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Emissions of Aerospace Fuels F-24 and Jet-A in a Jet Engine and Correlation with Combustion Characteristics from a Constant Volume Combustion Chamber

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Abstract

An investigation into emissions differences and their correlations with differing combustion characteristics between F24 and Jet-A was conducted. Raw emissions data was taken from a single stage jet engine by a FTIR gas analyzer. Measurements of H_2O, CO_2, CO, NOx, and total hydrocarbon emissions (THC) were taken at 60K, 65K, and 70K RPM. At 70K RPM Jet-A and F-24 the emissions were similar at approx.: 4% H_2O, 3% CO_2, 970 PPM CO, 28 PPM NOx. Jet-A THC emissions were approx.: 1200 PPM THC, F24 THC emissions were lower by over 60%. The significantly lower amount of THC emissions for F24 suggests more complete combustion compared to Jet-A.

Introduction

Climate Change & Sustainable Aviation Fuel

In recent decades, an increasing focus has been placed on the impact that emissions have on many current environmental and health issues, chiefly climate change exacerbated by greenhouse gases. The prevalence of climate change and its apparent effects has led to international agreements and national regulation [1, 2, 3]. One such agreement, the Paris Agreement, looks to limit global temperature rise to levels below 2°C.

To meet this goal, the global aviation industry, spurred on by initiatives like the SAF Grand challenge, which sets a goal for 100% use of sustainable aviation fuel (SAF) by 2050, has been looking for practical ways to manufacture SAF [4]. Sustainable aviation fuel is currently specified under ASTM D7566, which requires that it be blended with conventional petroleum derived kerosene to meet aircraft standards [5, 6]. The maximum blending volume percent varies between SAF feedstocks, with the highest being 50%. This means that currently SAF fuels are at least 50 % composed of conventional petroleum-based kerosene such as F24 or Jet-A. As a result, the composition and emissions of sustainable aviation fuels are still largely influenced by petroleum kerosene.

F24 and Jet-A Compositions and Combustion Characteristics

The difference in fuel properties between F24 and Jet-A are an important condition for the differences in the emissions and combustion behavior. F24 and Jet-A have been studied and declared very similar in their fuel properties. The main difference between F24 and Jet-A is an additive package originally specified for JP-8 [7, 8]. These additives are corrosion inhibitor/lubricity improver (CI/LI), fuel system icing inhibitor (FSII), and static dissipator additive (SDA). However, when examined critically, there are slight differences in the fuel composition that results in a difference in combustion behavior.

Some of these differences include those found by Ryu et al. [9]. This study sought to develop a chemical kinematic reaction mechanism for F24 based on an already existing Jet-A mechanism. The results found that F24 is nearly indistinguishable from Jet-A in terms of fuel properties except for the molecular weight and the flash point. It also found that the combustion properties were also found to be slightly different, especially in the negative temperature coefficient and low temperature ranges. These differences in fuel composition and combustion can be attributed to the additives of F24 as the hydrocarbon composition was found to be nearly the same (Figure 1).

FIGURE 1 Gas Chromatography of F24 and Jet-A [9].

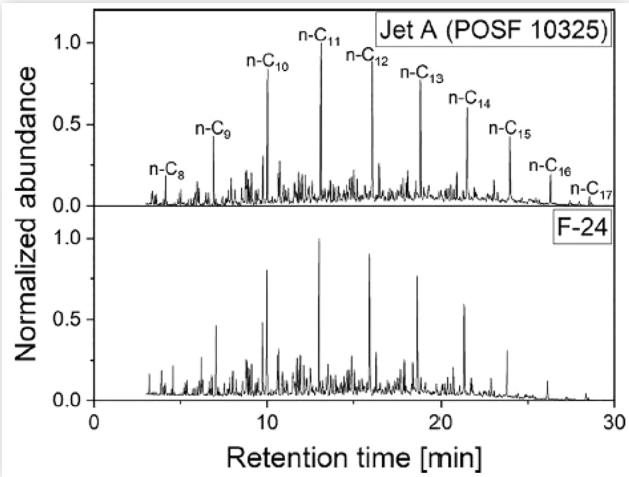


TABLE 1 Hydrocarbon Composition of F24 and Jet-A [10].

