NASA/TM—2010-213179

Water Injection on Commercial Aircraft to Reduce Airport Nitrogen Oxides

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March 2010

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Prepared for the
40th Joint Propulsion Conference and Exhibit
cosponsored by the AIAA, ASME, SAE, and ASEE
Fort Lauderdale, Florida, July 11–14, 2004

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March 2010

This work was sponsored by the Fundamental Aeronautics Program
at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by technical management.

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Summary

The Boeing Company and Rolls-Royce Corporation have been working with the NASA Glenn Research Center to study the effects of injecting finely atomized water into aircraft turbine engines during takeoff. This method of water injection will dramatically reduce nitrogen oxide (NO_x) emissions at the airport and will also reduce engine stress, most likely resulting in cost savings to aircraft operators.

Because of efforts to improve fuel efficiency, most new aircraft turbine engines have increased compressor pressure ratios. New combustors have been developed to help offset the exponentially higher NO_x that goes with these increased pressure ratios. However, achieving real NO_x emissions reductions at the airport has been a daunting task. Water injection is an old technology that is currently being investigated, with a new twist, as a possible NO_x emissions solution.

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. For each of these system designs, airframe hardware was configured for a commercial aircraft; then, the airplane performance was calculated. Additional thrust became available during water injection, but this was not used so that there would be no safety problems should the system fail.

In collaboration with the U.S. Air Force Research Laboratory at Wright-Patterson Air Force Base, NASA Glenn supplied Boeing with water-misting emissions test data. Glenn also calculated and supplied the effects on engine performance for all three water-injection types.

Rolls-Royce Corporation designed a similar LPC water-methanol misting system for use in emergency situations to boost engine power. This allowed the engines to be downsized and resulted in impressive engine performance and maintenance cost savings. The injected water droplets needed to be small enough (e.g., 5 to 10 μm) to completely evaporate and avoid being centrifuged onto, and cooling, the engine case.

These studies suggest that, if water atomization and evaporation into the LPC can be accurately controlled, this system would offer engine performance benefits over the other two designs. At a water-misting rate of about 2.2 percent, NO_x emissions could be reduced about 47 percent. On days above 59 °F, a fuel efficiency benefit of about 3.5 percent would be experienced. Reductions of more than 400 °F in turbine inlet temperature were also calculated; these would lead to increased hot section life. A slight noise reduction is anticipated with this system. A nominal airplane weight penalty of less than 400 lb (no water) was estimated for a midsized passenger airplane. Without including engine maintenance savings, the airplane system cost is estimated to be an additional $41 per takeoff, giving an attractive NO_x emissions reduction cost-to-benefit ratio. However, when maintenance costs are included, operating savings should result because water injection extends turbine life.

Achieving these levels of NO_x reduction would be a leap forward in making air travel an environmentally preferred means of transportation. If engine maintenance savings are realized and commercialization challenges are overcome, the technology should become attractive enough for airline operators to order it as an NO_x-reduction and cost-saving option.

1.0 Introduction

Emissions are an increasingly important consideration in the design of commercial aircraft as well as transport military aircraft. As environmental concerns have grown, airports have been implementing strategies, such as emissions-based landing fees, to encourage the development and operation of low-emissions aircraft. As other industrial sectors make further emissions progress and air traffic grows, airports will face increased environmental pressure. We must continue to explore options that will satisfy global environmental needs as well as the needs of airlines operating in a fiercely competitive market.

Aircraft have made great progress in reducing hydrocarbon and carbon monoxide emissions. However, nitrogen oxide (NO_x) emissions have been difficult to control, and NO_x is generally emitted at levels higher than for any other pollutant. As a result, NO_x has been the focus of continued regulatory action and of calls for industry cooperation to reduce its output.

The industrial power-generation sector was able to develop power and emissions-control technologies without the concerns of weight and size, and to some degree, without the safety and reliability constraints that the aviation sector had to address. Consequently, although the aviation sector abandoned water injection as a power-enhancement technology in the 1970s, the power-generation sector continued to use and develop this technology for power enhancement and, more recently, for NO_x-emissions control. Sufficient development has occurred that this technology should be considered for aircraft once again, but this time for emissions control (as well as other side benefits) (Ref. 1).

Applying industrial gas turbine water-injection schemes to reducing the NO_x emissions of future aircraft could effectively reduce airport pollution and aircraft operating costs as well as improve performance.

2.0 NO_x Generation

The generation of NO_x 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. However, 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 NO_x emissions.

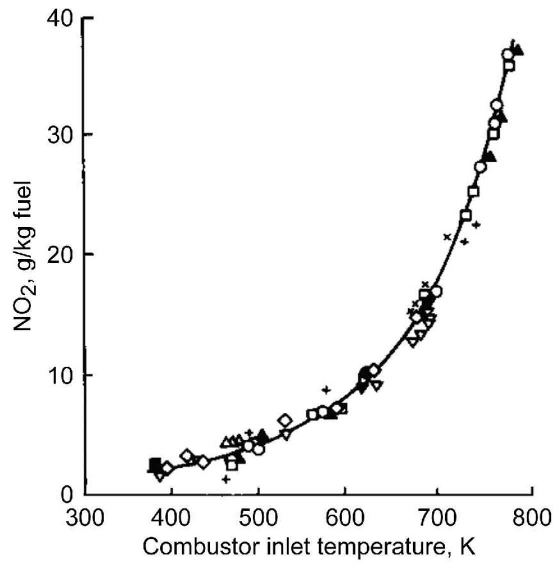

Figure 1.—NO_X increases rapidly as combustor inlet temperature (T3) increases (Ref. 2).

