Project 66 Evaluation of High Thermal Stability Fuels

University of Dayton and University of Dayton Research Institute

Project Lead Investigator

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University Participants

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- P.I.s:
    1. Joshua Heyne, Associate Professor
    2. Randall Boehm, Research Engineer
- FAA Award Number: 13-C-AJFE-UD, Amendments 27 and 30
- Period of Performance: June 5, 2020 to August 10, 2021
- Tasks:
    1. Identify / create model of jet engine including all components necessary to accomplish evaluation of the impact of fuel properties.
    2. Build and apply heat transfer model of fuel system.
    3. Identify engine cooling trades that could be leveraged to optimize engine / aircraft system efficiency.
    4. Estimate gains in fuel efficiency.

Project Funding Level

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

Cost share is provided by the University of Dayton and 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 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 effort on this project.
- Logan Scholla (University of Dayton) is a graduate student research assistant who is currently responsible for properties databases with additional responsibilities to be added as per capability.
- Giacomo Flora (University of Dayton Research Institute) is a research engineer who is serving in an advisory capacity on this project.
- Lily Behnke (University of Dayton) is an undergraduate student research assistant who is collecting information related to fuel thermal stability.

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][1], but fuel degradation and coking at high temperatures restricts how much heat can be put into the fuel. In some military applications, the performance benefits are large enough to justify the creation of specialty fuels such as JP7 and JPTS, which can tolerate much higher temperatures relative to petroleum-derived Jet A or Jet A1 (JP8) [2].[2] In land-based applications of gas turbines, weight is of little consequence, so the operations of waste heat recovery (WHR) for plant efficiency or the cooling of combustor inlet temperature for emissions reduction 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 the coking propensity or its impacts [5] are largely motived at the sponsorship level by these benefits.

More recently, sustainable alternative fuels (SAF) have received a lot of attention because they are, or can be, part of high-priority geopolitical goals to diversify energy supply chains and reduce greenhouse gas emissions. While the focus of most of these efforts have been around 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 of the stakeholders [6], there have also been discussions around characteristics of the synthetic blend component (such as low aromatics, high specific energy, and high thermal stability) that make them attractive to consider as potential specialty fuels (such as JPTS) or high performance fuels. Heyne, et al. recently published work highlighting the efficiency gain that can expected to result from use of fuels with high specific energy, which all traces back to lower aircraft weight at take-off, meaning less mass to move and hold against the force of gravity [7].

The weight of the fuel uplifted to an aircraft, as necessary to complete its mission, is certainly an important component to the integrated engine and aircraft energy demand and efficiency. There is also expected to be an impact on the energy efficiency of the engine related to other properties of the fuel, including:

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) and combustor exit temperature, even when the total enthalpy created at the combustor is unchanged.
2. **Viscosity**. Viscosity impacts the heat transfer coefficients that ultimately determine how much waste heat is recovered by the fuel (coolant) and delivered back into 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 also has some effect on heat transfer coefficients, but perhaps more importantly 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**. Also known as fuel thermal stability, the coking rate drives several high-level design decisions relating to the thermal management of an engine.

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

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

Research Approach

At some high 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 what we are proposing 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) was created to simulate the heat pickup of fuel in real engines. This model makes it possible to quantify the influence of fuel property variation on temperature rise and WHR within existing architectures. It also enables evaluations of conceptual level design changes that are intended to drive more heat into the fuel. A high-level engine performance model (EPM) was also created to enable evaluation and comparison of different conceptual designs that drive the same amount of total heat into the fuel (approximately 33*Cp more than baseline), but taking that heat from difference sources. The EPM also enables evaluation of 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 of fuel onboard an aircraft is not generally known. The final piece to 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 that are considered.