Hydrocarbon Species	F-24 (%)	Jet-A (%)
Paraffins	49.57	49.74
Olefins	10.93	6.58
Cyclohexanes	15.5	10.07
Alkylhexanes	11.47	13.55
Napthalenes	1.5	2.54
Bicyclics	1.68	1.32
Oxygenates	0.32	2.16
Cymeness	0.79	0.75
Xylenes	0.81	2.67
Alkynes	0.09	0
Other Compounds	0.1	0.5

A study analyzing the molecular and oxidation properties of F24, and Jet-A was done by Guzman et al [10]. This study investigated the compositional make-up of F24 compared to Jet-A and sought to validate the similarities in the oxidation process of the two fuels. The results of the study produced a compositional breakdown of each fuel, where the biggest difference in compounds were found in the oxygenates, xylenes, and olefins. Furthermore, the oxidation results between F24 and Jet-A were also compared, finding that the fuels were nearly identical.

The process of combustion is highly dependent on several parameters, including composition, temperature, pressure, and fuel-oxidizer mixture composition [11]. Fuels are often described with a DCN. The DCN describes the propensity of a fuel to auto ignite and is described by ID and CD [12].

In previous work differences in the combustion characteristics between F24 and Jet-A were investigated [12]. Combustion phasing plotted as AHRR in a CVCC can be broken into two phases: LTHR and HTHR. The LTHR is the region from the beginning of AHRR to the point at which combustion occurs. HTHR accounts for the rest of AHRR. The length of proportions of AHRR divided between LTHR and HTHR were found to be significantly different as seen in Table 2. The DCNs were also found to be different as seen in Table 3. These differences may be due to differences in composition.

TABLE 2 Combustion Region Duration Percentages for F24 and Jet-A [12].

Research Fuel	LTHR %	NTC %	HTHR %
Jet-A	55.7	20.5	44.3
F24	48	12	52
% Change	-13.8%	-41.4%	+17.4%

Amezcua et al. [13] investigated the ignition sensitivity of different jet fuels (including F24) for a compression ignition engine. The results found that the ignition assistance temperature had the strongest impact of ignition delay, with the ignition delay decreasing as the temperature increased.

Another source of F24 combustion properties can be found in the work conducted by Soloiu et al. [14]. This study found that the DCN of F24 was 44.35. Additionally, the cool flame temperature region of F24 was found to be slightly longer than the other fuels, and the negative temperature coefficient was found to be slightly shorter than the other fuels. This contributes to differences in combustion.

Fuel Chemistry and Combustion

A study comparing the combustion characteristics of Jet-A, JP8, and S8 was conducted by Hui et al. [15]. It was found that Jet-A's DCN was 45.3, its ignition delay was 3.47ms. This is a lower DCN and higher ignition time than all synthetic fuels tested besides IPK. This may be attributed to the majority of n-paraffins and iso-paraffins present in synthetic fuels like S8 and other GTL fuels. Properties between JP-8 and Jet-A were more similar. JP-8 contains the same additives as F24 [8].

Kang et al. [16] conducted a study comparing a variety of jet fuels such as JP5, JP8, and Jet-A, and synthetic fuels, such as S8, Shell IPK, Sasol IPK, and Camelina, are compared. Chromatography is conducted on these fuels, revealing that Jet-A and JP8 have similar amounts of carbon molecules, with Jet-A having slightly longer carbon molecules (C15 or higher). Having similar compositions Jet-A and JP-8 also had similar DCNs. These DCN values were found to also agree with work done by Won et al [17].

Guzman et.al conducted an experiment which showed how the fuel chemistry for both fuels despite having different fuel chemistry, because of their additives, performs equally within only a few percent. F-24 on three different jet fuel kinetic models and captured almost perfect oxidation at 50 bar and 7ms reaction with an uncertainty of 30% for the pre-exponential factor in the mechanism [18].

TABLE 3 Derived Cetane Numbers of F24 and Jet-A [12].

Research Fuel	Ignition Delay [ms]	Combustion Delay [ms]	Derived Cetane Number (DCN)
Jet-A	3.35	5.10	47.0
F24	4.10	5.79	43.4

Emissions

Emissions are highly dependent on the composition of the fuel and conditions of combustion. For example, NOX and THC are strongly correlated to temperature and combustion efficiency [19] and an increase in fuel hydrogen content is correlated with a reduction in nvPM [20].

Marina Braun-Unkhoff et. al. studied the combustion of synthetic jet fuels and their individual composition. The findings indicated that CO, CO_2, and NOx emissions are least impacted or decreased. In addition, the quantity of aromatics in jet fuel directly correlates with soot emissions [21, 22]. These comparisons can be used to show how emissions were affected by the fuel and how emissions might compare to this experiment that was conducted. This will help with the fundamental understanding of how the fuels perform.