During compression of air from the inlet of the engine to the inlet of the combustor, a temperature rise occurs as work is imparted to the fluid (air). After compression of the air by the compressor and introduction into the combustor, high temperatures oxidize the nitrogen in the air into oxides of nitrogen, collectively called NO_x. This process occurs at temperatures above 2780 °F (1800 K) and progresses rapidly as the temperature increases. Combustor flame temperature generally increases with increased combustor inlet temperatures. Figure 1 shows the relationship of combustor inlet temperature (and hence flame temperature) to NO_x formation. Injecting a small amount of water into the compressor or combustor of an engine with a high overall pressure ratio will decrease the flame temperature slightly and decrease NO_x greatly.

3.0 Water-Injection System Descriptions

Water injection has been used for over 60 years in aviation to augment thrust. For commercial aircraft applications, it was used 45 years ago on Boeing's first jet aircraft (the 707) and later on the largest commercial aircraft (747–100 and 747–200 series.) As gas turbine engines matured and were able to generate more thrust, water injection was abandoned for new engines. Until now, water injection has not been seriously considered for reducing aircraft NO_x emissions.

3.1 Early Water-Injection Systems

Four water-injected Pratt & Whitney JT3C–6 engines were used on early Boeing 707–120 Stratoliner aircraft to augment takeoff thrust on days above 20 °F. This system used a belly tank to store demineralized water and an electrically driven boost pump to deliver water to the four engines. At that point, an engine-driven mechanical pump increased the pressure to about 400 psi for injection before the low-pressure compressor (LPC) on days as cold as or colder than 40 °F and for injection into the high-pressure compressor (HPC) only on days between 40 and 20 °F.

The last water-injection system to be used on Boeing aircraft was for early 747s using Pratt & Whitney JT9D–3AW and JT9D–7AW engines. In its first application, water was injected into the compressor discharge airstream via spray bars located just upstream of the combustor and downstream of the HPC. The design of this system suggested that the water distribution was not as well controlled as in current industrial engines. The poor water distribution led to several engine maintenance problems. Many people still remember these problems, making them hesitant to revisit this technology.

3.2 Common Industrial Combustor Injection Systems

On later industrial engines, an improved water-injection technique sprayed water directly into the combustor dome via a dual fuel-water nozzle as shown in Figure 2.

Because the fuel and water were atomized together inside the combustor, a better distribution of water could be maintained. This also reduced the amount of water required because it was now directed only to where the water was needed—inside the combustor. This is still an attractive system to consider for aircraft because less water is needed and larger NO_x reductions are possible than for compressor misting systems. It is also a well-proven design with few, if any, unknowns for use in aircraft.

3.3 Compressor Water-Misting System

When water is sprayed into the compressor inlet, the evaporation of the water droplets lowers the temperature of the air and consequently, the air density, compressor delivery, and thrust are all increased (Ref. 3). The combustor inlet air temperature thereby drops, reducing NO_x formation. In addition, because boosting the mass flow through the engine increases the thrust, the throttles can be retarded slightly to keep the same level of thrust as before water misting. This further lowers NO_x formation. For all water-injection systems, adding water to the engine does reduce the combustor flame temperature, which would normally decrease fuel efficiency, but with compressor water-misting systems, these thermal losses are overcome by engine efficiency improvements.

Figure 3 shows a conceptual aircraft engine water-misting system that is very similar to the JT3C–6 engine system used on early Boeing 707 aircraft. This concept injects water into the LPC through 24 HPC air-assisted atomization nozzles. In addition, water can be delivered before the HPC during cold atmospheric conditions.

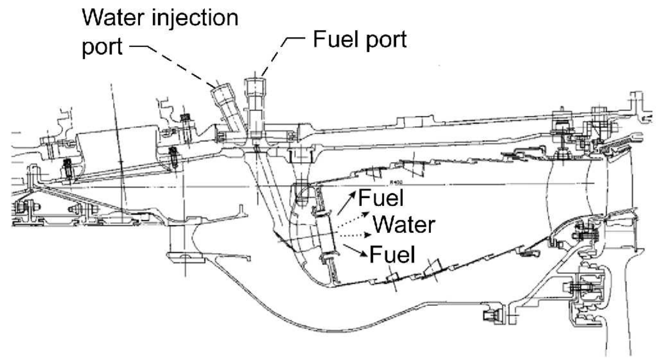

Figure 2.—Conceptual industrial water-injection system directly feeding water into the combustor.

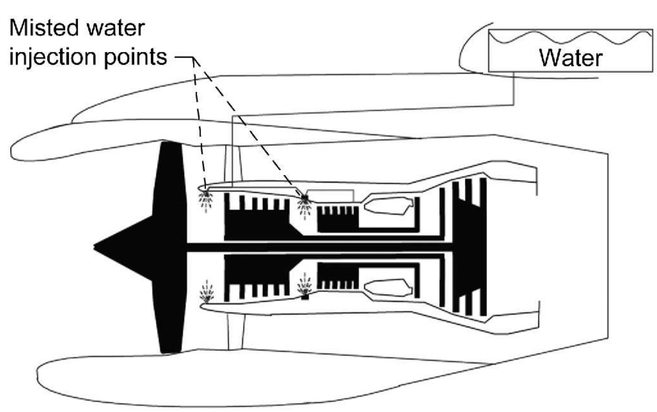

Figure 3.—Water-misting intercooler concept sprays water into low-pressure and/or high-pressure compressor, with high-pressure-compressor air to assist in water atomization.

