DTU

Engine Performance and Emission Characteristics of HEFA-SPK, FT-SPK, and ATJ- SPK Sustainable Aviation Fuels

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1. Three types of sustainable aviation fuel

1.1 Three types of sustainable aviation fuel

- HEFA-SPK - Hydroprocessed esters and fatty acids synthetic paraffinic kerosene
- FT-SPK - Fischer-Tropsch synthetic paraffinic kerosene
- ATJ-SPK - Alcohol-to-jet synthetic paraffinic kerosene

- These three types of SAF were chosen for this presentation because they exhibit high fuel and technology readiness levels and have been extensively studied in the literature.

SAF synthesis pathway	Technology readiness level (The highest level is 9)	Fuel readiness level (The highest level is 9)	Energy efficiency[a]	Available feedstocks	Year of authorization	Advantages and disadvantages	Ref.
HEFA-SPK	9	9	0.71-0.77	Bio-oils, animal fats (tallow and mixed fat) and waste oils	2011	Advantages Higher LHV than Jet A-1 and JP-8 Enhanced emissions performance Potential for use as 100% SAF High energy efficiency relative to other SAF production pathways Disadvantages Limited to oil- and fat-derived feedstocks Higher viscosity is detrimental to fuel evaporation	Ref. Lau, Dahal, Abrantes et al.
FT-SPK	6-8	6-7	0.40-0.53	Biomass, municipal solid waste (household waste, organic waste), natural gas, and coal	2009	Advantages Ability to utilize diverse feedstocks Enhanced emissions performance Higher LHV than Jet A-1 and JP-8 Disadvantages Low energy efficiency Substantial electricity demand	Ref. Lau, Dahal, Abrantes et al.

SAF synthesis pathway	Technology readiness level (The highest level is 9)	Fuel readiness level (The highest level is 9)	Energy efficiency[a]	Available feedstocks	Year of authorization	Advantages and disadvantages	Ref.
FT-SPK/A	6-8	6-7	0.40-0.53	Biomass, municipal solid waste (household waste, organic waste), natural gas, and coal	2015	Advantages Reach alkylated aromatic levels of up to 20 wt% Potential for use as 100% SAF Disadvantages Low energy efficiency	Ref. Lau, Dahal, Abrantes et al.
ATJ-SPK	7-8	7	0.91	Conventional biomass and cellulosic biomass, starch, and carbohydrates	2018	Advantages High energy efficiency A mature and well-developed ethanol production infrastructure, which can be utilized for ATJ-SPK production Advances in fermentation technology could increase alcohol yields and reduce production costs Disadvantages Lengthy production chains utilizing sugar and starch crops	Ref. Lau, Dahal, Abrantes et al.

Key sp SAFs.

