NOx Emissions Performance and Correlation Equations for a Multipoint LDI Injector

Zhuohui J. He, Clarence T. Chang, Caitlin E. Follen

NASA Glenn Research Center
21000 Brookpark Rd, MS 5-10
Cleveland, OH 44135
U.S.A.

Abstract

Lean Direct Injection (LDI) is a combustor concept that reduces nitrogen oxides (NOx) emissions. This paper looks at a 3-zone multipoint LDI concept developed by Parker Hannifin Corporation. The concept was tested in a flame-tube test facility at NASA Glenn Research Center. Due to test facility limitations, such as inlet air temperature and pressure, the flame-tube test was not able to cover the full set of engine operation conditions. Three NOx correlation equations were developed based on assessing NOx emissions dependencies on inlet air pressure (P3), inlet air temperature (T3), and fuel air equivalence ratio (Φ) to estimate the NOx emissions at the unreachable high engine power conditions. As the results, the NOx emissions are found to be a strong function of combustion inlet air temperature and fuel air equivalence ratio but a weaker function of inlet air pressure. With these three equations, the NOx emissions performance of this injector concept is calculated as a 66% reduction relative to the ICAO CAEP-6 standard using a 55:1 pressure-ratio engine cycle. Uncertainty in the NOx emissions estimation increases as the extrapolation range departs from the experimental conditions. Since maximum inlet air pressure tested was less than 50% of the full power engine inlet air pressure, a future experiment at higher inlet air pressure conditions is needed to confirm the NOx emissions dependency on inlet air pressure.

Keywords

Nitrogen oxide emission; Lean direct injection; Aircraft engine combustor; Correlation equation

Nomenclature

P3	[kPa]	Inlet air pressure
T3	[K]	Inlet air temperature
T4	[K]	Calculated adiabatic flame temperature
Φ, PHI	[-]	Fuel air equivalence ratio
N1	[-]	NOx emissions dependency on inlet air pressure
N2	[-]	NOx emissions dependency on inlet air temperature
N3	[-]	NOx emissions dependency on fuel air equivalence ratio
K	[-]	Correlation equation constant

Abbreviations

LDI	Lean Direct Injection
EINOx	Emission Index of nitrogen oxides
ICAO	International Civil Aviation Organization
CAEP	Committee on Aviation Environmental Protection
LTO	Landing and Take-Off cycle
ERA	Environmental Responsible Aviation

Introduction

Nitrogen oxides (NOx) emissions are harmful to the environment. They contribute to photochemical smog and green house gas generation as well as the depletion of the protective ozone layer in the stratosphere [1]. In aircraft engines, nitrogen oxides reduction relies on advanced combustor design. Lean Direct Injection (LDI) remains as NASA's most likely candidate combustor concept for ultra-high pressure engine cycles, in which the combustor inlet temperature is high, the ignition delay time is short, and very little time exists to premix the fuel before combustion starts. In its extreme form, LDI injects fuel into the flame zone directly, mixing quickly as the fuel burns, reducing the probability and intensity of hot spots and keeping average flame temperature low.

Screening new aircraft combustor concepts usually starts in a flame-tube test facility, where a single fuel injector is tested at various aircraft engine combustor operational conditions. Due to test facility limitations, such as inlet air temperature and pressure, flame-tube tests are usually not able to cover the full set of engine operation conditions. For example, the maximum combustor inlet air pressure is around 4.6 MPa for an aircraft engine with compression ratio of 45:1, while the maximum combustor inlet air pressure for Stand 1 of the CE-5 flame-tube test facility at NASA Glen Research Center is only about 1.7 MPa. To estimate NOx emissions at the unreachable high engine power conditions, test cell results can be extrapolated based on experimentally-established correlation functions.

For many multipoint LDI concepts reported previously [2-3], NOx emissions correlation equations were presented. These correlation equations were based on inlet air pressure, inlet air temperature, air pressure drop across the injector, calculated adiabatic flame temperature, and fuel air ratio. The NOx correlation equations' dependencies varied with each injector design. As a result, each injection concept has to be assessed separately to determine emission performance. The purpose of this paper is to assess the dependencies of NOx emissions on inlet air pressure, inlet air temperature, and fuel air equivalence ratio of the first design of Parker Hannifin Corporation's 3-zone LDI concept for NASA's Environmental Responsible Aviation (ERA) project and to estimate its aggregate NOx emissions performance for an ERA high-pressure engine operational cycle.

