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NO_x Emission Reduction in Commercial Jets Through Water Injection

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NO_X EMISSION REDUCTION IN COMMERCIAL JETS THROUGH WATER INJECTION

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Abstract

This paper discusses a method of the nitrogen oxides (NO_x) emission reduction through the injection of water in commercial turbofan engines during the takeoff and climbout cycles. In addition to emission reduction, this method can significantly reduce turbine temperature during the most demanding operational modes (takeoff and climbout) and increase engine reliability and life.

Introduction

The National Aeronautics and Space Administration (NASA) has set aggressive goals for reducing emissions of future aircraft by a factor of three within 10 years and by a factor of five within 20 years. Thus, the Ultra-Efficient Engine Technology (UEET) Program addresses local air quality concerns by developing technologies to reduce both takeoff and landing NO_x emissions by 70% from the 1996 International Civil Aviation Organization (ICAO) standards. Advanced concepts research for reducing carbon dioxide and NO_x, as well as analytical/ experimental research in control (through component design, control, and/or fuel additives) of aircraft exhaust emissions is sought.

In support of this effort, the authors have investigated using water injection-at-takeoff (WIT) as a method of reducing NO_x emissions from commercial turbofan engines. This method employs combustor temperature reduction through water injection in the inlet of the low-pressure compressor (LPC) or high-pressure compressor (HPC) and mixture ratio control to the level where a substantially lower amount of NO_x is generated and emitted. Water injection substantially reduces the required compressor work and significantly improves reliability. Potential applications for the WIT method include virtually any commercial jet currently in service or projected in the future. The WIT method can also be applied to ground applications. A similar method has proven to be the lowest cost technology for reducing NO_x emissions by 30% and increasing power output by 15% to 30% in the gas turbine power generation industry. MSE Technology Applications, Inc. (MSE) and the State of Montana are currently considering the use of this technology in power generation and natural gas distribution facilities in Montana.

This innovative idea will provide commercial aviation with a low cost, low risk technology to reduce NO_x production and extend the cycle/service life of commercial aircraft engines.

WIT Concept

Water injection is a relatively simple and straightforward technique for improving engine performance. It has been extensively studied and applied as a means to increase thrust, maximum altitude, and/or flight speed of turbine engines.[1–3]

The WIT concept has the potential to reduce NO_x production by 50% to 70% and also extend the service life in current technology turbofan engines. In the WIT concept, the combustor temperature is reduced by water injection at the inlet of the LPC or HPC and by control of the fuel mixture ratio, which substantially reduces NO_x production. Water injection significantly reduces air temperature of the compressor inlet air and combustion products, resulting in one or a combination of the following advantages:

– increased compressor pressure ratio;
– increased air flow through the engine;
– decreased turbine expansion ratio;
– decreased turbine gas temperature; and
– decreased turbine cooling bleed flow.

In addition, water injection supplements engine thrust at the reduced turbine temperatures through increased mass flow.

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The NASA Engine Performance Program (NEPP) was used for preliminary analyses of the high bypass turbofan engine, which is referred to hereafter as the "current technology baseline engine."[4] Engine performance and the NO_x emission index are similar to the General Electric GE90 and Pratt & Whitney PW4084 engines, both of which are employed on the Boeing 777 commercial jet.

Five different cases of water injection were examined. Water was injected in three different areas of the turbofan engine, including the LPC, HPC, and combustor. The water injection model used in this study assumed that the water was totally evaporated before entering these components. These cases used the same bleed air flow as the baseline engine. Two additional cases with water injection in front of the LPC and HPC were examined at reduced bleed air flow. Reduced air bleed was assumed to be possible due to significant turbine temperature reduction. Each case consisted of optimizing the fuel mixture ratio to maintain the desired combustion temperature drop (up to 300 K) and injecting water to maintain 85,000 pounds of thrust at takeoff.

Figure 1 is a schematic of the turbofan engine and the examined water injection points.

