Investigation of low emission combustors using hydrogen lean direct injection

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Abstract: *One of the key technology challenges for the use of hydrogen in gas turbine engines is the performance of the combustion system, in particular the fuel injectors. Tests were conducted to measure the nitrogen oxide (NOx) emissions and combustion performance at inlet conditions of 588 to 811 K, 0.4 to 1.4 MPa, and equivalence ratios up to 0.48. All the injectors were based on Lean Direct Injection (LDI) technology with multiple injection points and quick mixing. One challenge to hydrogen-based premixing combustion systems is flashback since hydrogen has a reaction rate over 7 times that of Jet-A.*

Key Words: *low emission combustor, lean direct injection, equivalence ratio, NOx emissions*

1. INTRODUCTION

One of the key technology challenges for the use of hydrogen in gas turbine engines is the performance of the combustion system, in particular the fuel injectors. To investigate the combustion performance of gaseous hydrogen fuel injectors flame tube combustor experiments were performed.

One key difference from previous hydrogen-based systems is the current requirement to address the ever increasing environmental emissions regulations. The use of hydrogen as an aircraft fuel has tremendous environmental benefits over current systems with the elimination of carbon monoxide (CO), carbon dioxide (CO2), sulfur oxides (SOx), unburnt hydrocarbons (UHC), and smoke. Emissions from hydrogen engines are relatively benign, comprising water and nitrogen oxides (NOx), each of which has some environmental impacts, however overall significantly less than conventional engines of today. The impact of NOx as a greenhouse gas is well known and steps can be taken to minimize these emissions in hydrogen gas turbine engines.

As a result, based on engine emissions, hydrogen provides an environmentally friendly option for use in future propulsion systems. While CO, CO2, SOx, UHC, and smoke all play a significant role in global climate change, for aircraft NOx may present the greatest concern. NOx is a collective term which refers to the combination of nitric oxide (NO) and nitrogen dioxide (NO2).

The chemical kinetics of hydrogen and nitrogen oxide formation rates are well known. 3 NOx production is highly dependant upon temperature (inlet air and combustion), residence time, mixedness, and engine pressure.

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The exact correlation varies with the configuration, but a representative equation is given by (1). Eq. (1) was used as a measure for the emissions.

$$ppm_{NO_x} = A'(143P_3)^{0.594}\exp\left(\frac{T_3-255}{194}\right)\left(\frac{f}{a}\right)^{1.6876}\left(100\frac{\Delta P}{P}\right)^{-0.56} \tag{1}$$

A’ = correlation constant for emission index based on Jet-A fuel
f/*a* = fuel to air ratio
*P*3 = fuel injector inlet air pressure (MPa)
*T*3 = fuel injector inlet air temperature (K)
Δ*p* = fuel injector air flow pressure drop (Mpa)
Δ*p*/*p* = fuel injector air flow pressure drop ratio (percent)
A’ = 14 for advanced LDI technology, used in this report
= 30 for current aircraft gas turbine combustors, AIAA–90–2004
= 53 for 1980 technology aircraft combustors, AIAA–90–2004

The test matrix consisted of approach (600 K, *P* = 0.7 to 1.0 MPa) cruise (700 K, *P* = 0.7 to 1.0 MPa) and reduced takeoff (800 K, *P* = 0.7 to 1.0 MPa) over the complete equivalence ratio range (0.1 to 0.48).