4.0 Study Method

Historical combustor and engine test data were gathered and compared with more recent tests (Ref. 4) of advanced combustors. These data were used to first establish a correlation between the water-injection rate and NO_x reduction rate. Ratios of water to air and water to fuel were calculated and used to predict the amount of water required for a 50-percent NO_x reduction rate. Combustor injection systems can achieve about a 90-percent NO_x reduction rate, but compressor injection systems are thought to be limited because of compressor surge issues when the water-misting rate climbs above a 3-percent water-to-air ratio.

Engine performance software "decks" from the Boeing Company (EDASA), an aeroderivative industrial engine company, and Glenn (NASA Engine Performance Program, NEPP) were used to estimate the performance impact of injecting water into a current-technology, 85 000-lb-thrust class engine. In an attempt to achieve a 50-percent NO_x reduction goal, the NASA deck was run with water-injection rates higher than was possible for either the Boeing or the industrial engine deck. The NASA performance model assumed complete vaporization of the water at the injection point. These NO_x reduction ratios were compared with historical data and found to agree fairly closely.

For the now-established water-injection rate, the airframe system and water tanks were designed to inject enough water for a 777-sized aircraft (305 passengers) to take off and reach a 3000-ft altitude (about 2.9 min) before exhausting the water supply. The increased available thrust was not used in takeoff so that there would be no safety concerns should the system fail. Weights, costs, and airplane performance data were then generated.

Water costs were estimated from historical data as well as input from water-conditioning companies. Airport infrastructure issues were addressed using Boeing internal resources.

Airline input was gathered from questionnaires sent to major air carriers to assess the desirability of potential water-injection systems.

For the LPC injection case, Rolls-Royce Corporation developed a three-dimensional aerothermal analysis code to accurately simulate water/methanol injection into the LPC (Ref. 5). This model also predicted the evaporation of the liquid droplets and its impact on engine performance. Engine tests on a Rolls-Royce (Allison) T56 engine were run to confirm the performance models and assess any operability issues.

5.0 Results

Data showed that the combustor injection system was nearly twice as effective as LPC injection in reducing NO_x and so required about half the water. Thus, two airframe systems were designed—one for the combustor injection system and one for the compressor injection system. In both designs, there was a centrally located panel for water fill and control that was ground accessible.

5.1 Airframe System for Combustor Injection

The calculated water consumption rate suggests that, to achieve roughly a 50-percent NO_x reduction, for a water-to-fuel ratio of 0.5:1, using standard times in mode for takeoff/climbout and fuel consumption rates for a large engine, the water tank capacity should be 135 gal. Figure 4 shows the airframe layout.

The advantage of this system is that it uses one high-pressure pump and requires less than half the water of the compressor misting system. It is also a well-proven design on aeroderivative industrial gas turbine engines. The disadvantage is that it requires a single, dedicated central water tank, which adds weight over the wing tanks.

5.2 Airframe System for Low-Pressure Compressor Injection

For the LPC injection system, more water would be required to achieve the same NO_x reduction as for the combustor injection system. Historical data for a 2.2-percent water-to-core-airflow ratio and the standard operating times in mode were used to estimate a water tank capacity of 300 gal for a 50-percent NO_x reduction level. Figure 5 shows the layout of such a system.

This system would use two water tanks, each one located in the forward part of each wing as shown in Figure 6. Each tank would use a single high-pressure (534- to 750-psig) pump capable of a 26 000-lb/hr flow rate.

For safety reasons, there are areas in the wing near the engines that do not contain fuel. In the event of a catastrophic engine failure (e.g., rotor burst), the areas around the engine where debris might penetrate the structure or wing are kept free of fuel. These areas are called dry bays and are ideally suited to serve as water tanks as shown in Figure 6.

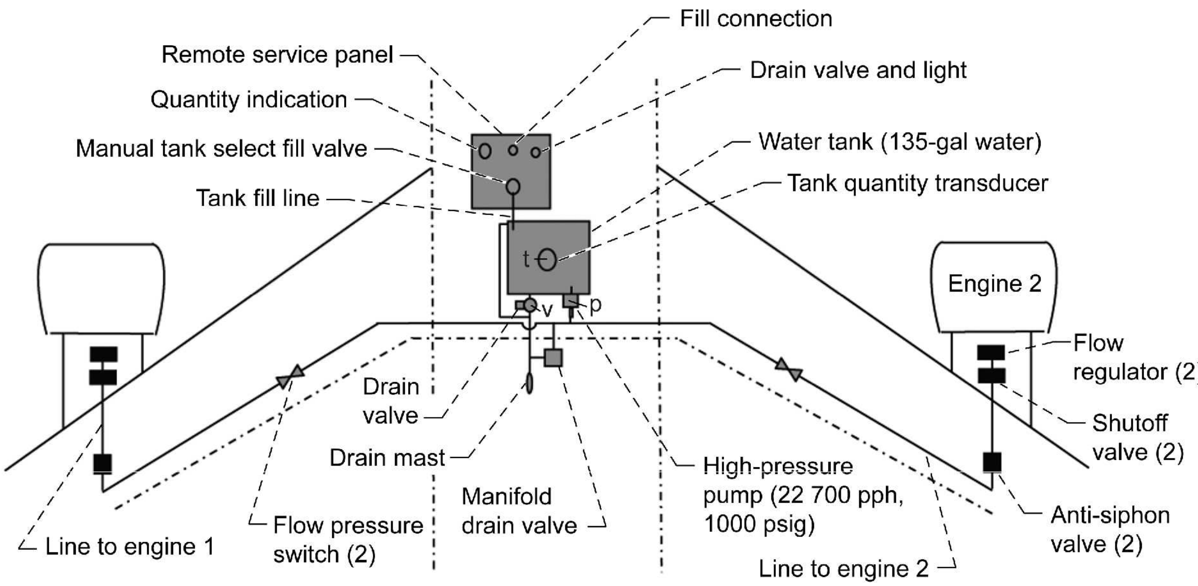

Figure 4.—Airframe water system for a direct combustion injection system; pph, pounds per hour.

