

Characterization of the Ultrafine and Black Carbon Emissions from Different Aviation Alternative Fuels

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ABSTRACT

This study reports gaseous and particle (ultrafine and black carbon (BC)) emissions from a turbofan engine core on standard Jet A-1 and three alternative fuels, including 100% hydrothermolysis synthetic kerosene with aromatics (CH-SKA), 50% Hydro-processed Esters and Fatty Acid paraffinic kerosene (HEFA-SPK), and 100% Fischer Tropsch (FT-SPK). Gaseous emissions from this engine for various fuels were similar but significant differences in particle emissions were observed. During the idle condition, it was observed that the non-refractory mass fraction in the emitted particles were higher than during higher engine load condition. This observation is consistent for all test fuels. The 100% CH-SKA fuel was found to have noticeable reductions in BC emissions when compared to Jet A-1 by 28-38% by different BC instruments (and 7% in refractory particle number (PN) emissions) at take-off condition. BC emissions from this fuel were lower than from Jet A-1 by 45-50% (and 25-26% in refractory PN) at idle or cruise condition. The 100% CH-SKA fuel was observed to have a minimum influence on non-refractory PN emissions. A lower volume in naphthalene in the 100% CH-SKA fuel was hypothesized to be one of the factors attributing to the reduced BC emissions when compared to Jet A-1 emissions. For the 50% HEFA-SPK fuel, BC emissions were lower than the BC emissions from Jet A-1 by 58-86% for various engine load conditions. BC emissions from the 100% FT-SPK fuel were lower than from the Jet A-1 by 70-98%. Both the refractory and non-refractory PN emissions from these fuels were lower by comparable magnitude when compared to that from Jet A-1.

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INTRODUCTION

The growth of the aviation industry depends on many local and global factors. Despite the year-to-year variation, the world aviation jet fuel consumption continues to climb and reaching over 5,200 thousand barrels per day in 2010 [1]. Increasing jet fuel consumption does not only increase pressure on jet fuel production, it also increases the amount of pollutants, such as carbon dioxide (CO₂) and particulate matter (PM), being emitted into the atmosphere, particularly at higher altitudes. In order to ensure a sustainable growth of the aviation industry, various organizations around the world have spent a significant amount of effort on developing new renewable fuels and to demonstrate these new fuels on different gas turbine engines. The use of aviation alternative and renewable jet fuel is important not only to reduce the reliance on fossil fuel; it also helps to reduce life-cycle greenhouse gas emissions [2]. In addition, the use of alternative fuels has also been shown to reduce particle number (PN), PM, and black carbon (BC) emissions making the use of alternative fuels as an attractive option [3, 4, 5, 6].

The use of renewable alternative jet fuels on current gas turbine engines also faces some challenges. One of them being the absence of aromatics from the first and second generation alternative jet fuels (e.g., fuels produced from the Fischer Tropsch (FT) and from the hydrotreating or hydroprocessing methods) which is important for the seals in the legacy aircraft and engine fuel systems [4, 7, 8]. Current generation alternative fuels typically consist of paraffinic hydrocarbons and therefore often referred to as synthetic paraffinic kerosene (SPK). Currently, these alternative fuels are only certified to be blended with jet fuel at a maximum of 50% for safety reasons. A recent renewable jet fuel candidate is the synthetic kerosene produced through the catalytic hydrothermolysis (CH) process [9]. Jet fuel produced from this process has similar physical and chemical properties as traditional jet fuel and naturally contains aromatics. This fuel was recently used in its neat form (i.e., unblended) during a demonstration flight test conducted by the National Research Council of Canada [10].

Besides BC particles, ultrafine volatile and semi-volatile materials have also been reported to be emitted from gas turbines and probable sources may include lubrication oil and even semi and intermediate volatile organic carbons (VOC) resulting from incomplete combustion [11, 12]. The emissions of the non-refractory materials at high altitudes could also have influences on contrail and cloud formation [13, 14].

