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Can Water-Injected Turbomachines Provide Cost-Effective Emissions and Maintenance Reductions?

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Abstract

An investigation has been performed to evaluate the effect of water injection on the performance of the Air Force Research Laboratory (AFRL, Wright-Patterson Air Force Base (WPAFB)) experimental trapped vortex combustor (TVC) over a range of fuel-to-air and water-to-fuel ratios. Performance is characterized by combustor exit quantities: temperature and emissions measurements using rakes, and overall pressure drop, from upstream plenum to combustor exit. Combustor visualization is performed using grayscale and color still photographs and high-frame-rate videos.

A parallel investigation evaluated the performance of a computational fluid dynamics (CFD) tool for the prediction of the reacting flow in a liquid fueled combustor (e.g., TVC) that uses water injection for control of pollutant emissions and turbine inlet temperature. Generally, reasonable agreement is found between data and NOx computations.

Based on a study assessing the feasibility and performance impact of using water injection on a Boeing 747–400 aircraft to reduce NOx emissions during takeoff, retrofitting does not appear to be cost effective; however, an operator of a newly designed engine and airframe might be able to save up to 1.0 percent in operating costs. Other challenges of water injection will be discussed.

Introduction

Aviation is anticipated to resume growing at about 5 percent per year, and in some sectors twice that rate is anticipated [1]. As such, environmental and fuels availability pressures will continue to mount and could invoke limits to the growth of commercial aviation. Therefore, the aviation community is putting more effort towards improving aircraft environmental, aerodynamic, and engine performance. Continued reductions in NOx emissions are an important part of the solution, yet are difficult to control as new engines utilize higher overall pressure ratios (OPRs) to enhance fuel efficiency. Without implementing new combustor technology, such increases in OPR will result in higher NOx emissions.

A method to control NOx emissions in industrial gas turbines is to inject water by misting the inlet air or direct injection into the combustor. Water injection has been used for over 60 years in aviation for engine cooling, which then enabled an added thrust capability. However, during the early years of its use, the side benefit of emissions reduction was not considered.

In the older Boeing 747–100s and 200s aircraft that used water injection, wing tanks held between 420 and 704 gallons of demineralized conditioned water for takeoff use. Associated maintenance problems included system corrosion, water freezing, increased engine maintenance, and occasional improper use of poor quality water (i.e., tap water).

These factors gave water injection a poor reputation in the aviation industry. However, lessons learned from this system, coupled with operating experience of industrial engines, and good design practices may make water injection again worthy of consideration for emissions reduction during takeoff. Based on experimental trapped vortex combustor (TVC) data, CFD results, and prior studies, a study was completed to assess the feasibility and performance impact of using water injection on a Boeing 747–400 aircraft to reduce NOx emissions during takeoff to 3000 ft (914 m) altitude. At a 1:1 water-to-fuel injection into the combustor, the engine's turbine inlet temperature (T4) would be reduced by over 120 °F (67 K). Engine NOx emissions are reduced up to 80 percent with hot section life improvement estimates up to a 29-percent increase in turbine life. Performance penalties include a 750-lb (340-kg) increase in aircraft empty weight due to the system components. This weight increase uses an additional 20 U.S. gallons more fuel on a 3000 nmi mission. About 400 gallons of conditioned water will be used onboard the aircraft during takeoff to 3000 ft altitude.

Trapped Vortex Combustor (TVC)

The new prototype TVC represents one type of compact, high-efficiency, high-turndown-ratio, low-emissions combustor that has been developed to control the NOx increases that come with higher OPR, more fuel efficient engines. However, it is increasingly difficult to constrain the specific NOx increase associated with higher OPR designs.

Water-Injected TVC

One of the methods used to control NOx emissions in industrial gas turbine engines is to inject water directly into the combustor. As the water-to-fuel injection ratio is increased to a 1:1 ratio, T4 decreases as the combustor flame temperature decreases, as visualized in Figure 1 [2]. This reduces NOx emissions and is also expected to improve turbine life.

CFD Simulations of Water-Injected TVC

Computational fluid dynamics (CFD) simulations are being performed utilizing a methodology that includes computer-aided design (CAD) air-solid modeling of the geometry, application of a flow solver with parallel processing capability and distributed over networked computers, and graphical and quantitative post-processing tools [3]. Physical models include liquid fuel droplet dynamics and evaporation, with combustion modeled using a hybrid finite-rate chemistry model developed for Jet-A fuel. CFD and experimental results with water injection are compared for cases with cavity-only fueling (Fig. 2) [3], while a numerical study of cavity and main fueling was also performed (Fig. 3) [3].

