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EMISSIONS ASSESSMENT OF ALTERNATIVE AVIATION FUEL AT SIMULATED ALTITUDES

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ABSTRACT

To address the global fuel challenges of energy security, economic sustainability and climate change the stakeholders of aviation industry are actively pursuing the development and qualification of alternative ‘drop-in’ fuels. New standards will be required to regulate the use of these new fuels, which requires not only fuel specification and rig/engine and flight testing but also an emission life cycle impact assessment of these fuels.

This paper reports on emission data measured at various simulated altitudes and engine speeds from a jet engine operated on conventional and alternative aviation fuels. The work was conducted as part of on-going efforts by departments within the Government of Canada to systematically assess regulated as well as non-regulated emissions from the use of alternative aviation fuels.

The measurements were performed on an instrumented 1000 N-thrust turbojet engine using a baseline conventional Jet A-1 fuel and a semi-synthetic (50/50) blend with Camelina based Hydroprocessed Renewable Jet (JP8-HRJ8) fuel. Emission results reported here include carbon dioxide, carbon monoxide, nitrogen oxides and particulate matter measured at several simulated altitudes and power settings. In order to ensure that the assessments have a common baseline, relevant engine performance and operability data were also recorded.

NEED FOR SYSTEMATIC EMISSIONS ASSESSMENT OF ALTERNATIVE AVIATION FUELS

Alternative drop-in aviation fuels hold the promise of energy supply diversification in the face of rising oil prices and possible scarcity of the conventional fuels. Targets for the mandatory use of alternative fuels in proportion to current traditional fuels and the growth of this proportion in comparison to the total fuel usage have been set by North American and European governments and by international aviation regulatory bodies like International Air Transport Association (IATA). Although economic sustainability in the production and distribution of these fuels has still not been achieved, these fuels definitely hold the potential to reduce environmental impact from aviation-related emissions [1]. Especially fuels derived from renewable resources, offer the potential for a reduction in greenhouse gas (GHG) emissions. Currently there is a general belief amongst aviation industry stakeholders that this GHG reduction is neither due to a change in fuel composition nor due to a change in engine performance; instead the reduction is due to a change in the GHG emissions that result from the extraction, production and use (combustion) of the alternative fuel (i.e., the life cycle of the fuel).

In order to ascertain the emissions reduction benefits that may result from the use of an alternative fuel, it is imperative to conduct a

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cradle-to-grave emissions life cycle assessment (ELCA). This analysis needs to start from feedstock extraction at the well to the wake behind the aircraft while encompassing all in between life-cycle stages [2].

According to the Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives (ASTM D4054) [3], potential new fuels need to pass through a detailed investigation of the fuel properties to prove that the fuel is suitable, or fit-for-purpose, for aircraft operations. Individual components, such as fuel nozzles, combustors, auxiliary power units and fuel gauging systems, as well as complete engine performance may be evaluated before the fuel is put on an aircraft for flight testing. The qualification process may also include testing the compatibility of the new fuel with specific materials found in both the internal wetted systems of aircraft, as well as any exterior surfaces that may be subjected to fuel spill-and-splash. Although one of the driving motives behind development and use of alternative fuel is climate change, the ASTM standards qualifying fuels for aircraft use do not exclusively stipulate evaluation of emissions from these fuels.

Nonetheless, the International Civil Aviation Organization (ICAO) through its Committee on Aviation Environmental Protection (CAEP) has been monitoring and regulating the standards for emissions like NO_x. Their recent focus involves formalizing regulations on the emission of particulate matter (PM) and reduction in fuel burn as a means to reduce net GHG production from the use of fuel, including alternative fuels, in aviation. This ICAO-CAEP focus has been one of the driving forces behind many current US and European research activities (for example NextGen and ACARE respectively) as well as efforts from the aircraft and engine OEMs.