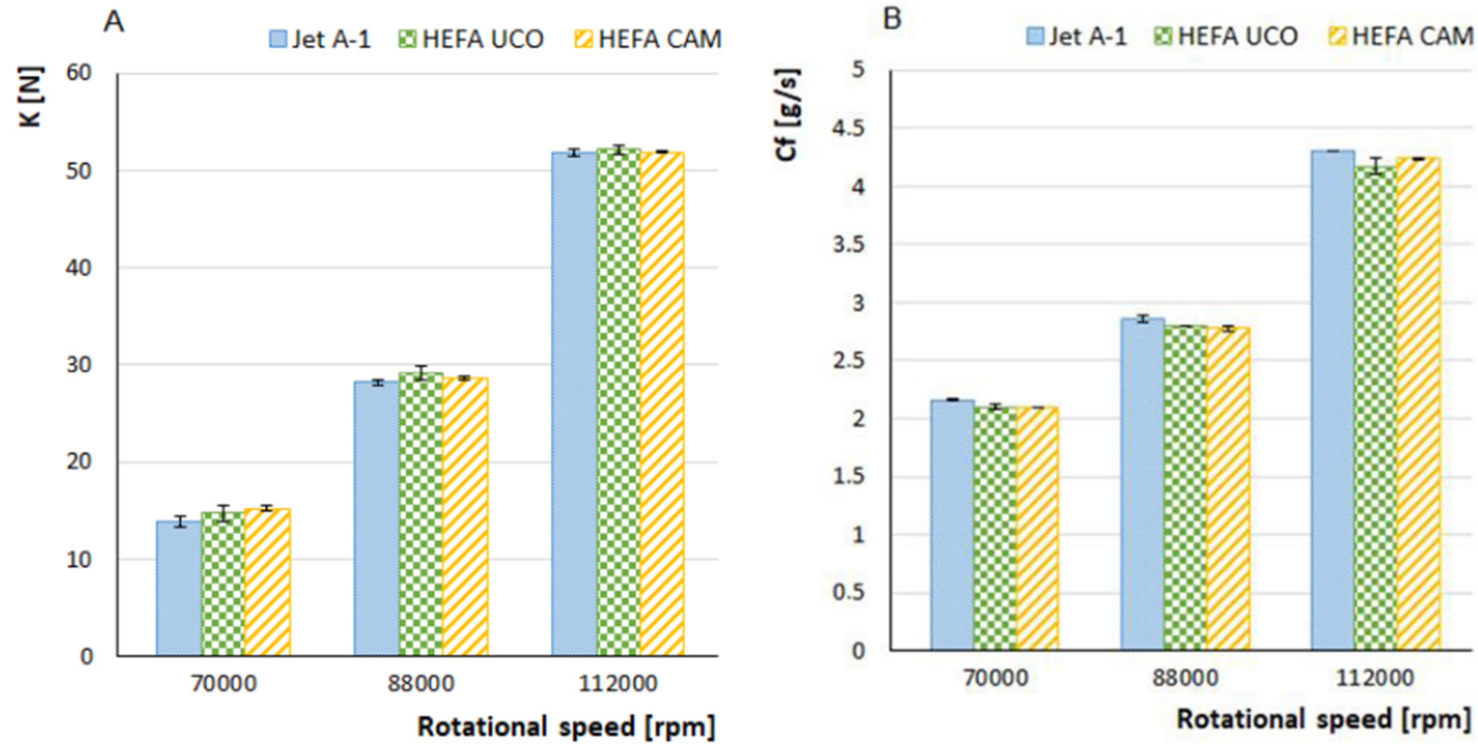
Test properties	Unit	ASTM D7566	ASTM D1655 (Jet A and Jet A-1)	Jet A-1 [71]	HEFA-SPK [72], [73]	FT-SPK [74], [75]	ATJ-SPK [76]
Aromatics	volume percent	Max 25	Max 25	18.3	0.31	< 0.1	0.01 (bio)
Sulfur	total mass percent	Max 0.3	Max 0.3	0.019	<0.001	-	<0.001
H/C ratio	-	-	-	1.92	2.10	2.17	2.2-2.3
Net heat of combustion	MJ/kg	Min 42.8	Min 42.8	43.1	44.2	43.8	43.40
Flash point	℃	Min 38	Min 38	54	42	39.5	47
Density at 15 ℃	kg/m^3	775 to 840	775 to 840	814.8	730 to 770	730 to 770	730 to 770
Viscosity at -20 ℃	mm^2/s	Max 8	Max 8	4.654	4.801	3.488	4.779
Freezing point	℃	Max -40 Jet A Max -47 Jet A-1	Max -40 Jet A Max -47 Jet A-1	-53.2	-54.4	< -64	-40
Final boiling point	℃	Max 300	Max 300	259.8	277.2	220.9	-

2. Properties and chemical composition of SAF

The contents of n-paraffins, iso-paraffins, mono-, di-, and tricycloparaffins, as well as other substances, in various aviation fuels.

Type of hydrocarbon	Jet A	HEFA	FT	ATJ
N-paraffins	20.97	8.53	0.39	-
Iso-paraffins	30.58	89.68	96.94	99.93
Monocycloparaffins	20.12	1.73	2.37	0.07
Di- and tricycloparaffins	24.41	1.73	2.37	-
Alkylbenzenes	15.46	0.03	0.20	-
Cycloaromatics	6.89	-	0.07	-
Alkylnaphthalenes	1.69	-	0.02	-

