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
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- Period of Performance: February 5, 2020 to August 10, 2021 (reporting here with the exception of funding level and cost share only for the period February 5, 2020 to September 30, 2020)
- Task:
    1. Evaluate Water Injection to Extend Operating Envelope and Reduce Emissions

Project Funding Level

FAA provided $600,000 in funding. Matching fund sources are approximately $140,000 from MIT, plus third-party in-kind contributions of $460,000 from NuFuels LLC.

Investigation Team

- Prof. Steven Barrett (MIT) serves as PI for ASCENT Project 51 as head of the Laboratory for Aviation and the Environment. Prof. Barrett coordinates internal research efforts and maintains communication between investigators in the various MIT research teams.
- Dr. Raymond Speth (MIT) serves as co-PI for ASCENT Project 51. Dr. Speth directly advises student research in the Laboratory for Aviation and the Environment focused on 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 ASCENT Project 51. Dr. Sabnis co-advises student research in the Laboratory for Aviation and the Environment. His research interests include turbomachinery, propulsion systems, gas turbine engines, and propulsion system–airframe integration.
- Jad Elmourad 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 investigating the integration of advanced combustion technologies into the aircraft system.
- Syed Shayan Zahid 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.

Project Overview

The purpose of this project is to identify design concepts for aircraft engine combustors which could decrease the combustor emissions for 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 temperature results 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 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 performance characteristics associated with these technologies and will leverage detailed combustion chemistry models to understand how changes to 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 adjustment 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 fuel flow rate is the only engine control parameter, the consequent variations in 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 have to operate over as wide a range of conditions, allowing 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), suggesting that the use of a fuel additive could be effective at reducing emissions during specific operating regimes.

Although water injection is not used in any current commercial aircraft engines, it was used in several engines as a means of augmenting thrust at takeoff, such as 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 provided increased thrust without increasing the turbine inlet temperature. The temperature reduction, and therefore density increase, from the evaporation of the injected water allows the engine to handle a larger mass flow rate of air, which results in greater thrust. In modern engines with higher compression ratios, water injection into the compressor may also serve to alleviate limitations due to compressor exit temperature. Water injection has also been evaluated for its ability to reduce takeoff NO_x emissions (Daggett, 2004). While older engines that used water injection were known to have higher soot production, controlling soot emissions was not a design goal of these engines, and this does not imply that a modern engine design employing water injection could not meet limits on nonvolatile particulate matter emissions.

The work proposed here builds on work done in other ASCENT projects. Work under ASCENT Project 39 has resulted in a combustor model that can be used to predict soot emissions from conventional combustor designs and uses detailed chemical kinetic models to allow evaluation of the effects of different fuel compositions on emissions. Work done 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, creating a consistent framework for modeling both ground and cruise emissions.

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

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Objectives

Water injection can be used to control temperatures in the engine, which may expand the design space and allow decreases in mission fuel burn and emissions. For this task, we will evaluate the impacts of water injection (1) at the compressor inlet, (2) into the diffuser (upstream of the combustor) and (3) into the combustor dilution zone. For each option, we will evaluate the effect of water injection on the engine cycle and 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. We expect that water injection can reduce peak temperatures and therefore NO_x formation. Tradeoffs with soot formation will also be evaluated. Options to enable operation without the use of water injection will also be considered in order to address potential safety concerns. 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, justifying the need to conduct analyses on its feasibility.

Research Approach

The research targets three sections for analysis: a thermodynamic cycle analysis, a chemical emissions analysis, and a weight analysis.

Preliminary 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. There are, in general, two potentially competing effects affecting engine performance when using water injection as an emission-reduction approach. Injecting water into the thermodynamic cycle could lower the thermal efficiency due to its cooling effect on the flame temperature. At the same time, it has the potential to increase the engine thrust obtained. A preliminary thermodynamic cycle analysis was performed to assess the dominant effect of water injection at different points in the cycle to determine how much the performance parameters such as the thermodynamic states at various cycle locations, thrust, burner exit temperature, and the overall thrust-specific fuel consumption (TSFC) were affected as a result of this approach.

PyCycle, an open-source code for thermodynamic cycle analysis, was chosen as a tool for this preliminary analysis due to the added flexibility of making modifications to the source code in order to simulate water injection. Currently, other engine performance evaluation tools such as NPSS, do not include the flexibility to easily change the source code. Initially, manual calculations were performed as part of a zero-order analysis to observe the overall effects of water injection on engine performance using specified engine design variables as inputs. The PyCycle results will be compared to the performance trends obtained as a result of the zero-order approach.

Preliminary Chemical Analysis

ASCENT Project 47 yielded 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 add the capability to vary the engine design and configuration in order to simulate new emission-reduction technologies for a wider range of engines and observe the overall effect on emissions. In general, NO_x formation depends on complex reaction mechanisms that depend on the local temperatures and composition inside various zones of a combustor. In order to evaluate the effect of novel engine technologies on the amount of NO_x and other emissions, Cantera will be used to estimate the emissions index (EI) of NO_x inside the combustor. This chemical analysis will use the engine performance results obtained from the thermodynamic cycle analysis as inputs, such as the TSFC, burner inlet temperature, etc. The estimated emissions would help compare the benefits and disadvantages associated with water injection as a function of injection location and state of water being injected.

Preliminary Weight Analysis

Water injection can reduce NO_x formation inside the combustor by lowering the combustor temperatures. This leads to a lower emission index for NO_x, where the emission index represents the amount of NO_x emitted per amount of fuel consumed. However, this does not necessarily 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., and this extra weight would require additional fuel burn (assuming 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 coming from the additional weight and the additional fuel burn associated with carrying the water injection system. A preliminary weight analysis was performed to assess whether this penalty would be significant and limiting to the use of water injection.

The results of the weight analysis depend on several factors including the weight of the water injection system, the mission range, the effect of water injection on the TSFC, the desired NO_x reduction, and the associated water flow rate. Therefore, a complete weight analysis would require input from a thermodynamic cycle analysis, specifically the relationship between the water flow rate and the TSFC, as well as input from a chemical analysis, specifically the relationship between the water flow rate and the NO_x formation.

Milestones
A literature review was conducted to evaluate the known effects of water injection on aircraft performance and emissions, and the appropriate tools for evaluating the change in performance and emissions as a result of water injection were identified.

Major Accomplishments
Literature review
A survey of the existing literature on water injection techniques was conducted and the relevant information was used to conduct zero-order preliminary analyses on emission reduction as a result of water injection. The preliminary chemical emissions analysis will aim to verify the validity of the emission reductions proposed in the literature as a function of the amount of water injected at different cycle locations.

Preliminary analysis
Tools were identified to conduct preliminary analyses on the thermodynamic cycle and the resulting emissions. PyCycle was selected to simulate water injection and compare the feasibility of injecting water at different locations in the cycle to determine the optimum approach. This will help confine and focus the scope of this project before making modifications to the existing Pycaso model.

Publications
N/A

Outreach Efforts
N/A

Awards
None

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

Plans for Next Period
After conducting the preliminary analyses, the best approach to water injection will be identified. This approach will add to the modeling capabilities of Pycaso in order to simulate water injection for different aircraft engine designs. The results will enable us to compare water injection with other emission-reduction technologies.

References

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