B. Gawron et. Al showed the performance and emission characteristics of a miniature turbojet engine using a Jet-A-1/HEFA blend. These tests were according to a determined engine test profile along with the various operating modes of the miniature jet engine. It was concluded that the Jet-A-1/HEFA blend had better emission indices of the chosen exhaust gases, for example CO, CO_2, and NOX in comparison to normal Jet-A-1 fuel [23]. This shows the change in emissions that can occur from different compositions.

Zhang et al. [24] performed a numerical study on an experimental low- emission stirred swirl (LESS) combustor, It was found that maximum NOx formation is seen in the region adjacent to the zero-value axial velocity where the fluid experiences the highest residence time in the chamber as well as the highest temperatures.

Joy et al. [25] conducted a numerical investigation of a reverse flow micro gas turbine SR-30 to understand the pollutant formation characteristics and the effect of dilution air placement. With the baseline model, the maximum temperature was observed between the outer and inner liner at the injector exit. At this location, the high temperature causes the dissociation of nitrogen and oxygen which leads to NOx product formation. Additionally, the formation of nitrous oxide at this location further promotes combustion, increasing temperature and further contributing to NOx product formation.

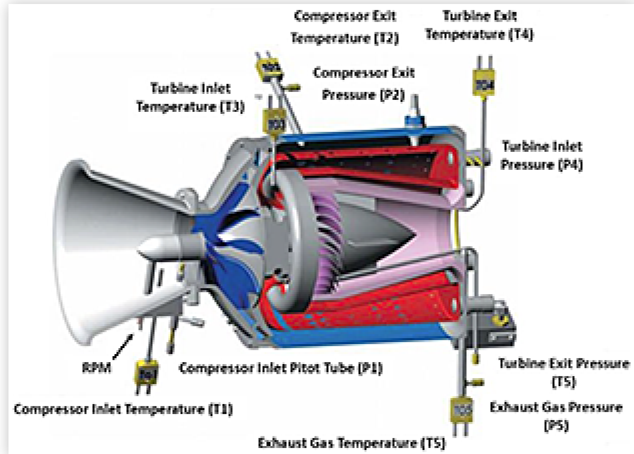
Another study was conducted on the SR-30 reverse flow engine by Badami et al. comparing Jet A, Synthetic Gas to Liquid (GTL) fuel, and a blend of 30% Jatropha Methyl Ester (JME) and 70% Jet-A [26]. The synthetic fuel and biofuel showed similar NOx and CO trends compared to Jet-A, while the UHC is roughly 25% lower for the biofuel blend over the entire range of test speeds.

Methods

Turbojet Instrumentation

To test fuels, a SR-30 single stage turbojet engine was used, as shown in Figure 2. The SR-30 can produce up to 40 lbf of thrust and has a maximum speed of 87,000 RPM, with a specific fuel consumption rate of 1.22 lb fuel/lb-hr. Its pressure ratio is 3.4 to 1. The engine was instrumented with several sensors throughout to measure its flow and thermodynamic properties and calculate its efficiency. These include 5 K-type thermocouples and 5 Setra Model 209 pressure sensors located at the essential sections of the engine, at the different stages within the turbojet. The turbojet is also equipped with a Futek Model LLB400 load cell to measure the thrust of the turbojet.

FIGURE 2 Cutaway Schematic of SR-30 Turbojet [27].



To get a broad view of the emissions at different turbine conditions, it was run at 60,000 RPM, 65,000 RPM, and 70,000 RPM. Each speed was maintained for 90 seconds. This allowed for steady average data at each speed. The fuels F24 and Jet-A were both run separately under these conditions.

Emissions Instrumentation

Emissions were captured and analyzed with an MKS 2030 FTIR Spectrometer. This spectrometer allowed for the measurement of emissions species concentration in the exhaust of the turbojet. Turbojet exhaust was analyzed for the emissions species H_2O, CO_2, CO, NOx. THC emissions were measured by an AVL FID 4000HH.

The MKS 2030 FTIR passes a helium neon infrared laser beam through a sample and determines the quantity of energy absorbed at each wavelength. A Fourier transform is then used to plot the prominence of species within the sample. Measurements are taken at 1 Hz which allows the measurement of 30+ components simultaneously. Measurement uncertainty is given in Table 4.