Method

(1) Experimental Configuration

Experimental data used in this study were collected on Stand 1 of the CE-5 flame-tube test facility at NASA Glenn Research Center [4]. Non-vitiated air was pre-heated to maximum temperature of 830 K and maximum pressure of 1.74 MPa. Commercial JP-8 aviation fuel was used. Fuel flow rates were measured by turbine meters and coriolis flow meters, and the air flow rate was measured by a venturi meter. The fuel-air mixture was injected into a flame-tube with a cast ceramic liner. The test section was 300 mm long. A gas probe was placed 200 mm downstream of the injector to collect combustion products for analysis. The rest of the combustion products were cooled down to 500 K by mixing with sprayed water before exiting to an altitude exhaust system. The combusted gas samples were analyzed according to the standard gas-analysis procedure, SAE-ARP1256 [5]. The simultaneous chemiluminescence method was used to measure NO and NO_2.

The fuel injector tested in this experiment was the first multipoint LDI concept developed by Parker Hannifin under the Environmental Responsible Aviation (ERA) project. Fifteen fuel-air mixers are arrayed in three outwardly-canted panels in place of a traditional single conventional fuel injector. Each fuel-air mixer consists of an air passage with an air swirler, and a fuel nozzle is inserted through the center of the air swirler. Three progressively-larger fuel circuits fed the Pilot, Main1, and Main2 fuel stages. Each fuel stage controlled different number of fuel-air mixers. An older 3-zone design with more injectors is shown in Figure 1 to illustrate the configuration.

The test matrix was designed to maximize the test facility capacities while scaling the operational parameters. Inlet air pressure (P3) varied from 0.69 to 1.72 MPa, and inlet air temperature (T3) varied from 590 to 830 K. Air pressure drop across the dome was 4.0%. Fuel air equivalence ratio varied from 0.2 to 0.6. All three fuel stages were used where higher overall fuel air ratio conditions exist. Emission data for this configuration was named as Three F-Stages. For lower power engine conditions where overall fuel air ratios are low, only Pilot and Main1 were used, and the emission data for this configuration was named as Two F-Stages. Light off was done using only the Pilot.

(2) Correlation Methodology

The format of the correlation equation used was similar to the one that had been reported in many previous LDI studies [2-3] as in Equation (1):

$$EINOx = K * P_3{}^{N1} * e^{\frac{T_3}{N2}} * \Phi^{N3} \hspace{4cm} (1)$$

With this equation, the NOx emissions Index value is a function of combustor inlet air temperature (T3, K), inlet air pressure (P3, kPa), and fuel to air equivalence ratio (Φ). K is a constant. N1, N2, and N3 are the dependencies of NOx emissions on P3, T3, and Φ. These three values were found by plotting the graphs: EINOx vs. P3, EINOx vs. T3, and EINOx vs. Φ. Using these N1, N2, and N3 values as initial guesses, multiple regressions method in Excel was used to estimate the last unknown variable, K.

Results and Discussion

Figure 2 shows the EINOx values at various calculated adiabatic flame temperatures (T4) and at three inlet air pressure (P3) conditions: 1,034 kPa, 1,379 kPa, and 1,724 kPa. This set of data was taken when all three fuel flow manifolds were on (Three F-Stages), and local fuel air ratios were about the same among the fifteen fuel-air mixers. Figure 2a shows the NOx emissions data that taken at inlet air temperature (T3) of 828 K. This chart shows couple clear trends. First, the EINOx data taken at different inlet air pressures are almost parallel to each other. With increased inlet air pressure, the EINOx value increases. In addition, the NOx emissions increase with the calculated adiabatic flame temperature, and the rate of change increases above T4 of 1810 K. At constant inlet air temperature, the adiabatic flame temperature is approximately a linear function of fuel air equivalence ratio. As a result, the NOx emissions dependency on fuel air equivalence ratio also changed at T4 above 1810 K. Figure 2b shows the NOx emissions data taken at an inlet air temperature of 735 K. Similar trends are observed. However, the data are more scattered than the data taken at T3 of 828 K, especially at lower calculated adiabatic flame temperature.