Results are summarized in Figures 2 through 4 and in Table 1. Figure 2 shows water fraction as a percentage of the core air flow versus NO_x emission reduction for all five examined cases. It can be seen that injection in the LPC with reduced bleed provides the most economical means of NO_x reduction in terms of the required amount of water. The worst case corresponds to water injection in the combustor, as it requires 5 to 6 times more water for the same NO_x reduction effect compared to the LPC with a reduced bleed case. Other cases are closer to the best case, meaning that some flexibility exists in injection point selection.

Table 1. Engine performance corresponding to 50% NO_x reduction.

Fuel saving, % of total fuel	0.046
Water fraction, % of total fuel	0.42
Water fraction, % of GTOW	0.19
High-pressure turbine inlet temperature drop, K	233
Low-pressure turbine inlet temperature drop, K	127
LPC exit temperature drop, K	27
HPC exit temperature drop, K	43
High-pressure rpm ratio	0.966
Low-pressure rpm ratio	0.998

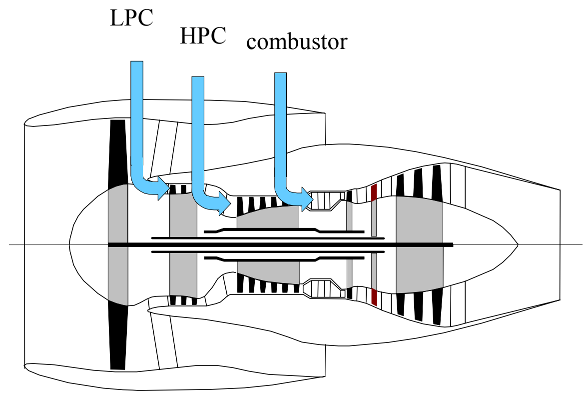

Figure 1. Turbofan engine and examined water injection points.

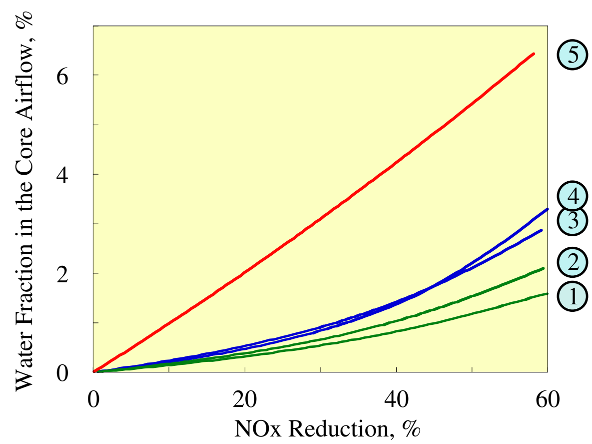

Figure 2. Water fraction in the core air flow versus NO_x reduction when water is injected at the inlet of: 1) LPC, reduced cooling air bleed; 2) HPC, reduced cooling air bleed; 3) LPC, normal cooling air bleed; 4) HPC, normal cooling air bleed; and 5) combustor.

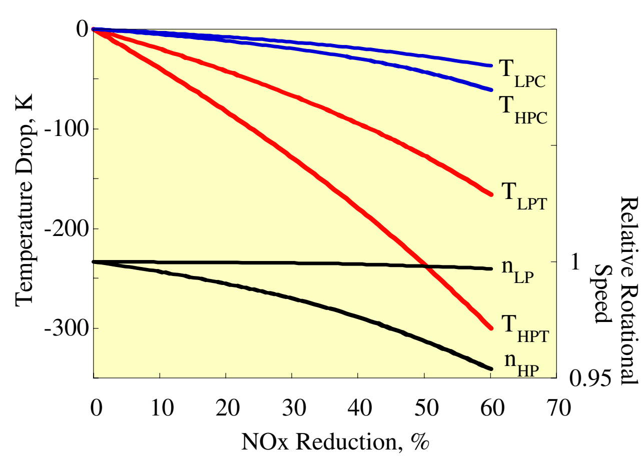

Figure 3. Change of temperatures and rotor speed versus NO_x reduction when water is injected at the inlet of the LPC with reduced cooling air bleed.