TABLE 4 Measurement Uncertainty of Emissions Species Measurements.

Emissions Species	Measurement Uncertainty
CO	± 1.0 ppm
CO_2	± 0.1%
H_2O	± 0.125%
NOX	± 0.5 ppm
THC	± 1.0 ppm

FIGURE 3 Test Stand with Emissions Heat Exchanger.

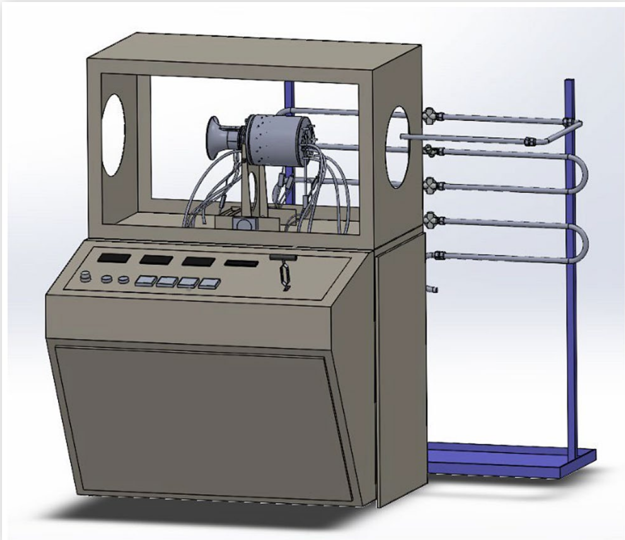


FIGURE 4 Temperature vs. RPM of F24 and Jet-A.

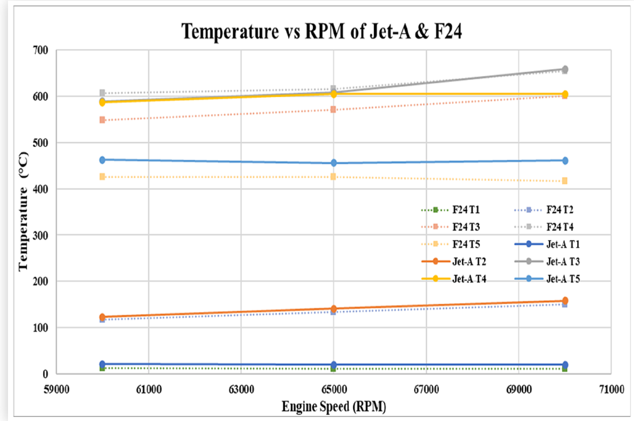
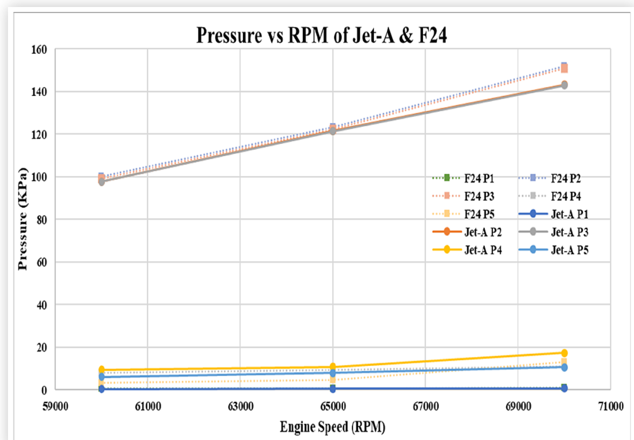


FIGURE 5 Pressure vs. RPM of F24 and Jet-A.



The AVL FID 40000HH utilizes the ionization of organically bound carbon atoms in a hydrogen flame to measure THC. Measurement uncertainty is given in Table 4.

Prior to reaching the spectrometer exhaust was cooled in a heat exchanger to keep it within range of operating parameters (Figure 3). Emissions were averaged over a 90 second period at 60k, 65k, and 70k RPM to allow for an average data set. This minimized the effects of shifting combustion temperatures and RPM throughout the taken measurements.