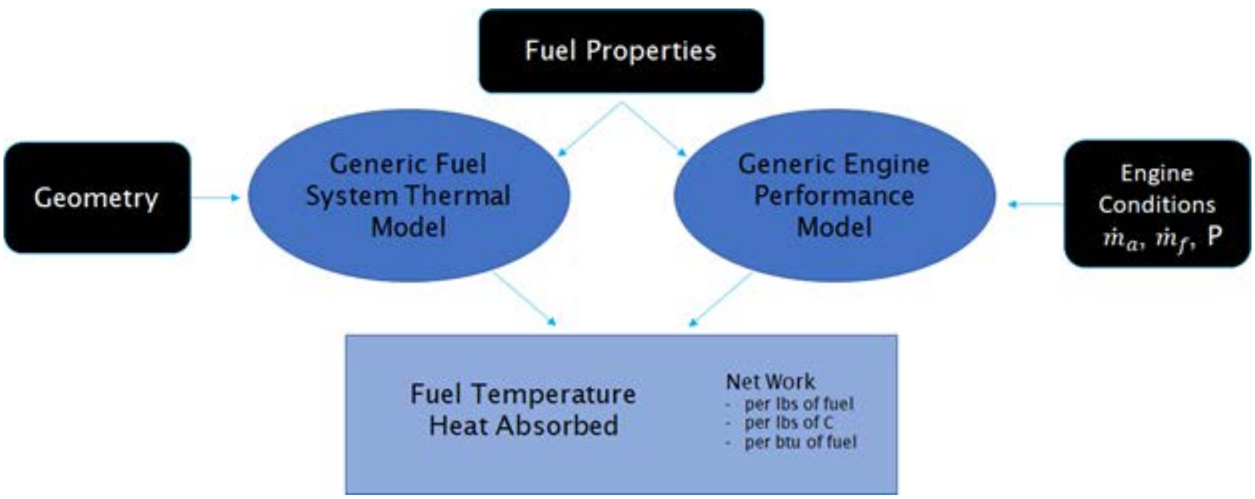

Figure 1. Fuels effects and conceptual design evaluation flow chart.

A distribution of properties, for potential SAF, is created by virtually blending individual molecules together by random association of mole fractions, whose values are also randomly determined, to each of forty-nine specific molecules with known physical and chemical properties [9]. Each fuel property of the mixtures is derived from the mixture definition and constituent properties according to ideal mixture blending rules which have been documented elsewhere [7]. 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 it passes this filter, it is included within the distribution that is input to the FSTM and EPM as part of a Monte Carlo simulation. 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, and none include pressure dependence.

For bookkeeping convenience, the total enthalpy supplied to the engine per unit time, (W_f * LHV), is to be conserved for all simulations. The net work per unit time (P_{net}) from the engine (expansion plus compression) will vary in these simulations depending on fuel and conceptual design, which is counter 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.

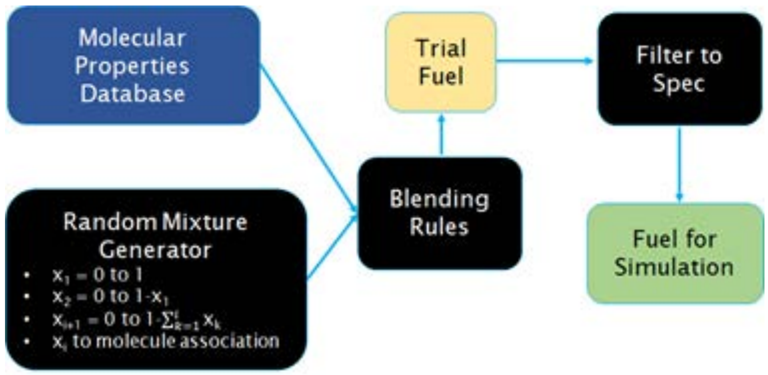

Figure 2. Monte Carlo fuel creation flow chart.

The Monte Carlo simulations will result in population distributions plotted against heat delivered to the combustor (H), covering the output from the FSTM, and to cover output from the EPM, the populations will be plotted against P_{net}. The predicted impact on fuel burn is determined by iteratively running the EPM until P_{net} of the trial fuel and design concept matches P_{net} of the reference fuel and design concept. The predicted savings depends on several assumptions that are part of the EPM. The impact of these assumptions on the target output of the study (fuel savings) will be discussed and evaluated for select cases by replacing the high-level EPM used for the Monte Carlo simulations, with a higher-fidelity engine performance model, built and simulated within the NPSS architecture distributed by NASA [10].

