Project 051 Combustion Concepts for Next-Generation Aircraft Engines

Massachusetts Institute of Technology

Project Lead Investigator

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University Participants

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- PI: Professor Steven R. H. Barrett
- FAA award number: 13-C-AJFE-MIT, Amendment Nos. 061, 071, and 079
- Period of Performance: February 5, 2020 to August 31, 2022 (reporting here with the exception of funding level and cost sharing only for the period October 1, 2020 to September 30, 2021)
- Task:
    1. Evaluate water injection to extend the operating envelope and reduce emissions

Project Funding Level

This project received $600,000 of FAA funding and $600,000 of matching funds (approximately $140,000 from MIT plus third-party in-kind contributions of $460,000 from NuFuels LLC).

Investigation Team

- Professor Steven Barrett (MIT) serves as PI for the A51 project as head of the Laboratory for Aviation and the Environment. Professor Barrett coordinates internal research efforts and maintains communication among investigators in the various MIT research teams.
- Dr. Raymond Speth (MIT) serves as co-PI for the A51 project. Dr. Speth directly advises students on research in the Laboratory for Aviation and the Environment focused on the assessment of fuel and propulsion system technologies targeting reduction of aviation’s environmental impacts. Dr. Speth also coordinates communication with FAA counterparts.
- Dr. Jayant Sabnis (MIT) serves as co-investigator for the A51 project. Dr. Sabnis co-advises students on research in the Laboratory for Aviation and the Environment. His research interests include turbomachinery, propulsion systems, gas turbine engines, and propulsion system–airframe integration.
- Syed Shayan Zahid is a graduate student in the Laboratory for Aviation and the Environment. He is primarily responsible for evaluating the impacts of emissions reduction technologies on fuel consumption and making engine cycle models in pyCycle to evaluate the feasibility of new technologies in different engine configurations.
- Yang Chen is a graduate student in the Laboratory for Aviation and the Environment. He is primarily responsible for extending engine and emissions models to incorporate advanced combustion concepts and to expand the types of pollutants simulated in Pycaso.

Project Overview

The purpose of this project is to identify design concepts for aircraft engine combustors that could decrease the combustor emissions of future aircraft engines that incorporate higher pressures and temperatures. The need to increase the thermal efficiency of the gas generator in aircraft engines has required designers to increase the overall pressure ratio (P_{03}/P_{02}) as well as the temperature ratio (T_{04}/T_{02}). A higher pressure ratio increases the overall temperature in the combustor, thereby accelerating NO_x production. Increased combustor exit temperatures result in higher cooling air requirements for the engine cycle, thus reducing the air available for NO_x reduction within the combustor. Hence, higher-thermal-efficiency engine cycles frequently result in higher NO_x production. The current state of the art requires a trade-off between engine fuel consumption and NO_x. In this project, we plan to develop numerical models for engine design concepts with promising new technologies. We will determine and compare the performance characteristics associated with these technologies and will leverage detailed combustion chemistry models to understand how changes in fuel composition affect engine performance and emissions characteristics.

The design of combustors for aircraft engines is governed by the simultaneous need to ensure operability at low-power conditions (i.e., preventing combustion instabilities, blowout, etc.) and enabling operation at high power without excessive NO_x or soot emissions. For aircraft engines, the flight conditions and thrust setting of the engine fully determine the inlet conditions of the combustor, i.e., the temperature, pressure, and fuel flow rates, with very little adjustments to increase stability or decrease emissions being available. However, the introduction of additives into the engine at specific locations would provide secondary inputs that could be used to extend stability limits or reduce emissions.

When the fuel flow rate is the only engine control parameter, the consequent variations in the equivalence ratio result in wide variability in the combustion characteristics, e.g., flammability limits and flame speeds, that must be accommodated across thrust settings ranging from idle to takeoff. Previous work has shown that the addition of a high-reactivity additive while holding the equivalence ratio constant can extend the lean blowout limit in a gas-turbine-like combustor (Speth and Ghoniem, 2009). By changing the fuel composition to counteract the effect of the equivalence ratio, the combustor would not need to operate over as wide a range of conditions and consequently allow for more opportunities to optimize the combustor to control emissions at its design point. Furthermore, variations in fuel composition have been shown to decrease soot emissions from aircraft engines (Moore et al., 2015; Speth et al., 2015), thus suggesting that the use of a fuel additive could be effective in reducing emissions during specific operating regimes.