With the format of the correlation equation, the NOx emissions dependencies on inlet air pressure, inlet air temperature, and fuel air equivalence ratio are assumed to be constant and independent of each other. Since the NOx emissions dependency on fuel air equivalence ratio changes above T4 of 1810 K, two equations are used to correlate this set of data across the flame temperature range - one for below and one for above T4 of 1810 K.

The first parameter that was examined is the NOx emissions dependency on fuel air equivalence ratio. Figure 3 shows EINOx vs. Φ chart for the Three F-Stages data taken at T4 less than 1810 K. At an inlet air temperature of 828 K (Figure 3a), the lines are almost parallel to each other with the slopes (N3) ranging from 0.778 to 0.880. These data indicate the NOx emissions dependency on fuel air equivalence ratio is nearly independent of inlet air pressure. At inlet temperature of 735 K (Figure 3b), the range of the slopes (N3) is widened, from 0.856 to 1.430. Due to limited data points, it is hard to conclude that the dependency of fuel air equivalence ratio is varied with inlet air pressure.

To examine the dependency on inlet air pressure or inlet air temperature, the NOx emissions data must be taken at the same fuel air equivalence ratio. As shown in Figure 3, this is not the case. Nevertheless, knowing the dependency on fuel air equivalence ratio, a specific EINOx value (EINOx$_{specific}$) at a specific fuel air equivalence ratio (Φ$_{specific}$) could be estimated along with the known experimental NOx emissions (EINOx$_{experimental}$) values that taken at various fuel air equivalence ratios (Φ$_{experimental}$) by using Equation (2):

$$\ln(EINOx_{experimental}) - \ln(EINOx_{specific}) = N3 * (\ln(\Phi_{experimental}) - \ln(\Phi_{specific})) \hspace{2cm} (2)$$

Using the Three F-Stages (T4 < 1810 K) experimental NOx emissions data, the EINOx values at various T3, various P3, and Φ of 0.37 are estimated.

Figure 4a assesses the NOx emissions dependency on inlet air pressure (N1) for the Three F-Stages data (T4 < 1810 K). At inlet air temperature of 735 K, the NOx emissions depend on inlet air pressure to the 0.49 power, and at inlet air temperature of 828 K, it depends on inlet air pressure to the 0.48 power. For the inlet air temperature dependency (Figure 4b), NOx emissions are an exponential function of T3/170, except at inlet air pressure of 1,034 kPa, T3/147.

Using these N1, N2, and N3 values as initial guesses, multiple regressions method in Excel was used to estimate the last unknown variable, K. The NOx emissions correlation equation for the Three F-Stages data (T4 < 1810 K) is listed as the second equation in Table 1. Two more correlation equations were developed with the same approach (listed in Table 1): one for Three F-Stages data (T4 > 1810 K) and one for the Two F-Stages data. Figure 5 to Figure 8 are the relative charts that demonstrate the assessments on the NOx emissions dependencies. The experimental vs. calculated EINOx emission data are plotted in Figure 9a. The R-squared value is 0.99.

Comparing these three equations, the variations in NOx emissions dependencies on inlet air pressure (N1) and inlet air temperature (N2) are relatively small. NOx emissions vary as inlet air pressure exponent of 0.46 to 0.60 and an exponential function of T3/132 to T3/200. In comparison, the dependency exponent of NOx emissions on fuel air

3

equivalence ratio (N3) varies more than 3 times (from 0.97 to 3.32 power) as fewer fuel injection points are used (Two F-Stages) or when theoretical adiabatic flame temperature exceeds 1810 K with three fuel stages on.

