

# Performance of synthetic jet fuels in a meso-scale heat recirculating combustor



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## HIGHLIGHTS

- Performance of alternative fuels examined in meso-scale heat recirculating combustor.
- Performance of the alternative fuels compared with conventional petroleum-based fuel.
- Global combustion behavior as well as thermal efficiency was analyzed.
- Instabilities observed for combustion of petroleum fuel but not in alternative fuels.
- Fuel component impact flame stability and thermal performance in meso-scale combustor.

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## ABSTRACT

The performance of two synthetic aviation fuels was evaluated in a meso-scale heat recirculating combustor and the respective results compared with the combustion characteristics of a conventional petroleum-based jet fuel. One of the alternative jet fuels was synthesized via a Fischer–Tropsch (F–T) fuel process, while the other was produced from tallow (bio-jet fuel). The petroleum-based fuel used in this study was JP-8. The combustion and extinction behavior of the above fuels and their mixtures (50% synthetic fuel and 50% JP-8 by volume in JP-8) in the meso-scale combustor using oxygen under fuel-rich and fuel-lean non-premixed combustion conditions was examined. The synthetic fuels exhibited stable combustion over a range of equivalence ratios at each fuel flow rate; however, stable combustion was not achieved for JP-8 under any of the examined conditions. The mixtures also exhibited somewhat unstable combustion phenomena as those seen with JP-8, but dampened enough such that mostly stable combustion could occur. Fuel characterization analysis was performed for each fuel, and their respective thermal performances evaluated. Both the F–T and bio-jet fuels reached a maximum thermal efficiency of about 95% near their respective rich extinction limits. The mixtures exhibited somewhat poor thermal performances, with a maximum thermal efficiency of about 75%. The results reveal that composition of the fuel plays a prominent role in the flame stability and thermal performance in meso-scale combustors, as more complex species (such as aromatics, found in JP-8) have a slower reaction rate than simple species. The short residence time available in the combustion zone of the micro-combustion chamber does not allow to fully combust the complex fuel species, resulting in flame instability and formation of soot.

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## 1. Introduction

With the ever-growing demand for fossil fuels, the development of viable alternative fuels has garnered much interest. Two widely tested alternative fuels that may feasibly replace conventional aviation fuels are Fischer–Tropsch (F–T) fuels and hydro-treated renewable jet fuels (HRJ). Fischer–Tropsch fuels are synthesized via a process in which carbon monoxide and hydrogen

gases are converted into liquid hydrocarbons. As these fuels are composed primarily of paraffins, they are often termed “synthetic paraffinic kerosene” (SPK). Hydrotreated renewable jet fuels, or bio-jet fuels, are extracted from bio-matter, including substances such as seed oil and animal fat. Gas chromatographic analyses of F–T and HRJ fuels, performed both in this study and by other researchers [1] have shown that these two types of alternative fuels have similar molecular distributions, despite their different feedstocks. This similarity indicates greater flexibility in fuel choice between the two [2]. Many studies have been performed comparing the flame characteristics and global combustion behavior of these types of alternative fuels with conventional petroleum-based

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fuels [2–6]. An HRJ fuel produced from camelina oil has been researched and shown to perform on par with petroleum-based fuels, but with significantly lower (>67%) greenhouse gas emissions [5]. Hui et al. [2] studied three F–T SPK fuels, three HRJ fuels, and conventional Jet-A fuel to observe their respective combustion characteristics. It was found that the six synthetic fuels ignited faster and were more resistant to extinction than the Jet-A fuel, indicating more versatility for different operating conditions and combustion systems. Their findings also indicate that fuels consisting mostly or exclusively of alkanes tend to have wider stable combustion regimes. Any fuel that may potentially replace conventional fuel must be compatible with the existing infrastructure, as it would not be economically feasible to replace every single engine currently in use. Kick et al. [6] measured the flame velocity of an F–T SPK fuel and compared it to that of a petroleum-based kerosene fuel. The study showed promising results for the feasibility of F–T fuels superseding petroleum fuels; however, the researchers indicated that slight engine redesigns or modified operating conditions may be needed before they can be used in actual aircraft engines. This is due primarily to the fact that, for such large scale applications as aircraft engines, the more complex species found in petroleum fuels serve to lubricate the moving parts, and alternative fuels tend not to contain these species. These fuels have been extensively tested for large-scale applications within the aviation industry, but not as much work has been done to examine the combustion behavior of synthetic jet fuels at a smaller scale.