Although water injection is not used in any current commercial aircraft engines, it has been used in several engines to augment thrust at takeoff, such as in the J-57 engines used on the B-52 and the JT9D engines used on the 747-200 (Daggett, 2004). The use of water injection at takeoff provides increased thrust without increasing the turbine inlet temperature. The temperature reduction, and therefore the density increase, from the evaporation of the injected water allows the engine to accommodate a larger mass flow rate of air resulting in greater thrust. In modern engines with higher compression ratios, water injection into the compressor may also alleviate limitations due to compressor exit temperature. Water injection has also been evaluated for its ability to reduce takeoff NO_x emissions (Daggett, 2004). Although older engines that used water injection were known to have higher soot production, controlling soot emissions was not a design goal of these engines; however, this aspect does not imply that a modern engine design using water injection could not meet limits for nonvolatile particulate matter emissions.

The work proposed here builds on work performed in other ASCENT projects. Work under ASCENT Project 39 has provided a combustor model that can predict soot emissions from conventional combustor designs and can use detailed chemical kinetic models to enable evaluation of the effects of different fuel compositions on emissions. Work performed under ASCENT Project 47 has extended this model to include predictions of NO_x formation, as well as coupling the model to an engine cycle model, thereby creating a consistent framework for modeling both ground and cruise emissions.

Task 1 - Evaluate Water Injection to Extend the Operating Envelope and Reduce Emissions

Massachusetts Institute of Technology

Objective(s)

Water injection can be used to control temperatures in the engine, which may expand the design space and enable decreases in mission fuel burn and emissions. For this task, we evaluated the impacts of water injection (a) at the low-pressure compressor inlet, (b) at the high-pressure compressor inlet, and (c) at the combustor inlet. For each option, the effect of water injection on the engine cycle was evaluated to determine engine designs, which are optimized for the impacts of water injection, i.e., considering allowable limits on compressor discharge temperature and turbine inlet temperature. Water injection is expected to reduce peak temperatures and therefore NO_x formation. Tradeoffs with soot formation will also be evaluated. In the past, water injection was primarily used for thrust augmentation purposes when emissions were not thoroughly evaluated as part of the aircraft design process. For this reason, the existing literature on the effect of water injection on tailpipe emissions is sparse, thus justifying the need to conduct analyses on its feasibility.

To determine the effectiveness of water injection as a potential emission reduction technique, water injection will also be evaluated using different combustor configurations, including both rich-quench-lean (RQL) and staged lean-burn combustors. The impacts of water injection using different burner configurations will then be compared to determine whether an optimal configuration to incorporate this technology exists. Even though water injection is expected to decrease NO_x emissions, the incorporation of water injection in lean-burn staged combustors may pose challenges, because lean combustion is acoustically less stable than rich combustion. Therefore, before implementation of this technology, the benefits of water injection will eventually need to be weighed against feasibility and operability considerations.

Research Approach

This research targets three sections for analysis: a thermodynamic cycle analysis, a chemical emissions analysis, and an overall mission analysis. To evaluate the feasibility of this technology, a water evaporation model was also developed. A zero-order analysis for contrail formation was considered to evaluate potential trade-offs that need to be taken into consideration for this technology.

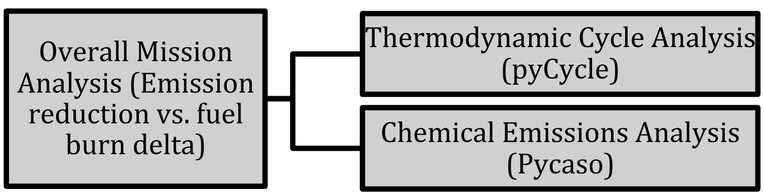

Figure 1. Evaluating the feasibility of water injection: analysis approach.

Thermodynamic Cycle Analysis

Water injection at different points in the Brayton cycle has varying effects on engine performance, depending on the state of the water being injected. A thermodynamic cycle model was developed to assess the dominant effect of water injection at different points in the cycle to determine the extent to which performance parameters—such as the thermodynamic states at various cycle locations, thrust, burner exit temperature, and overall thrust-specific fuel consumption (TSFC) are affected as a result of this approach.

