Project 066 Evaluation of High Thermal Stability Fuels

University of Dayton and University of Dayton Research Institute

Project Lead Investigator

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- P.I.(s):
    1. Joshua Heyne, Associate Professor
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- FAA Award Number: 13-C-AJFE-UD, Amendments 27 and 30
- Period of Performance: June 5, 2020 to August 26, 2022
- Tasks:
    1. Identify/create a jet engine model including all components necessary to evaluate the impact of fuel properties
    2. Build and apply a heat transfer model for the fuel system
    3. Identify engine cooling tradeoffs that can be leveraged to optimize engine/aircraft system efficiency
    4. Estimate gains in fuel efficiency
    5. Identify critical blend components and solvents to study
    6. Create and test blends for thermal stability in JFTOT and QCM

Project Funding Level

FAA provided $284,997 in funding which is allocated between amendments 27 and 30 as indicated below:

- 13-C-AJFE-UD-027: $184,997
- 13-C-AJFE-UD-030: $100,000

Cost sharing is provided by DLR Germany.

Investigation Team

- Joshua Heyne (University of Dayton) is the project lead investigator, responsible for building the team and coordinating team activities, driving toward the completion of major milestones.
- Randall Boehm (University of Dayton) is a research engineer with 20 years of relevant industry experience and is responsible for leading the technical efforts on this project.
- Lily Behnke (University of Dayton) is a graduate student research assistant who is responsible for integration of the engine performance models (EPMs) and the fuel properties models with JudO, a tool developed internally to help optimize fuel composition against user-defined objectives.
- Jack Hoog (University of Dayton) is an undergraduate student research assistant who is assisting with the implementation of a Python program option to mix aircraft operating conditions used as the basis of fuel impact comparisons.

- Jeffrey Spruill (General Electric [GE]-Aviation) is a product performance engineer who is responsible for applying audited EPMs as necessary to judge potential drop-in fuel effects on a variety of engines for various mission points, environmental conditions, and engine deterioration levels. Additionally, Jeff is responsible for estimating non-drop-in fuel effects that arise from conceptual design changes to engine thermal management systems that lead to increased reliance on fuel as a coolant instead of compressed air.
- Gurhan Andac (GE-Aviation) is a combustion engineer who is responsible for coordinating the efforts at GE in support of this project.

Project Overview

It has long been understood that increasing the reliance on jet fuel as a primary coolant for both the engine and the aircraft has significant performance and efficiency benefits relative to the use of air as a coolant [1], but fuel degradation and coking at high temperatures restrict how much heat can be put into the fuel. In some military applications, the performance benefits are sufficiently large to justify the creation of specialty fuels such as JP7 and JPTS, which can tolerate much higher temperatures than petroleum-derived Jet A or Jet A1 (JP8) [2]. In land-based applications of gas turbines, weight is of little consequence; thus, the operations of waste heat recovery (WHR) for plant efficiency or the cooling of combustor inlet temperature for emission reductions can be accomplished in a wide variety of ways, all of which are impractical for flight because of their impact on the mass of the power plant. Nonetheless, these applications provide some common examples of how controlling the air temperature along its flow path through the engine can have a large impact on performance, durability, and energy efficiency [3]. The flurry of works relating to fuel deoxygenation [4] and other ways to decrease coking propensity and its impacts [5] is largely motived at the sponsorship level by these benefits.

More recently, sustainable alternative fuels (SAF) have received much attention because they can contribute to high-priority geopolitical goals to diversify energy supply chains and reduce greenhouse gas emissions. Most of these efforts have focused on streamlining the evaluation and approval processes to use synthetic fuels at some blend ratio with petroleum-derived jet fuel to create a so-called drop-in fuel that can be used within existing infrastructure without objection from any stakeholders [6],. Additionally, there have been discussions regarding characteristics of synthetic blend components (such as low aromatics, high specific energy, and high thermal stability) that would make these components attractive to consider as potential specialty fuels (such as JPTS) or high-performance fuels. Kosir et al. [7] recently published work highlighting the efficiency gain that can be expected from the use of fuels with high specific energy, which relates to a lower aircraft weight at take-off, corresponding to a lower mass that must be moved and held against the force of gravity.

The weight of fuel uplifted to an aircraft, as necessary to complete its mission, is certainly an important component to consider in assessing the integrated engine/aircraft energy demand and efficiency. The energy efficiency of the engine is also expected to be influenced by other fuel properties, including the following:

1. **Hydrogen/carbon (H/C) ratio**. Through its impact on combustor exhaust gas composition, this ratio has a small impact on the ratio of heat capacities (gamma), combustor exit temperature, and work extracted during expansion through the turbine, even when the total enthalpy created at the combustor is unchanged.
2. **Viscosity**. Viscosity impacts the heat transfer coefficients, which ultimately determine how much waste heat is recovered by the fuel (coolant) and delivered back to the engine via the combustor.
3. **Energy density**. Energy density, measured in joules per liter (J/L), impacts volumetric flow rates, which also impact heat transfer coefficients.
4. **Specific heat**. The specific heat influences heat transfer coefficients but, perhaps more importantly, also has a direct impact on the temperature rise in the fuel per unit of heat energy absorbed, which in turn may impact the coking rate.
5. **Coking rate**. The coking rate drives several high-level design decisions relating to the thermal management of an engine. Coking rate is also known as fuel thermal stability,