Much research has been done to further develop micro- and meso-scale combustion systems. The main obstacle in this type of system is that, when scaling down the combustion system, the heat loss to heat generation ratio (surface area to volume) becomes larger, which can induce flame quenching when the system is sufficiently small. There are several techniques currently in development to overcome thermal quenching in these small-scale combustion systems. Wu et al. [7] employed an asymmetrical “whirl” combustor, in which the recirculating flow served as a source of enthalpy and radical species to stabilize flames close to the quenching distance. In this combustor, there were no heat exchangers between the products and reactants, allowing for smaller overall geometry, but the characteristic length of the combustor was larger than the quenching distance at standard conditions. Ahn et al. [8] increased the amount of heat loss the system could support before succumbing to thermal quenching by using Pt catalysts to provide a reaction pathway with decreased activation energy. The use of catalysts was shown to widen the extinction regime in the low Reynolds number (low heat load) direction, and to keep chamber temperatures lower during operation. Systems utilizing structural conduction to transfer heat from the products to the reactants have been developed and analyzed by several researchers [8–14]. This technique enables combustion in “sub-quenching” dimensions, meaning any space in which the smallest dimension is smaller than the quenching distance when the reactants and the wall are held at ambient conditions. A key example of this type of combustor is the heat-recirculating, or “swiss-roll” combustor, which uses a spiral counter-current heat exchanger to preheat the reactants and is designed such that the products are always exchanging heat with the reactants. Jones et al. [15] studied this concept on a larger scale, using the combustor to burn low energy content fuels and to extend the lean flammability limits of conventional fuels. This extension in flammability limits allows flexibility for use in either energy production or thrust generation, depending on the geometry and operating conditions. Shirsat and Gupta [9] studied the meso-scale swiss-roll combustor concept in the context of thrust generation, and determined that a single-turn combustor was the optimal design to sustain a flame while minimizing heat loss and maximizing exhaust enthalpy.

The current study utilizes a single-turn heat-recirculating combustor to burn an F–T fuel, a bio-jet fuel, and a conventional JP-8 fuel with oxygen in a non-premixed injection configuration. The objective of this study is to determine the effect of reducing the scale of the combustor on the performance of each fuel, and subsequently to ascertain the influence of the fuel composition on the flame stability. The global combustion characteristics and thermal performance of each fuel are observed and evaluated.

## 2. Experimental

### 2.1. Combustor and fuels

#### 2.1.1. The micro-combustor

A single turn heat recirculating combustor similar to that developed by Shirsat and Gupta [9] was used. The fuel and the oxidizer were introduced non-premixed, with the fuel being injected through a porous alumina/zirconia ceramic heat recuperator. The non-premixed design was chosen because Shirsat and Gupta [9] reported that combustion of kerosene was not possible under any operating conditions when the fuel and oxidizer were premixed. Other researchers have utilized similar arrangements with kerosene-like fuels that have poor volatility and achieved successful vaporization [16]. This recuperator was placed inside the combustion chamber, so as to receive heat directly from the flame. The precise location was chosen such that rapid mixing and flame stabilization could occur based on the aerodynamics of the combustion volume and injected fuel. The flame is aerodynamically held within the combustion chamber by a step entrance to the chamber, which creates a vortical flow structure and a local recirculation zone, recirculating both heat and active species from the products to the reactants, with the fuel injected directly into the center of the vortex. Fig. 1 shows a schematic diagram of the combustor, highlighting the O<sub>2</sub> and fuel inlets, the combustion zone, and the direction of heat transfer between the products and reactants.

The combustor was fabricated from a monolith alumina silicate block using conventional micro machining tools. The material has a thermal conductivity of 1.98 W/m K in its green state, and has a low porosity relative to other more thermally insulating materials, such as zirconium phosphate, which has a thermal conductivity of 0.8 W/m K [9]. This makes it a suitable material for combustion with liquid fuels. Additionally, the low thermal conductivity of the material ensures large temperature gradients through the channel walls, enabling high heat transfer rates from products to reactants. Low thermal conductivity materials also allow for less heat loss from the combustion chamber, thus increasing the resistance to thermal quenching [13,17]. After machining, the combustor was heat treated for 45 min at 1050 °C with a ramp rate of 2 °C per minute. This process increased the hardness and strength of the alumina silicate, thus lessening the possibility of the material cracking due to thermal stresses.

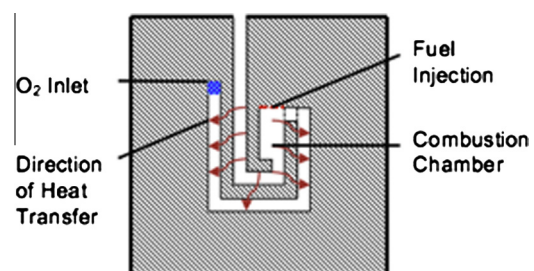


Fig. 1. Combustor schematic adapted from Shirsat and Gupta [9].

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