PyCycle, an open-source code for thermodynamic cycle analysis, was chosen as a tool for this cycle analysis because of its flexibility in modifying the source code to simulate water injection. First, psychrometry calculations were performed to ensure that the amount of water injected into the system under the assumption of complete evaporation does not exceed the saturation limits (100% relative humidity) at the injection locations. After establishing the cutoff limits for each injection location, the pyCycle model was run to size the engine according to the amount of water injected. The thrust and combustor outlet temperatures were set to be constant across runs to evaluate the effect of water injection on fuel consumption for an engine designed to operate with water injection. The pyCycle results were then used as inputs to the combustor model as well as the overall mission analysis to determine the change in fuel consumption and the emission indices of the pollutants of interest for different missions. The approach to determine the feasibility of water injection is shown in Figure 1.

Chemical Emissions Analysis

The ASCENT 39 project developed an emissions model (Pycaso) based on Cantera to predict the NO_x and soot formation inside a CFM56-7B engine by using a reactor network to simulate the combustor. We aim to expand this model to simulate different combustor configurations and to cover various engine operating conditions. Evaluating new emission reduction technologies for a wider range of engines will help determine the overall effect on emissions. In general, the formation of pollutants, such as NO_x, CO, nvPM, and SO_2, depends on complicated reaction mechanisms. Thus, in emissions modeling, Cantera will be used with appropriate reaction mechanisms to calculate the species reaction rates in the combustor. Moreover, the emission model (Pycaso) will be utilized to calculate the total emissions level by solving a set of conservation laws that are properly simplified. Approximations such as a well-stirred reactor and plug-flow reactor sufficiently capture the flow field structure and greatly reduce the computational cost relative to that of three-dimensional computational fluid dynamics (CFD) simulations. Shown below is the one-dimensional reactor network structure for an RQL-type combustor used in the Pycaso emissions model.

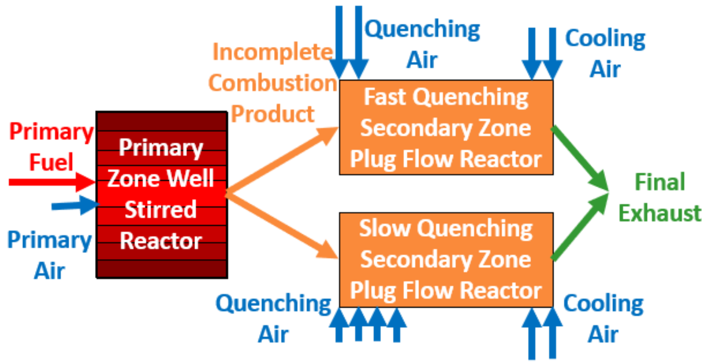

Figure 2. Pycaso combustor emissions model.

Inputs to the Pycaso emissions model are taken from the pyCycle thermodynamic cycle analysis, which includes the combustor inlet mass flow rate and thermodynamic state at the inlet. The estimated emissions help quantify the benefits and disadvantages associated with water injection as a function of design parameters such as combustor configuration and water injection location.

Overall Mission Analysis

Water injection can reduce NO_x formation inside the combustor by lowering the combustor temperature. This leads to a lower emission index for NO_x, where the emission index is the mass of NO_x emitted per mass of fuel consumed. However, this does not imply that the total amount of NO_x emitted per mission decreases, because the amount of fuel consumed could increase for a mission using water injection. The use of water injection could add significant weight to the aircraft in terms of the weight of the water and the associated system such as pumps, tanks, etc. This extra weight would require additional fuel burn (if the other aircraft parameters, such as the lift-to-drag ratio, remain unchanged). Therefore, when considering the benefit of using water injection to reduce NO_x emissions, it is important to account for the penalty due to the additional weight and the additional fuel burn associated with carrying the water injection system. A simplified overall mission analysis was performed using the Breguet range equation to assess whether this penalty would be significant and therefore limit the use of water injection. The results of the weight analysis depend on several factors, including the weight of the water to be injected, the mission range, the effect of water injection on the thrust-specific fuel consumption (TSFC), the desired NO_x reduction, and the associated water flow rate.