3. Performance characteristics of SAF-fueled engines
HEFA-Based aviation fuels

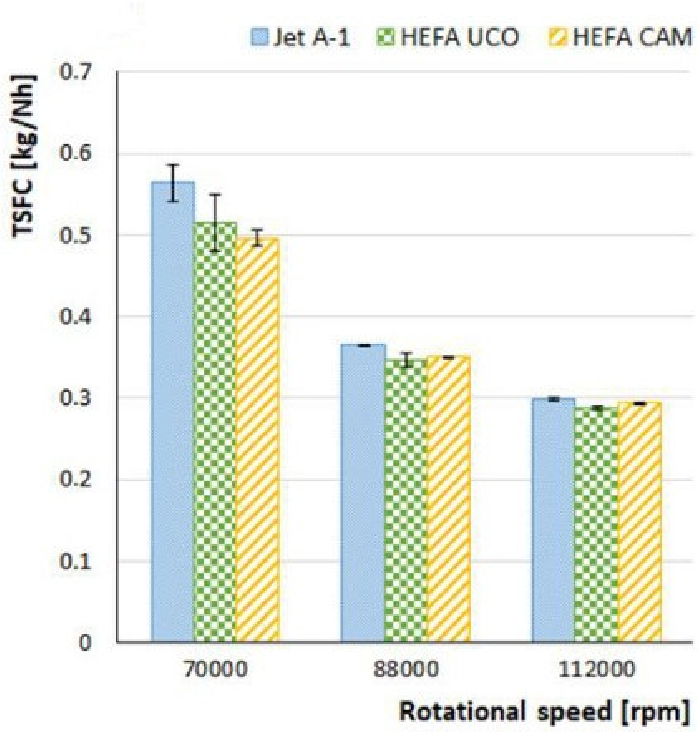


The fuel consumption of HEFA shows reductions of 1.6%-3.2% under the identical engine speed conditions.

Thrust and fuel consumption of Jet A-1-fueled, HEFA UCO-fueled, and HEFA CAM-fueled GTM-140 turbojet engines at various rotational speeds. (Ref. Gawron et al.)

3. Performance characteristics of SAF-fueled engines

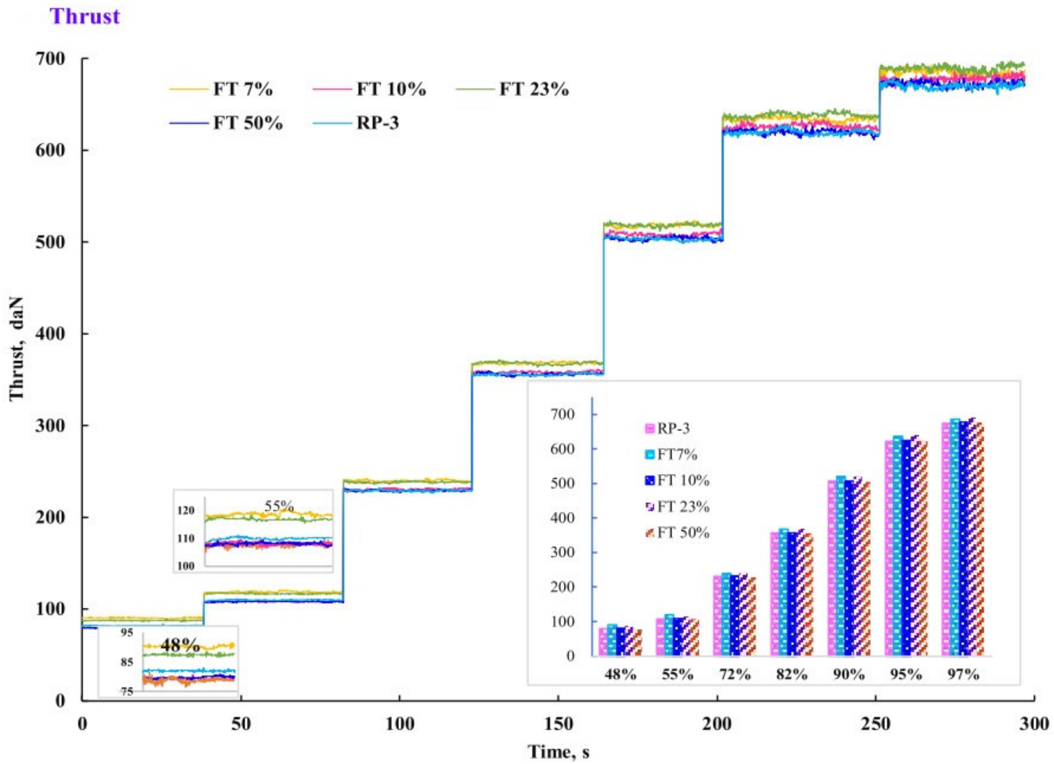
HEFA-Based aviation fuels



- *TSFC of Jet A-1-fueled, HEFA UCO-fueled, and HEFA CAM-fueled GTM-140 turbojet engines at various rotational speeds. (Ref. Gawron et al.)*
- *The TSFC of HEFA shows reductions of 2.63%-4.82% under the identical engine speed conditions.*
- *A higher hydrogen content in the fuel would increase the intrinsic overall efficiency as a result of the higher heat value. The lower C/H ratios of the SAF fuels and their subsequent effects on the energy density of fuel lead to a reduction in the fuel flow at various speed settings, which in turn is reflected in the reduction the engine TSFC.*