Results & Discussion

Turbojet Operational Analysis

Temperature and pressure measurements taken throughout the turbojet were recorded in Table 5 and plotted in Figures 4 and 5. Throughout most of the turbojet temperatures were highest for Jet-A. This occurred at T1, T2, T3, and T5. F24 temperature readings were higher than Jet- A at T4, which is the turbine exit temperature. The highest temperature at T4 was 655°C for F24 at 70k RPM compared to 605°C for Jet-A, which is a percent difference of 8.26%. The opposite trend occurred with pressure measurements, where F24 pressure readings were higher compared to Jet-A. Jet-A had higher pressure measurements at P4, which represents turbine inlet pressure. The highest pressure at P4 was 17.3 kPa for Jet-A at 70k RPM. This is a percent difference of 57.3%. These have an impact on the formation of emissions as temperature and pressure play in the prevalence of several species such as NOX and CO [19].

TABLE 5 Temperature and Pressure at Engine Speeds of F24 and Jet-A.

	Jet-A			F24		
Engine Speed [RPM]	60k	65k	70k	60k	65k	70k
T1 [°C]	20.9	19.9	20.0	12.3	11.6	11.4
T2 [°C]	123	141	158	117	134	150
T3 [°C]	589	609	659	548	570	600
T4 [°C]	587	605	605	607	616	655
T5 [°C]	462	456	461	426	426	417
P1 [kPa]	0.418	0.548	0.761	0.541	0.709	0.946
P2 [kPa]	97.7	122	143	100	123	152
P3 [kPa]	97.7	121	143	99.1	122	151
P4 [kPa]	9.47	10.8	17.3	7.88	9.21	11.0
P5 [kPa]	6.01	7.92	10.7	3.21	4.65	13.2

Turbojet Emissions Analysis

Of the measured emissions, the difference in CO_2 and CO between F24 and Jet-A were negligibly different as shown in Table 6 and Figures 6–12. From this a few things can be derived. Close levels of CO and CO_2 emissions at each engine speed suggests closeness in proportion of carbon in both fuels.

H_2O emissions were significantly different between the fuels. The starkest contrast was at 60k RPM where F24 had a

TABLE 6 Average Emissions of F24 and Jet-A.

Engine Speed [RPM]	Jet-A 60k	Jet-A 65k	Jet-A 70k	F24 60k	F24 65k	F24 70k
H_2O %	4.02	4.06	4.10	2.89	3.01	3.33
CO_2 %	2.93	2.95	3.04	2.35	2.50	2.87
NOx [ppm]	21.5	23.7	27.9	18.1	21.7	27.6
CO [ppm]	1195	1063	968	1088	990	953
THC [ppm]	2231	1812	1186	952	668	481

FIGURE 6 Average H_2O & CO_2 of Jet-A & F24 at 60,000 RPM.

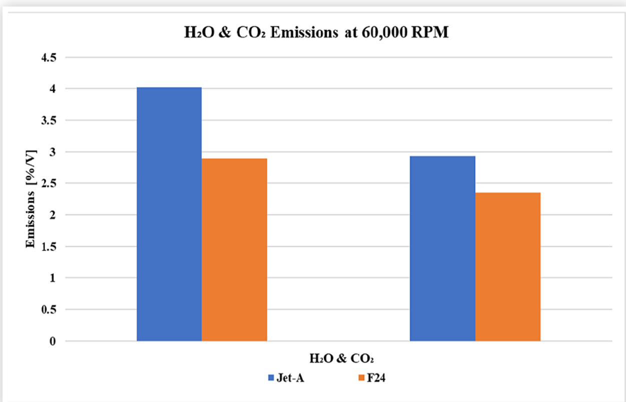
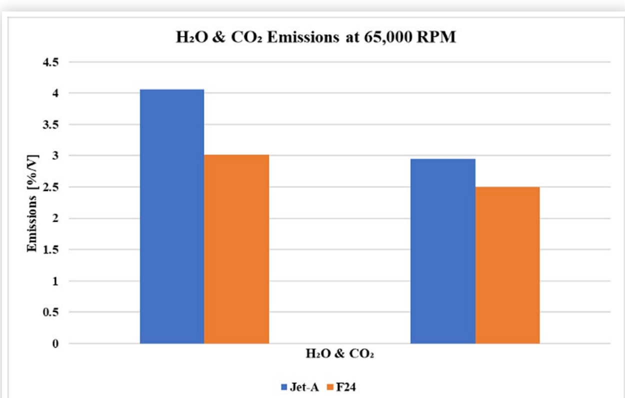


FIGURE 7 Average H_2O & CO_2 of Jet-A & F24 at 65,000 RPM.



percent volume of 2.89% compared to 4.02% for Jet-A. This is a percent difference of 28.1%. Differences in amounts of H_2O in the emissions from F24 and Jet-A suggest some differences in hydrogen content in the homogeneous mixture of both fuels and possible interference from variable outdoor humidity in the jet engine test bed.