In addition, the US Energy Independence and Security Act (EISA) has placed a unique greenhouse gas emission requirement on all Federal agencies involved in the procurement of mobility-related fuels. To be in EISA compliance, producers of alternative and synthetic fuels must be able to demonstrate that the fuel's GHG emissions is less than or equal to fuel produced from conventional petroleum sources. This requires a "well-to-wake" assessment of all GHG emissions and therefore, it is being recognized that Life Cycle Assessments (LCA) for both a baseline petroleum fuel and alternative fuels must be developed. As a result, aviation stakeholders have taken up the challenge to assess the alternative fuel environmental impacts. For example, the PARTNER program that is jointly sponsored by Transport Canada, Federal Aviation Authority and National Aeronautics & Space Agency is pursuing a number of projects on the subject, where LCA on a variety of alternatives fuels is being conducted.

However, these present efforts assume constant combustion carbon dioxide (CO_2) for all type of alternative fuels pathways being considered. This assumption is based on the general belief that all aviation certified alternative fuels will have almost the same physical and chemical properties, per ASTM D1655.

Recent engine qualification tests conducted at National Research Council (NRC) Canada, in collaboration with Canadian Department of National Defense (DND) and Environment Canada (EC) show that the constant combustion CO_2 assumption being used in the current LCA models may be an over-simplification. The NRC tests were conducted using a Semi-Synthetic Jet Fuel (SSJF) comprising 50% Fischer-Tropsch (F-T) Synthetic Paraffinic Kerosene (SPK) blended with 50% JP-8 fuel. Although no significant differences in the engine performance were noted between the conventional and synthetic fuels usage, the CO_2 emissions measured using SSJF were found to be consistently lower compared to baseline conventional Jet A-1 fuel [5]. This actual engine test result is very much in agreement with results reported by other studies (for example Ref. 6), which claim that the combustion of synthetic fuels results in about 4% lower CO_2 emissions as compared to conventional jet fuel.

From the point of view of setting regulations, there is an additional issue that seems to be overlooked in the current efforts to compile the life cycle assessment. The issue relates to the oversight in recognizing that the sole reason why aviation generated emissions (although very small in comparison to other emission sources) is of concern is because the majority of emissions are released at higher altitudes [7]. Very limited efforts have been directed to gather emission data under either simulated-altitude conditions in a test cell or actual airborne flights.

The current life cycle assessments on alternative fuels therefore lack completeness. While at present it is not possible to conduct airborne emission measurement because of the non-availability of large amounts of alternative fuels required for flight testing, valuable and comprehensive emission and performance measurements can very economically be conducted in altitude test-cells using smaller (but representative of state-of-art) engines and Auxiliary Power Units (APUs).

This paper reports on emission data measured at various simulated altitudes and engine speeds from a jet engine operated on conventional and alternative aviation fuels. The work was conducted as part of on-going efforts by departments (NRC, DND and EC) within the Government of Canada to systematically assess regulated as well as non-regulated emissions from the use of alternative aviation fuels. The collaboration between these departments was created in recognition of the need for emission life cycle assessments and the deficiencies in the current state of knowledge as well as non-availability of relevant data.

TEST PLAN, TEST FACILITY AND ENGINE INSTRUMENTATION

The work was conducted under a Government of Canada funded research program aimed towards creating an alternative fuels emissions life cycle assessment (ELCA) database. The broad objective of the program is to evaluate the relative environmental impacts of current and potential alternative aviation fuels with a comparable basis of engine performance. For the sake of ensuring that comparisons have a common baseline, the program also includes an assessment of the possible impacts of fuel-type variability on engine life cycle, e.g. performance and durability.

The engine testing was conducted at NRC's Research Altitude Test Facility. The facility is capable of simulating altitudes up to 12 km and Mach Numbers defined by a maximum air flow rate of 4.5 kg/s. Both pressure and temperature altitudes can be independently controlled. The facility test cell, as shown in Fig. 1, is 10 m long with an internal diameter of 3 m.