An exploratory contrail analysis was also conducted by considering ambient conditions as well as flight conditions to determine the extent to which water injection changes the likelihood of contrail formation, through evaluation of the Schmidt–Appleman criterion for different water injection ratios.

Milestone(s)

The existing pyCycle model was modified to include water injection capability, and the results were compared with a thermodynamic cycle model developed manually in Python to verify the accuracy of the results. After the results were obtained from the pyCycle model as well as the pyCaso model for various water injection quantities, an overall mission analysis was successfully performed to obtain the results and evaluate the feasibility of this technology. A combustor model was also developed for the twin-annular, pre-mixing swirler (TAPS) II burner used in the CFM LEAP engine. This model is currently being validated.

Major Accomplishments

The thermodynamic cycle model for water injection revealed increased cycle efficiency in the case of water injection before the compression in both pre-LPC and pre-HPC water injection cases. This is because the evaporative cooling effect of water reduces the work required to compress the same amount of air to the desired pressure after compression. The pre-LPC water injection case yielded the maximum benefit, followed by the pre-HPC water injection up to the saturation limits. When water is injected upstream of the combustor after the compression has already occurred, the evaporation no longer yields the compression work benefit, and the cooling effect implies only an increase in the heat input required to raise the temperature to the same level. Hence, the fuel consumption increases, as shown in Figure 3. The Pycaso emission model was expanded to simulate water injection in an RQL-type combustor. The NO_x emissions index (EI) was obtained as shown in Figure 4.

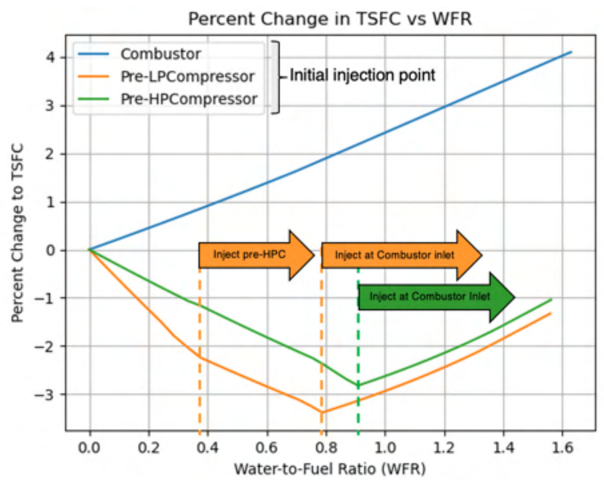

Figure 3. Thermodynamic cycle analysis: effect of water injection on fuel consumption.

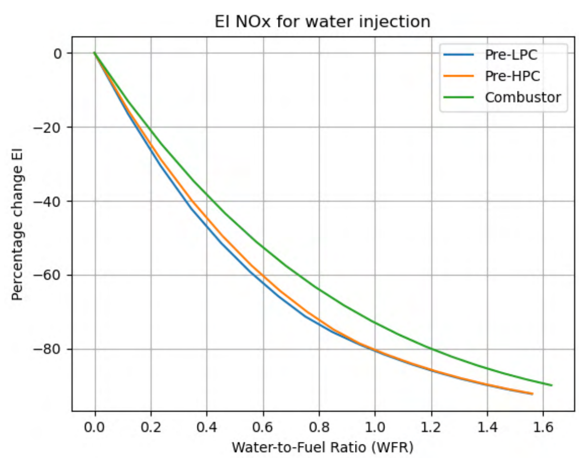

Figure 4. Combustor analysis: effect of water injection on NO_x emissions.

Finally, the results were combined for the most beneficial (pre-LPC) case to study the overall effect of water injection on fuel consumption and NO_x emissions. It was assumed that water is injected for the entire cruise duration at a cruise speed of 900 kph, and a lift-to-drag ratio of 16 was considered for all the ranges. As shown in Figure 5, water injection is more beneficial for shorter range flights because of the lower weight of water carried.