Task 1 – Identify/Create Model of Jet Engine Including All Components Necessary to Accomplish Evaluation of the Impact of Fuel Properties

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Objectives

This work has three primary objectives. The potential impact of fully synthetic SAFs on the specific fuel consumption (SFC) of a jet engine with no associated change in engine design or logic will be assessed in Phase 1. In Phase 2 the impact of leveraging the high thermal stability of SAF candidates by increasing WHR up to a limit driven by the requirement that the fuel vapor pressure must remain below the normal working fuel pressure for all operating conditions will be evaluated. To achieve an increased WHR for this phase of the assessment, only straightforward, evolutionary design changes will be considered. In Phase 3, the aim is to identify and examine the coupled influence of increased WHR with optimized cooling flow schedules [8] will be identified and discussed.

Research Approach

At some level, one might argue that the maximum additional WHR is determined by the proposed shift in the maximum fuel temperature requirement, for instance, (160-127)*Cp, where 160 °C is the proposed temperature for high-thermal-stability fuels, 127 °C is the requirement corresponding to petroleum-derived Jet A, and Cp is the heat capacity of the proposed fuel. While this is true at some level, it provides only part of the story. For this study, a fuel system thermal model (FSTM, Figure 1) was created to simulate the heat pickup of fuel in real engines. This model allows us to quantify the influence of fuel property variations on the temperature rise and WHR within existing architectures. This model also enables evaluations of conceptual-level design changes that are intended to drive more heat into the fuel. A high-level EPM (Figure 2) was created to enable evaluations and comparisons of different conceptual designs that drive the same amount of total heat into the fuel (approximately 33*Cp more than baseline) but take heat from difference sources. The EPM also enables evaluations of the H/C impact on combustor exit temperature and turbine work extraction, which is usually neglected in performance models because it is thought to be a small impact and the H/C ratio of fuel onboard an aircraft is generally not known. The final component in the overall impact on system efficiency is the weight, including the difference (decrease) in fuel weight necessary to complete the same representative mission, as well as the difference (increase) in weight created by the conceptual-level design changes being considered.

A distribution of properties for potential SAFs is created by virtually blending individual molecules by a random association of mole fractions, whose values are also randomly determined, with specific molecules possessing known physical and chemical properties [9,10]. The fuel properties of the mixtures are derived from the mixture definition and constituent properties according to ideal mixture blending rules, which have been documented elsewhere [11]. This trial guess at a SAF candidate is then passed through a filter to determine whether it is expected to pass ASTM D1655 and ASTM D7566 fuel specifications. If the candidate passes this filter, it is included within the distribution that is input to the FSTM and EPM as part of a simulation. See Figure 3 for a graphical representation of the fuel selection methodology. The motivation behind this approach was to maintain a physical link between different properties, as the full set of properties is derived from each fuel and the property variation is driven by fuel composition variation rather than arbitrary simulation. All liquid fuel properties include first-order temperature dependence, whereas none of the properties include pressure dependence.

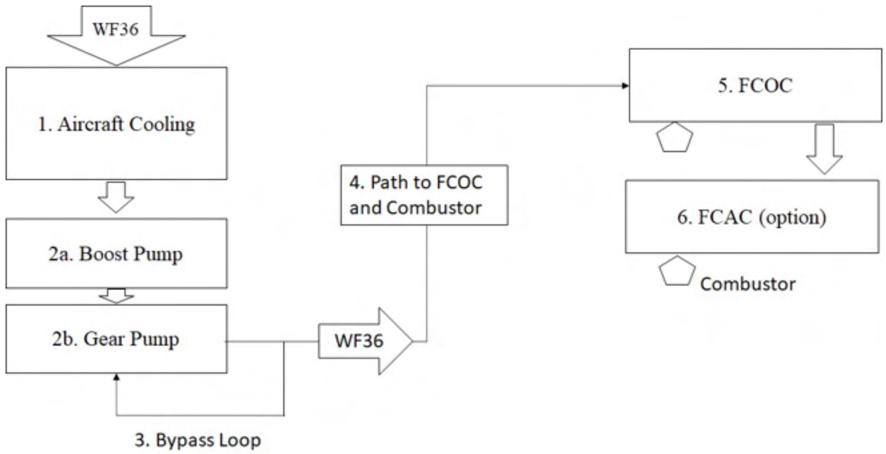

Figure 1. Block diagram of Fuel System Thermal Model for the pilot study [12] and fuel optimization. The optional sixth element is a fuel-cooled air cooler.