The measurements were performed on a specially instrumented 1000 N-thrust turbojet engine (Microturbo TRS-18). This small engine was chosen to keep the test fuel requirements to the minimum, in view of the non-availability of alternative fuels in bulk quantities. In addition to the conventional Jet A-1, which was used as the baseline fuel, three alternative aviation fuels were used in the test campaign: fully-synthetic Fischer Tropsch Iso-Paraffinic Kerosene (FT-IPK), semi-synthetic 50/50 blend of JP-8 and FT-IPK, and semi-synthetic 50/50 blend of JP-8 and Camelina based Hydroprocessed Renewable Jet (JP8-HRJ8). However, results reported here pertain to comparisons between Jet A-1 and semi-synthetic JP8-HRJ8 fuels only. The semi-synthetic fuel, because it was blended with JP-8 and not Jet A-1, also contained Fuel System Icing Inhibitor (0.12 % volume), Corrosion Inhibitor/Lubricity Improver (15 ppm) and Static Dissipation Additive (1.5 ppm). The main fuel specification and properties were analyzed on both fuels before and after the tests according to the standard ASTM adopted methods. A summary of fuel analysis results is given in Appendix 'A'.

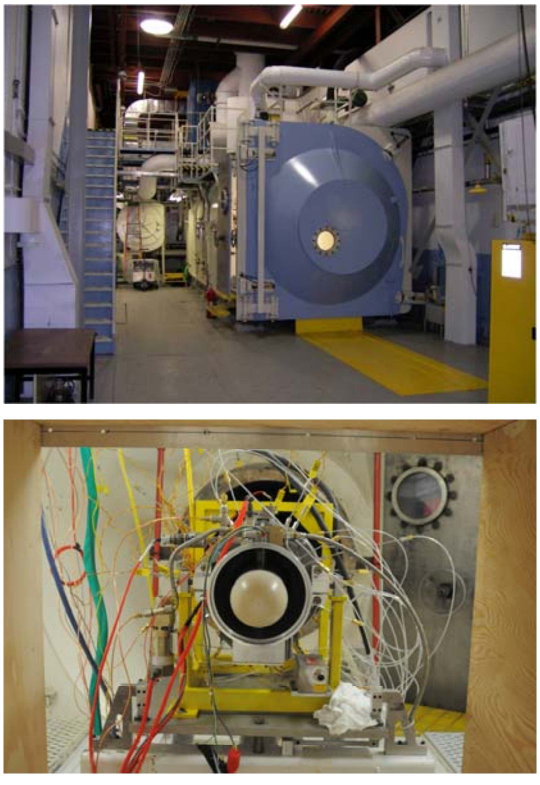

Figure 1: The Research Altitude Test Facility at National Research Council Canada (Top). The instrumented TRS-18 engine, as installed in the test cell (Bottom).

The engine investigations were performed at five test-cell simulated nominal altitudes of 1525, 3050, 6095, 9145 and 11280 m (covering the full range of the cell's capability) and at selected engine speeds of flight idle, 31000, 35000, 37000, 39000, 41000 rpm and another higher rpm that was dictated by the maximum allowable EGT limit. The RAM pressure was adjusted to simulate a constant indicated air speed of 120 m/s. The runs were conducted by first establishing the inlet conditions and then stabilizing the engine at these conditions for a minimum of two to three minutes followed by another two to three minutes of data collection at steady state condition. Measurements were repeated at several set points to ensure repeatability. However, as shown in Table B-1, because of the limitations of higher idle engine speed at elevated altitudes on one side and maximum EGT limitations on the other side, measurements were not possible at all speeds at all altitudes.