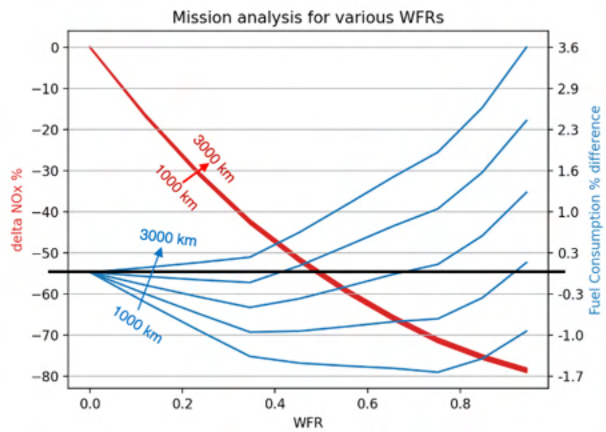

Figure 5. Overall mission analysis: effect of water injection on total fuel consumption and NO_x emissions.

The Pycaso emission model was also expanded to simulate a staged lean-burn combustor type, such as TAPS or TAPS II. Both experimental and computational fluid dynamics (CFD) data of the combustor internal flow field and reaction field were used in model construction. A simple fuel splitting technique is assumed, which dictates a fixed fuel flow rate ratio between the pilot flame and the main flame fuel injection during staging. Water injection can be performed into combustor pilot flow swirlers, the main flow premixing passage, and the final dilution region. Coupling with an engine model that resembles the CFM-LEAP-1A engine, the simulated NO_x and CO emissions at the sea level static condition have been found to be consistent with the experimental emissions measurements from the International Civil Aviation Organization Aircraft Engine Emissions Databank. The impact of water injection on emissions with the staged lean-burn combustor will be investigated in the future.

An exploratory contrail analysis was also performed for all flights flown in the year 2016. Water injection was found to yield a significant increase in persistent contrail formation, because of the higher tendency of water vapor to condense in the plume. The increase in the proportion of flight distance leading to persistent contrail formation is shown in Figure 6 for varying water-to-fuel ratios.

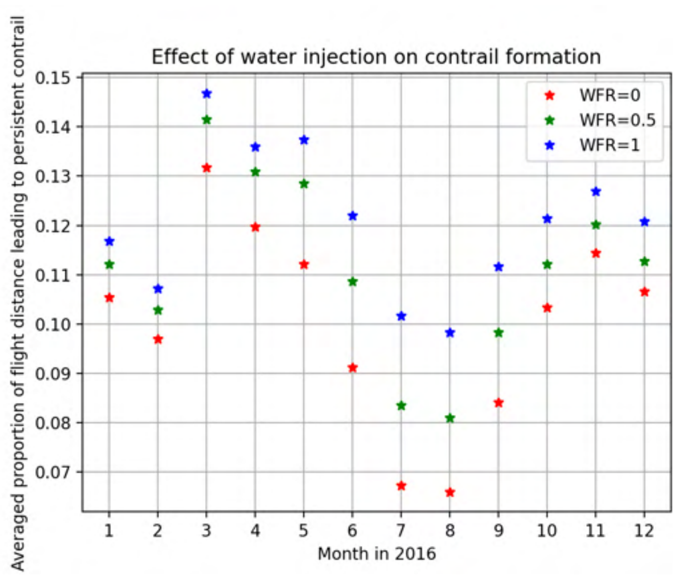

Figure 6. Effect of water injection on contrails.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
This task was conducted primarily by Yang Chen and Syed Shayan Zahid, graduate research assistants working under the supervision of Dr. Jayant Sabnis and Dr. Raymond Speth.

Plans for Next Period
This model is based on a key assumption that considers the full evaporation of the water droplet under study. In addition to the thermodynamic analysis already conducted, it is also important to evaluate the time required for the injected water droplets to evaporate with the residence time available at the location of interest in the engine. This evaluation will be performed by modeling the energy and mass conservation equations for the injected water droplets to calculate the evaporation time. The water injection strategy will be explored for other parts of the mission, such as takeoff and climb-out, to determine the marginal benefit of this technology at different power conditions. Finally, a sensitivity analysis will be conducted for various engine parameters, such as the overall pressure ratio (OPR) and fan pressure ratio (FPR).

In terms of extending the functionality of the Pycaso emission model, the impacts of water injection on NO_x and CO emissions will be further studied for different combustor configurations, such as the TAPS combustor. Emissions of other types of pollutants, such as soot, will also be simulated by the Pycaso model.

References

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