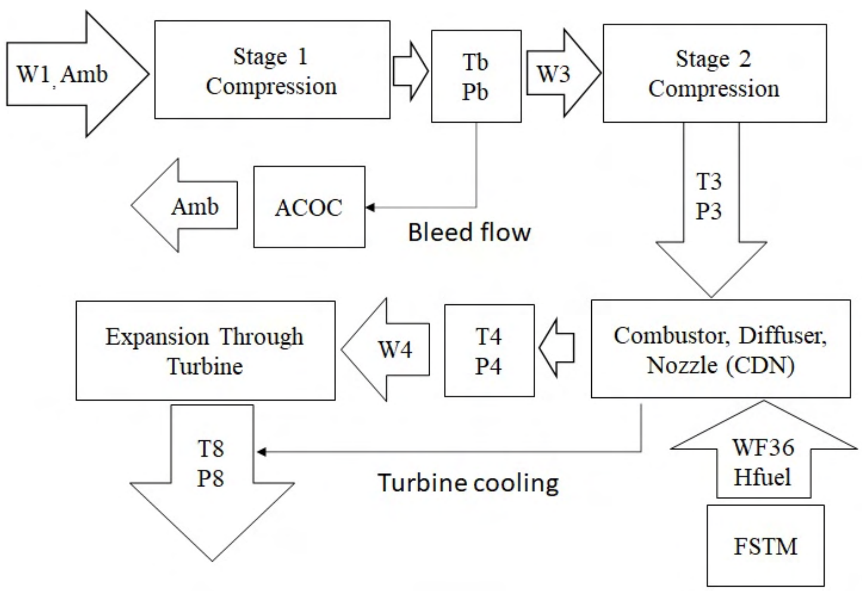

Figure 2. Block diagram of Engine Performance Model for the pilot study [12] and fuel optimization.

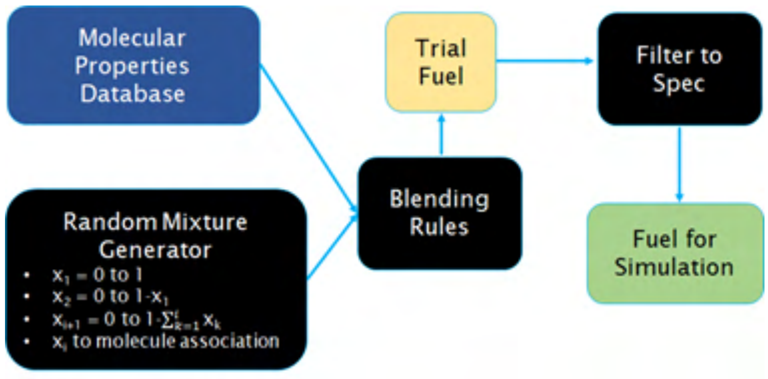

Figure 3. Fuel creation flow chart.

For bookkeeping convenience, the total enthalpy supplied to the engine per unit time, (W_f * LHV), is to be conserved for all initial simulations. The net work per unit time (P_{net}) from the engine (expansion plus compression) varies in these simulations depending on fuel composition and conceptual design, in contrast to real applications, where thrust * air speed (~P_{net}) would be conserved and the fuel flow (W_f) would be changed to meet that demand. Once the initial calculation is made, the fuel flow is varied in the simulation, as it would be in a real engine, until P_{net} is equal to its value for the baseline engine model and reference fuel. The relative difference in fuel flow between the initial and final calculation is the energy savings.

A graphical summary of the methodology is provided in Figure 4. Major inputs include the diameters and lengths of each element in the FSTM, engine operating conditions such as the pressure ratio and air flow splits at each station in the EPM, the baseline fuel-to-air ratio, and temperature boundary conditions for the FSTM. Several fuel properties are provided to the FSTM, while the EPM receives the H/C ratio and lower heating value (LHV) as input.

A validation of this model, relative to fuel property influences and cooling strategy, will be accomplished by comparison to audited performance models of jet engines produced by GE-Aviation.