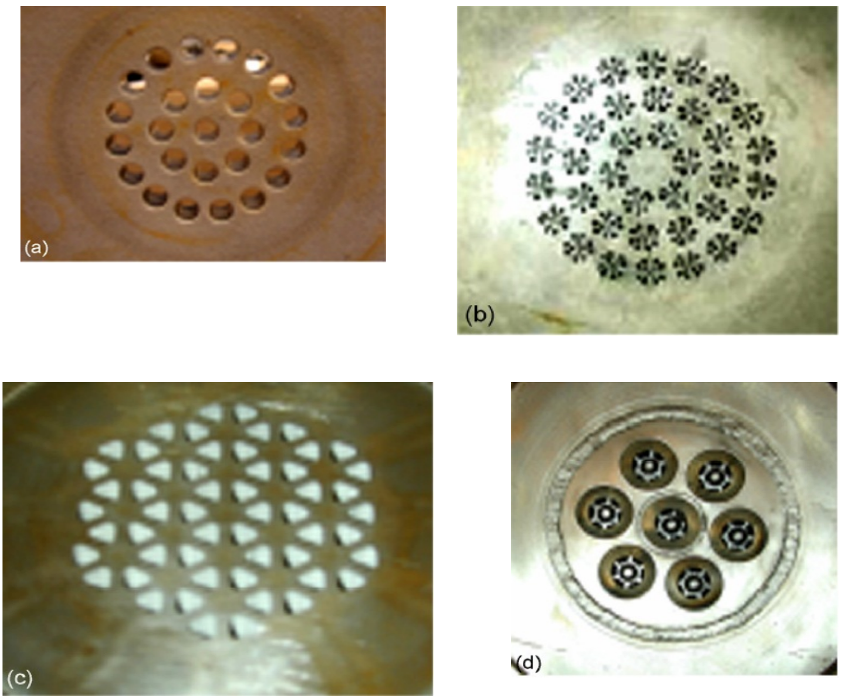

Figure 1.Four injectors tested. (a) NASA N1 injector. (b) Configuration C1. (c) Configuration C2. (d) Configuration C3 and Mod C4 [21].

2. CONFIGURATION OF N1 INJECTOR

The NASA Glenn (N1) injector, shown in Fig. 3, used two opposing hydrogen jets in the mixing tube. The jet penetration and mixing was designed using the jet in cross flow program. The result was a design that created a very short area of premixing as the flow exited the main elements. In this configuration air flows through the 25 injection elements with side injection of gaseous hydrogen located at two positions 180 degrees apart. The air elements are 0.635 cm in diameter, and the hydrogen injection holes are 0.051 cm in diameter. The NASA injector was fabricated with a simple method from three rings as shown in Fig. 2.

These rings could be drilled through from the outside and then seam welded together to form a hydrogen tight configuration.

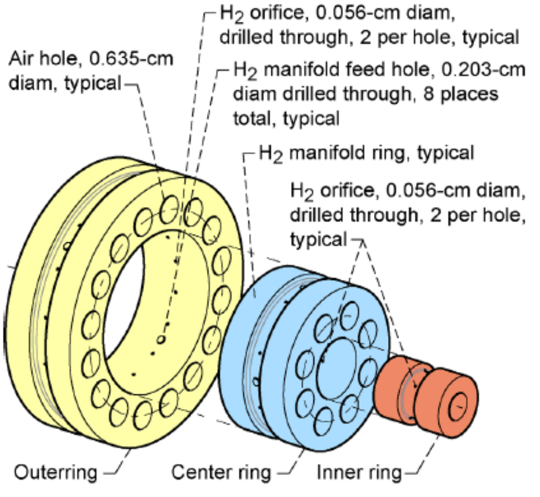

Figure 2. Three-piece injector brazing assembly detail—25 air holes total [21].

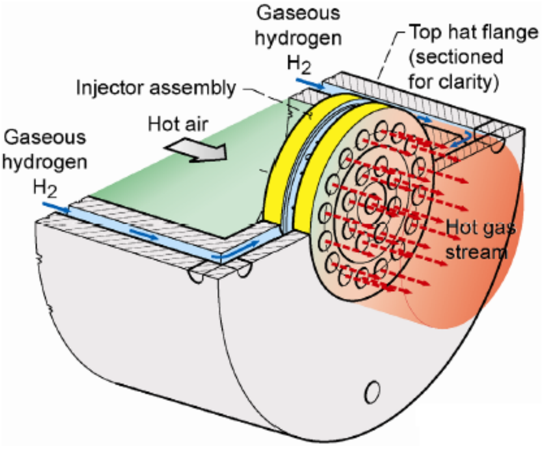

Figure 3. NASA low-emissions LDI hydrogen combustor assembly [21].

3. EXPERIMENTAL AND NUMERICAL RESULTS

Table 1. Comparative data between Jet-A [21] – LDI Jet-A NOx emissions [calculated] of N1 injector when p_3=0.7 MPa

a) Emissions Index at T_3=600K

Equivalence ratio	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55
Ppm NOx Jet-A			9	17	19	30	50	90	

Ppm NOx LDI Jet-A	1.816	2.951	4.301	5.85	9.506	11.596	13.853	16.27	18.844

b) Emissions Index at T_3=700K

Equivalence ratio	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55
Ppm NOx Jet-A		10	17	20	28	40	57	78	
Ppm NOx LDI Jet-A	3.041	4.941	7.201	9.795	12.706	15.917	19.417	23.196	27.243

c) Emissions Index at T_3=800K

Equivalence ratio	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55
Ppm NOx Jet-A	17	18	20	22	25	30	38		
Ppm NOx LDI Jet-A	5.092	8.274	12.057	16.4	21.274	26.652	32.512	38.839	45.617

One observes that when maintaining constant pressure in the combustion chamber equipped with N1 injector, p_3=0.7 MPa and T_3= ranging between 600 and 800 K, results obtained with hydrogen injection are until 3 times lower than using only Jet-A.