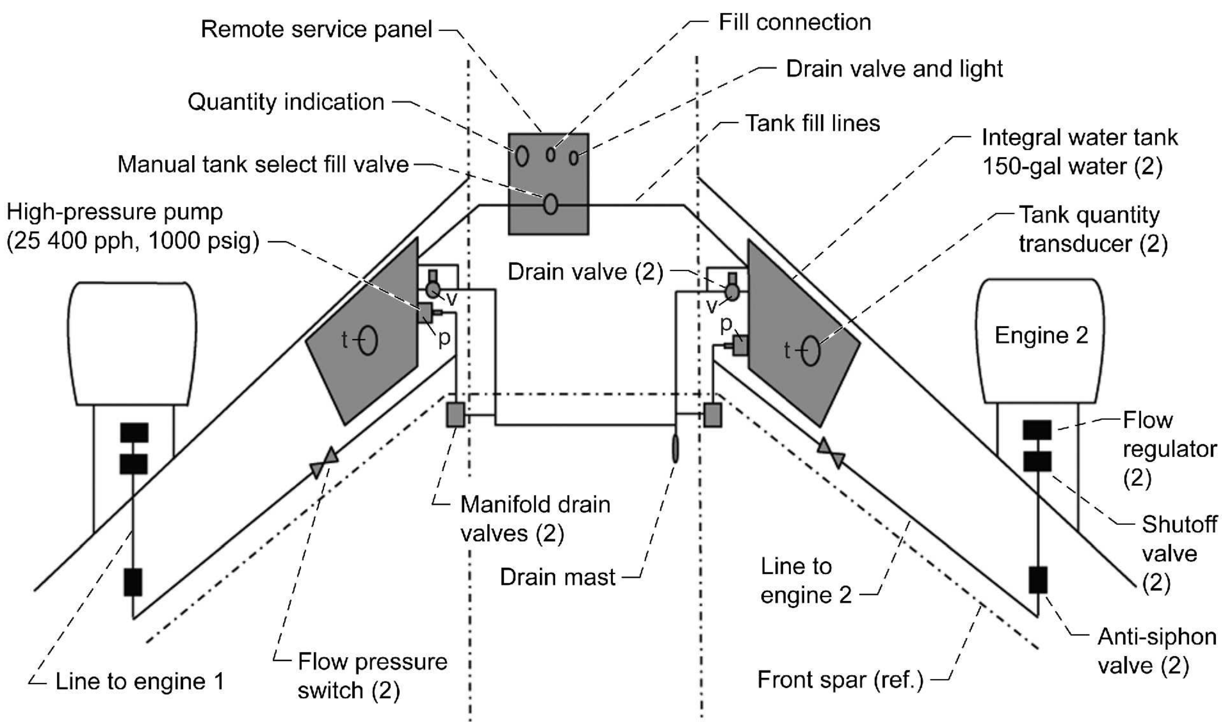

Figure 5.—Airframe water system for a low-pressure compressor injection system; pph, pounds per hour.

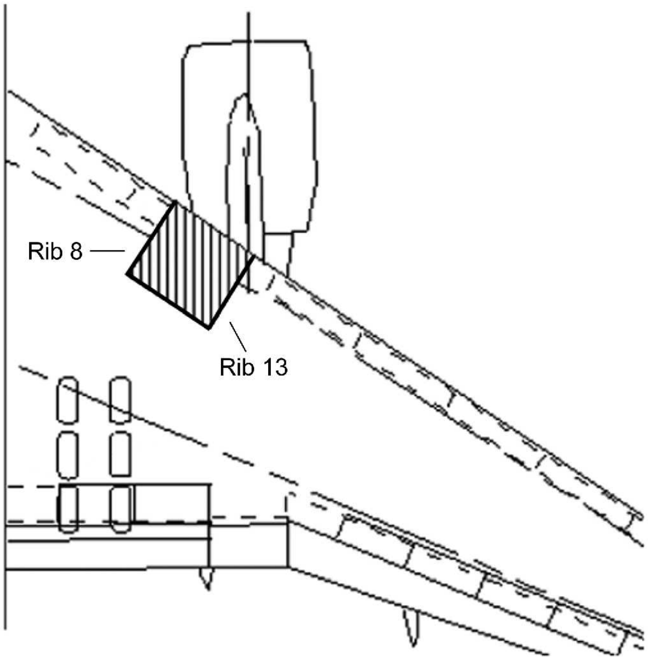

Figure 6.—A 150-gal tank is located in the dry bay of each wing.

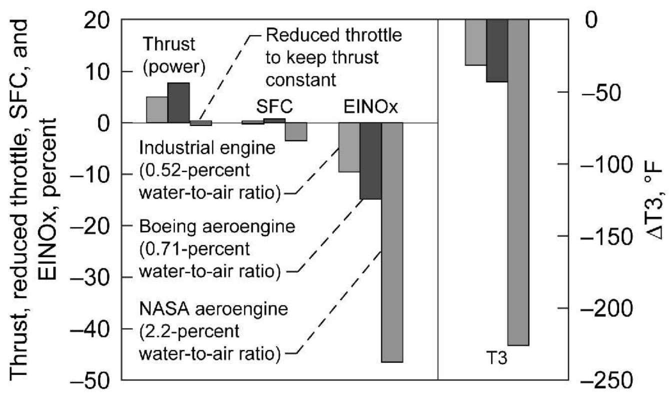

Figure 7.—Increasing water-to-air ratio to 2.2 percent further reduces NO_X, turbine inlet temperature (T4 or T41), and specific fuel consumption (SFC): EINOx, Emissions Index NO_X.