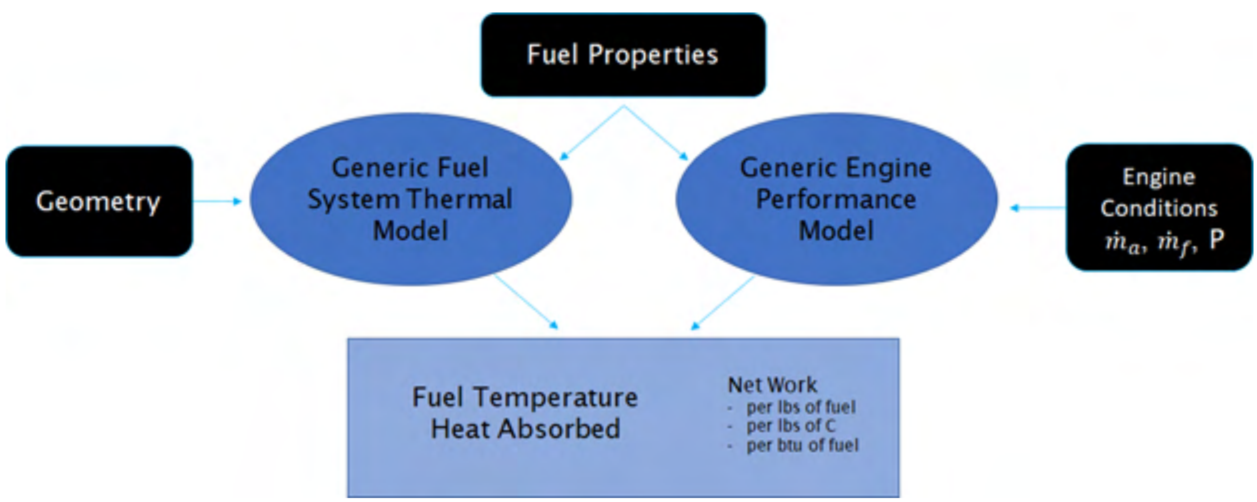

Figure 4. Flow chart of fuel effects and conceptual design evaluation.

Task 2 – Build and Apply a Heat Transfer Model for the Fuel System

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Objective

The goal of this task was to create a model that would output heat absorption, representative of real jet engine fuel systems, based on applied boundary conditions such as fuel properties, fuel velocity and momentum, and hot-side temperatures.

Research Approach

The fuel system was broken down into elements for which the author had experience-based guidance relating to fuel inlet and outlet temperatures. In concert with experience-based guidance relating to fuel momentum and system pressure losses, the fuel system geometry, including the flow diameter and length, and hot-side boundary conditions were established for a baseline fuel flow through the modeled fuel system. This model then became the basis for assessing the impact of varying fuel properties.

In the pilot study [12], Monte Carlo simulations resulted in population distributions plotted against the normalized waste heat recovery (WHR), as shown in Figure 5. In this context, the recovered waste heat is defined as the total heat absorbed by the fuel in route from the fuel tank to the combustor, which is then divided by the reference enthalpy of the fuel ($LHV*W_f$) supplied to the combustor for the initial calculation of P_{net}. At high power, the fuel flow rate is approximately ten times higher than it is at low power, and the flow within the fuel system is turbulent regardless of the fuel properties. Under these circumstances, heat transfer coefficients are not very sensitive to fuel property variations, and thus, the two curves representing high-power operation are nearly vertical. At low-power operation, the flow within the fuel system starts out as laminar and transitions to turbulent as the viscosity drops with increasing fuel temperature. Under these circumstances, heat transfer coefficients are quite sensitive to fuel property variations, and thus, the two curves representing low-power operation show 0.2% variation in the normalized WHR.

This term is not expected to have a large impact on the overall system efficiency because relatively little fuel is used at low power (top of descent) relative to take-off, climb, or long-haul cruise and because WHR is small compared with $LHV*W_f$. Nonetheless, this savings is worth optimizing because it can be potentially realized without sacrificing any other measure of fuel performance and without any change to the engine. We have already begun to optimize the fuel composition to maximize the LHV and total savings resulting from WHR, which will be discussed further under Task 4. In support of this goal, we have collected the necessary property data for thousands of molecules, which have been pruned to 1,124 molecules based on volatility, expected thermal stability, data completeness, and data consistency relative to similar molecules. We have also added the capability to predict the smoke point for each random composition.

