissions. This combustor design concept was previously developed under NASA's Environmentally Responsible Aviation (ERA) project in 2014, culminating in a three sector ACS combustor designed by P&W for larger size N+2 subsonic aircraft engine, and demonstrated in NASA testing to provide 88% NO_x emissions reduction relative to the ICAO CAEP/6 standard [1].

The small-core ACS combustor built under NASA's AATT N+3 combustor contract is a single sector combustor, representing one of fourteen sectors from a core-size 2.0 engine nominally rated to 15,000 lbf thrust at sea-level take off (SLTO). Under the contracted work, a preceeding sector combustor was built with water-cooled combustor liners (walls) and tested in UTRC's High Pressure High Temperature (HPHT) combustion rig up to full

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engine cycle conditions at all LTO power settings from idle to takeoff. That hardware was used to screen injectors and combustor feature combinations. The best combustor configuration was selected, and a single sector combustor with conventional air-cooled liners was built and tested in NASA Glenn Research Center's CE-5 combustion rig. This final hardware is the test article in this manuscript. Nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM) emissions data collected in NASA's CE-5 single sector combustor testing are reported here. NO_x correlation equations are generated to describe the NO_x emission trends of this combustor over the range of engine operating conditions, and the percentage NO_x emissions reductions relative to the ICAO CAEP/6 LTO standard and a 2005 "best in class" cruise value are calculated.

II. Experimental Facilities and Hardware

The experimental data used in this study were collected on Stand 1 of the CE-5 combustion test facility at NASA Glenn Research Center [2]. The facility provides non-vitiated air pre-heated to a maximum inlet air temperature of 922 K and a pressure of 19 bar. Jet-A aviation fuel was used in this test. Fuel flow rates were measured by Coriolis flow meters, and the air flow rate was measured by a venturi meter. A traversing gas probe was placed at the exit of the combustor to collect combustion products for gas emissions analysis, and a gas particle sampling probe was placed 20 cm behind the combustor exit for particulate matter sampling. The rest of the combustion products were cooled down to 500 K by mixing with sprayed water before exiting to an altitude exhaust system. Gas sample analysis followed the SAE ARP-1533B standard [3], and particulate matter sample analysis was adapted from the SAE ARP-6320 standard [4].

The ACS sector combustor hardware was a single sector configuration. A picture of the combustor hardware and illustration of the injector layout is shown in Figure 1. Like the previous P&W axially staged combustor, fuel injection splits into two stages: pilot and main. Pilot-stage injectors are located on the front dome plate of the combustor, and main-stage injectors are positioned on the top of the combustor liners downstream. Top and bottom liners were cooled with a portion of the combustion air. Both left and right side walls were made of metal plates and were back-side impingement cooled by a separate air source.

There are two fuel injection operating modes. The Low-power mode only uses the pilot-stage injectors, while the High-power mode utilizes both pilot-stage and main-stage fuel injectors. To handle the staging, three fuel circuits were used in this test. One fuel circuit supplied fuel to the main fuel injectors. Two fuel circuits served the pilot stage injectors. These circuits allowed for individual fueling of the two stages.