This paper summarizes the gaseous and particle emissions from a turbofan engine core on four different fuels, including a standard Jet A-1 and three alternative fuels. Focus will be put on understanding the differences in ultrafine particle emissions from these fuels and the refractory nature of these emitted particles.

EXPERIMENTAL SECTION

Engine Platform and Test Fuels

The engine used in this study was a General Electric CF-700-2D-2 turbofan engine. During the emission testing, the fan and LP turbine were removed from the engine. The three alternative fuels being investigated in this study apart from the Jet A-1 fuel include: (1) fully synthetic kerosene with aromatics (SKA), (2) 50% volume mixed Hydro-processed Esters and Fatty Acid (HEFA) paraffinic kerosene with Jet A-1, and (3) fully synthetic Fisher Tropsch (FT) fuels.



Figure 1. CF700-2D-2 turbofan engine core set up at NRC Canada.

The SKA fuel used in this study was derived from industrial oilseeds *carinata* (*Brassica carinata*) through the catalytic hydrothermolysis (CH) process [9]. *Carinata* is a non-food and drought-resistant crop that is well-adapted to marginal regions and can easily be incorporated into off-season cropping, fallow cropping, relay cropping, and other non-traditional cropping systems [15, 16]. The CH-SKA fuel produced from this process typically contains hydrocarbons such as cyclo-paraffins, iso-paraffins, and aromatics, thus resulting in physical properties similar to the properties of typical Jet A-1 fuel (Table A1, Appendix).

The HEFA fuel used in this study was derived from the camelina (*Camelina sativa L.*) oilseeds through a hydro-treating and cracking process, which produce fuel that consists of paraffinic hydrocarbons

with no sulfur or aromatics [17]. Similar to *carinata*, camelina is also a non-food crop and is often grown as a rotational crop with wheat and other cereal crops on fallow land [2].

The FT fuel is a synthetic fuel derived from synthesis gas (e.g., from natural gas or coal) using the Fischer-Tropsch process, which typically consist of a complex mixture of paraffins and isoparaffins but contain neither sulfur nor aromatics [7].

Emission Test Procedure

The emission test procedure is discussed in detail in Reference 18. An example of a typical complete test cycle and engine throttle definitions are summarized in Figure A1 in the Appendix. Briefly, on each day, the engine started from cold on Jet A-1 fuel and set to idle (~8000 rpm) until engine parameters and emissions were stabilized. Then the emission test cycle began from idle, then accelerated to 95% engine load (~16,000 rpm), dropped to 80% engine load (~14,000 rpm), and eventually returned back to idle condition. The 85% and 95% engine loads represent the cruise and take-off engine conditions, respectively. At each steady state condition, the engine was stabilized at the same setting for about 5 minutes and then for another additional 2-3 minutes for emission measurements. The emission test cycle finished with a rapid acceleration from idle to 95% engine load (slam) and then followed by a rapid deceleration from 95% engine load to idle (chop). On each test day, the complete throttle cycle is repeated three times, first with Jet A-1 then switching to the test fuel, and finally switching back to Jet A-1 fuel before shutting down the engine.

During the emission testing, fuel switching was conducted during idle engine condition without shutting down the engine (Figure A1, Appendix) to minimize emission testing time and fuel line flushing time. This arrangement was made possible in the test cell with the use of electro-solenoid valves that connect the engine fuel system to different fuel tanks. During the emission tests, the fuel switching was verified through real-time particle number and mass measurements as they always showed distinct increases or decreases in emissions depending on order of the fuel switching. Emission measurements for the new fuel only resumed when all gaseous and particle emissions measurements were stabilized.