For the best operating economics, the water tanks are designed to be filled each time the airplane lands and not to carry water to the destination. The water lines and water dump mast are heated so that water can be jettisoned if it is not used during takeoff and so that the lines can be drained of any remaining water.

These preliminary airframe system designs, along with NASA-supplied engine performance models were used in Boeing aerodynamic performance models to calculate the effects on airplane performance.

5.3 Engine Performance With Low-Pressure Compressor Injection

Current industrial engines use LPC water misting with a 0.52-percent water-to-core-airflow ratio on a 59 °F day to boost power output. This results in a small NO_x emissions index (i.e., grams NO_x per kilograms fuel) improvement. The water flow rate was increased to 2.2 percent to increase the NO_x reduction level. This injection rate should be achievable, and levels as high as 3 percent may even be reached (Ref. 6). The NO_x reduction level for the 2.2-percent injection rate was modeled to be 47 percent, which was close to the 50-percent goal.

Figure 7 compares the data points for an industrial aeroderivative turbine engine at a 0.52-percent water-injection rate, a Boeing-modeled 85 000-lb thrust aeroengine with a 0.71-percent water-injection rate (the highest injection rate that Boeing was able to model), and a similar generic 85 000-lb-thrust aeroengine modeled by Glenn at a 2.2-percent water-injection rate.

For the industrial engine, a slight power increase was experienced with little SFC impact while the NO_x emissions index decreased because of a decrease in the combustor inlet temperature (T3).

For the aeroengine case, the same trends were observed, but to a higher degree because of the increased water-injection rate. The aeroengine data were not expected to match the industrial engine case exactly because of differences in engine type, water-injection assumptions, and modeling.

For the NASA generic aeroengine case, engine fuel flow was reduced to keep the same takeoff thrust, which resulted in a 3.5-percent decrease in SFC. The NO_x emissions index decreased 47 percent because of the large T3 decrease. The turbine inlet temperature (T4 or T41) was calculated to decrease at least 436 °F.

5.4 Engine Performance With High-Pressure Compressor Injection

Evaporation of misted water after the LPC and before the HPC resulted in less performance improvement than when injection was before the LPC. SFC only improved 1.7 percent for HPC injection instead of 3.5 percent for LPC injection, NO_x decreased 44 percent instead of 47 percent, and T4 decreased 335 °F instead of 436 °F.

5.5 Combined Low-Pressure Compressor and High-Pressure Compressor Injection

In freezing conditions, it may be preferable to inject water directly into the HPC instead of the LPC so that the water does not freeze. However, because the LPC injection method showed a better SFC performance benefit than the HPC injection method, LPC injection was considered to be a better choice during this study.

5.6 Engine Performance With Combustor Injection

Traditional combustor water-injection systems have the advantage that, for a given NO_x reduction, they require much less water than an LPC or HPC injection system. Such systems also can achieve much larger NO_x reductions and have many more years of operating experience, which may ultimately make them more attractive to aircraft designers. However, there are some disadvantages that need to be considered.

One of the disadvantages of a combustor injection system is the thermal efficiency loss of the engine during takeoff and climbout. In this system, the injected water partially quenches the combustor flame temperature, which leads to a reduction in pressure and, eventually, in thermodynamic efficiency. Unlike the LPC system, this system does not have an improved compressor mass flow to offset the thermal loss.

Figure 8 shows that, as the water-injection rate into the combustor increases, NO_x and thermal efficiency both decrease, but power can be increased by increasing the water and fuel flow rate.

Figure 9 shows these relationships as modeled in NEPP, but with a constant power output. On a standard 59 °F day, with a water-to-fuel ratio of 0.5:1, the combustor water-injected engine would experience an adverse 2.0-percent increase in SFC. The engine would achieve a 50-percent NO_x reduction, an 81 °F T4 decrease, and an unchanged T3.

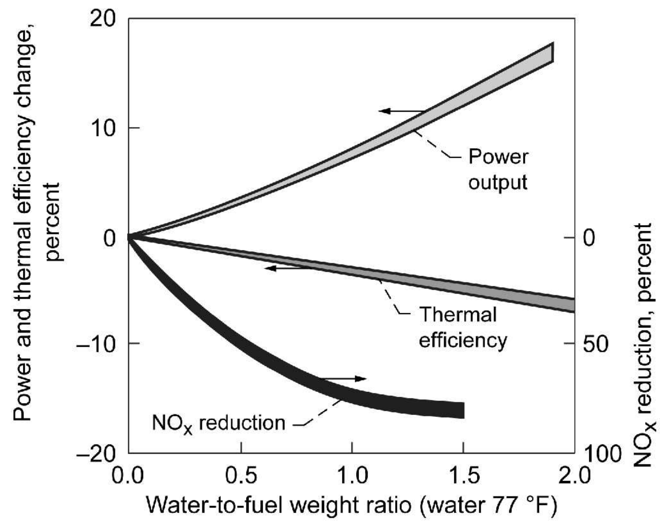

Figure 8.—Power output increases, but thermal efficiency and NO_X decrease as water-injection rate increases (Ref. 7).