EMISSIONS MEASUREMENT SETUP AND DATA ANALYSIS METHODOLOGY

Emission measurements were made to record gaseous species of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx) and total unburnt hydrocarbons (THC), as well as the particulate matter (PM) number size distributions. A Non-Dispersive Infrared analyzer was used for CO_2 and CO measurements while Heated Chemiluminescent and Heated Flame Ionization detectors were used for NOx and THC measurements respectively. Engine Exhaust Particle Sizer spectrometer was used to measure the particle number size distributions. Because the total sulphur content was extremely low in both the fuels (refer Table A-1), the measured sulphur oxide (SOx) was found to be around the lower measurable range of the analyzer. Because of the accuracy concerns the SOx measurements are not reported here.

A multi-hole sampling probe was designed and fabricated to obtain uniform sampling across the engine exhaust. The emission probe was installed 50 mm downstream of the engine nozzle exit plane. As shown in Fig. 2, the exhaust sample from the engine was extracted from the altitude chamber and a fraction of this exhaust was diluted to prevent condensation and to reduce the particle and gaseous concentrations to appropriate levels acceptable for the analyzers. The dilute exhaust was then transferred to the analyzers via a heated line set at a temperature of 191°C. The voltage output from each of the analyzers was logged at a rate of 1 Hz and converted to ppm using calibration curves. Analyzers were zeroed and spanned three times over each sampling period, at the beginning, in the middle and at the end of each test day with calibration gases certified to ±1% purity.

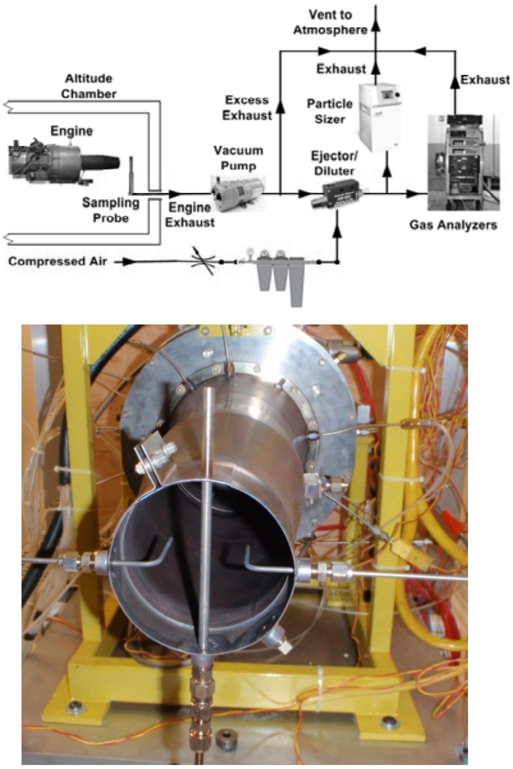

Figure 2: Schematic diagram of emissions measurement setup (Top). Vertical emission probe, located 50 mm downstream of the engine nozzle exit plane along with two angled-probes for the measurement of total temperature and pitot pressure at the exit (Bottom).

For the purpose of analyzing the raw emissions data, the measured gaseous concentrations (in ppm) for various species were first converted to mass concentrations (in g/m^3) using ideal gas law relationship and then converted to emission indexes (in g/kg of fuel burnt) based on the calculated exhaust volumetric flow rate (in m^3/hr) and the measured fuel flow rate (in kg/hr). The exhaust flow rate was calculated by following a method similar to one outlined in ISO 8178-1 [8]. The molecular weight of the fuel, as determined by the fuel analysis, was applied to the measured fuel mass flow rate to determine the number of moles of fuel burnt per unit time. This information was used to determine the corresponding number of moles of CO_2 formed during the combustion process (assuming complete combustion and applying carbon balance) and finally converted to exhaust volumetric flow rate based on standard ambient conditions (20 °C and 1 atm).

RESULTS

The details of the engine performance assessment, when operating on the two fuels, are presented in a companion paper (GT2011-45132) [9]. No significant differences were observed in the engine performance between the Jet A-1 and the JP8-HRJ8 fuels at any of the test altitudes. However, it was observed that the engine was unable to operate at altitudes above 9145 m when using the JP8-HRJ8 fuel. In comparison, the Jet A-1 results were obtained up to and including 11,280 m.