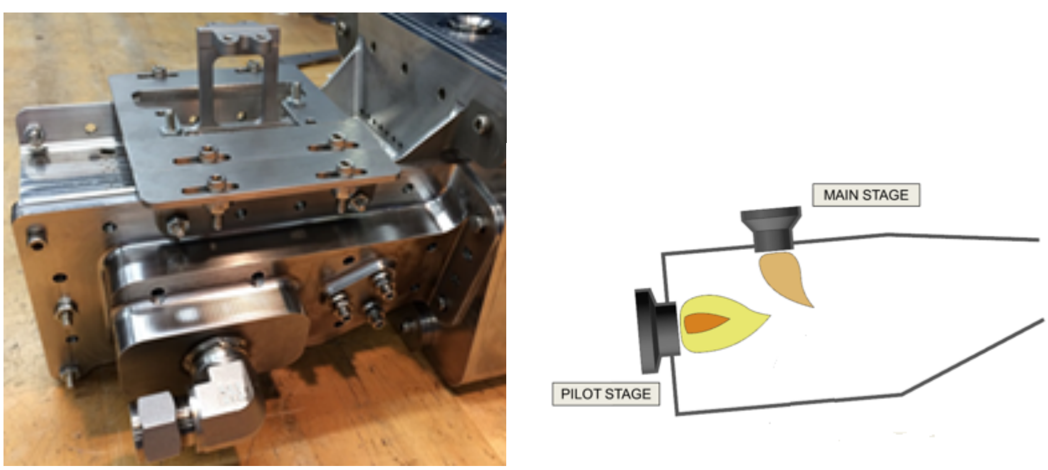


Figure 1: Pictures of the combustor hardware and drawing of the combustor concept.

III. Results and Discussions

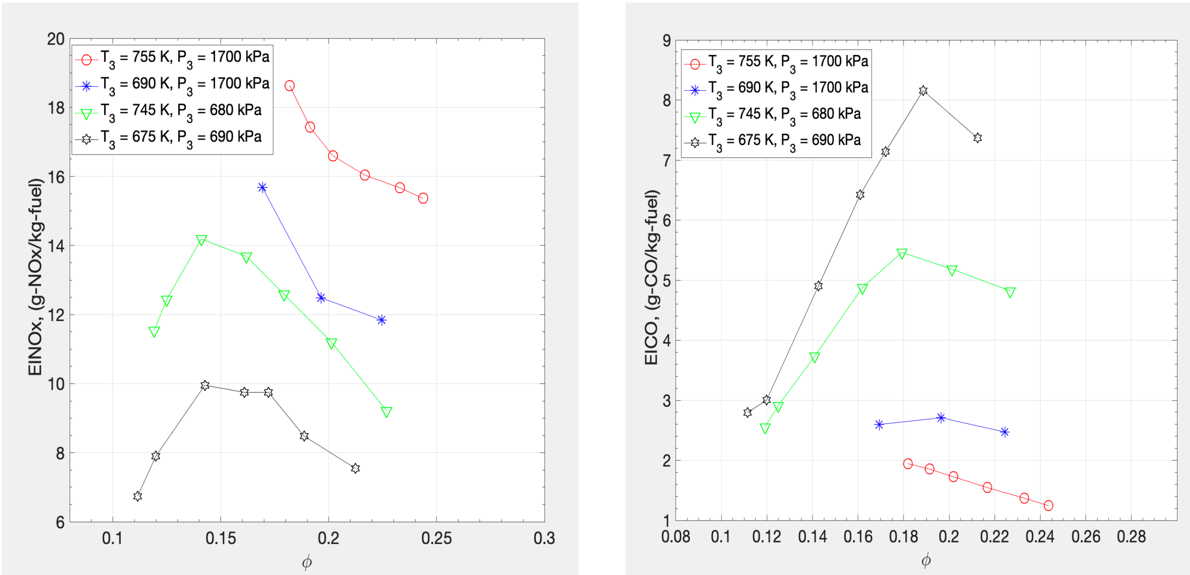
NO_x and CO emissions

With the same ACS design concept, the NO_x emissions characteristics of this N+3 combustor are similar to the one developed under the NASA ERA N+2 combustor project [1]. For Low-power operation (up to 30 % engine power), the overall fuel air ratio is low, and only the pilot-stage injectors are used for fuel injection to maintain a relatively fuel rich pilot zone to stabilize the flame. The Low-power mode operates similar to a rich-front-end combustor. The pilot injectors are located at the dome face. After fuel injection, the fuel rich air mixture from the combustor front end is quickly mixed with the air injected through the main fuel injector air passages before exiting the combustor. The NO_x emissions are mainly a function of pilot zone flame temperature, which increases then decreases with a peak at the combustor front end local equivalence ratio near stoichiometric. As shown in Figure 2a, the NO_x emissions is the highest at around overall (combustor exit, or mixed) fuel air equivalence ratio of 0.15 for a given inlet air temperature and pressure condition, and increases as inlet air temperature (T3) and pressure (P3) increase.