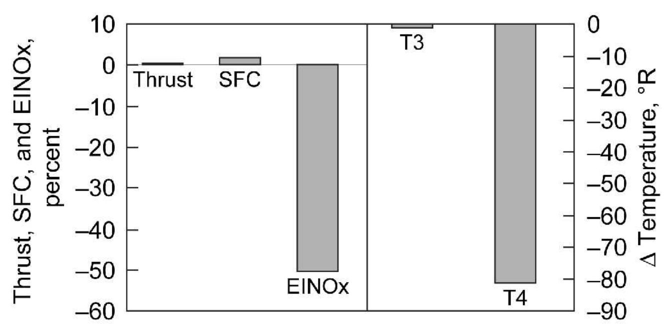

Figure 9.—Injecting water into the combustor increases specific fuel consumption (SFC) while decreasing NO_X and turbine inlet temperature, T4. Results for Sea Level Standard (SLS), 59 °F day, and water-to-fuel ratio of 0.5:1.0. T3, combustor inlet temperature; EINOx, Emissions Index NO_X.

5.7 Weights

The dry weights of the water misting and combustor injection systems were derived from the historical weight of the 747–200 water-injection system. The weight of both systems was estimated to be less than 360 lb. This additional weight represents the weight penalty the airplane has to carry over the mission after the water has been exhausted.

Although the combustor injection system requires only one pump, it needs a dedicated water tank, whereas the LPC and HPC misting systems can use the dry bays in the wing as water tanks with little weight penalty.

The water weight of the combustor injection system is 1127 lb. The water weight of the LPC injection system is 2505 lb (300 gal at 8.35 lb/gal). Both systems would consume about 30 percent of the water during the takeoff roll and the rest during the initial climbout period.

5.8 Takeoff, Climb, and Range Performance

When the LPC system was designed and aerodynamic models run, it was found that the water lasted until a 3560-ft altitude: slightly over the planned 3000-ft exhaustion point.

During takeoff and climbout, because SFC is affected by the type of injection system used, the combustor injection system would use 51 lb more fuel than an aircraft with no water injection would, and the LPC system would use 90 lb less fuel. All the water would be consumed by the time the aircraft reached 3560 ft.

For aircraft that are range limited by the volume of fuel that can be carried, there would be a slight range penalty of 7 nmi for carrying the water-injection system.

For aircraft that are weight limited, fuel would have to be offloaded to accommodate the 2505 lb of water. Thus, the aircraft range would be reduced by 80 nmi. However, for this extreme case, an operator could choose to not use the optional water injection during takeoff or to load only enough water for the takeoff roll (750 lb).

5.9 Fuel Use

For the combustor injection engine, a 2-percent thermal efficiency loss was experienced during takeoff (Fig. 9). This resulted in a 51 lb (7.6 gal) fuel-use penalty for this flight phase. For the LPC injection system, a 3.5-percent SFC improvement is anticipated under standard day conditions. This would result in a 90 lb (13.4 gal) fuel savings.

During cruise, any weight increase of the airplane would require additional fuel. For the study airplane on a 3000-nmi mission, a 63 lb (9.3 gal) fuel-use penalty could be expected during cruise for carrying the water-injection hardware.

Thus, for the entire mission, the combustor injection system would use 114 lb more fuel than an aircraft with no water injection would, and the LPC misting system would use 19 lb less fuel.

5.10 Emissions

The takeoff and climbout phases contribute most of an airplane's NO_x emissions in the landing-takeoff cycle.

Figure 10 shows the standard NO_x-generation profile, the reduced NO_x profile using LPC water misting, and the NASA NEPP results and Boeing airplane performance/emissions decks for validation. At 3560 ft (11 mi), the 300 gal of water was exhausted. At this point, the amount of NO_x saved would have been 49.2 lb, achieving a 47 percent reduction in takeoff and climbout NO_x. This includes the NO_x reduction due to the overall fuel savings of using LPC water misting.

This amount of NO_x savings was higher than that calculated for a normal landing-takeoff cycle because water misting was used to 3560 ft instead of the standard 3000 ft.

For engines with high overall pressure ratios, hydrocarbon and carbon monoxide emissions have been shown to remain relatively unaffected for the water-injection rates being considered in this study (Ref. 8). At higher rates (e.g., a 1:1 water-to-fuel ratio), both hydrocarbon and carbon monoxide emissions can climb precipitously.

The impact on the smoke emissions of new engines is unknown, but previous data have shown that water-to-fuel ratios up to 1:1 may be beneficial in reducing smoke emissions (Ref. 9).

5.11 Noise

The mass and velocity of the gases leaving a turbine engine determine its ultimate thrust. When water is added to the core of an engine, the total mass flow increases. Core and fan flow velocities have to be reduced in order to maintain a constant takeoff thrust for this particular engine cycle. The mass flows and velocity of the core and fan flow determine the noise level of the engine. Figure 11 shows that as the engine core mass flow increased with the addition of water, the core velocity was reduced as well as the fan mass flow and velocity. Together, these averaged flows decreased engine noise less than 1 dB.

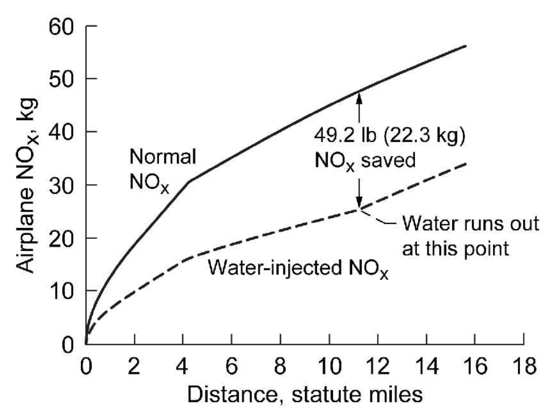

Figure 10.—NO_x is reduced 46.5 percent during takeoff and climbout, saving 49 lb of NO_x emissions to 3560 ft (beyond the normal landing-takeoff cycle altitude).