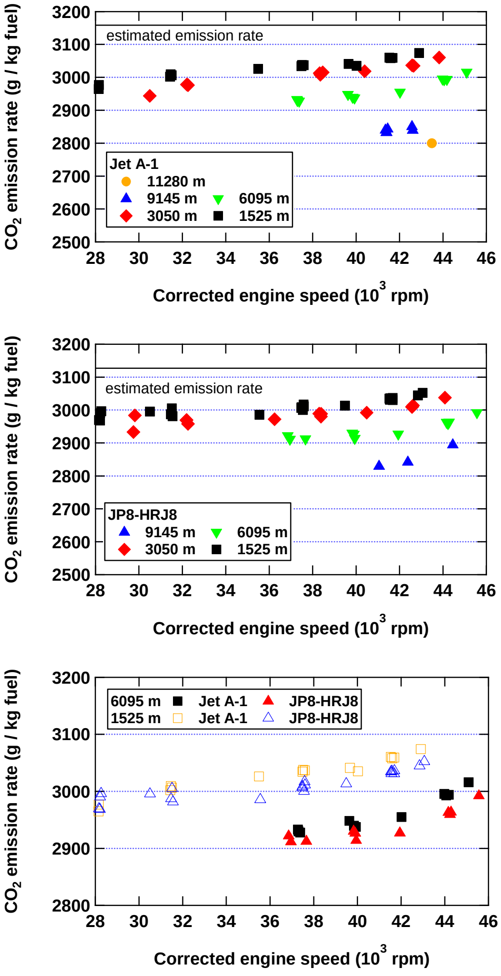

Figure 3: Measured and calculated CO_2 emission index at the tested altitudes for the two fuels, Jet A-1 (Top), JP8-HRJ8 (Middle) and comparison at 1525 m and 6095 m altitudes (Bottom).

The results discussed here cover only the emission assessment. For the sake of clarity of the figures, results for the individual fuels are presented at all the tested altitudes, but the comparison between the two fuels is shown at 1525 m and 6095 m altitudes only.

The CO_2 emission index as calculated from the fuel analysis data (Table A-2) was found to be 3168 g/kg for Jet A-1 and 3135 g/kg for JP8-HRJ8. These estimated limiting values along with the measured CO_2 emission indexes are plotted in Fig. 3 against the engine rotor speed (corrected to 288 K). Similar trends in CO_2 emissions are observed for both the fuels, i.e., decrease in emissions with the increase in altitude at any given engine speed. In comparison, a 0.63~0.75% (averaged over all engine speeds at each of the fixed altitudes) decrease in CO_2 was observed when running the engine on the semi-synthetic blend. This decrease is primarily due to the reduction in carbon to hydrogen ratio in the JP8-HRJ8 fuel (Table A-2), and is consistent with the estimated reduction of 1% from carbon-balance calculation.

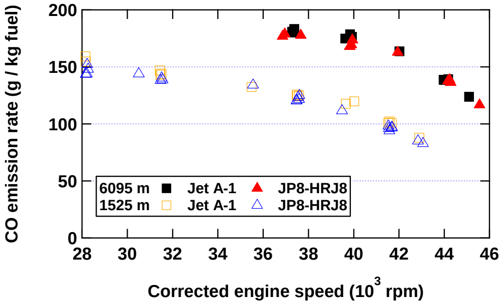

Figure 4: Carbon Monoxide emission index for the two fuels and at two altitudes.

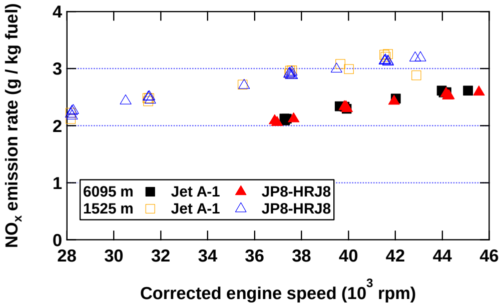

Figure 5: Nitrogen Oxides emission index for the two fuels and at two altitudes.