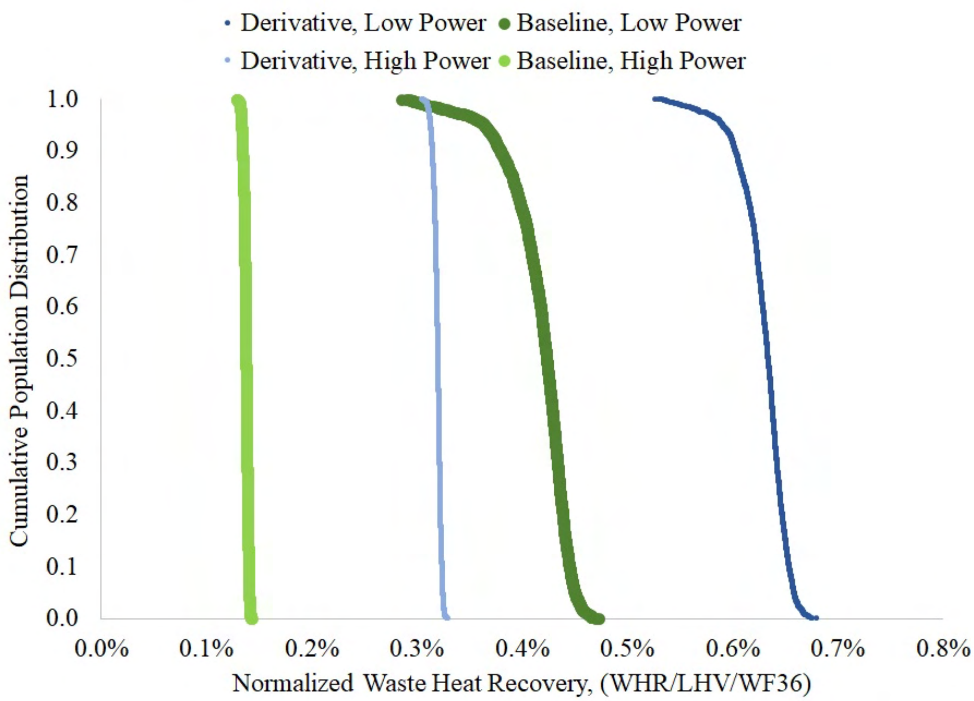

Figure 5. Impact of fuel properties on heat recovered from the engine by the fuel.

Task 3 – Identify Engine Cooling Trades That Can Be Leveraged to Optimize Engine/Aircraft System Efficiency

University of Dayton and GE-Aviation

Objective

The goal of this task was to document ideas relating to how OEMs might design an engine thermal management system to minimize air pressure losses due to cooling or to reduce the overall system weight by capitalizing on the improved thermal stability of fully synthetic SAFs. This task also focused on estimating the savings afforded by each design change concept.

Research Approach

One advantage of simplified EPMs is that they facilitate conceptual design trades. For this project, we have considered four conceptional design variations to the thermal management system that increase the reliance on fuel as a coolant. The simplest concept is to add a heat exchanger anywhere in the system, sized such that the fuel temperature at the limiting design point is increased from its current limit, taken as 127 °C, up to a new higher limit, taken as 160 °C. The current limit is driven by fuel thermal stability. Once this limit is elevated via high-quality synthetic fuel, the next temperature limit is driven by elastomeric material specifications or platform/fuel volatility requirements, which coincidentally are both near 160 °C for existing elastomeric seals and conventional jet fuels. Provided that the heat recovered by this new heat exchanger is truly waste heat and neglecting the impact of the exchanger's weight on aircraft fuel efficiency, the afforded energy savings of this configuration can be determined without an EPM or FSTM under the design-limiting operating condition, although the FSTM is necessary for other operating conditions. This simple configuration is labeled as "D" in Figure 6. In the next simplest concept, the fuel-cooled oil cooler is enlarged just enough to enable elimination of the air-cooled oil cooler. Such a configuration would be lighter than the baseline engine, which would provide some fuel efficiency benefit at the system level, but this aspect is neglected in the calculations summarized in Figure 6. This configuration is labeled as "C" in Figure 6. The large difference between the savings at high power and the savings at low power for this configuration arises because the sink pressure (altitude-dependent ambient pressure) is unrelated to the pressure ratio achieved by the first stage of compression. The savings at the design point are driven by an input to the model, namely, the fraction of heat taken out of the lube oil by air, with the remaining heat taken out by fuel. Presently, there is significant uncertainty in the aero-savings estimate for this configuration; thus, work is underway at GE-Aviation to make a much better estimate by using a derivative of an audited performance model of a GE engine for a narrow-body airframe. This estimate will also include the influence of the weight savings. However, based on an NPSS map function representation of the heat exchanger performance, GE has

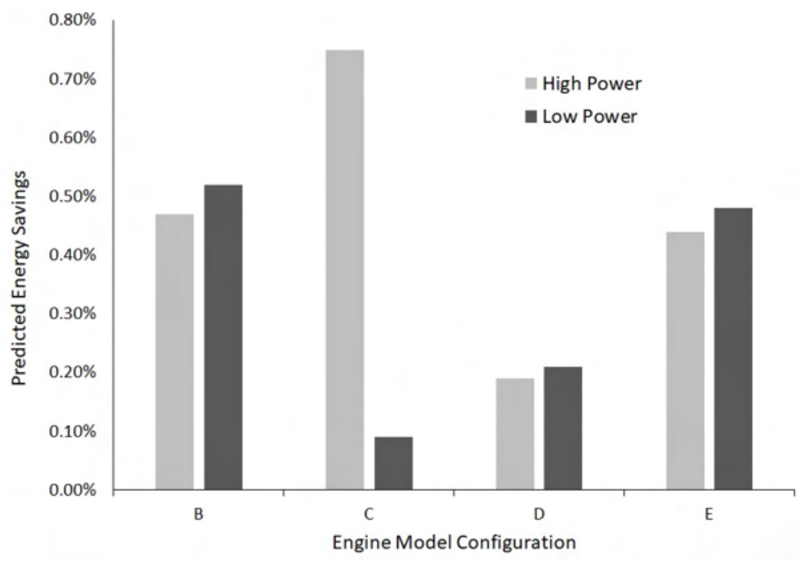

Figure 6. Summary of predicted energy savings for a variety of engine model configurations. B. Cooled cooling air with a reduced cooling flow. C. Enlarged fuel-cooled oil cooler in place of an air-cooled oil cooler. D. Cooled cooling air alone. E. Cooled cooling air and improved turbine efficiency (0.700 to 0.701)