When the chamber pressure is rising until p_3=1 Mpa, figure 4 shows the NOx emissions (ppm) depending on the equivalence ratio.

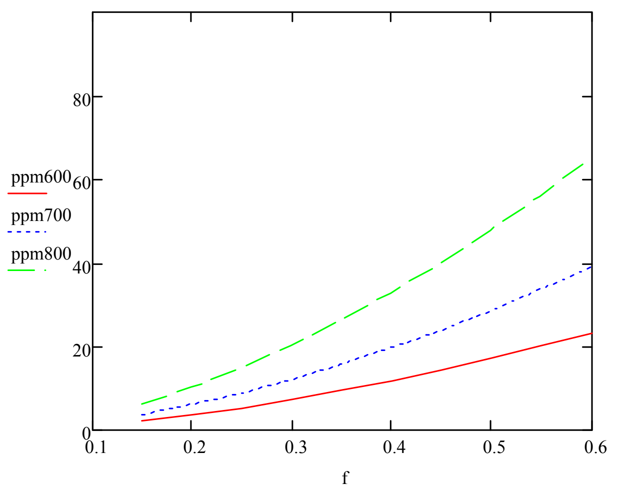

Figure 4. NOx emissions [ppm] depending on the equivalence ratio at p_3=1 MPa=ct, T_3=600, 700, 800 K

Hereafter is presented the evolution of the NOx emissions for the combustors with hydrogen injection over decades, knowing that the first plane equipped with hydrogen combustor was B-57 in 1956.

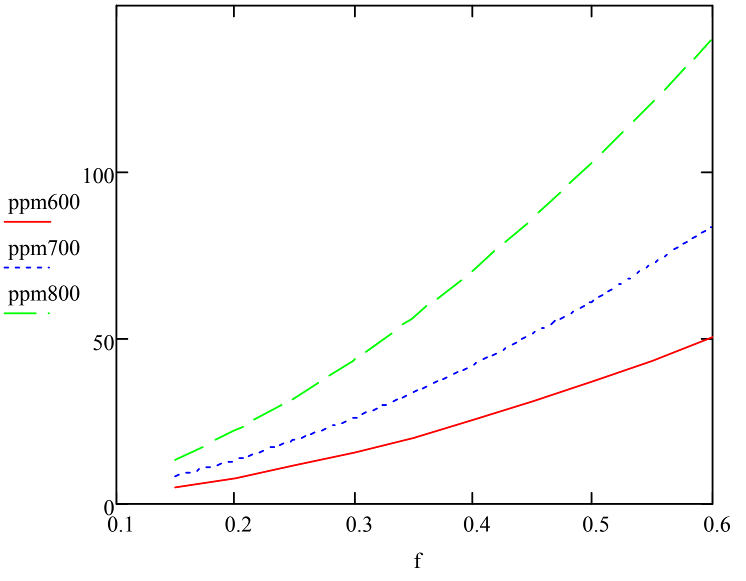

Figure 5. NOx emissions [ppm] depending on the equivalence ratio at p_3=0.7 MPa=ct, T_3=600, 700, 800 K; A'=30 (current aircraft gas turbine combustors)

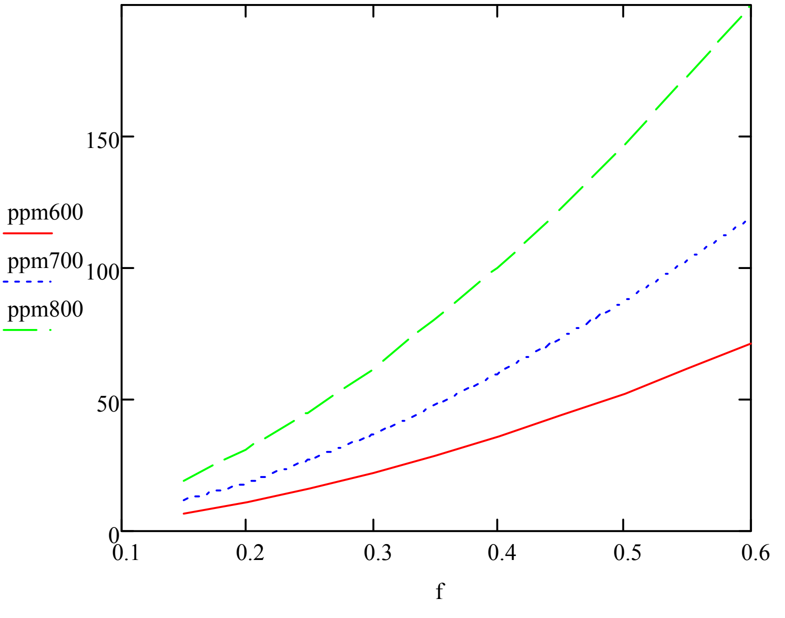

Figure 6. NOx emissions [ppm] depending on the equivalence ratio at p_3=0.7 MPa=ct, T_3=600, 700, 800 K; A'=53 (1980 technology aircraft combustors)

It is a well-known fact that the pressure has an important role in burning perfection and also it has a great influence on the NOx emissions. The next figures show the influence of the pressure p_3 ranging between 0.7 Mpa and 1 Mpa on to the NOx emissions depending on temperature T_3 .