As for the emissions of CO and NOx, sample data are shown in Fig. 4 and 5 respectively, over the range of corrected engine speeds for the two fuels at two sample test altitudes of 1525 m and 6095 m. As may be noted, for either fuel, altitude has a significant effect on the emission rates. The CO emissions increase with the increase in altitude, while NOx emission rates show an opposite trend with the increase in altitude. Increasing altitude from 1525 m to 6095 m leads to an increase of CO by about 41% and decrease in NOx by about 21%. However, when switching fuel from Jet A-1 to JP8-HRJ8 no significant difference is observed in either CO or NOx emissions at any given altitude and engine speed.

The decrease in NOx emissions with the increase in operating altitude was found to be consistent with the combustor temperature profiles, as shown in Fig. 6. These temperature measurements were made on the combustor centerline and mid-way between the inlet and exit of the combustor, using a custom-built thermocouple probe. The combustor temperatures show a strong dependency on the altitude (decreasing with the increase in altitude at any given engine speed) but no considerable dependence on the fuel type. This observation is consistent with the anticipated changes from cycle analysis considerations.

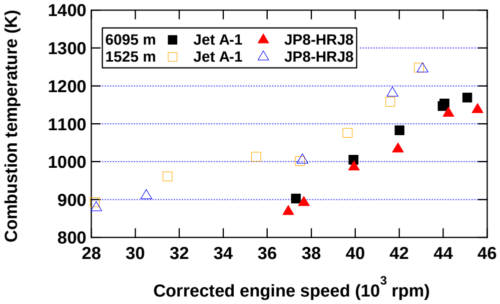

Figure 6: Mid-combustor temperatures for operation with the two fuels and at two altitudes of 1525 m and 6095 m.

As for the PM emissions, the number emission rates were calculated from the number size distributions while the geometric mean diameter for the distribution was estimated by fitting the distribution with a log-normal function. Figure 7 shows the number emission rate of the particles for the two fuels over the range of engine speeds and at all the tested altitudes. Results show that PM emission rates decrease for both the fuels with the increase in altitude. For example, increasing altitude from 1525 m to 6095 m, there is a reduction of about 34% and 50% in particle number emission for Jet A-1 fuel at 43,000 rpm and 37,000 rpm, respectively. For JP8-HRJ8 fuel, these reductions are nearly 50% and 53% at the same two engine speeds, respectively.

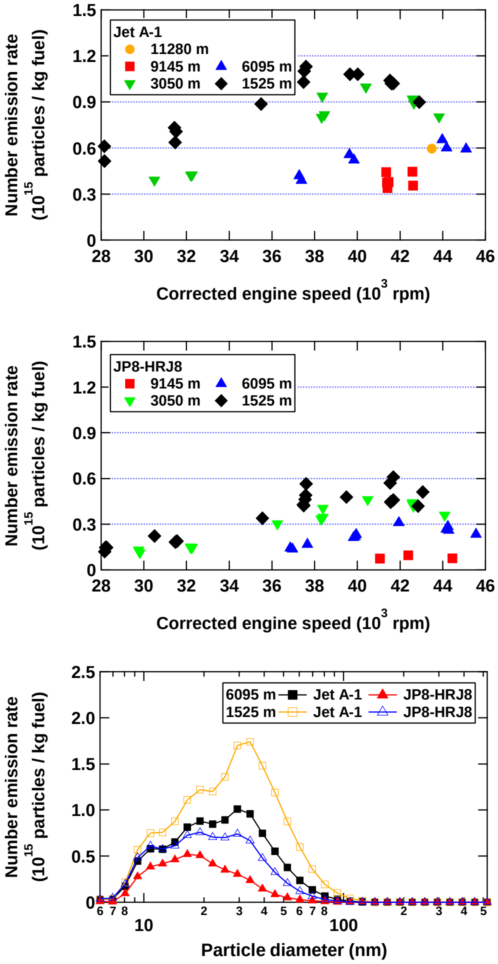

Figure 7: Measured PM number emission rate at the tested altitudes for the two fuels, JetA-1 (Top), JP8-HRJ8 (Middle) and comparison of PM number size distributions for the two fuels at 1525 m and 6095 m altitudes (Bottom).