determined that complete elimination of the ACOC in this application would not be possible unless the maximum fuel temperature limit were raised by 107 °C instead of the 33 °C increase presumed for this analysis based on the fuel system material limits (e.g., elastomers) and fuel volatility. In the most involved concept, the cooled cooling air is coupled with active clearance control of the turbine airfoils. The configuration representing this concept is labeled as "E" in Figure 6. The turbine efficiency is an input to the EPM, and the difference between the savings of configuration E and the savings of configuration D is primarily driven by this input. The fuel savings is approximately double the increase in turbine efficiency because the Brayton cycle efficiency (i.e., overall engine efficiency) is approximately 50%. While this term is represented by the arbitrary choice of a 0.1% improvement in turbine efficiency for all operating conditions, a detailed design of an active clearance control concept is needed to estimate how airfoil clearances change with cooling airflow split variation. The airflow supplied to the regions that most need cooling (usually the mid span of the blades and vanes) can be reduced when the cooling air is cooled. This frees up air flow that can be used to cool the case (outer diameter) under operating conditions (usually high power) in which the clearance between the case and the blades is highest. To determine the impact on gap height, a detailed heat transfer analysis is required, and to gauge the impact of a gap height change on the aerodynamic efficiency of the engine, a detailed fluid dynamics calculation is needed. These analyses require a full definition of product geometry, which is obviously OEM-proprietary. Although we have requested that GE-Aviation include representative results of such a concept as part of their contribution to this project, they have not agreed to this request. Because turbine inefficiency is generally the largest source of engine inefficiency after accounting for the unavoidable heat engine (Brayton cycle) inefficiency, there is a strong possibility that cooled cooling air can be utilized most effectively by coupling it with active clearance control.

The configuration labeled as "B" in Figure 6 is the same configuration labeled as "derivative" in Figures 5 and 7. For this configuration, the total turbine cooling air flow budget is reduced such that the change in enthalpy of the cooling air is matched to that of the baseline configuration at high power. In this study, the cooling flow was reduced to 29.75% of W3, compared with 30.00% of W3 for the baseline configuration, where 30% was an input to the model. By comparing the results for configuration B with those for configuration D, we can see that the savings achieved by reducing parasitic air flows can exceed the savings obtained from improvements in WHR.

By definition, none of the thermal management system design changes considered here correspond to drop-in fuel benefits. To take advantage of the higher thermal stability of SAFs relative to conventional jet fuel and to improve specific fuel consumption, some design changes are necessary. Such changes should be expected to afford an improvement of 0.5%, which compares favorably with the savings that could potentially be realized on a drop-in basis, as discussed in the next section.

Task 4 – Estimate Gains in Fuel Efficiency

University of Dayton and GE-Aviation

Objectives

The first goal of this task is to estimate the impact of fuel property variation on engine-level fuel consumption (specific fuel consumption (SFC). The second goal is to optimize fuel composition in order to minimize the SFC while maximizing the specific energy (LHV), which could minimize aircraft fuel consumption where fuel LHV is factored into the mass of fuel uplifted into the aircraft.

Research Approach

To accomplish the first goal, the tools developed in Tasks 1 and 3 were used in conjunction with a Monte Carlo simulation of fuel composition derived from a database of 94 molecules, where a filter was used to eliminate random compositions that led to certain properties outside of fuel specifications or fit-for-purpose properties, as predicted via algebraic blending rules. For the second goal, we improved our approach regarding the SAF volatility requirements, added a requirement for the smoke point, and placed a limit on the number of ingredients allowed in the fuel. In addition, the database was expanded to 1,124 molecules. A small (un-converged) Monte Carlo simulation serves as the starting point for optimizing the randomly chosen mole fractions of each molecule from the master database. The engine-level fuel economy and LVH are maximized via mixed-integer distributed ant colony optimization (MIDACO). To arrive at a global solution set, this process is repeated multiple times until all molecules in the database have been chosen at least once by the initializing small Monte Carlo simulation.

