Most effective combustion technologies for reducing Nox emissions in aero gas turbines

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ABSTRACT
The growth in air transportation volume has important global environmental impacts associated with the potential for climate change. Jet aircraft emissions are deposited directly into the upper atmosphere and some of them have a greater warming effect than gases emitted closer to the surface. One of the key issues that is addressed in virtually every aero gas turbine application is emissions, particularly Nox emissions. There are different technologies for nitrogen oxide emission control in aircraft gas turbines. In this paper, we have briefly reviewed the technologies with the greatest potential to reduce Nox emissions in aero engines.

Keywords: Aviation emissions; Nox emissions; Nox control technologies; aero gas turbines.

1. INTRODUCTION

With more and more commercial aircrafts traveling each day to different parts of the world, the air pollution caused by them is on the rise. Concerns about the impact of aviation emissions on the global atmosphere motivated advances to improve the reduction of gaseous and particulate aircraft engine emissions. However, nitrogen oxide (Nox) emissions have been difficult to control, and Nox is generally emitted at levels higher than for any other pollutant Much of this effort has focused on quantifying Nox emissions [1, 2, 3].

The most significant man-made sources of pollution of the higher troposphere and lower stratosphere are exhaust emissions from civil subsonic aircraft at cruise altitude (8–12 km). Nox emitted at typical commercial aircraft cruise altitudes contributes to ozone formation at high altitude [4]. When transmitted to or emitted directly into the stratosphere, nitrogen oxides act as catalysts in chemical reactions that contribute to the depletion of the ozone layer [5].

At lower altitudes, aircraft emission products may contribute to the occurrence of acid rain and ground level smog. These effects may cause serious environmental problems in the foreseeable future [6]. The problem of increasing Nox emissions goes beyond aviation. For example, the EPA indicates that since 1970, emissions of all principal air pollutants other than Nox decreased between 1970 and 1999, while Nox emissions increased by approximately 10% [7, 8].

Aircraft main engine emissions performance is also improving. All manufacturers are working on advanced emissions combustion technologies alongside work to deliver improved fuel efficiency mainly though driving for higher overall engine pressure ratios.

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Several technologies have been presented in recent decades for reducing Nox emissions in aircraft gas turbines. The most well known are the Water/Steam Injection, Rich burn-Quick Quench-Lean Burn (RQL), Lean Premix Pre-vaporized (LPP), and the Lean-Direct-Injection (LDI) engine. A short description of the different technologies is presented in this study.

2. NOX FORMATION

Nitrogen oxides (also called Nox) are one of the most toxic pollutants in the atmosphere and are well known as a destroyer of the ozone layer and a precursor of the acid rain. It has notable effects on the composition of the atmosphere, in particular with respect to ozone formation in the upper troposphere and lower stratosphere [9, 10]. The high temperatures that provide such a wide range of environmental benefits also tend to increase Nox. The major source of Nox in jet engines is thermal Nox emissions created through high-temperature reactions of nitrogen and oxygen present in the combustion air. As the name implies, flame generated Nox occurs in the flame front, created on the short time scale associated with primary combustion reactions. There are a variety of chemical mechanisms involved all linked to intermediate combustion species that exist only in the reaction zone of the flame. High temperatures within the flame zone cause atmospheric nitrogen molecules to break apart, creating nitrogen radicals. These nitrogen radicals then react with atmospheric oxygen molecules to form Nitrogen monoxide. The reaction is highly temperature-dependant and therefore thermal Nox formation can be reduced through control of peak flame temperature [11, 12].

The generation of Nox gases is closely linked to the engine combustor flame temperature that is, in turn, influenced by the overall pressure ratio of the engine's compressor. So, there is generally a temperature tradeoff between improved cycle efficiency, material constraints and low Nox emission. Engines that have high pressure ratios are desirable since this tends to reduce specific fuel consumption (SFC). Thus, SFC gains are often traded off against increased Nox emissions [13].

The combustion chamber of an aero engine is generally composed of three zones: the first zone or primary zone is the combustion zone, the second zone, or intermediate zone, and the third zone or dilution zone. The majority of the Nox gases is formed in the first zone. This zone receives compressed air and injected fuel which mix and burn instantaneously to produce high temperatures for dissociation of nitrogen, oxygen and hydrogen. Dissociated nitrogen and oxygen later combine to form of Nox [14].