The carbon monoxide (CO) emissions also increase then decrease as the fuel air ratio increases, with a peak at around overall fuel air equivalence ratio of 0.18 (Figure 2b). However, higher inlet air temperature and inlet air pressure help reduce the CO emissions, in contrast to the trend for NOx emissions. For Low-power operation, the CO emissions of the combustor depend on the pilot zone CO production rate and the conversion rate of carbon monoxide to carbon dioxide after the pilot zone. Higher inlet air temperature and pressure give better fuel vaporization and fuel air mixing to lower the CO production, and increased overall fuel air ratio gives higher flame temperatures that help convert more CO to CO_2 before the combustor exit..

For High-power operation, both pilot-stage and main-stage injectors are fueled. The main-stage injectors are located axially downstream of the pilot-stage injectors on the outside diameter (O.D.) liner of the combustor. The combustor operates in a lean-lean mode; the fuel air ratios in the combustor are mostly lean locally and globally. To achieve good combustion (combustion efficiency higher than 99%), high inlet air temperature or fuel air ratio is required. As shown in Figure 3, the lowest fuel air equivalence ratio with stable combustion was 0.39 at an inlet air temperature of 755K, while at higher inlet air temperatures of 807 K and 855 K, the lowest fuel air equivalence ratios were 0.36 and 0.34 respectively. Higher inlet air temperature gives better fuel vaporization, and better fuel air mixing to create a more stable flame. Higher fuel air equivalence ratios give more fuel to mix with the air, which give relatively higher local flame temperatures near the fuel injectors and higher overall flame temperatures to stabilize the flame. Another way to achieve good combustion is to increase the front end pilot flame zone local fuel air ratio. A stable pilot flame zone could stabilize the flame at lower overall fuel air ratio. However, the NO_x emissions would increase correspondingly due to higher pilot flame zone temperature. As shown in Figure 4, as the local front end pilot fuel air equivalence ratio increases, the $EINO_x$ numbers increase and the combustion ineffiencies descrease.

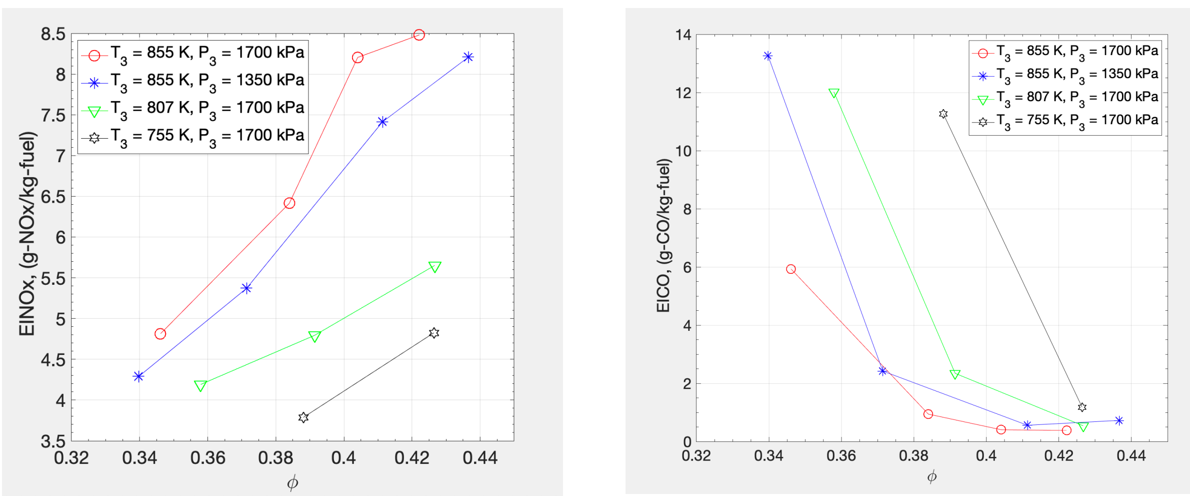
Most of the NO_x production comes from the combustor front end pilot zone. The test result shows the NO_x emissions is strongly dependent on the front end pilot local fuel air equivalence ratio, $\emptyset^{2.72}$, while dependence on overall fuel air equivalence ratio is low, only $\emptyset^{0.11}$. For High-power operation, a large portion of the fuel is injected through the main injectors. A small percentage of fuel shift from the main-injectors to the pilot injectors would increase the NO_x emissions dramatically.