With only two fuel stages (Pilot and Main1) on, the NOx emissions depend on fuel air equivalence ratio to the 3.03 power. Two F-Stages usually applies at low engine power conditions, where inlet air temperature and pressure are low, and less than half of the 15 fuel-air mixers are used for fuel injection. As the results, local fuel air ratio and the fuel drop size are relatively higher and larger than for the Three F-Stages configuration. As the local fuel air ratio increases, more local hot spots might arise and create more NOx emissions. Thus, NOx emissions are more sensitive to fuel air equivalence ratio.

When comparing the two Three F-Stages correlation equations, NOx emissions dependencies on inlet air pressure, inlet air temperature, and fuel air equivalence ratio increase at theoretical adiabatic flame temperature above 1810 K. As for fuel air equivalence ratio, the NOx emissions dependency (N3) has increased more than three times. This raise might be due to the increase in thermal NOx production. According to Lefebvre [6], thermal NOx production is an exponential function of the flame temperature. At flame temperature above around 1850 K, the thermal NOx production proceeds at a significant rate compared to other NOx production mechanisms for lean pre-mixed flame.

The ICAO Landing and Take-off (LTO) cycle involves four engine power conditions: 100% (take-off), 85% (climbing), 30% (approaching), and 7% (taxiing). Using the three correlation equations, the NOx emissions for these four conditions are estimated and listed in Table 2. The total LTO NOx emissions value is found to be 16.4 g-NOx/kg-fuel, 66% below the ICAO CAEP-6 standard using a 55:1 pressure-ratio engine cycle. This value is calculated as overall NOx emissions over the total fuel burn during the LTO cycle. It depends on EINOx emission value, fuel burning rate, and cyclic time of each power condition.

The influence of scaling inlet air temperature and pressure from the test condition to the full-power condition in this case is roughly about equal. The resulting scale up factors for the inlet air temperature and pressure corrections are respectively 2.7 and 2. For 85% and 100% engine power conditions, the EINOx values are respectively 24.7 and 52.4 g-NOx/kg-fuel. These two numbers account for about 90% of the ICAO LTO NOx values. Uncertainty with these extrapolations would heavily affect the validity of the NOx level for the ICAO LTO cycle. If NOx emissions dependency on inlet air pressure increases from exponent of 0.516 to 0.53, the total LTO NOx value would increase from 16.4 to 17.8 g-NOx/kg-fuel.

NOx emissions at a higher inlet air pressure were previously measured with Parker's first generation 25-points LDI concept [3]. The Three F-Stages correlation equations are used to estimate the NOx emissions at the same test conditions, inlet air pressure of 1380, 2068, and 2760 kPa and inlet air temperature of 810 K at various fuel air equivalence ratios. The experimental EINOx values (from the 25-points LDI concept data) vs. calculated EINOx values are shown on Figure 9b with R-squared value of 0.69. The NOx emissions trend is similar between the two, but the calculated EINOx values are higher than the experimental EINOx values. This result further indicates each injection concept has to be assessed separately to determine emission performance. For each injector design, residence time and flow path of the combustion products are different. These two factors heavily affect the NOx emissions.

Conclusions

Three correlation equations were developed for a 3-zone multipoint LDI injector by examining the NOx emissions dependencies on inlet air temperature, inlet air pressure, and fuel-to-air equivalence ratio. These results showed the NOx emissions is a strong function of combustion inlet air temperature and fuel air equivalence ratio but a weaker function of inlet air pressure. Other than these three design parameters, many other engine design and operational parameters could also affect the NOx emissions, such as air pressure drop across the injector and fuel flow split among the fuel-air mixers. Thus, to increase the flexibility of the equations, additional design parameters should add to the correlation equation once the corresponding NOx emissions dependency is determined. Small inaccuracy with inlet air pressure extrapolation would heavily affect the validity of the NOx level for the ICAO LTO cycle. Since maximum inlet air pressure tested was less than 50% of the full power engine inlet air pressure, future experiment at higher inlet air pressure condition is needed to confirm the NOx emissions dependency on inlet air pressure.

Acknowledgements

References

[1] Chowen Wey, and Lourdes Q. Maurice, Exploring Aviation's Environmental Impact, AIAA-2003-5993, 2003.

[2] Robert Tacina, Phil Lee, and Changlie Wey, A Lean-Direct-Injection Combustor Using A 9 Point Swirl-Venturi Fuel Injector, ISABE-2005-1106, 2005.