When comparing THC emissions between F24 and Jet-A, a large difference was seen. Considering 60k RPM, Jet-A emitted 2231 ppm and F24 emitted 952 ppm of THC, as shown in Table 6. This is a difference of 57.3%. Higher concentration of THC emissions suggests less complete combustion for Jet-A. This is not likely due to the difference in temperature of

FIGURE 8 Average H_2O & CO_2 of Jet-A & F24 at 70,000 RPM.

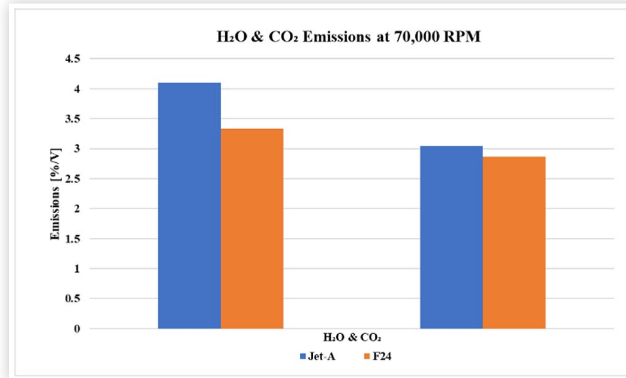


FIGURE 9 Average CO & THC Emissions of Jet-A & F24 at 60,000 RPM.

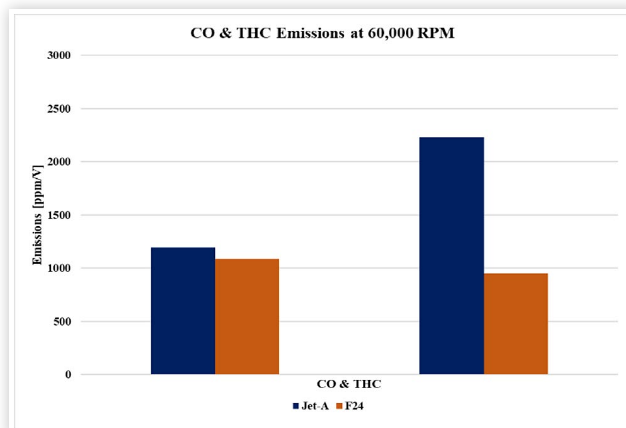


FIGURE 10 Average CO & THC Emissions of Jet-A & F24 at 65,000 RPM.

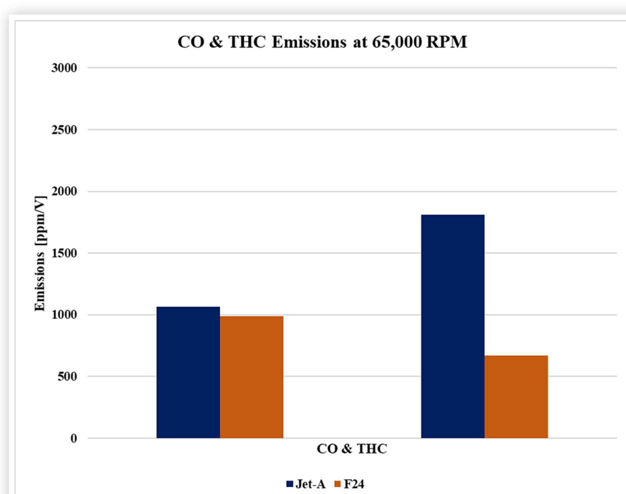


FIGURE 11 Average CO & THC Emissions of Jet-A & F24 at 70,000 RPM.