a) NO_x emissions

b) CO emissions

Figure 2: NO_x and CO emissions during Low-power operation.



a) NO_x emissions

b) CO emissions

Figure 3: NO_x and CO emissions during High-power operation.

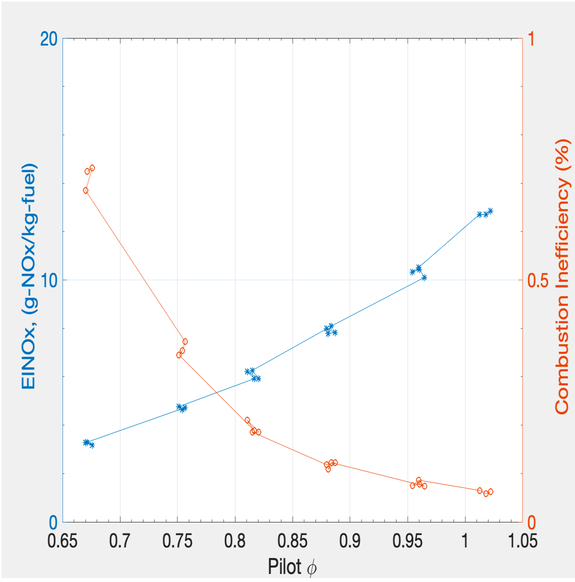
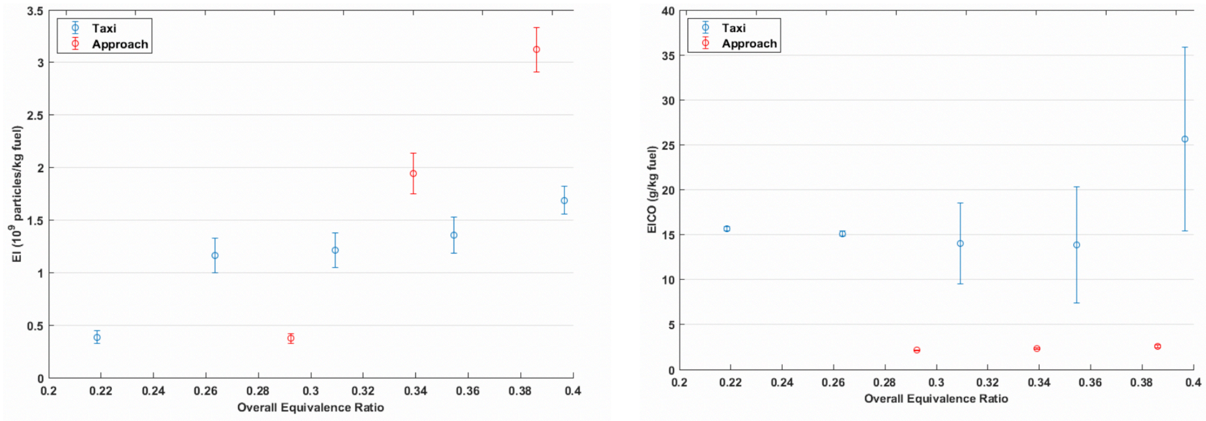


Figure 4: NO_x and combustion inefficiency vs. pilot Ø at a fixed overall Ø.