Predicted and measured trends in combustor exit temperature, CO and NOx are in general agreement at the different water-to-fuel loading rates, although quantitative differences exist between the predictions and measurements (Fig. 3) [3].

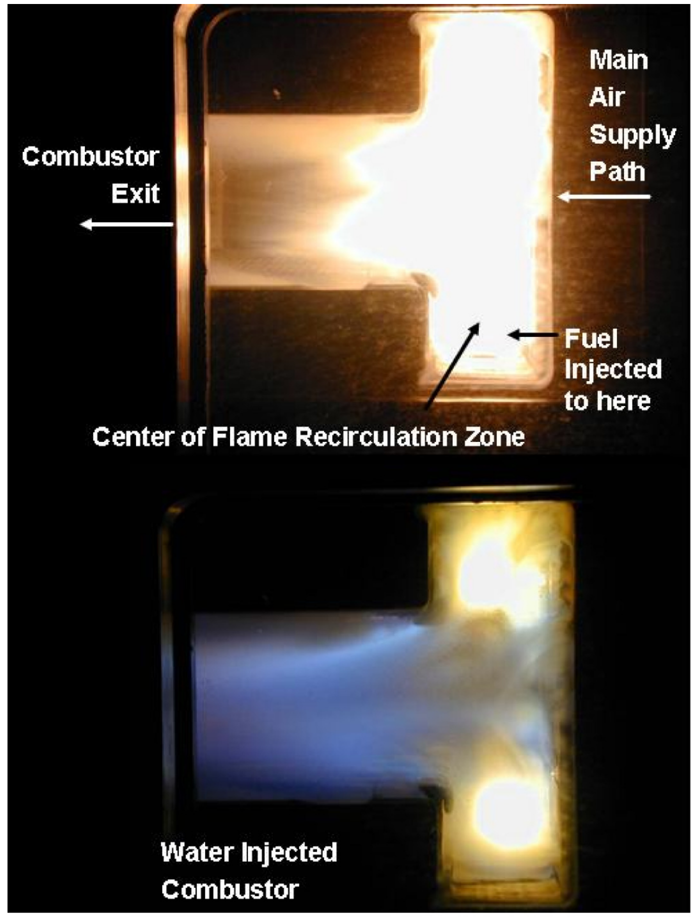

Figure 1.—Photos indicate temperature differences between baseline (top) and cooler, water-injected combustor (bottom).

The NOx–OPR Challenge

Although excellent progress has been made in reducing aircraft engine hydrocarbon and carbon monoxide emissions, NOx has been difficult to control. A tradeoff exists between engine fuel efficiency and NOx emissions. As engine fuel efficiency is improved by increasing the Overall Pressure Ratio of the engine's compressor, the increased compressor exit gas temperature (T3) that goes with the higher OPR usually results in higher specific NOx emissions.

Based on experimental TVC data, combustor CFD modeling results and prior test data, a study was completed to assess the feasibility and performance impact of using water injection on a Boeing 747–400 aircraft to reduce NOx emissions during takeoff [2 and 4].

Earlier studies of Roquemore et al. [5] and Burrus et al. [6] compared the combustor performance of the TVC with the current aircraft fleet and projected combustor designs. Normalizing these results in terms of a current fleet engine fuel burn (baseline: 767 airplane), increases in fuel economy are gained through increasing OPR, but at the expense of NOx increases. NASA's Ultra Efficient Engine Technology (UEET)