3. Performance characteristics of SAF-fueled engines

FT-SPK-Based aviation fuels

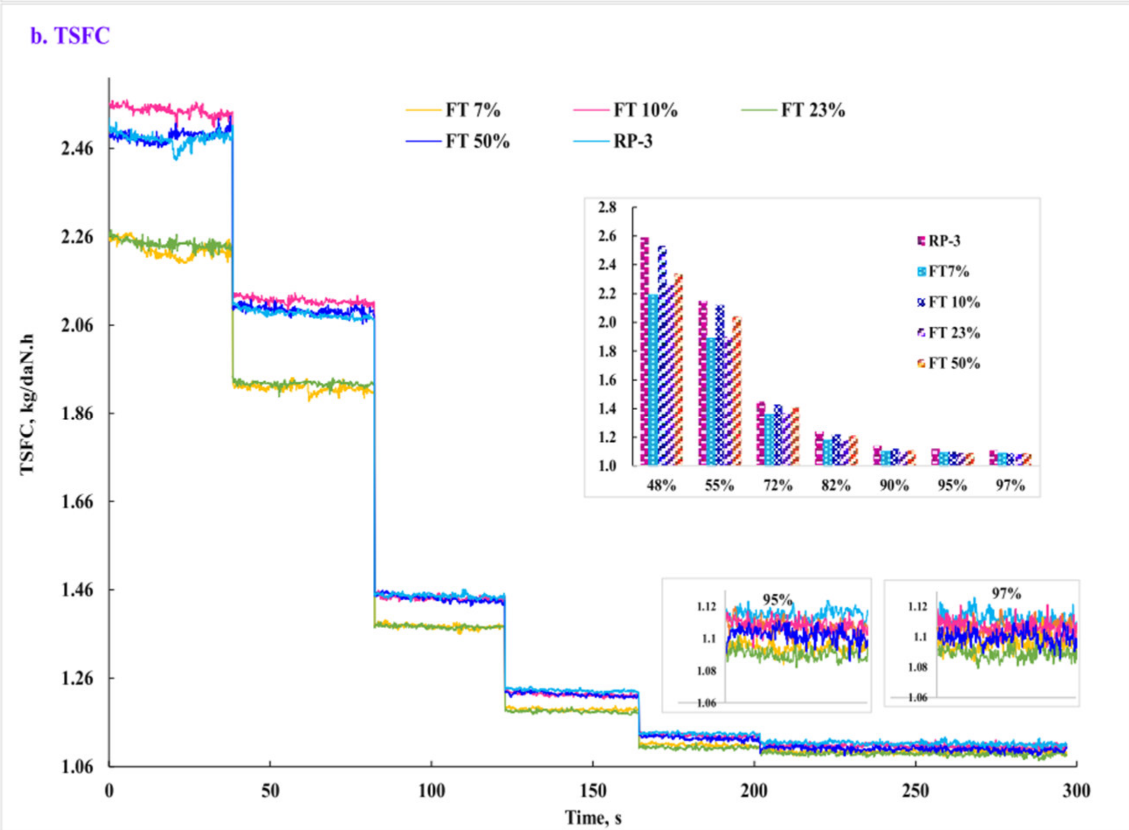


- *Thrust performance of a ZF850 jet engine with different FT-SPK blends and neat RP-3 at various speed settings (the engine speed varied over time). (Ref. Liu et al.)*

- The test results showed that, across various operating speeds, the engine fueled with a 7% FT-SPK blend produced 8.18% higher thrust compared to RP-3, while the 23% FT-SPK blend yielded a 7.27% increase.