Particulate Matter emissions

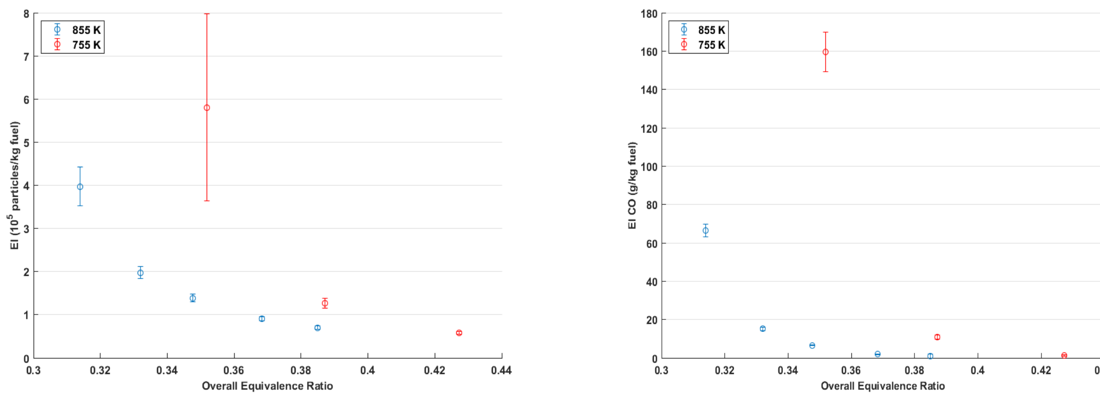
Similar to carbon monoxides, particulate matter (PM) are produced in the front end fuel rich pilot zone, and are consumed (burned out) in the downstream region where oxygen is plentiful (for the Low-power mode or rich front end type of combustor) [5]. The CO emissions are highest when the pilot is slightly richer than stoichiometric, and become lower as the fuel air ratio further increases. The CO emissions increase again at very high fuel air ratio. This trend was observed in the previous NASA ERA N+2 ACS combustor test, and also the N+3 combustor shown in Figure 2b and Figure 5b. Particulate matter production requires a richer fuel air mixture than CO, however, PM is not highest near stoichiometric but instead increases as fuel air ratio increases. Shown in Figure 5a, the PM number Emission Index (EI) increases as fuel air equivalence ratio increases and ranges from 0.4 to 3.5 $x10^9$. PM measurements have been reported previously [6,7] where the combustion samples were collected directly from aircraft engine exhaust. In these previous reports, the PM number EI was greater than $1x10^{12}$ under all engine power conditions, which is 10^3 times higher than the numbers obtained in this test. This difference in PM number EI might be due to line losses. The PM sampling system in the CE-5 combustion rig included a long sampling line and valves to reduce the sampling pressure, which might greatly reduce the PM number EI. Although the PM numbers presented here cannot be compared directly to those from established methods, the extractive measurement itself is self-consistent. Therefore, the trends are still meaningful.

PM emissions for High-power operation are much lower than for Low-power operation. At High-power, the PM number EI range from 0.5 to $8x10^5$ (Figure 6a). Keeping the combustor burning in lean-lean mode avoids regions of high local fuel air ratios in the combustor and reduces PM emissions. Figure 6 shows that PM emissions and CO emissions (for High-power operation) increase as the overall fuel air equivalence ratio decreases. This trend is opposite that of Low-power operation. The PM and CO burnout rates might decrease as flame temperature (fuel air equivalence ratio) decreases and lead to increased PM and CO emissions. As seen in Figure 6, at any given equivalence ratio, increasing the inlet air temperature from 755 K to 855 K reduces both PM and CO emissions.



a) PM number b) CO emissions

Figure 5: PM and CO emissions during Low-power operation.



a) PM number b) CO emissions

Figure 6: PM and CO emissions trends during High-power operation at two combustor inlet temperatures.