Sampling Setup and Measurement Principles

A simplified schematic diagram of the exhaust sampling system is given in Figure A2 (Appendix). Raw exhaust was extracted from a J-probe and transferred to different analyzers through 3/8-inch OD stainless steel lines. The residence time through the sampling line was minimized by an external pump operated at about 50 L/min flow rate and raw exhaust sample was extracted from different sections of the sampling line and directed to various analyzers before reaching the external pump. For gaseous measurements, raw samples were introduced directly to the SEMTECH-DS gaseous analyzer through a heated line operated at 191 °C. Part of the raw exhaust was diluted using an AirVac ejector diluter to prevent condensation. This diluted exhaust was sent to a custom built high sensitivity laser induced incandescence (HS-LII) instrument for BC mass measurements through a 25m carbon-impregnated heated line operated at 61 °C.

Part of the diluted exhaust was extracted before the heated line and further diluted using a Dekati ejector diluter to reduce particle number and mass concentration before directing to a TSI 3090 Engine Exhaust Particle Sizer (EEPS) to measure particle number size distribution and a Magee Scientific AE51 microaethalometer to measure BC mass concentration.

The SEMTECH-DS analyzer measures CO₂ and CO based on non-dispersive infrared absorption technique. The NO and NO_x were measured by non-dispersive ultraviolet absorption while the THC was measured by heated flame ionization detection.

The EEPS size selects the particle based on the electrical mobility of the corona charged particles and then determines the particle counts based on the released charges when the charged particles impact the electrometers.

The microaethalometer and HS-LII instruments detect BC mass concentration using different principles. The HS-LII used in this study is a custom built instrument based on the same operating principle of the commercial version of the Artium Technologies LII300, which uses the auto-compensating LII technique and two color pyrometry to determine particle temperature from the incandescence signal [50]. The major change in the HS-LII used in this study compared to the LII300 is that the former was modified to equip with an enlarged sampling cell and a more powerful laser (200 mJ/pulse, 7 ns FWHM duration, 1064 nm wavelength). This allows the detection of ambient BC mass concentration level as low as 15 ng/m³ (i.e., 8×10^{15} in soot volume fraction) [39]. Inside the HS-LII, particles absorb energy from a pulse laser and are heated to nearly the BC sublimation temperature (~ 3800 K) where the BC particles incandesce. The instrument determines the BC mass concentration, the primary particle diameter, and the active surface area based on temperature of the BC particles, absolute magnitude of the incandescence signal, and the rate of heat losses to the surrounding [19, 20, 21]. Due to the operating principle, the mass concentration measured by the LII principle represents refractory mass concentration. In this article, BC will be used to represent the refractory material mass measured by the HS-LII.

The microaethalometer collects particles on a Teflon-coated borosilicate glass filter ticket and compares the light intensities, derived from a LED source at 880 nm, through the sampled and reference blank spots continuously to determine the light attenuation. The light attenuation is then used to calculate the light absorption and thus the BC mass concentration [22, 23, 24]. In this study, the microaethalometer real-time BC mass measurements were first smoothed to reduce instrumental noise [25] before applying the sample artifact corrections to obtain the correct BC mass concentration [23, 26].

Emission Index Calculations

Calibrations were performed for each gaseous compound at the beginning, middle, and at the end of each test day using corresponding span and zero gases that were certified by the supplier to $\pm 2\%$. Prior to the emission study, all gas cylinders were individually verified in-house against various NIST standard

reference gas cylinders to $\pm 1\%$ purity. For all the particle and BC instruments, sampling from the High-Efficiency Particulate Air (HEPA) filter were performed periodically to ensure no baseline-drifting over time. The electrometers on the EEPS were cleaned at the end of each test day.

Concentrations for all gaseous compounds were reported in parts per million (ppm) by the SEMTECH-DS analyzer. The concentrations were converted to mass emission indices (EIs) based on the Society of Automotive Engineering (SAE) Aerospace Recommended Practice (ARP) 1533A [27].