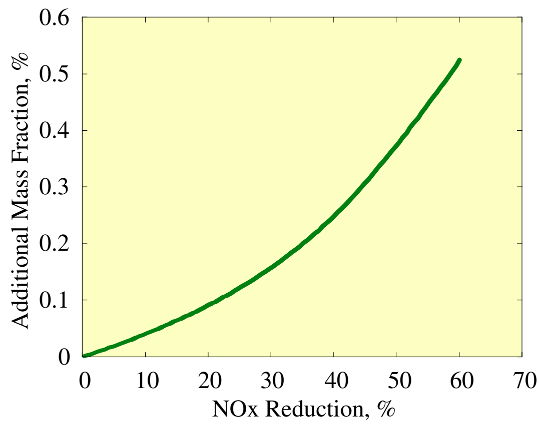

Figure 4. LPC additional water mass as a fraction of total fuel mass versus NO_x reduction.

It should be noted from Case 1 of Figure 2 that the amount of water injected (1% to 1.6% of the core air flow) is comparable with natural air humidity levels.

Figure 3 displays the drop of key temperatures and rotor speeds versus NO_x reduction at constant engine thrust. The most important high-pressure turbine temperature, T_{HPT}, can be reduced by as much as 300 K. The maximum obtained temperature drop behind HPC T_{HPC} is as much as 60 K. Low-pressure turbine speed is only slightly lower; however, high-pressure turbine speed is nearly 5% lower than that of the baseline engine.

In terms of specific impulse (I_{sp}) [inverse thrust specific fuel consumption (TSFC)] to reduce NO_x by 1%, 1.5% of the I_{sp} should be sacrificed in the case of water injection in the combustor and only 0.6% in the case of water injection in front of the LPC at reduced bleed. Specific impulse includes jet fuel and water.

The sacrifice of I_{sp} for NO_x reduction is a disadvantage; however, the reduction in NO_x emissions is a critical issue only during the two shortest modes of the four modes of the landing and takeoff cycle (LTO) and not at all during the remainder of a typical flight profile. Then, the time in the takeoff mode would be used to estimate the total NO_x emissions. The Federal Aviation Administration (FAA) breaks down an LTO cycle into four modes:

1) Takeoff – full-throttle operation until the aircraft reaches 500 to 1,000 feet altitude (power setting 100%, time 0.7 min);
2) Climbout – time following takeoff that ends when the aircraft leaves the mixing zone (power setting 85%, time 2.2 min);
3) Approach – time the aircraft enters the mixing zone when it lands (power setting 30%, time 4 min); and
4) Idle – time the aircraft is taxiing before takeoff and after landing (power setting 7%, time 26 min).

The above numbers, which correspond to turbofan engines of the GE90 or PW4084 type, are taken from the FAA Engine Emission Database (FAEED), Version 2.1, 1995.

Water injection would only be needed until the aircraft reaches the mixing zone height, which encompasses two of the four modes, takeoff and climbout. The mixing zone height is the height at which the aircraft emissions can have an effect on the ground-level pollutants at the airport being considered. The maximum height is variable and is dependent on the environmental conditions, location, and time of year.

In this study, the FAEED was used to evaluate the LTO of a Boeing 777-200 aircraft equipped with two PW4084 turbofan engines. The default mixing height in this program is 3,000 feet. A gross takeoff weight (GTOW) of 545,000 pounds and a fuel capacity of 31,600 gallons were assumed. The resulting FAEED Boeing 777-200 analysis estimated the time in the takeoff and climbout modes to be 0.7 and 2.2 minutes, respectively. The above data (GTOW and fuel capacity) were combined with the results from the NEPP WIT system analysis (LPC water injection with reduced bleed flow), which resulted in the summary of the engine performance and system characteristics.

Several Important Observations

Data for the WIT method with 50% NO_x reduction are given in Table 1. The following observations can be drawn from Table 1:

1. The total amount of water required to reduce NO_x emissions using the WIT method is insignificant (0.42% of total fuel storage on a mass basis). Additionally, little fuel saving (in the amount of one-tenth of required water) can be obtained.
2. Several important temperatures defining engine durability are significantly reduced compared to the baseline engine. This observation shows the opportunity to significantly reduce NO_x emissions along with engine durability extension through strength increase and stress reduction due to the lower temperatures in all the engine components and the lower high-pressure shaft speed.
3. The turbine temperature in the "current technology baseline engine" (similar to the GE90 or PW4084) drops from 1,715 K during takeoff operation to

1,482 K during the cruise segment of the flight. If the WIT technology were applied, the turbine temperature could be kept constant or nearly constant (on the order of 1,482 K) during both the take off and cruise modes.