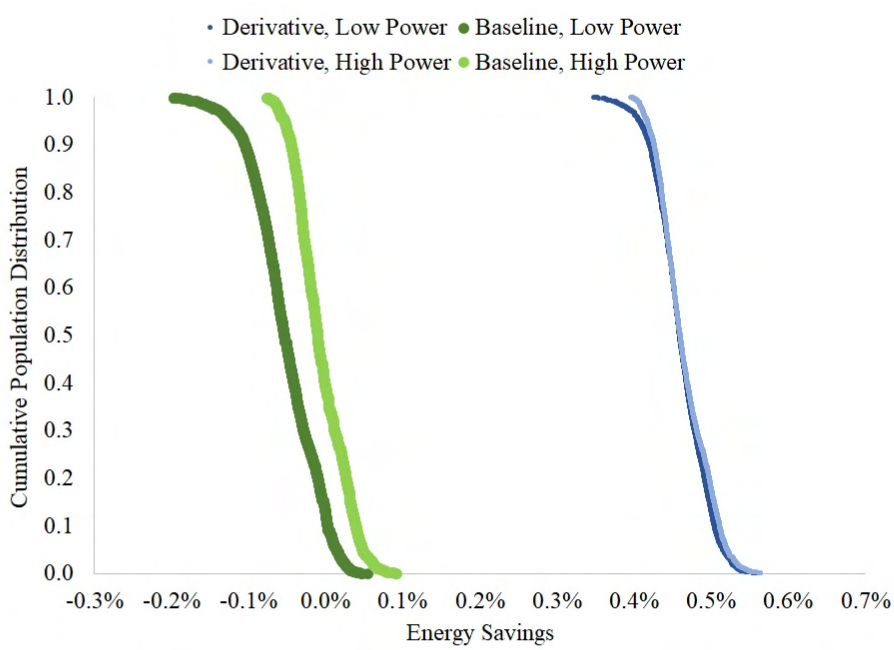

Figure 7. Impact of design and fuel property on fuel energy savings.

A summary of the predicted energy savings relative to the baseline EPM model and the reference petroleum fuel labeled as "A-2" by the National Jet Fuel Combustion Program is provided in Figure 7, which shows the following key trends. First, by leveraging the improved thermal stability, the design change has a significantly larger impact on savings (i.e., fuel efficiency) than fuel property variation. Second, the impact of fuel property variation, including the width of each curve (shown) and the rank order of SAF candidates (not shown), is nearly the same for each EPM configuration, hinting at insensitivity to engine-to-engine variation. Third, the impact of fuel property variation changes for various engine operating conditions (note the differences in curve width and how much of each baseline (green) curve is above 0%). While not evident from this plot, the primary driver of this sensitivity is the fuel-to-air ratio. For a high fuel-to-air ratio and high fuel flow rate, the composition of the combustor exhaust air (driven by the fuel H/C ratio) has the greatest effect. In contrast, for a low fuel-to-air ratio and low fuel flow rate, the WHR is just as important as the vitiated air composition. This sensitivity has directed us to generate a realistic mission mix of operating conditions as a basis for assessing drop-in fuel effects on engine efficiency.

Our pilot study showed that ~20% of the 2,000 randomly chosen SAF candidates afford some savings relative to the reference fuel (A-2) at low power, while 50% afford some benefit at high power. The status of our SAF composition has identified two SAF candidates with an engine SCF benefit as well as a weight savings relative to A2 and hundreds of solutions that offer one or the other, as shown in Figure 8. The candidates on the lower end of this range have higher LHVs than those on the higher end of this range.

While the SAF composition optimization is in progress, GE-Aviation is also working to provide an estimate of savings that could result from configurations B and C (see Figure 6). If they determine that the savings from configuration C exceed our estimate for both B and C, it may be unnecessary to make an estimate for B because C is viewed as a configuration that is relatively easy to implement, while configuration B would be met with skepticism and resistance from the turbine design team.

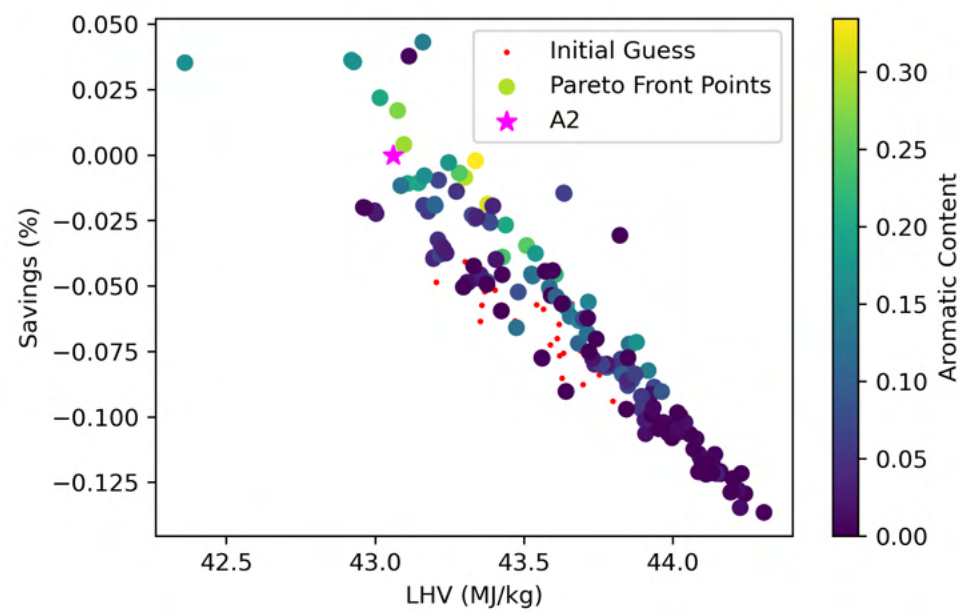

Figure 8. Current status of SAF composition optimization.