Compared to Jet A-1 fuel, the use of JP8-HRJ8 fuel leads to a reduction in particle number emission at 1525 m by 48-56% over an engine speed range from 37,000 to 43,000 rpm. At 6095 m altitude, the corresponding reduction is about 60%. Also shown in the figure (bottom plot) is a sample comparison of the PM size distributions for the two fuels as measured at an engine speed of 41000 rpm and simulated altitudes of 1525 m and 6095 m. As may be noted, the PM emitted from the engine used in the study is very small in general (particle diameter less than 0.1 micron). With the use of JP8-HRJ8 fuel, a decrease in particle geometric mean diameter of about 25% is observed for both altitudes.

As a result of the decrease in PM size and number density, when switching to JP8-HRJ8 fuel, the mass emission rate of PM per kg of fuel burnt also decreases significantly. The mass size distribution was calculated using the measured number size distribution. To provide a more realistic estimate of particle mass, this quantity was calculated using the effective density for non-spherical soot particles [10]. The comparison of mass emissions from the two fuels at the two sample altitudes and over the range of engine operation is shown in Fig. 8.

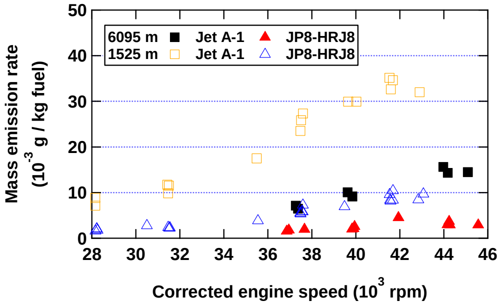

Figure 8: Particulate matter mass emission rate for the two fuels at two altitudes of 1525 m and 6095 m.

As seen in Fig 8, for Jet A-1 fuel, a maximum reduction of about 60% is observed in particulate mass emission when the operating altitude is increased from 1525 m to 6095 m. In comparison, for the same change in altitude, the use of JP8-HRJ8 fuel gives a maximum reduction of 68% in PM mass emission. Comparing the two fuels, PM mass emissions for JP8-HRJ8 are almost 72% less than those from Jet A-1 at 1525 m altitude and 80% less at 6095 m altitude.

The relative reduction in both the PM number and mass emission when switching fuel from Jet A-1 to JP8-HRJ8, as observed in the results presented here may be attributed to a combination of factors. As reported in other studies [11, 12], soot formation depends on fuel properties like aromatic contents and H/C ratio. As such the reduced aromatic content and higher H/C ratio of JP8-HRJ8 fuel (Table A-1), leads to lower PM emission.

CONCLUSIONS

Comparison of jet engine emissions was made between conventional Jet A-1 and semi-synthetic 50/50 blend of a Camelina based JP8-HRJ8. These measurements were made at a number of test-cell simulated, operationally relevant altitudes and over a range of engine operating conditions.

The results show that for either fuel, change in operating altitude has a significant impact on the emission rates. The CO emissions increase with the increase in altitude, while NOx and PM emission rates show an opposite trend with the increase in altitude. However, when switching fuel from Jet A-1 to JP8-HRJ8 no significant difference was observed in CO and NOx emissions at any given altitude and engine speed.

As for the PM, a decrease in particle mean diameter, number density and thus mass emission rate is observed when the engine is operated at higher altitudes. Reductions in these quantities are also observed when using JP8-HRJ8 fuel in comparison to Jet A-1 at any given altitude and engine speed.