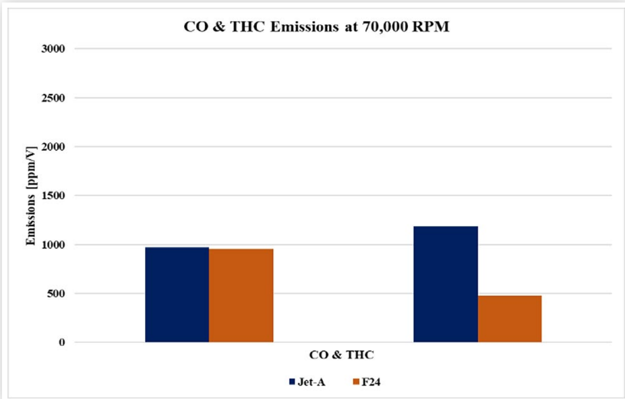
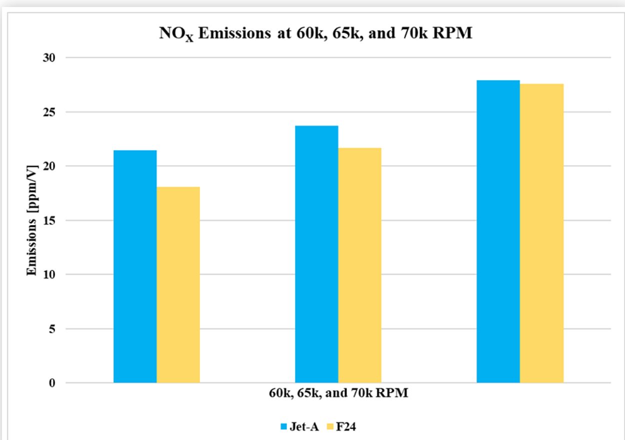


FIGURE 12 Average NOX Emissions of Jet-A & F24 at 60k, 65k, & 70k RPM.



combustion, as Jet-A experienced higher temperatures and similar peak temperature observed in previous CVCC work [12]. Previous work also showed a 12.5% longer combustion time for F24 as well as a 33.5% longer HTHR compared to Jet-A. F24 also had a correspondingly shorter LTHR. This extended time at higher temperature could explain the smaller amount of THC emissions.

The NOX emissions of both fuels show slight differences, but higher values for throughout for Jet-A. The biggest difference occurred at 60k RPM, where Jet-A was 21.5 ppm and F24 was 18.1 ppm. This is a percent difference of 15.8%. NOX emissions are largely driven by combustion temperature and oxidizer mass flow rate, which is constant in this case [19].

Given the differences of NOX emissions, temperature and pressure would be expected to be different in the combustor and turbine exit of with both fuels. This was seen to be true as previously discussed and presented in Figure 12. This higher temperature is also reflected in the higher DCN of Jet-A, found to be 47.0 compared 43.4 for F24, observed in previous work [12]. The NOX emissions are also seen to increase as CO emissions decrease for both fuels as engine speed increases, seen in Figures 9–12. This is due to the increase in engine temperature and oxidizer flow rate [19], which lowers the amount CO, increasing oxygen available for the formation of NOX.

Summary/Conclusions

The emissions' characteristics were investigated and compared between the fuels F24 and Jet-A in a single stage turbojet engine. This paper also discussed connections to combustion characteristics of the two fuels that were investigated in previous work.

A SR-30 turbojet was subjected to tests at 60k, 65k, and 70k RPM. Temperature and pressure measurements were taken throughout the engine, finding that F24 had a higher temperature across engine speeds at the turbine exit, having a temperature of 655°C versus 605°C for Jet-A. This is a percent difference of 8.26%. Jet-A had a higher pressure reading at the corresponding pressure reading location, having a pressure of 17.3 kPa compared to 11.0 for F24. This is a percent difference of 57.3%.

F24 was previously found by the authors to have a 12.5% longer overall combustion duration which was 33.5% longer in HTHR. It was also previously found that F24 had a lower DCN, which was 43.4 compared to 47.0 for Jet-A. F24 also had a correspondingly longer AHRR than Jet-A overall. This longer period of higher temperature and AHRR correlated well with less THC emissions, likely due to more complete combustion.

Emissions from the turbojet were measured with an MKS 2030 FTIR gas analyzer. H_2O emissions were also found to have different values, with F24 H_2O emissions being 28.1% less than that of Jet-A. The largest disparity occurred between the THC emissions of F24 and Jet- A, of which F24 had a 57.3% lower amount. This correlates with the higher temperatures for F24 seen at the turbine exit which suggest more complete combustion. Some difference was also observed in the NOX emissions between the fuels, of which F24 was 15.8% lower at 60k RPM.

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Definitions/Abbreviations

AHRR - Apparent Heat Release Rate

CD - Combustion Delay

CVCC - Constant Volume Combustion Chamber

DCN - Derived Cetane Number

HTHR - High Temperature Heat Release

ID - Ignition Delay

LTHR - Low Temperature Heat Release

SAF - Sustainable Aviation Fuel

THC - Total Hydrocarbon

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