[3] Robert Tacina, Changlie Wey, Peter Liang and Adel Mansour, A Low NOx Lean-Direct Injection, MultiPoint Integrated Module Combustor Concept for Advanced Aircraft Gas Turbines, NASA/TM-2002-211347, 2002.

[4] J. Bianco, NASA Lewis Research Center's combustor test facilities and capabilities, AIAA-1995-2681, 1995.

[5] Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines, SAE ARP1256-2006, 2006.

[6] Lefebvre, Arthur H, Gas Turbine Combustion, Taylor and Francis, Philadelphia, 2nd edition, 1998, P328.

Table 1: The three NOx emissions correlation equations for Parker Hannifin's multipoint LDI injector.

(1) Two F-Stages	$EINOx = 0.364 * P_3{}^{0.60} * e^{\frac{T_3}{200}} * \Phi^{3.03}$
(2) Three F-Stages (T4 < 1810 K)	$EINOx = 0.0052 * P_3{}^{0.46} * e^{\frac{T_3}{170}} * \Phi^{0.97}$
(3) Three F-Stages (T4 > 1810 K)	$EINOx = 0.0058 * P_3{}^{0.516} * e^{\frac{T_3}{132}} * \Phi^{3.32}$

Table 2: Landing and Take-off cycle NOx emissions using a 55:1 pressure-ratio engine cycle.

Power condition	Cyclic Time (min)	NOx,EI (g/kg)
7%	26	1.68
30%	4	3.57
85%	2.2	24.7
100%	0.7	52.4
Total LTO NOx		16.4
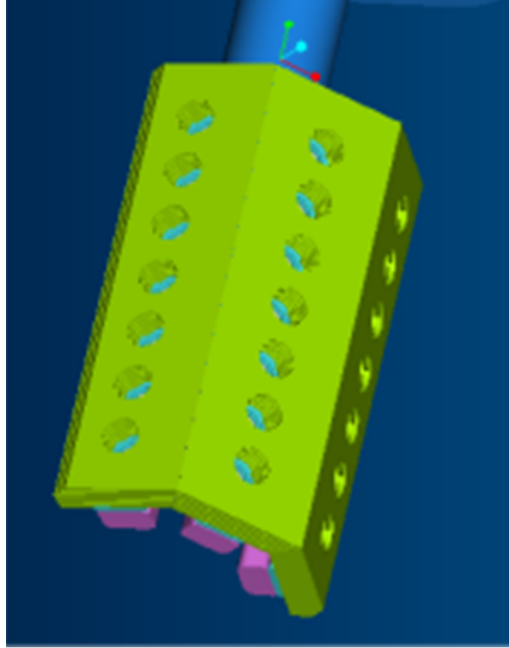
Figure 1: Picture of an older 3-Z LDI design with more injectors by Parker Hannifin.