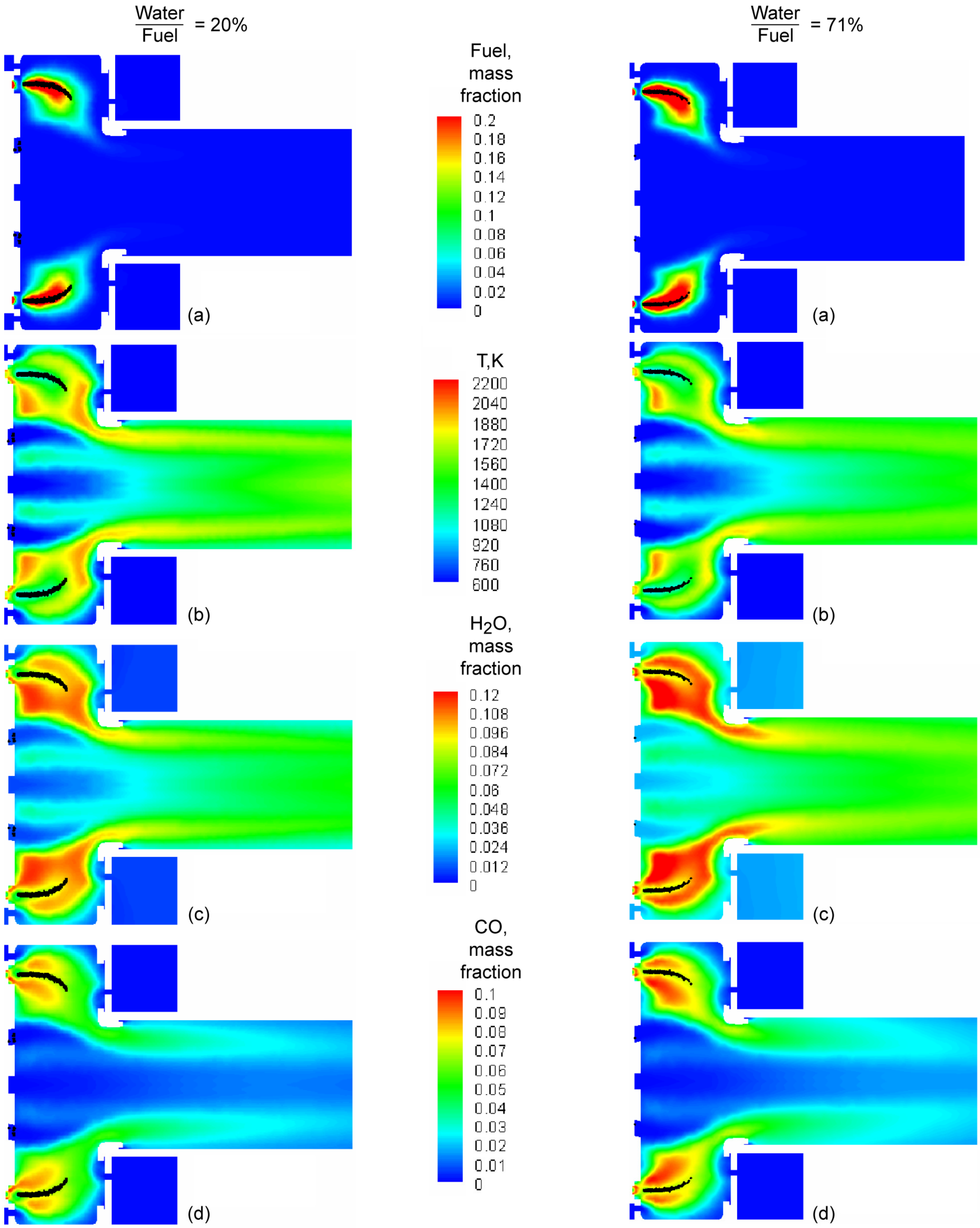

Figure 2.—TVC cavity-only fueling cases, corresponding to two experimental runs (from Brankovic et al. [3]). Midplane contours of combustion quantities, including (a) evaporated fuel, (b) static temperature, and (c) water and (d) carbon monoxide mass fractions (of combustor mass flow). Spray droplets instantaneous positions are shown. Left column shows water-to-fuel loading at 20 wt%. Right column shows water-to-fuel loading at 71 wt%.