3. Performance characteristics of SAF-fueled engines

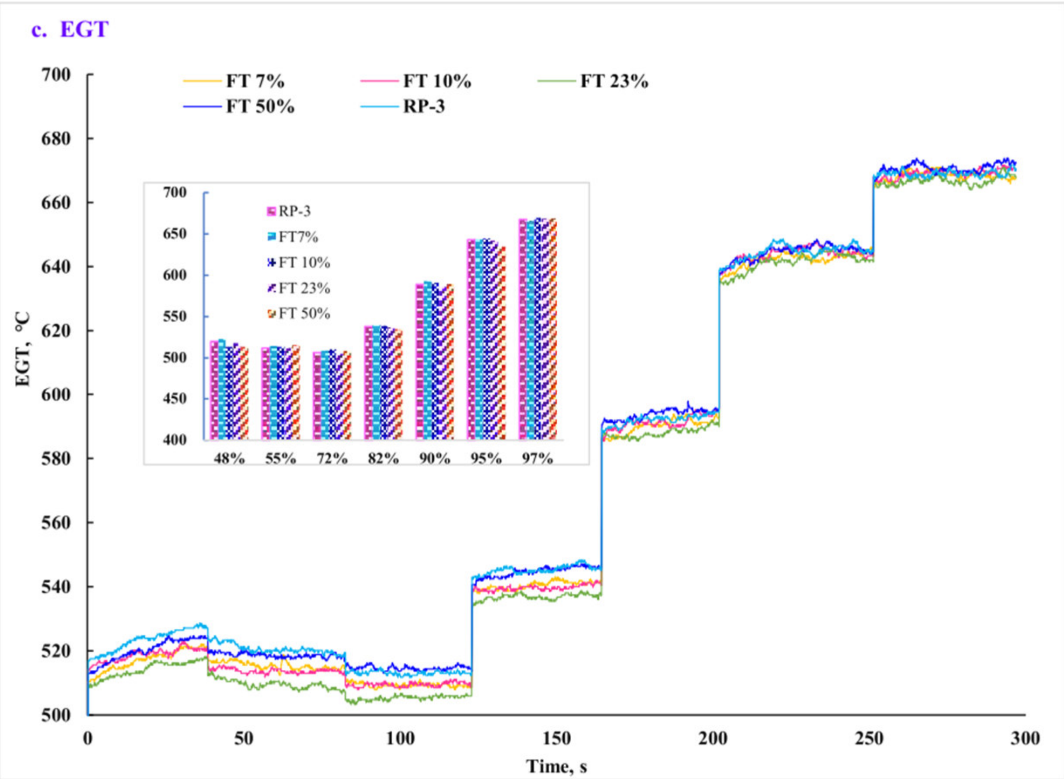
FT-SPK-Based aviation fuels



- *TSFC performance of a ZF850 jet engine with different FT-SPK blends and neat RP-3 at various speed settings (the engine speed varied over time). (Ref. Liu et al.)*

3. Performance characteristics of SAF-fueled engines

FT-SPK-Based aviation fuels

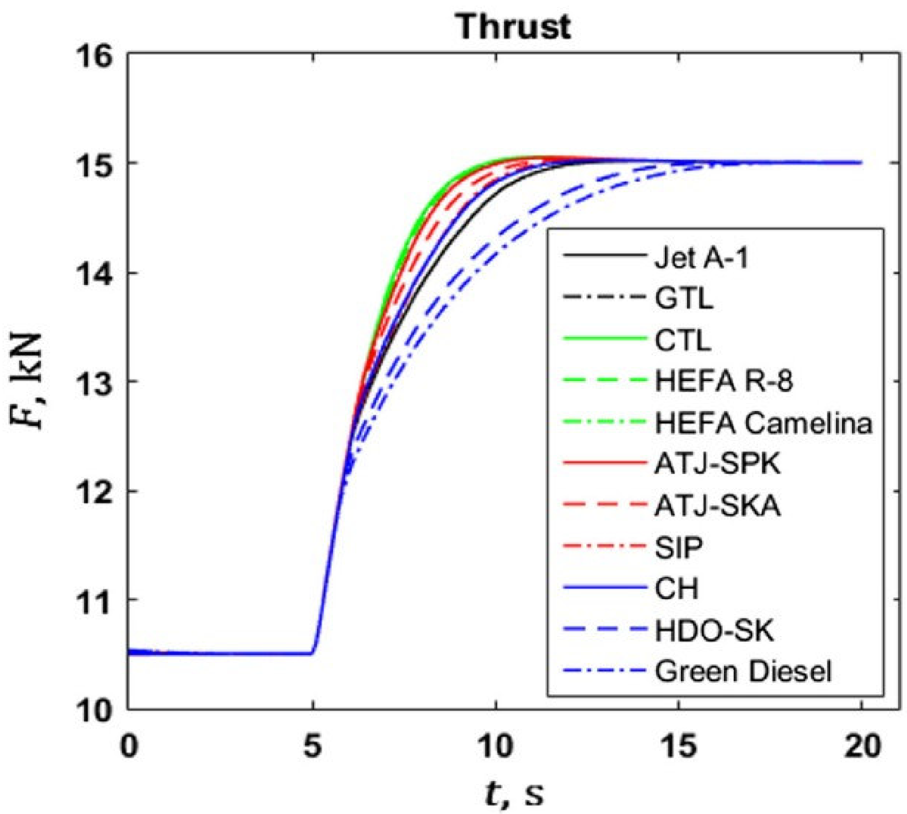


- *EGT of a ZF850 jet engine with different FT-SPK blends and neat RP-3 at various speed settings (the engine speed varied over time). (Ref. Liu et al.)*