a)   b)
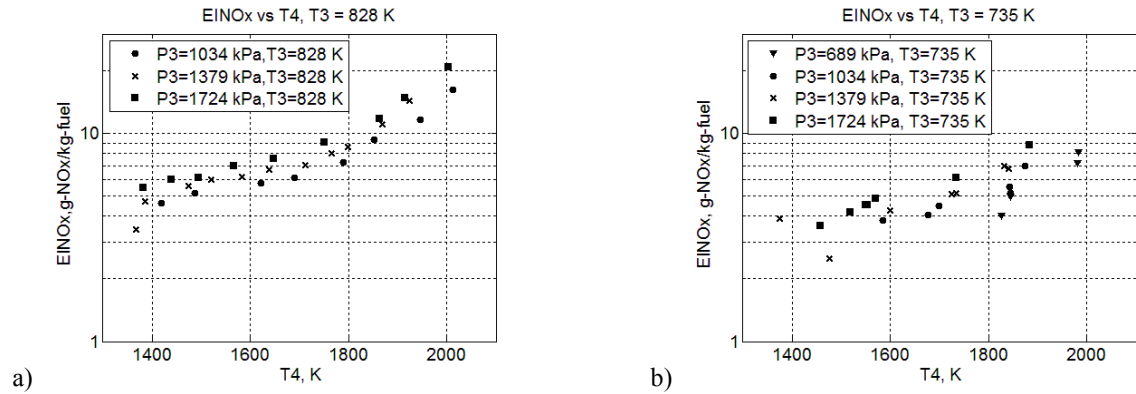
Figure 2: EINOx vs. T4 at various inlet air pressures and two inlet air temperatures: (a) 828 K and (b) 735 K.
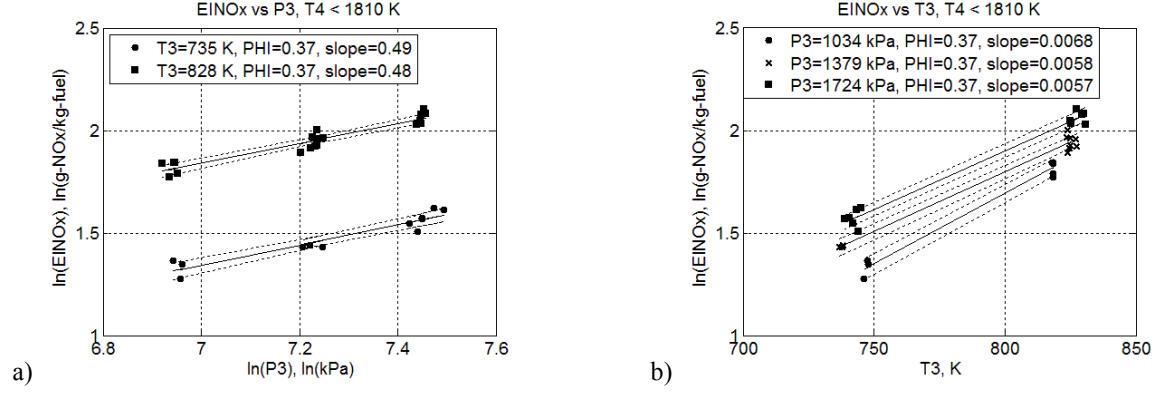

a)   b)
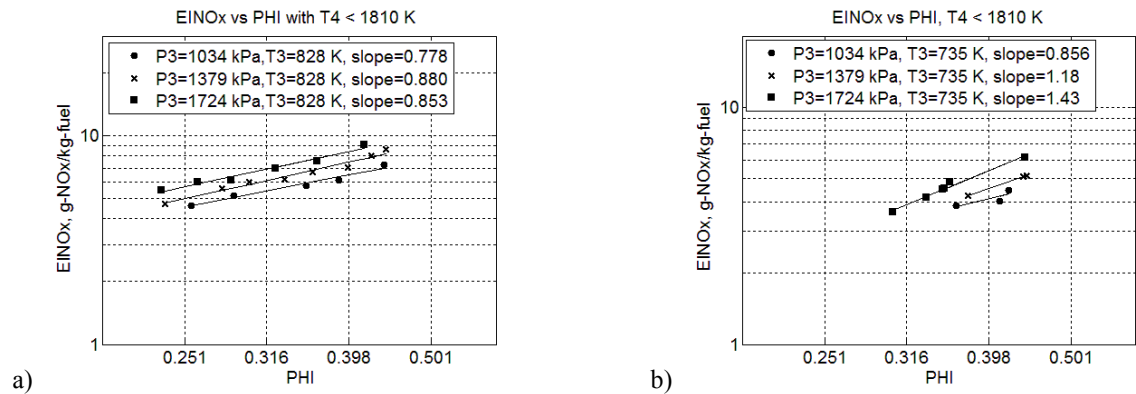
Figure 3: EINOx vs. PHI at three inlet air pressures and two inlet air temperatures: (a) 828 K and (b) 735 K (for Three F-Stages data taken at T4 <1810 K).