Progress toward assessment of SAF impacts on SFC

To date, significant milestones include: (1) the creation of the database of fully synthetic SAF candidates, (2) development and verification of the FSTM and EPM, and (3) completion of a case study which includes 2000 potential fuels.

The predictions suggest that viscosity has the largest impact on WHR at low power while volumetric flow rate (represented by energy density) has the largest impact on WHR at high power, as shown in Figure 3. A likely cause for the shift in the importance of viscosity is that flow throughout the fuel system transitions between laminar and turbulent when operating at low power conditions while it is fully turbulent at high power conditions. The net power is influenced most strongly by WHR when operating at low power and by H/C ratio (combustion products, Cp, and γ) when operating at high power, as shown in Figure 4. A likely cause for the shift in the importance of WHR is that its variation is a larger fraction of P_{net} at low power conditions compared to high power conditions, while a likely cause for the shift in the importance of H/C ratio is that the fuel to air ratio is twice as high at high-power conditions relative to low-power conditions.

The impact to fuel energy consumption varies sharply with cycle conditions (low versus high), as well as engine design concept and component efficiencies. For the Phase 1 cases we have completed, given the set of assumptions we have made, the impact to fuel energy consumption ranges from -0.3% to +0.2% at high power. Application of this set of assumptions to Phase 2 (elimination of the air cooled oil cooler (ACOC) with concurrently a larger fuel cooled oil cooler (FCOC) installed) and Phase 3 (introduction of a FCOC to extract heat from the turbine cooling air and reduce its flow) efforts leads to a prediction of 10-15% savings at high power. Since this number is simply too high to believe, we are currently in the process of auditing our in-house EPM to understand why this prediction is so large, and concurrently we are working toward building the NPSS engine performance model.

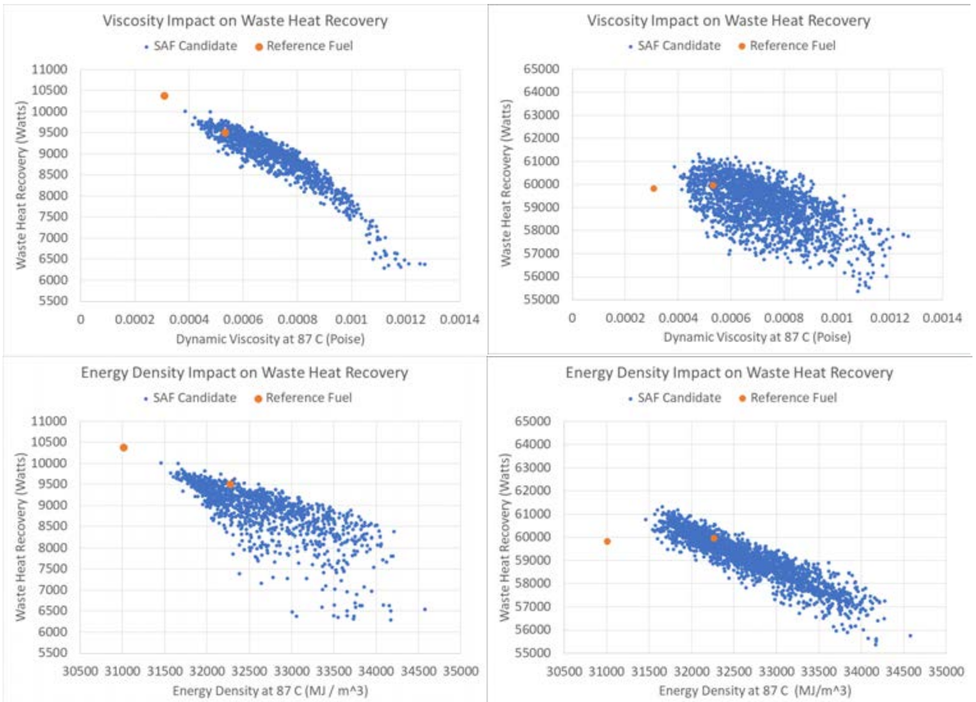

Figure 1. Main effects on waste heat recovery at low (left) and high (right) power.