- *A lower TSFC per thrust output or a lower EGT at the same engine speed setting can be attributed to a high engine efficiency.*

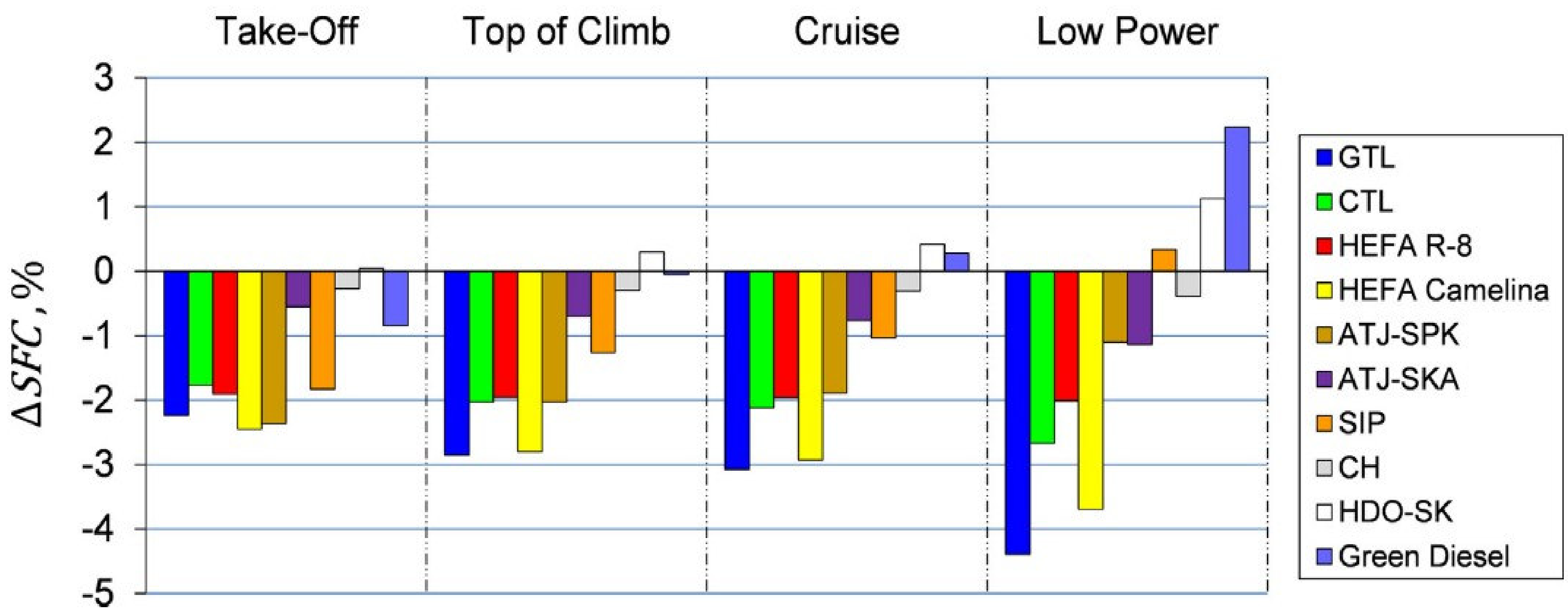
3. Performance characteristics of SAF-fueled engines

ATJ-SPK-Based aviation fuels



- *Thrust performance of ATJ-SPK, other alternative fuels, and Jet A-1 in a small two-spool turbofan engine model under transient conditions. (Ref. Gaspar et al.)*