3. MAIN NOX REDUCTION TECHNOLOGIES

Nox reduction can be achieved through combustion modification techniques. The principles of all of these techniques are based on Nox formation chemistry and focus on minimizing peak combustion temperatures and the residence time at peak temperature.

3.1. LEAN PREMIXED PREVAPORIZED (LPP) COMBUSTION

A method of reducing the combustion temperature of various fuels that has gained popularity in the past few decades is to mix fuel and air in fuel lean proportions before the combustible mixture reaches the reaction zone [15, 16]. The Lean Premixed Prevaporization (LPP) concept involves premixing the fuel and combustion air upstream from the combustion zone. Premixing and prevaporizing the fuel produces a lean, homogeneous mixture, which significantly reduces Nox emissions [17–19]. However, in lean premixed combustion, the fuel and air are premixed prior to the flame in order to give a homogenous reaction temperature below the temperatures at which Nox production rates are high. Premixing allows careful control over the local flame temperatures in the combustion zone to avoid any potential Nox-forming hotspots Lean Premixed Prevaporized combustors can cause a drastic reduction in Nox emissions. However, their lean flammability limit is narrow and they tend to cause flashbacks, depending on the fuel concentration and flow velocity, compared with the commonly used diffusive combustion method [20–22].

Combustor designs of this kind are very complex because they require sophisticated harde-ware for proper staging of the combustion process. Also, preventing autoignition of the fuel-air mixture is difficult [23]. At supersonic cruise conditions, autoignition can occur very quickly, typically within one to four milliseconds after the start of premixing. Thus, the premixing process must be accomplished very quickly. This is difficult with liquid fuels because of practical limitations on the number of fuel injection points can be used [24].

Another difficulty with this approach is that the air flow from inactive injectors can quench the boundary of the fiame from operating injectors, raising CO emissions, but this can be addressed with good aerodynamic design. Staging in this manner is used on commercial engines [25, 26]. Both the leaner mixture and premixing techniques are aimed at controlling the gas temperature in the flame zone to reduce the Nox formation by allowing combustion at fuel-air ratios much less than stoichiometric (lean combustion). The swirl-can technique provides some capability for lean combustion and also reduces the residence time because the flame zone is broken down into many small zones instead of one large one [27].

3.2. LEAN DIRECT INJECTION (LDI)

Lean Direct Injection (LDI) combustion was developed as a low Nox alternative to Lean Prevaporized Premixed (LPP) combustion for aircraft gas turbines, where the inherent flashback and dynamic instability concerns of LPP combustion are considered too great of a risk for flight application.

In LDI combustors, liquid fuel is directly injected from a venture into the combustion chamber, where it is mixed with air in the shortest possible distance. The intent is to provide an essentially lean premixed fuel/air mixture that burns in a low Nox flame, similar to LPP combustors, which are discussed in the Premixed Combustion section below [28, 29]. In Low Direct Injection (LDI) technique the combustor operates fuel-lean without a rich front end. All of the combustor air except that used for liner cooling enters through the combustor dome. Like other lean burn combustion concepts, LDI reduces Nox emissions by minimizing flame temperature, since Nox is an exponential function of temperature. The flame structure can be very complex and locally range from non-premixed to premixed burning. To eliminate local hot spots that produce high levels of Nox, lean burn combustion concepts rely on the fuel and air being well-mixed before burning occurs. Thus, LDI requires rapid fuel vaporization and uniform fuel-air mixing. LDI achieves this by using a multi-element concept with small fuel/air mixers [30, 31].

Tacina in NASA Glenn Research Center [32] presents the flametube results for five swirl venturi lean direct injection (SV-LDI) configurations. The SV-LDI configurations differ in the size and number of the fuel/air mixers: 4-point (“large” fuel/air mixers), 9-point (“medium”), and 16-point (“small”). Results shows that the 4-point configuration (with the largest fuel/air mixers) has the highest Nox emissions but that the 9-point and 16-point configurations have approximately the same Nox emissions.

3.3. RICH BURN, QUICK MIX, LEAN BURN (RQL)

The Rich Burn, Quick Mix, Lean Burn (RQL) staged combustor is a low nitrogen oxide (Nox) combustion concept that has the potential to provide better combustion stability than lean premixed combustion systems while achieving low emissions. RQL combustion is a growing technology in aerospace gas turbines and it was introduced in 1980 as strategy to reduce oxides of nitrogen (Nox) emission from gas turbine engines [33].