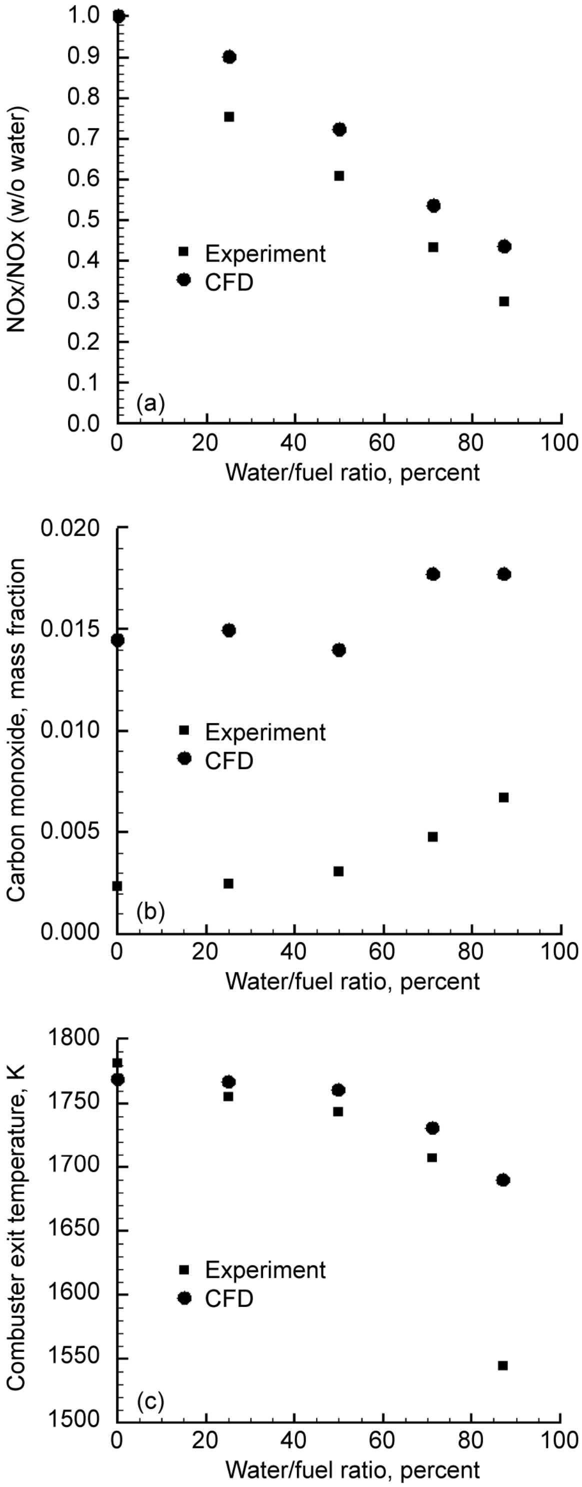

Figure 3.—Parametric study of water injection in aircraft engine for water-to-fuel ratios ranging from 0 to 87 percent showing mass-averaged quantities at combustor exit plane. Comparison with experimental data. (a) NOx: Ratio of quantities with water-injection to those without. (b) Carbon monoxide. (c) Combustor exit temperature. (from Brankovic et al. [3]).

new engine cycle and combustor goals have increased OPRs to between 50 and 57 and have set NOx emissions goal at 70 percent ICAO-1996 which translates to EINOx = 36 and 24 g/kg of fuel at 100 and 85 percent power, respectively, for OPR = 55, 85.8 klb_f (382 kN), 100 percent class engine. At these pressure ratios, the TVC NOx emissions would be 70 percent of the baseline, but still higher than the more aggressive goal of 80 percent reduction. Augmenting the TVC with a 1:1 water injection ratio would readily achieve the emissions reduction goal.

Other NOx emissions reduction technologies, such as Talon X[1] and TAPS[2] combustors offer some degree of emissions reduction during takeoff and are a crucial part of the solution as they do provide emissions reductions during cruise.

Potential Benefits and Liabilities

For the primary Pratt & Whitney PW4062 engine studied for the Boeing 747–400 aircraft, injecting water directly into the combustor was determined to be less problematic and offer greater NOx emissions reduction capability than injection into the compressor. Test data from several sources and engine types showed that using a 1:1 water-to-fuel injection ratio should yield an 80 percent NOx reduction as shown in Figure 4 [2].

Recent test results, as well as historical data, showed that there could be a large potential reduction in smoke emissions when using water injection during takeoff. For noise considerations, water injection adds mass to the engine exhaust. When keeping thrust constant, a corresponding decrease in jet velocity was calculated to result in a small reduction in noise.