Particle number and mass EIs were calculated based on ideal gas law and are summarized by Eq. (1) and (2) [5, 18].

$$EI_N = N_p \times 10^6 \times \frac{Q_{exh}}{M_{fuel} \times 0.4535924} \quad (1)$$

$$EI_M = BC_m \times 1000 \times \frac{Q_{exh}}{M_{fuel} \times 0.4535924} \quad (2)$$

Here, EI_N and EI_M are particle number and mass emission indices in the units of particles/kg fuel and g/kg fuel, respectively. N_p is the particle number concentration in particles/cm³, M_{fuel} is the corrected mass flow rate in lb/h, and Q_{exh} is the volumetric exhaust flow rate in m³/h. The exhaust flow rate was estimated based on carbon mass balance calculations using fuel carbon mass fraction and raw CO₂ concentrations correcting for background contribution.

Particle Number and BC Mass Dilution Factors

The dilution factors used for the particle number and mass EIs calculations were determined from a separate laboratory experiment. In the experiment, soot particles produced from a Jing Real Soot Generator Combustion Aerosol Standard (RSG-miniCAST) instrument were introduced into the same sampling system used during the engine emission study. The particle number size distributions and BC mass concentrations were measured at various sampling locations before and after different dilution stages to determine the specific dilution factors used for particle number and mass EIs calculations. In addition, BC mass measurements before and after the heated line were also compared to estimate the BC particle mass losses through the heated line. These dilution factors and BC mass loss corrections were then applied to the corresponding measurements during engine test EIs calculations.

Figure 2 shows the particle number and BC mass concentration time series measured during one typical calibration experiment. Measurements started from the upstream location to determine the pre-diluted particle number and mass concentrations. Then measurements were subsequently taken after different stages of dilution and heated line. These sampling locations represent the same locations where individual particle instruments were sampled during the engine emission study.

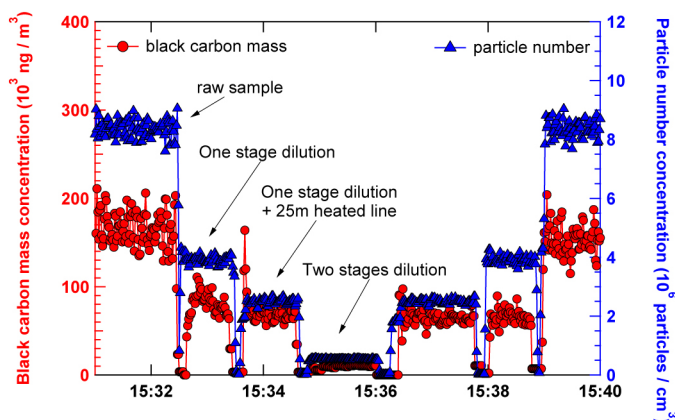


Figure 2. Particle number concentration and BC mass concentration time series during one typical run of the calibration experiment.

Figure 3 compares the averaged particle number size distributions measured at various sampling locations. These measurements show that the changes regarding the shape of the particle number size distributions after subsequent diluters were negligible when compared with the raw concentration, suggesting particle losses for various sizes particle were not substantially different and this can be accounted for through dilution correction.

In comparison, when measuring after the 25m heated line (used for the HS-LII measurements), data show that there were small increases in particle number concentration for the 40-80 nm particles. Residence time through the 25m heated line is estimated to be about 6 seconds and this can potentially lead to a small degree of particle coagulation which increases particle diameter. In addition, higher particle losses were also observed for the 10-30 nm particles due to the faster diffusion losses for these particles compared to other larger particles as well as for potential particle coagulation losses. Integrating the particle number size distributions shows that particle number concentration measured downstream of the heated line is lower by 50% compared to the concentration upstream the heated line as a result of particle losses and possible coagulation. However, this only leads to a reduction of 8% in BC mass because larger particle contribute more mass, the reduction in ultrafine particles number did not result in large reduction in BC mass.