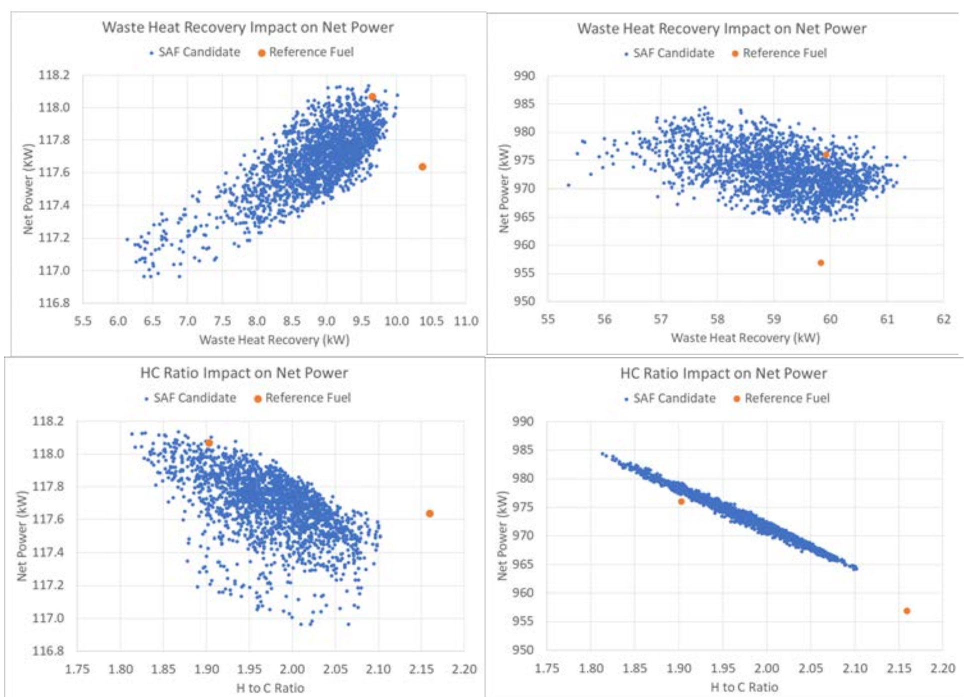

Figure 2. Main effects on net power from engine at low (left) and high (right) power.

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Milestones

1) The conceptual design of the model jet engine to serve as tool for evaluating the impact of fuel property variation on jet engine fuel efficiency was completed- 08/31/2020.
2) The preliminary construction of this model, including integration with Monte Carlo methods and verification of heat transfer coefficient correlations was completed- 10/29/2020.
3) Potential cooling trades leveraging active clearance control have been identified. A model to estimate W36/W3 as a function of heat extracted from the turbine cooling air, by the proposed FCOC has been built and will serve as a baseline for subsequent trades involving active clearance control.
4) The creation of the database of 2,000 fully synthetic SAF candidates and a variety of reference fuels was completed- 11/17/2020.
5) The simulations necessary to support Phase 1 of the project were completed- 11/25/2020.

Major Accomplishments

Construction and verification of the FSTM and EPM and their integration with Monte Carlo methods was a major accomplishment, which was necessary to complete almost all of the remainder of this project.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

- Logan Scholla (University of Dayton) is a graduate student research assistant who is currently responsible for properties databases with additional responsibilities to be added as per capability.
- Lily Behnke (University of Dayton) is an undergraduate student research assistant who is collecting information related to fuel thermal stability.

Plans for Next Period

- Complete heat audit of the EPM and report its findings.

- Complete rollup of weight change estimates associated with the design changes considered for Phase 2 and the weight of fuel and document these estimates.
- Develop NPSS performance model of engine and collaborate with experts who are familiar with engine mission cycles and high-fidelity performance models in order to gain confidence in the assumptions used in this program.
- Write draft manuscript of first peer-reviewed article to result from this work.
- The framework for assessing the impact of cooling trades will be laid out and some examples will be described. For example, what if the ACOC is eliminated versus what if the turbine cooling air flow is reduced, as enabled by fuel cooling of some fraction of that bleed flow.
- Expand database of molecules used to create the SAF candidates and revise the filters based on what we have learned so far to create a second set of candidates that are more likely to result in significant fuel savings.
- Add to the database of reference fuels to provide additional fidelity to the comparisons drawn.