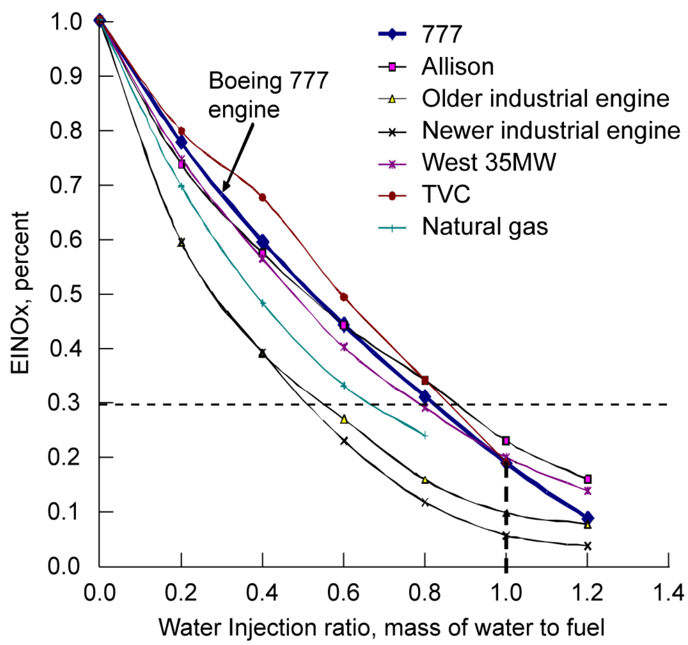

Figure 4.—Test results illustrating that 1:1 water-to-fuel injection ratio should reduce NOx emissions about 80 percent and that this is fairly consistent across engine and combustor types (from Daggett et al. [2]).

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[1]Pratt & Whitney, East Hartford, CT, and MTU Aero Engines GmbH, Munich, Germany.

[2]General Electric Company, Fairfield, CT, and CFM International.

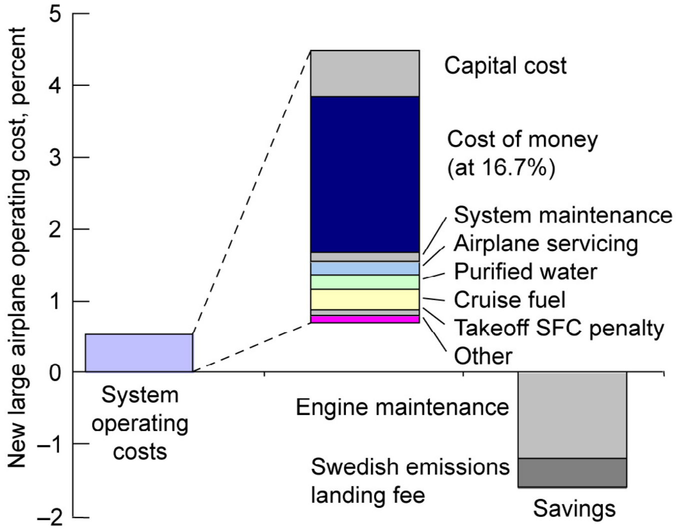

Figure 5.—Water injection in aircraft engines may result in up to 1.0 percent savings in overall operating costs when emissions-based landing fee savings are considered (from Daggett et al. [2]).

The engine's turbine inlet temperature was calculated to be reduced by over 120 °F (67 K). Engine operation at reduced temperatures also holds the potential for hot-section life improvement. According to the estimates obtained from one engine company, up to a 29 percent increase in turbine life may be expected.

Performance penalties include approximately a 750-lb (340-kg) increase in aircraft weight that could reduce range by 60 nmi. Carrying this additional weight requires about 20 U.S. gallons more fuel on a 3000 nmi mission. Another challenge of water injection is its increased propensity to cause the compressor to stall (i.e., reduces the stall margin). Addressing this issue may result in redesign issues and fuel efficiency penalties on older engines. Active compressor stall control systems could address these concerns on newly designed engines (e.g., [7]). These engine operability issues need to be addressed along with the requirements of significant testing and certification.

The resulting high development costs, coupled with engine performance penalties on older engine designs, will make the system unattractive as a retrofit option. However, for a newly designed engine and airframe, some of these costs and penalties may be reduced. If one considers the full impact of reduced landing fees and potential of the longer lived turbine's positive impact on engine maintenance costs, the system was estimated to have potential savings for an operator of a newly designed airplane of up to 1.0 percent in operating costs (Fig. 5) [2].

Conclusions

If the engine operational uncertainties can be overcome, water injection may become an attractive option to consider for future aircraft in dramatically reducing takeoff NOx and possibly smoke emissions. Although water injection is an old technology, further study and tests are required in order to validate the potential for this technology to be used on newer, higher performing engines. A change of this magnitude in engine and airplane systems architecture can only be made with well-understood technology.

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