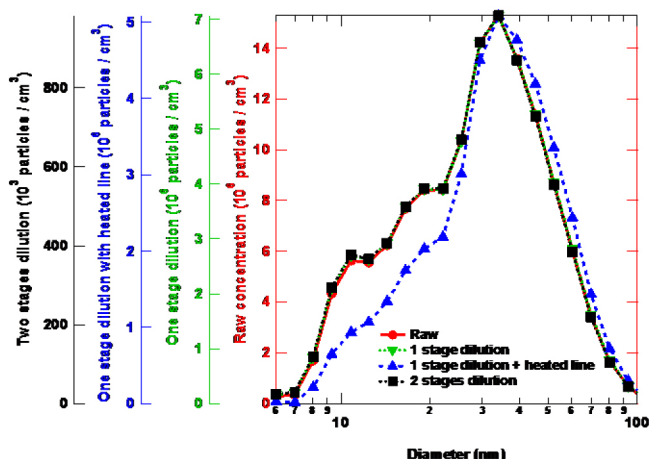


Figure 3. Comparison of the measured particle number size distributions at different stages of dilution during a typical calibration experiment.

Particle Effective Density and Particle Mass Estimation

Combustion generated BC particles vary in shape from complex fractal-like structure to nearly spherical particles with reported fractal dimension ranging from 1.36 to 2.8 [28, 29, 30, 31, 32, 33, 34, 35]. As a result, the electrical mobility diameter of a BC particle does not necessarily equal to the volume equivalent diameter. This causes the effective density, defined as the ratio of the actual particle mass to the spherical volume of the particle calculated from mobility diameter, to decrease with increasing mobility diameter. Various studies from automotive testing showed that the effective particle density of combustion generated particles could vary from 1-2 g/cm³ at 50 nm, to 0.3-0.6 g/cm³ at 200 nm, and even as low as 0.24 g/cm³ at 300 nm [29, 30, 31, 32, 36, 37]. A recent study on turbine engine also showed that BC particles exhibit similar fractal structure and the effective densities were generally in comparable magnitude although this parameter can be dependent on various factors, such as engine load and possibly fuel types [52]. In general, all studies pointed to similar conclusion that soot particles behave as fractal-like agglomerates, and particle mass (M_p) can generally be approximated using the mobility diameter (D_m) and fractal dimension or some referred to as mass mobility exponent (d_f) through the relationship:

$$M_p \propto D_m^{d_f} \quad (3)$$

To estimate particle mass, Maricq and Xu [30] provided an empirical equation considering the soot fractal-like structure:

$$M = N_o \frac{\pi}{6} \rho_o d_o^{(3-d_f)} \mu_g^{d_f} e^{d_f^2 (\ln \sigma_g)^2 / 2} \quad (4)$$

where N_o is the particle number concentration, ρ_o and d_o are the primary particle density and diameter, μ_g and σ_g are geometric mean diameter and standard deviation, d_f is the fractal dimension. In this study, PM was estimated by applying Eq. (4) to the measured number size distributions using parameters given by Maricq and Xu [30] (i.e., $\rho_o = 2$ g/cm³, $d_o = 20$ nm, $\sigma_g = 1.7$, $d_f = 2.3$), which represent conditions for typical fuel and engine settings.

RESULTS AND DISCUSSION

Gaseous Emissions

CO₂ and NO_x emissions from the test campaign have been reported and discussed in detail in Reference 18 and therefore will not be repeated here. For the objective of this paper, discussions will focus only on the CO and THC emissions. All gaseous EI for various fuels and different engine load conditions are tabulated in Table A2 (Appendix).

Figure 4 summarizes the CO EI for all fuels at different engine conditions. Measurements show that CO EIs for various fuels at idle condition were higher by a factor of about 3 when compared to the CO EIs at 80% engine load. When compared to the CO EIs at 95% engine load, idle CO EIs were higher by a factor of about 6. During complete combustion, all carbon mass in the fuel should be converted to CO₂ while in case of incomplete combustion, some of the carbon