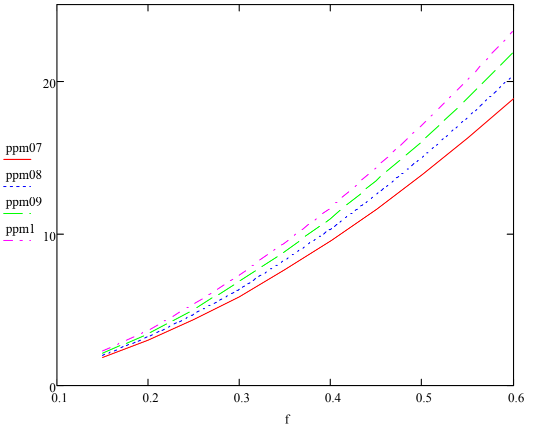

Figure 7. NOx emissions [ppm] depending on the equivalence ratio at
T_3=600 K, p_3= 0.7, 0.8, 0.9, 1 MPa ; A'=14 (advanced LDI technology)

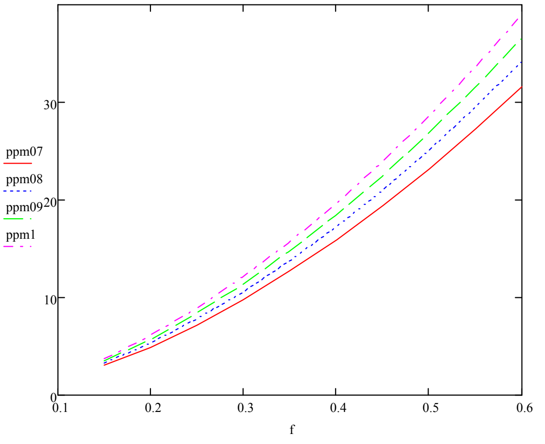

Figure 8. NOx emissions [ppm] depending on the equivalence ratio at
T_3 =700 K, p_3 = 0.7, 0.8, 0.9, 1 MPa A'=14 (advanced LDI technology)

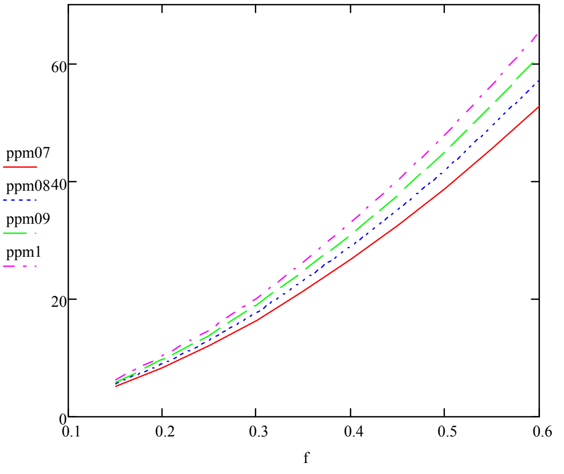

Figure 9. NOx emissions [ppm] depending on the equivalence ratio at
T_3=800 K, p_3= 0.7, 0.8, 0.9, 1 MPa A'=14 (advanced LDI technology)

When constant temperatures (600, 700 and 800 K) is maintained in the combustion chamber at pressures ranging between 0.7 and 1 MPa a small difference of the NOx emissions increase with p_3 pressure can be observed.

3. CONCLUSIONS

Several designs were tested in NASA Glenn Laboratories. All of the LDI configurations performed well and were very stable. All of the lean direct injectors LDI configurations did result in low levels of nitrogen oxides NOx. No flashback or auto ignition phenomena were encountered.

One observes that when maintaining constant pressure in the combustion chamber equipped with N1 injector, p_3=0.7 MPa and T_3= ranging between 600 and 800 K, results obtained with hydrogen injection are until 3 times lower than using only Jet-A.

When constant temperatures is maintained in the combustion chamber at pressures ranging between 0.7 and 1 MPa a small difference of the NOx emissions increase with p_3 pressure can be observed.

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