Figure 4: (a) EINOx vs. P3 and (b) EINOx vs. T3 at fuel air equivalence ratio of 0.37 (for Three F-Stages data taken at T4 < 1810 K).
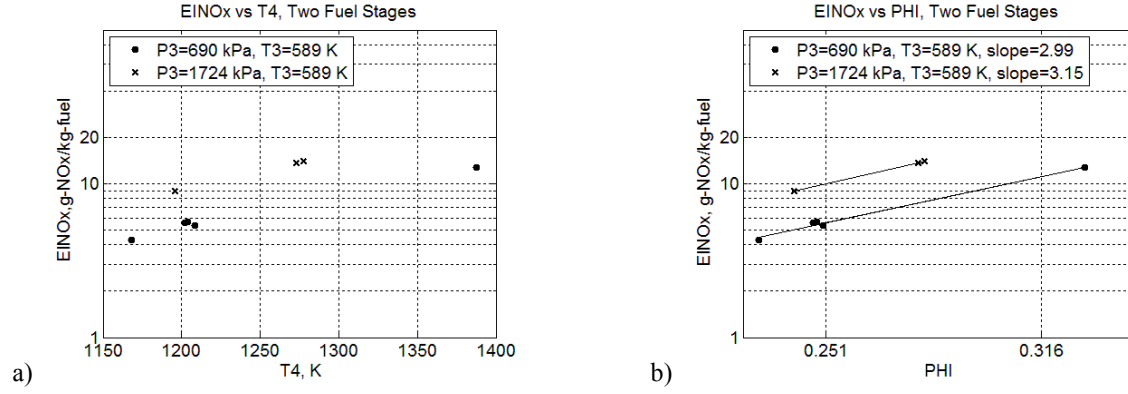
Figure 5: (a) EINOx vs. T4 and (b) EINOx vs. PHI at various inlet air pressures for Two F-Stages data.
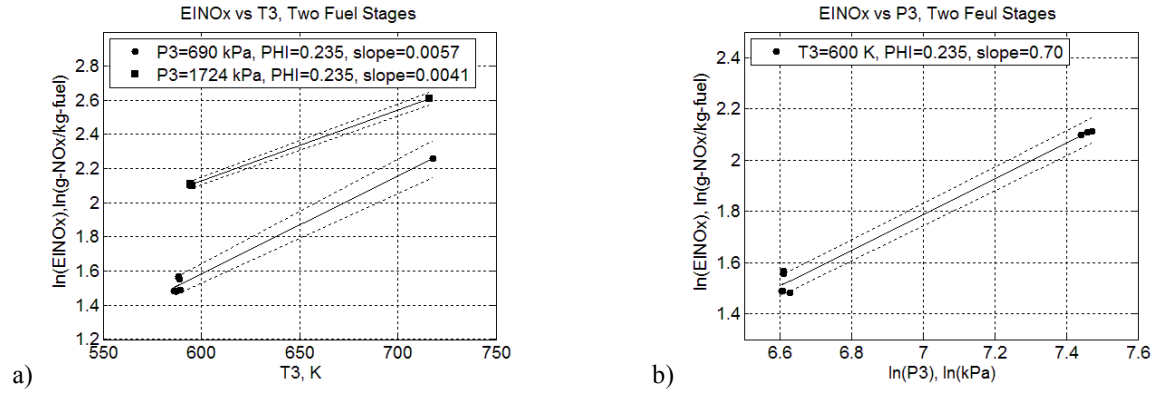