Based on the results of the study it is concluded that there is no detriment in terms of gaseous emissions associated with the usage of JP8-HRJ8 fuel. In fact, there is a benefit in terms of CO_2 emissions (around one percentage point) due to chemical composition of the fuel. In addition, there is a significant benefit (reduction of more than 72%) in terms of PM mass emissions.

ACKNOWLEDGEMENTS

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Appendix ‘A’ – Fuel Specifications

Table A-1: Selected properties of the two fuels used in the project with reference to the Canadian General Standard Board (CGSB) standards for JP-8 fuel.

Description	**CGSB Specification Limits [Ref. 10]**	**Jet A-1**	**JP8-HRJ8**
Net Heat of Combustion [MJ/kg] ASTM D4809	**42.8 min**	46.51	45.97
Smoke Point [mm] ASTM D1322	**18.0 min**	24	32
Aromatics [% by volume] ASTM D1319	**25**	22.0	10.4
Water Separation Characteristic			
ASTM D3948	**70 min**	57	65
ASTM D7224	**85 min**	90	95
FSII [% by volume] ASTM D5006	**0.10 - 0.15**	0.02	0.12
Flash Point [^{o}C] ASTM D5006	**38.0 min**	53.0	43.5
Existent Gum [mg/100ml] ASTM D321	**7 max**	0.50	0.30
Density [kg/m^{3}] ASTM D4052	**report**	821.0	784.7
Copper Corrosion ASTM D130	**No.1 max**	1b	1b
Kinematic Viscosity ASTM D445			
@ -20^{o}C [cSt]	**8.0 max**	5.200	4.477
Water Reaction ASTM D1094			
Interface	**1b max.**	1b	1b
JFTOT ASTM D3241			
Tube Deposit	**3 max**	<1A	1
Filter Pressure Drop [mm Hg]	**25 max**	0.2	0.1
Freezing Point [^{o}C] ASTM D5972	**-47**	-52.0	-53.0
Particulate Contamination [mg/L] ASTM D5452	**0.44 max**	0.24	0.10
Electrical Conductivity [pS/m] ASTM D2624	**50-600**	155	86
Distillation Temperature [^{o}C] ASTM D86			
IBP	**report**	172.2	155.8
50%	**report**	208.4	205.1
90%	**report**	240.8	256.2
FBP	**300 max**	258.0	268.5
Residue [% by volume]	**1.5 max**	1.2	1.2
Lubricity BOCLE Test [mm] ASTM D5001	**0.85 max**	0.76	0.60
Total Sulfur [% by mass (ppm)] ASTM D5453	**0.3 (3000)**	0.0136 (136)	0.0244 (244)
Cetane Index ASTM D976	**report**	38.9	52.9

Table A-2: Fuel analysis data

Property	Jet A-1	JP8-HRJ8
H/C ratio SNCUT ASTM D5291	1.89	2.03
Molecular weight [g/mole] Freezing Point Depression	161	163
Carbon Number	11.6	11.6
Molecular Formula	$C_{11.6}H_{21.9}$	$C_{11.6}H_{23.6}$
Calculated maximum CO_2 emission [g/kg-fuel]	3168	3135

Appendix 'B' – Test Matrix

Table B-1: Test conditions for the investigation

Nominal Altitude [m]	Nominal Uncorrected Engine Speed [RPM]						
	Idle	31,000	35,000	37,000	39,000	41,000	Max. EGT Limited
1525	▨	▨	▨	▨	▨	▨	▨
3050	▨	▨	▨	▨	▨	▨	▨
6095	▨			▨	▨	▨	▨
9145	▨				▨	▨	▨
11280	▨					▨	

1. The gray cells indicate the conditions were data was recorder.
2. Measurements were repeated at 31,000 rpm, 37,000 rpm and 41,000 rpm where applicable