3. Performance characteristics of SAF-fueled engines
ATJ-SPK-Based aviation fuels



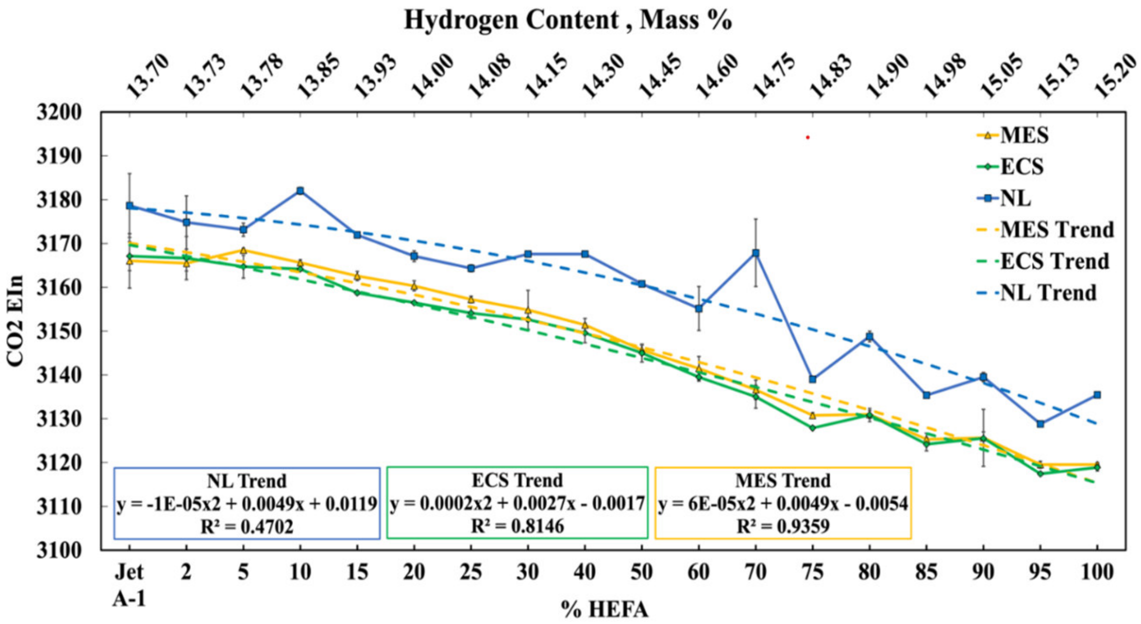
Comparison of specific fuel consumption for ATJ-SPK and other alternative fuels relative to Jet A-1 in a small two-spool turbofan engine model under various operating conditions. (Ref. Gaspar et al.)

3. Performance characteristics of SAF-fueled engines
ATJ-SPK-Based aviation fuels

- *Based on ignition delay and time-to-light, engines fueled with ATJ-SPK exhibited inferior ignition performance compared to Jet A, F-24, and JP-5. This was primarily attributed to the lower cetane number of ATJ-SPK relative to conventional aviation fuels. Moreover, the chemical ignition delay increased with higher ATJ-SPK blend ratios, largely due to the formation of relatively stable isobutene that required extended oxidation times. The combustion efficiency of ATJ-SPK was approximately 2–4% lower than that of Jet A, a reduction mainly associated with its slightly higher viscosity and boiling point, which hindered fuel atomization and evaporation, thereby limiting combustion efficiency.*