Figure 6: (a) EINOx vs. T3 and (b) EINOx vs. P3 for Two F-Stages data at fuel air equivalence ratio of 0.235.
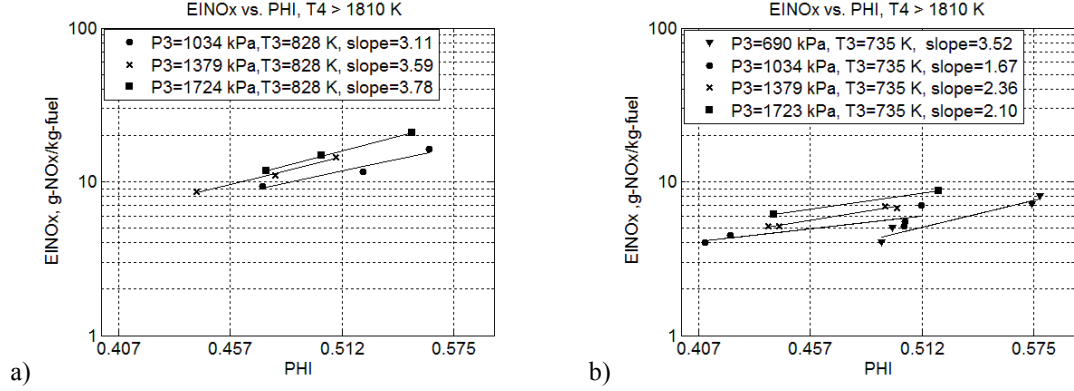
Figure 7: EINOx vs. PHI at three inlet air pressures and two inlet air temperatures: (a) 828 K and (b) 735 K. (for Three F-Stages data taken at T4 >1810 K).
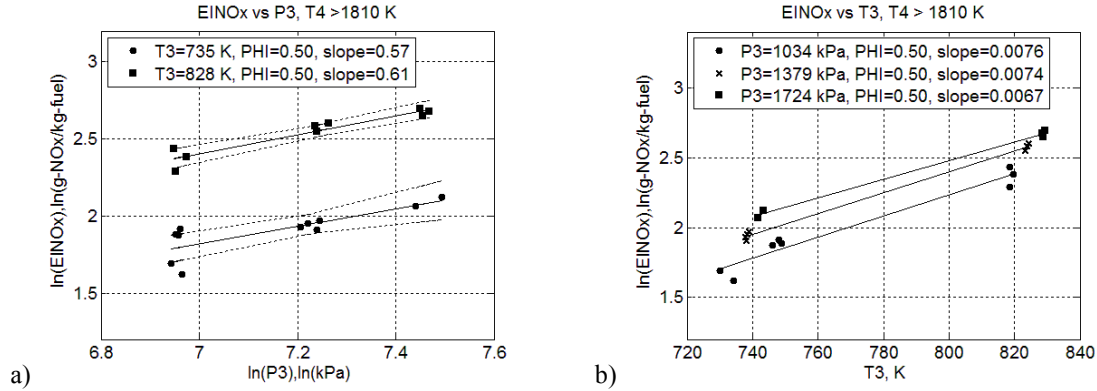

Figure 8: (a) EINOx vs. P3 and (b) EINOx vs. T3 at fuel air equivalence ratio of 0.50 (for Three F-Stages data taken at T4 >1810 K).
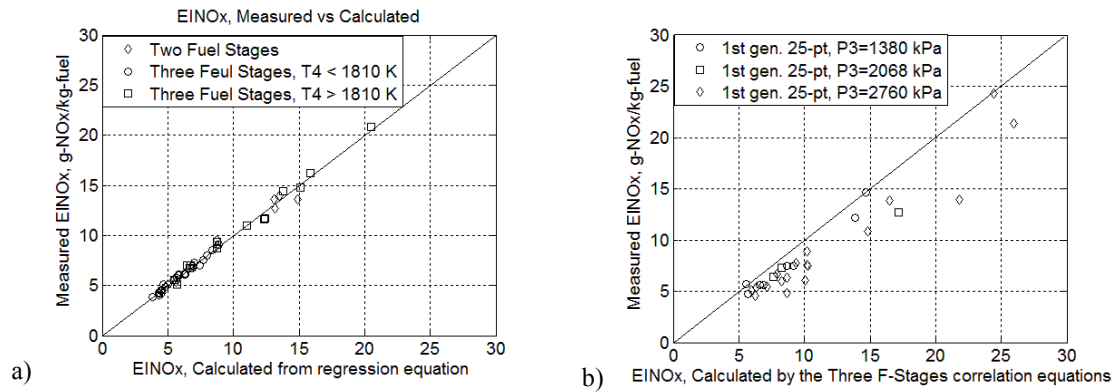

Figure 9: (a) measured vs. calculated NOx emissions for the new 3-zone LDI concept with R-square value of 0.99 and (b) measured EINOx (P3=1380, 2068, and 2760 kPa, T3=810 K) at various Φ vs. calculated EINOx by the Three F-Stages correlation equations for Parker's 1st generation 25-pt LDI concept [3] (R-square=0.69).