In the Rich burn Quick mix Lean burn combustor, the jets are used to abruptly change the fuel rich conditions in the first stage of the combustor to fuel lean conditions. The fuel is burnt by the fuel-rich condition in the primary combustion zone. The combustion air is diluted and cooled rapidly with a large amount of air. It is burnt by the fuel-lean condition in the secondary combustion zone. As a result, it becomes low Nox by shortening the combustion time in the area where NOx is rapidly generated [34]. The low oxygen concentration in the fuel rich stage creates an environment that diminishes the potential of fuel bound nitrogen to react with oxygen radicals and form Nox [35]. The goal is to (1) achieve an overall lean stoichiometry, and (2) avoid high temperature stoichiometric conditions that cause high Nox producing conditions [36].

In RQL combustors, the combustor liners must be cooled without film air cooling, which is used in current combustors. Film air cooling is unacceptable because the cooling air would create stoichiometric fuel-air mixtures, which produce high levels of Nox in regions close to liner. Most of the air flow in RQL combustors bypasses the rich first stage and it introduced further downstream to complete the combustion process. The bypass air must be mixed very rapidly with the combustion products from the rich first stage to suppress Nox formation as the rich gases are diluted. Suppressing Nox formation during this rapid mixing process is especially difficult during high power operation because of the high combustor inlet air temperatures [37].

However, the ability of RQL to minimize the formation of nitrogen oxide (Nox) is heavily dependent on the jet mixing in the quick-mix section. Jet mixing in a crossflow can be seen in the primary, secondary, and dilution jets of the combustor where the jets are used to manage the stoichiometry and mixing in the combustor. The jet mixing must be rapid and uniform to avoid prolonged residence times at near-stoichiometric conditions during the transition from the fuel rich to fuel lean conditions. In addition, optimizing the performance of the quick-mix section lowers the residence time of high temperature pockets. Optimizing the jet mixing relies on the orifice configuration [38, 39].

3.4. WATER/STEAM INJECTION

One of the methods used to control Nox emissions in aero gas turbine is Water/Steam injection. Water injection is an old aviation technology that was previously used to enable an increase in engine power during takeoff [40]. In recent years much effort has been performed to estimate the effects of water injection on commercial turbofan engine to reduce specific fuel consumption (SFC), Nox emissions, and the engine hot-section temperatures while maintaining constant thrust [41–43].

Boeing and Glenn investigated three types of engine water-injection techniques: (1) misting water before the low-pressure compressor (LPC), (2) misting water before the high-pressure compressor (HPC), and (3) directly injecting atomized water into the combustor [44].

In first way, water does not readily evaporate into the airstream. Therefore, the water droplet size needs to be sufficiently small in order to avoid being centrifuged to the outside of the engine case. Larger droplets can cause engine case distortions that must be avoided.

Another challenge of water misting is its increased propensity to cause the compressor to stall or reduce the stall margin [45]. An engine performance model of the water misting system predicted that the increased water mass flow through the compressor would result in an unacceptable 9 percent reduction in stall margin for the low-pressure compressor and

3 percent for the high-pressure compressor. While this concept affords the best overall engine performance, because of the cooling action of the evaporating water [46].

The water injection study assessed the potential turbine blade life benefits and maintenance cost reductions due to lowered operating temperatures in the engine hot section. Low cycle fatigue, creep and oxidation were identified as the principal failure mechanism in turbine blades [47].

Using water injection technology for airport Nox reduction will be weighed against the cost of ever increasing emissions-based landing fees. Additionally, a side benefit of water injection is to reduce engine turbine inlet temperatures [45]. Even though water injection is quiet successful in reducing Nox emissions during takeoff, low emission combustors are still needed for the cruise and climb portions of the flight.

4. CONCLUSIONS

Reducing Nox was the focus of the research due to ozone destruction in the stratosphere and the emission of Nox from aero engines has been progressively regulated because of increasing concerns about the environment. Nox emissions released in the stratosphere directly attack and destroy the ozone layer that protects the earth from ultraviolet radiation in the stratosphere. In this work, we have presented a brief review of most effective technology for Nox emissions reducing in aero engines.

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