$EINO_x$ correlation equations and ICAO LTO NOx reduction

The method used in developing the $EINO_x$ correlation equations is described in a previous study on Parker Hannifin's multipoint LDI injector [7]. Shown in Table 1 are the three $EINO_x$ correlation equations that describe NASA's measured NO_x emissions behavior for this N+3 ACS combustor, as a function of overall fuel air equivalence ratio ($\emptyset$), pilot local fuel air equivalence ratio ($\emptyset_{pilot}$), inlet air pressure ($P3$) and inlet air temperature (T3). Two equations are used to describe the Low-power NOx emissions and one equation is used for the High-power NOx emissions. To better fit the experimental data, a polynomial term was used to describe the NO_x emissions dependence on overall fuel air equivalence ratio for Low-power operation. Inlet air pressure dependence is described by a power term, and inlet air temperature dependence is described by an exponential term. A NO_x emissions dependence term for pilot local fuel air equivalence ratio is also used for High-power operation, which is as high as ${\emptyset_{pilot}}^{2.72}$ while the NO_x dependence on the overall fuel air equivalence ratio is as low as $\emptyset^{0.11}$. With these three equations, the mean and median percentage difference between the experimental and calculated $EINO_x$ values are respectively 3.5% and 2.8%. The standard deviation is 3.25%.

The ICAO LTO NO_x emissions is the total NO_x emissions during the four LTO cycle conditions (taxi, approach, climb, and take-off) over the thrust of a given aircraft engine. Shown in Table 3 are two sets of $EINO_x$

values estimated using the $EINO_x$ correlation equations of Table 1. When the High-power NO_x correlation equation is used, the local pilot fuel air equivalence ratio is set to 0.6. One set of values is calculated with NASA's N+3 small core engine LTO cycle (conditions listed in Table 2), and another set is calculated with UTRC's N+3 engine LTO cycle. Table 3 lists the results, and shows that the percentage NO_x reductions relative to the ICAO CAEP/6 standard are 82% and 89% (for the UTRC and NASA N+3 engine cycles, respectively). These results exceed the NASA N+3 NO_x reduction goal of 80% reduction compared to CAEP/6.

The NASA N+3 cruise NOx goal is to achieve emissions that are 80% below a 2005 "best in class" baseline, which NASA defines as the 737-800 with a CFM56-7B engine. Since there is no existing ICAO cruise NOx standard – and therefore no existing cruise NOx metric – a measure is needed representing the quantity of NOx deposited in the atmosphere for any given flight mission. For this purpose, a useful metric for comparing cruise NOx emissions from different engines is NOx per thrust, or more specifically grams NOx emitted per minute per kN thrust at cruise. This can be calculated from measured NOx emissions (for cruise combustor conditions), along with the engine cycle's cruise Thrust Specific Fuel Consumption (TSFC). Since TSFC is usually quoted in units of lbm/hr fuel flow per lbf thrust, we have:

Cruise_NOx = (g_NOx / min) / kN_thrust = 1.7*EINOx*TSFC

A NASA engine systems model was used to provide cruise TSFC and NOx emissions values for the 2005 best-in-class aircraft cycle and the NASA N+3 aircraft cycle. The N+3 cycle cruise NOx was calculated from correlations (Table 1) based on the ACS flametube experiments, while the 2005 best-in-class aircraft cycle cruise NOx was calculated from an in-house CFM56-7B correlation. Using the above equation for evaluating cruise NOx, the percentage cruise NOx reduction of this new combustor design in an N+3 cycle is 87% relative to the baseline 2005 best-in-class aircraft.

The NO_x emissions over the engine power settings are shown in Figure 7. This combustor uses a rich front end design for low power operation to stabilize the flame which leads to higher NO_x emissions at low power. As engine power increases, the increase in overall fuel air ratio enables lean-lean operation inside the combustor and thus reduces NO_x emissions at higher engine power.

Table 1: $EINO_x$ correlation equations.