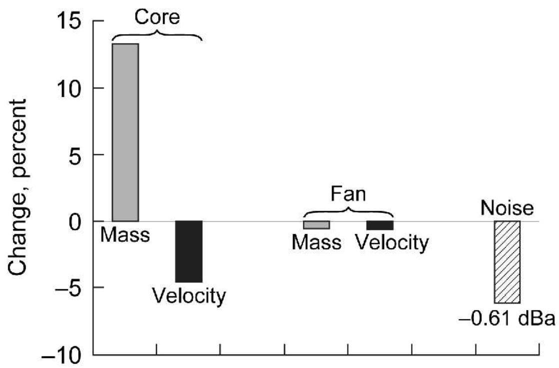

Figure 11.—Noise decreases slightly because mass-averaged jet velocity decreases; dBa, decibels.

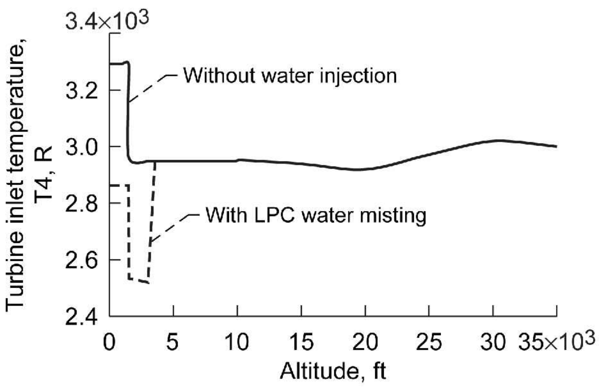

Figure 12.—Water injection reduces peak T4 temperatures right when needed during the takeoff cycle.

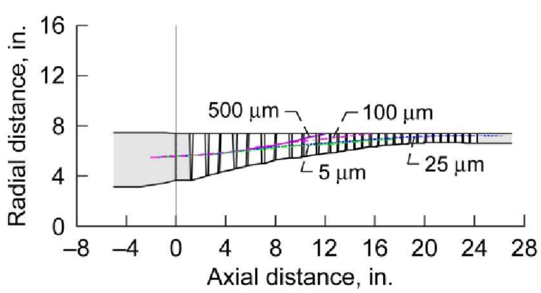

Figure 13.—Larger water droplets are centrifuged outwards toward the engine case.

5.12 Maintenance

Because of the large decreases in turbine inlet temperature while using water injection, it is likely that engine hot section life would increase (Ref. 10). This has yet to be fully quantified but would no doubt play a large part in reducing engine operating costs.

Figure 12 shows the base turbine inlet temperature (T4) profile from takeoff to the top of climb for the study engine. When water injection was used, a 436 °F temperature reduction was achieved (dotted line). Using water-injection would reduce the peak temperatures during the harshest operating period of takeoff and could greatly increase the life of the engine hot-section components. In addition, combustor wall radiative heat loading might be reduced, which would reduce wall temperatures and could increase combustor and turbine life.

5.13 Water Atomization in the Low-Pressure Compressor

In a specific LPC water/methanol injection design study and engine test, it was determined that the degree of water atomization before the LPC is very important (Ref. 5). The distance between the water injection point and the LPC also is important because it determines the degree of water vaporization.

Figure 13 shows the modeling results of various droplet sizes and their trajectories in the LPC. Droplets larger than 10 µm tended to be centrifuged toward the outside of the case, which further reduced water evaporation and also cooled the case (which upset the compressor blade tip clearance.)

Figure 14 shows the evaporation rate for various droplet sizes and distances from the LPC. The further the distance, the more time evaporation had to take place. Smaller droplets evaporated in less distance and time.

The atomization of the liquid also would affect the droplet size. A simple plain jet atomizer would require very high pressures (e.g., 750 to 1000 psid) to achieve sufficiently small droplet sizes. Tests were conducted that showed air-assisted nozzles can drop the pressure required to less than 250 psid to achieve a 10-µm water/methanol droplet size (Ref. 5).

Tests and analysis showed that a droplet size of 5 to 10 µm is required, and possible, for LPC water injection. This would ensure sufficient evaporation to prevent centrifuging of the droplet, achieve engine performance enhancement from inlet temperature reduction, and prevent compressor blade erosion from water droplet impingement.

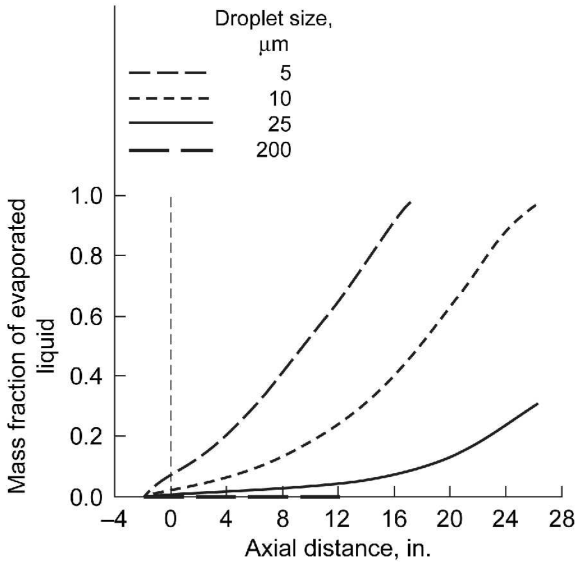

Figure 14.—Larger droplets or those very close to the low-pressure compressor do not evaporate completely.

Figure 14 shows the evaporation rate for various droplet sizes and distances from the LPC. The further the distance, the more time evaporation had to take place. Smaller droplets evaporated in less distance and time.

