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Black carbon emissions reductions from combustion of alternative jet fuels

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HIGHLIGHTS

- Recent measurements suggest alternative jet fuels reduce BC emissions.
- We develop the ASAF correlation to estimate these emissions reductions.
- ASAF explains 72% of the variability in BC number and 56% for BC mass emissions.

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ABSTRACT

Recent measurement campaigns for alternative aviation fuels indicate that black carbon emissions from gas turbines are reduced significantly with the use of alternative jet fuels that are low in aromatic content. This could have significant climate and air quality-related benefits that are currently not accounted for in environmental assessments of alternative jet fuels. There is currently no predictive way of estimating aircraft black carbon emissions given an alternative jet fuel. We examine the results from available measurement campaigns and propose a first analytical approximation (termed 'ASAF') of the black carbon emissions reduction associated with the use of paraffinic alternative jet fuels. We establish a relationship between the reduction in black carbon emissions relative to conventional jet fuel for a given aircraft, thrust setting relative to maximum rated thrust, and the aromatic volume fraction of the (blended) alternative fuel. The proposed relationship is constrained to produce physically meaningful results, makes use of only one free parameter and is found to explain a majority of the variability in measurements across the engines and fuels that have been tested.

1. Introduction

Aviation accounts for approximately 3% of global anthropogenic CO_2 emissions and (due to non-CO_2 effects) ~5% of anthropogenic radiative forcing (Lee et al., 2009). Existing studies on greenhouse gas emissions of alternative jet fuels have usually focused on life-cycle CO_2, N_2O and CH_4, emissions, but have generally omitted non-CO_2 combustion emissions such as black carbon (BC) (Seber et al., 2014; Staples et al., 2014; Stratton et al., 2011b). An exception is Stratton et al. (2011a) who showed that non-CO_2 effects for alternative jet fuels are important when considering the relative reduction in climate impacts, and included the potential effect of soot reductions. They assumed a range of 60–95% reduction in soot emissions as an uncertainty range based on the limited data then available, which consisted of measurements using one Fischer–-Tropsch (FT) fuel in a single turboshaft engine and two FT fuels in a single turbofan engine.

Formulations have previously been developed to estimate aircraft black carbon emissions, e.g. FOA3 by Wayson et al. (2009) and the newer FOX by Stettler et al. (2013a, 2013b). These apply only to conventional jet fuels. No relations currently exist to estimate BC emissions associated with use of alternative jet fuels. Here we draw upon a set of recent measurement campaigns to propose a relationship, which we designate 'ASAF' (Approximation for Soot from Alternative Fuels), between fuel aromatic content and black carbon emissions. ASAF as developed here is applicable to FT and hydroprocessed esters and fatty acids (HEFA) alternative fuels (and potentially other paraffinic alternative fuels), which constitute the

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major fraction of currently available and certified alternative jet fuels.

Potential applications for ASAF include environmental analyses of alternative fuels related to climate and air quality impacts. For example, Stettler et al. (2013a) showed that the radiative forcing (RF) from aircraft BC emissions may have been significantly underestimated and could be equivalent to as much as a third of the present-day RF from aviation CO_2. This is indicative of the scale of direct BC-related climate benefits associated with combustion of alternative jet fuels. In addition, contrail RF is uncertain but is of the same order as the present-day aviation CO_2 RF, and potentially larger (Burkhardt and Kärcher, 2011; IPCC, 2013). Reducing BC emissions would reduce the number of available ice condensation nuclei in a contrail, thereby potentially reducing contrail optical depth (and RF) (Kärcher and Yu, 2009; Schumann, 2012). Although no studies to date have quantified the effect of alternative jet fuels on contrail RF, the present study will enable such an estimate to be made. Finally, population exposure to BC is thought to result in increased health risk. For example, Yim et al. (2013) estimated that BC emissions at UK airports results in ~110 early deaths per year. A model of reductions in BC emissions associated with blending alternative jet fuels will enable estimation of the health benefits of such a measure.

Table 1
Summary of alternative jet fuel particulate matter emissions measurements. ID corresponds to the matching row in Table 2.