4. The reduced temperature and reduced shaft speed (See Figure 3 and Table 1) will also translate into a smaller thermal and mechanical expansion of the rotor blades during the takeoff cycle; therefore, the possibility exists to reduce the turbine tip clearance and increase the turbine efficiency during the cruise mode.

Figure 4 shows water mass fraction (additional water mass as a fraction of total fuel mass) versus NO_x reduction with the assumption that all the water is evaporated before entering the LPC. From this figure, it can be clearly seen that increased water injection further reduces NO_x emissions. However, large amounts of liquid water entering the compressor are not desirable since this may cool and shrink the compressor case and promote rotor blade tip rub and blade erosion. Hardware demonstration of the WIT technology is required to identify the injection limits.

The WIT method can also provide the aircraft with the ability to take advantage of mass-augmented thrust through water injection as described in References 1–3. This could give the aircraft the ability to achieve a cruise altitude in less time or to increase the GTOW; however, the NO_x reduction would be sacrificed in these situations. **The possibility to taking off 200 K to 300 K of high-pressure turbine inlet temperature and 40 K to 60 K of HPC exit temperature during the most demanding mode (i.e., takeoff) can change commercial jet design philosophy and increase engine durability.**

Supersonic transport aircraft could also benefit from the WIT method. This type of aircraft could use the WIT method to not only reduce NO_x emissions during the takeoff and climbout modes but also to increase acceleration through the transonic region with mass-augmented thrust. Supersonic transport designers would also have the ability to size the aircraft propulsion system more for the cruise mode than for the transonic mode of operation, which would make the aircraft more economical to operate.

It was also found in this study that the jet velocity is reduced when injecting water and could help noise levels in the surrounding area of the airport. Further investigation of the possible noise reduction with the WIT method is required.

Technology Issues

The WIT method of NO_x reduction would add a small amount of complexity to the existing system, since storage space would be required for the water. Airports would need to have a supply of demineralized water to replenish aircraft water supplies; therefore, a cost analysis is required to define the economical merits of the WIT technology.

Technology Benefits

A summary of the unique benefits of the WIT method include:

– NO_x emissions reduced by 50% to 70%. To reduce LTO NO_x emissions of the “current technology baseline engine” by 50%, a small amount of water (0.4% of the total fuel for the aircraft of the Boeing 777 type) is required;
– the WIT method could be combined with other methods of NO_x reduction;
– a minimum amount of water is required for the same emission reduction effect when water is injected in front of the LPC rather than the HPC or combustor;
– a flexible thrust profile including thrust increase during the takeoff and climbout modes;
– increased fuel efficiency;
– increased engine reliability due to maximum turbine temperature reduction (by 200 K to 300 K) during demanding takeoff operations (maximum compressor temperature can be reduced by 40 K to 60 K); and
– the WIT is a promising technology for economical transonic operation for supersonic jets.

References

1) Henneberry, H. and C. Snyder, *Analyses of Gas Turbine Engines Using Water and Oxygen Injection to Achieve High Mach Numbers and High Thrust*, NASA/TM—1993-106270, NASA Glenn Research Center, 1993.
2) Walker, J.; S. Thomas; and R. Sorge, *Demonstration of J85-21 Turbojet Operation at Mach 3 Using Pre-Compressor Water Injection*, NASA/TM—1999-209397, NASA Glenn Research Center, 1999.
3) Balepin, V. and G. Liston, *The SteamJetTM: Mach 6+ Turbine Engine with Inlet Air Conditioning*, AIAA–2001–3238, 2001.
4) Klann, J.L. and C.A. Snyder, *NEPP Programmers Manual (NASA Engine Performance Program) Volume: Technical Description*, NASA Technical Memorandum 106575, NASA Glenn Research Center, September 1994.

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