Tasks 5 & 6 – Identify, Create, and Test Blends for Thermal Stability in JFTOT and QCM

Objective
The goal of these tasks is to evaluate the solutions identified by Task 4, goal 2 for thermal stability.

Research Approach
The solutions identified in Task 4.2 will be analyzed to find common threads in terms of fuel properties and compositions. It is expected that a relatively small number of molecules will show up with high concentration in several solutions, and we will discuss these molecules with experts regarding their potential impact on thermal stability. Any such molecule, judged by subject-matter experts to present an elevated risk of coking relative to isoparaffins, will be targeted for experimental evaluation of thermal stability at varying concentrations. Other factors to consider in these selections include availability of the molecule and its potential impact on seal swelling and freeze points.

These tasks cannot be initiated until more progress is made on the fuel optimization. Meanwhile, significant progress (under FAA project 65) toward a simple and reliable blending rule for the freeze point may facilitate automated evaluation of freeze points of solutions along the pareto front, which could significantly narrow the scope of the thermal stability evaluations.

Milestones
1) The conceptual design of a model jet engine to serve as a tool for evaluating the impact of fuel property variation on jet engine fuel efficiency was completed (Aug. 2020).
2) Preliminary construction of this model, including integration with Monte Carlo methods and verification of heat transfer coefficient correlations, was completed (Oct. 2020).
3) Three potential cooling trades have been identified, and the sub-models needed to execute these trade studies were built (Nov. 2020).
4) A database of 2,000 fully synthetic SAF candidates and a variety of reference fuels was created (Nov. 2020).
5) The simulations necessary to support the proof of concept were completed (Nov. 2020).
6) A scientific paper summarizing this progress was accepted for publication (Jul. 2021).
7) The number of entries in the molecular properties database was increased from 94 to over 2,000 (Jul. 2021).
8) Data consistency and completeness were verified (Oct. 2021).
9) A model was built and validated to generate smoking propensity data for all molecules in the database (Oct. 2021).
10) A scientific paper covering smoking propensity models was submitted for publication (Nov. 2021).
11) All models used in proof-of-concept work were integrated into JudO, which has been previously used [7] to optimize fuel composition against defined objectives (Sep. 2021).
12) A smoke point filter was added to JudO, and volatility-related predictions and filters were streamlined (Aug. 2021).
13) The first successful evolution toward optimized SAF composition was achieved (Nov. 2021).

Major Accomplishments
- As a major accomplishment, we constructed and verified the FSTM and EPM and their integration with Monte Carlo methods, which was necessary to complete most of the remainder of this project.
- A proof-of-concept paper was published in the journal *Fuel*.
- All tools needed to assess fuel effects on SFC were integrated into our internal code for SAF optimization (JudO).
- The molecular properties database was expanded 10-fold.
- A model was created to estimate the smoking propensity of potential SAF constituents.

Publications
Boehm, R. C., Scholla, L. C., & Heyne, J. S. (2021). Sustainable alternative fuel effects on energy consumption of jet engines. Fuel *304*, 121378. https://doi.org/10.1016/j.fuel.2021.121378

Boehm, R. C., Yang, Z., & Heyne, J. S. (2021). *Threshold sooting index of sustainable aviation fuel candidates from composition input alone: Progress toward uncertainty quantification. energy and fuels.* Manuscript submitted for publication.

Outreach Efforts
None

Awards
None

Student Involvement
- Logan Scholla (University of Dayton) is a graduate student research assistant who was responsible for the properties databases used in the proof-of-concept work during his tenure of involvement with this project.
- Lily Behnke (University of Dayton) is a graduate student research assistant who integrated the fuel efficiency models in JudO and is responsible for the ongoing fuel optimization. She will also be primarily responsible for Tasks 5 and 6 going forward.
- Jack Hoog (University of Dayton) is an undergraduate student research assistant who is assisting with the implementation of a mission mix of engine operating conditions for assessing the fuel effects on SFC determinations. Hoog is also helping with the evaluation of SAF definitions produced by JudO / MIDACO.

Plans for Next Period
- Complete integration of the mission mix into the energy savings objective function
- Complete engine cooling and weight trade studies
- Complete a sketch/map of fuel effects on engine performance
- Complete SAF composition optimization
- Identify a set of molecules that strongly contribute to optimized SAF compositions (golden molecules)
- Evaluate the seal swell, freeze point, T90–T10, and producibility options for a random selection of pareto-front SAF candidates
- Evaluate system energy savings by integrating fuel weight effects on aircraft energy consumption with engine energy savings
- Submit a scientific paper on high-performance SAF candidates
- Qualitatively evaluate the coking risk of golden molecules and hand-picked pareto-front SAF candidates
- Execute thermal stability tests of promising SAF candidates

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