ID	Engine designation	Representative aircraft	Measurements	Alternative fuel	References
1a	CFM56-2C	Douglas DC-8	EI_N(total) EI_m(BC)	50/100% coal-to-liquids FT 50/100% gas-to-liquids FT	AAFEX1 (Beyersdorf et al., 2014; Bulzan et al., 2010)
1b				50%/100% HEFA	AFFEX2 (Anderson, 2012)
1c					ACCESS (Anderson and Moore, 2013)
2	CFM56-7B	Boeing 737	Relative EI_N(total) Relative EI_m(BC)	50/100% FT	Timko et al. (2011)
3	PW308	Dassault Falcon 2000DX	Relative EI_N(total) Relative EI_m(BC)	50/100% FT	Timko et al. (2010)
4	PW2000 (F117)	Boeing 757	Relative EI_N(total)	50% HEFA 25% HEFA, 25% FT	Corporan et al. (2010a)
5	JT3D (TF33)	Boeing B-52	Relative EI_N(total)	50% FT	Corporan et al. (2012)
6a	Allison 250 (T63-A)	Bell 206	Relative EI_N(total) EI_m(BC)	0–100% gas-to-liquids FT	Corporan et al. (2007)
6b			Relative EI_N(total)	50/100% Shell FT 50/100% Sasol FT 50/100% Rentech FT 50% Syntroleum FT 100% HEFA	Corporan et al. (2011)
6c			EI_N(total) EI_m(BC)	100% Sasol FT	Cain et al. (2013)
7	T701C	Sikorsky UH-60	EI_N(total) EI_m(BC)	100% FT	Corporan et al. (2010b)

2. Materials and methods

We base our work on the results of recent measurement campaigns which measured black carbon emissions for at least one paraffinic alternative fuel and conventional fuel used in a turbofan or turboshaft engine. The engines, fuels, and measurements for these campaigns are summarized in Table 1.

For the current work, we restrict our analysis to alternative jet fuels produced via FT or HEFA processes, and blends of these with conventional jet fuel. These processes produce fuels consisting principally of iso- and normal paraffins, with typically less than 10% cycloparaffins and less than 1% aromatics (Corporan et al., 2012). With the exception of the ACCESS (Anderson and Moore, 2013) study, all measurements have been taken at sea level static conditions. We note that this means that further modifications may be appropriate to account for cruise conditions, which have not been made at this stage, e.g. as applied by Stettler et al. (2013a) based on the work of Döpelheuer and Lecht (1999).

The instrumentation and measurement techniques used in each campaign are summarized in Table 2.

As recommended by Petzold et al. (2013), we report the instruments used to make both mass and number emissions measurements. While the measurement techniques used in these studies to determine the particle number emissions index, EI_N(total), are strictly speaking applicable to non-volatile particulate matter, previous research shows that to within instrumentation limits, these emissions consist only of refractory carbon soot particles (Onasch et al., 2009) which we assume here to be a form of black carbon. In all campaigns except the ACCESS campaign, samples were collected within 1 m of the engine exit plane, diluted near the probe location with nitrogen or dry air, and transported through heated sample lines to the measurement instruments. In each campaign, the fuel aromatics content was measured using either the ASTM D1319 or D6379 test methods. The influence of differences between these test methods is minimized by normalizing the aromatics content of the alternative fuels by that of the conventional fuel used in the same campaign and tested using the same test method.

Table 2
Summary of instrumentation and measurement techniques used in particulate matter emissions measurements. ID corresponds to the matching row in Table 1. Abbreviations: condensation particle counter (CPC); multi-angle absorption photometer (MAAP); particle soot absorption photometer (PSAP); tapered element oscillating microbalance (TEOM).

ID	Number instrument	Mass instrument	Probe distance from engine exit	Measurement count	Aromatics test (ASTM)
1a	TSI 3775 CPC	Thermo Scientific 5012 MAAP	1 m	28	D6379
1b				18	D1319
1c	TSI 3010 CPC	PSAP	250–500 m	6	–
2	TSI 3022A CPC	MAAP	1 m	11	D1319
3	TSI 3775 CPC	Thermo Scientific 5012 MAAP	1 m	8	D6379
4	TSI 3022A CPC	n/a	0.4 m	8	D1319
5	TSI 3022A CPC	n/a	–	4	D1319
6a	TSI 3022A CPC	R&P Series 1105 TEOM	–	16	D1319
6b		n/a		28	D1319
6c		MAAP		16	D6379
7	TSI 3022A CPC	R&P Series 1105 TEOM	0.3 m	3	D1319