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5.14 Operability and System Issues

Previous LPC water-injection tests have shown a decrease in compressor surge margin (Ref. 11), but this may correlate with compressor blade tip clearance. When the water was insufficiently atomized, it was centrifuged by the compressor blades to the case, which then ran cooler and reduced blade tip clearance. Tests showed that this resulted in compressor blade rubs that reduced compressor surge margin (Ref. 5).

There could be other unforeseen effects on the engine, such as turbine blade coating effects or compressor blade erosion from unvaporized water droplets, which would need to be resolved by performing engine endurance tests. It is essential that no engine operability issues arise in service that would endanger the certification of aircraft operating under extended range operating rules.

5.15 System Costs

Preliminary system costs were calculated. These included (1) the capital costs of purchasing the water-injection system, (2) the water-servicing cost at the airport, (3) the cost of the conditioned water (which is substantially less expensive now because of new reverse osmosis systems), and (4) fuel impact. Engine maintenance cost savings were not included. This resulted in an additional operating cost of less than $41.00 per takeoff for a midsized passenger airplane on a 3000-nmi mission.

6.0 Conclusions

The potential nitrogen oxide (NO_x) reductions, cost savings, and performance enhancements identified in these initial studies strongly suggest that water-injection technology be further pursued. The potential for engine maintenance cost savings from this system should make it very attractive to airline operators and assure its implementation.

Further system tradeoff studies and engine tests are needed to answer the optimal system design question. Namely, would a low-risk combustor injection system with 70- to 90-percent NO_x reduction be preferable, or would a low-pressure compressor (LPC) misting system with only 50-percent NO_x reduction but larger turbine inlet temperature (T4) reductions be preferable? The LPC injection design and operability issues identified in the report need to be addressed because they might prevent implementation of the LPC type of water-misting system.

If water-injection technology challenges are overcome, any of the systems studied would offer dramatic engine NO_x reductions at the airport. Coupling this technology with future emissions-reduction technologies (Ref. 12) will allow the aviation sector to address the serious challenges of environmental stewardship, and NO_x emissions will no longer be an issue at airports.

References

1. Daggett, D.L.: Water Misting & Injection of Commercial Aircraft Engines to Reduce Airport NO_x. NASA/CR—2004-212957, 2004.
2. Lefebvre, A.: Gas Turbine Combustion. Taylor & Francis, 1998.
3. Mee III, T.R.: Reduction of Gas Turbine NOx Emissions by Inlet Air Fogging. MEE Industries, Monrovia, CA, 1999.
4. Hendricks, R.C.; Shouse, D.; and Roquemore, M.: Water Injected Turbomachinery. The 10th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, 2004 (NASA/TM—2005-212632).
5. Eames, D.J.H.: Short Haul Civil Tiltrotor Contingency Power System Preliminary Design. NAS3–97029, 1998.
6. Hines, W.R.: Gas Turbine Engine With Water Injection. U.S. Patent 6,012,279, January 11, 2000.
7. Castaldini, C.: Evaluation of Water Injection Impacts for Gas Turbine NOx Control at Compressor Station. GRI–90/0124, Gas Research Institute, June 1990.
8. Bahr, D.W.: Technology for the Reduction of Aircraft Turbine Engine Exhaust Emissions. Atmospheric Pollution by Aircraft Engines, AGARD CP–125, Advisory Group for Aerospace Research & Development, 1973.
9. Marchionna, N.R., et al.: The Effect of Water Injection on Nitric Oxide Emissions of a Gas Turbine Combustor Burning ASTM Jet-A Fuel. NASA TM X–2958, 1973.
10. Balepin, V.; Ossello, C.; and Snyder, C.: NO_x Emission Reduction in Commercial Jets Through Water Injection. AIAA Paper 2002–3623, 2002.
11. The Aircraft Gas Turbine Engine and Its Operation. Pratt & Whitney Aircraft, E. Hartford, CT, May 1974.
12. Daggett, D.L.; Eelman, S.; and Kristiansson, G.: Fuel Cell APU for Commercial Aircraft. AIAA Paper 2003–2660, 2003.

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*
01-03-2010

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Water Injection on Commercial Aircraft to Reduce Airport Nitrogen Oxides

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Daggett, David, L.; Fucke, Lars; Hendricks, Robert, C.; Eames, David, J.H.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS-22-5000-0013

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-14674

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2010-213179

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 07, 01, 03, and 05
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The potential nitrogen oxide (NO_x) reductions, cost savings, and performance enhancements identified in these initial studies of water-injection technology strongly suggest that it be further pursued. The potential for engine maintenance cost savings from this system should make it very attractive to airline operators and assure its implementation. Further system tradeoff studies and engine tests are needed to answer the optimal system design question. Namely, would a low-risk combustor injection system with 70- to 90-percent NO_x reduction be preferable, or would a low-pressure compressor (LPC) misting system with only 50-percent NO_xreduction but larger turbine inlet temperature reductions be preferable? The low-pressure compressor injection design and operability issues identified in the report need to be addressed because they might prevent implementation of the LPC type of water-misting system. If water-injection technology challenges are overcome, any of the systems studied would offer dramatic engine NO_xreductions at the airport. Coupling this technology with future emissions-reduction technologies, such as fuel-cell auxiliary power units will allow the aviation sector to address the serious challenges of environmental stewardship, and NO_x emissions will no longer be an issue at airports.

15. SUBJECT TERMS
Emissions; NO_x; Water injection; Gas turbine engines; Commercial aircraft

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email:help@sti.nasa.gov)
U	U	U	UU	17	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18