Operational conditions	**NO_x correlation equations**
Low-power configuration **0.07<Ø < 0.15**	$EINOx = 0.141 \times (-19.14 - \frac{4.411}{\emptyset} + \frac{0.07856}{\emptyset^2} + \frac{17.56}{\sqrt{\emptyset}}) \times P3^{0.515} \times e^{\frac{T3}{298}}$
Low-power configuration **0.35 > Ø > 0.15**	$EINOx = 0.016 \times (21.7 + \frac{4.39}{\emptyset} + \frac{0.064}{\emptyset^2} - \frac{17.44}{\sqrt{\emptyset}}) \times P3^{0.327} \times e^{\frac{T3}{287}}$
High-power configuration **Ø > 0.30**	$EINOx = 2.56e^{-3} \times P3^{0.48} \times \emptyset_{pilot}{}^{2.72} \times \emptyset^{0.11} \times e^{\frac{T3}{168}}$

- P3 in kPa, T3 in K

Table 2: NASA N+3 engine cycle for 120.4 kN, 37.6 OPR (sea-level) engine.

% engine power	LTO condition	P3 (bar)	T3 (K)	Ø	Fuel (kg/s)
100	SLTO	38.0	870	0.354	0.585
85	Climb	32.7	835	0.325	0.479
30	Approach	14.1	661	0.185	0.147
7	Taxi	7.1	553	0.102	0.048

Table 3: Land-and-takeoff (LTO) NO_x emissions and percentage reduction in relative to ICAO CAEP/6.

% engine power	**conditions**	**NASA N+3 cycle $EINO_x$**	**UTRC N+3 cycle $EINO_x$ ***
100	SLTO	4.65	4.02
85	Climb	3.48	3.09
30	Approach	10.2	10.7
7	taxi	3.46	6.12
	cruise	2.56	1.6
		% ICAO reduction	**% ICAO reduction**
		89%	82%

* Calculated from correlations developed from NASA test data.
* The NO_x emissions results are humidity corrected

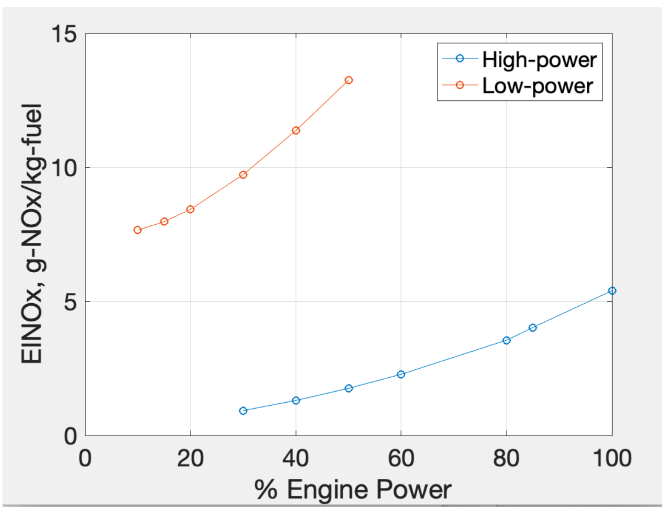


Figure 7: NOx emissions estimation over NASA's N+3 engine power setting.

IV. Conclusions

NO_x, CO and PM emissions of an ACS single sector combustor are reported in this study. This combustor is designed for a small core high OPR aircraft engine. It uses a similar design concept as a previous ACS combustor developed under NASA's ERA N+2 project. As a result, the NO_x and CO emissions characteristics are similar between these two versions of ACS combustors. With low power configuration (pilot only operation), the PM emissions trends of the new ACS combustor are similar to CO emissions with an exception at high fuel air ratio as inlet air temperature and pressure conditions change from taxi to approach. A more detailed mapping study is needed to get better understanding of PM emissions. Three NO_x correlation equations are generated to describe the NO_x emissions trends of this combustor. The percentage NO_x reduction of this N+3 ACS combustor is between 82% and 89% relative to the ICAO CAEP/6 standard, which meets the NASA N+3 NO_x reduction goal of 80% reduction from CAEP/6.

Acknowledgments

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