4. Emission characteristics of SAF-fueled engines

HEFA-Based aviation fuels

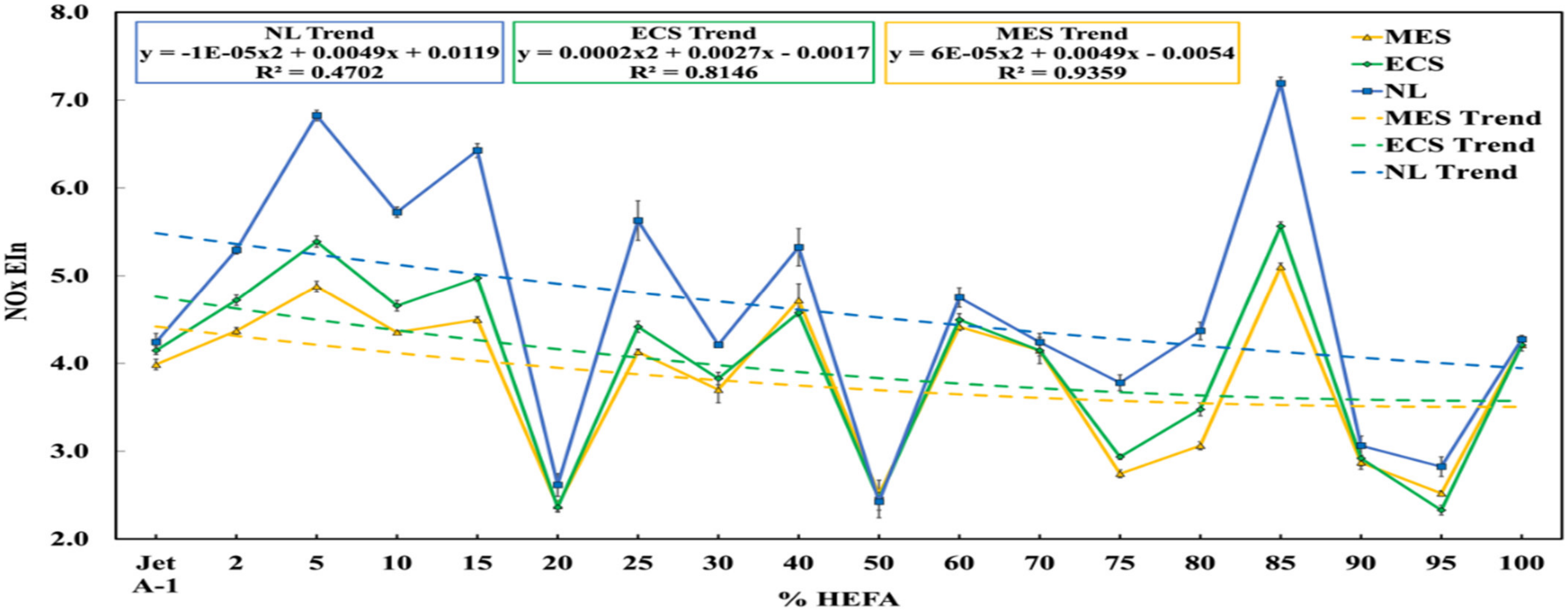


CO_2 emissions across varying HEFA blending ratios, Jet A-1, and hydrogen contents. (Ref. Undavalli et al.)

- *This trend is attributable to the higher hydrogen content of HEFA (An increase in the HEFA blending ratio was accompanied by a corresponding rise in hydrogen content), which increases the fuel's heating value, thereby reducing specific fuel consumption and consequently lowering CO_2 emissions.*

4. Emission characteristics of SAF-fueled engines

HEFA-Based aviation fuels



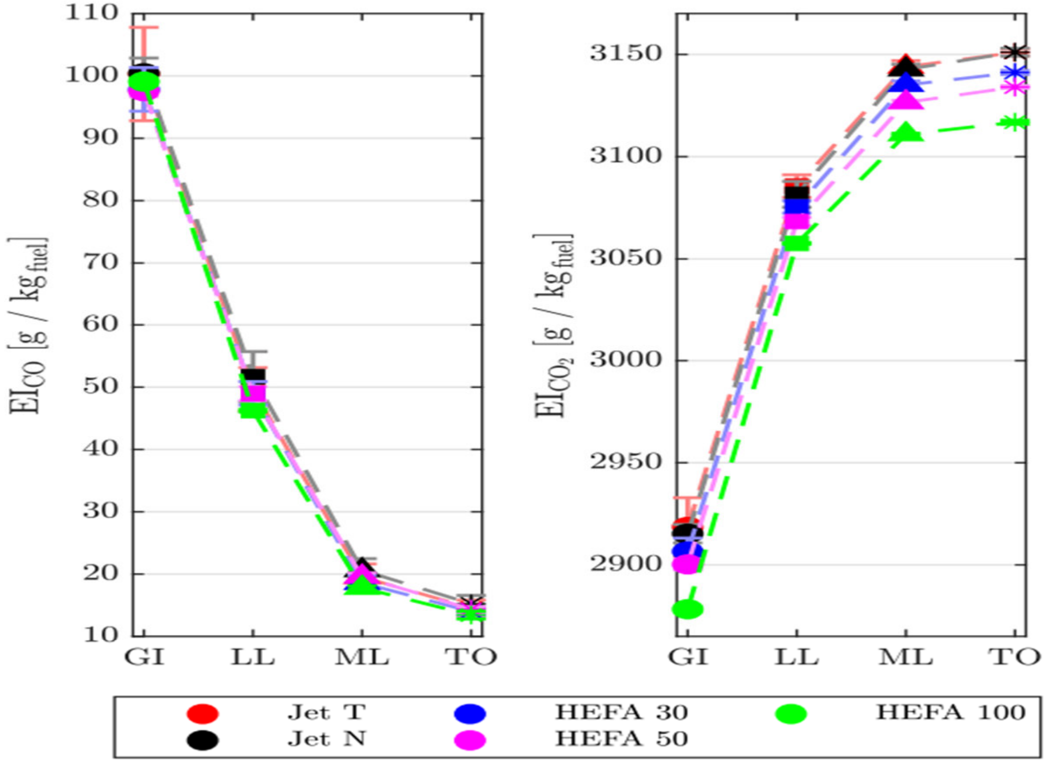
NOx emissions across varying HEFA blending ratios, Jet A-1, and fuel energy density. (Ref. Undavalli et al.)

4. Emission characteristics of SAF-fueled engines

HEFA-Based aviation fuels

- *This trend was closely associated with variations in combustion chamber pressure, adiabatic flame temperature, and oxygen concentration.*

4. Emission characteristics of SAF-fueled engines



Comparison of the emission indices of carbon monoxide EICO (left) and carbon dioxide EICO2 (right) of the different fuels for difference Power settings. (Ref. Rabl et al.)

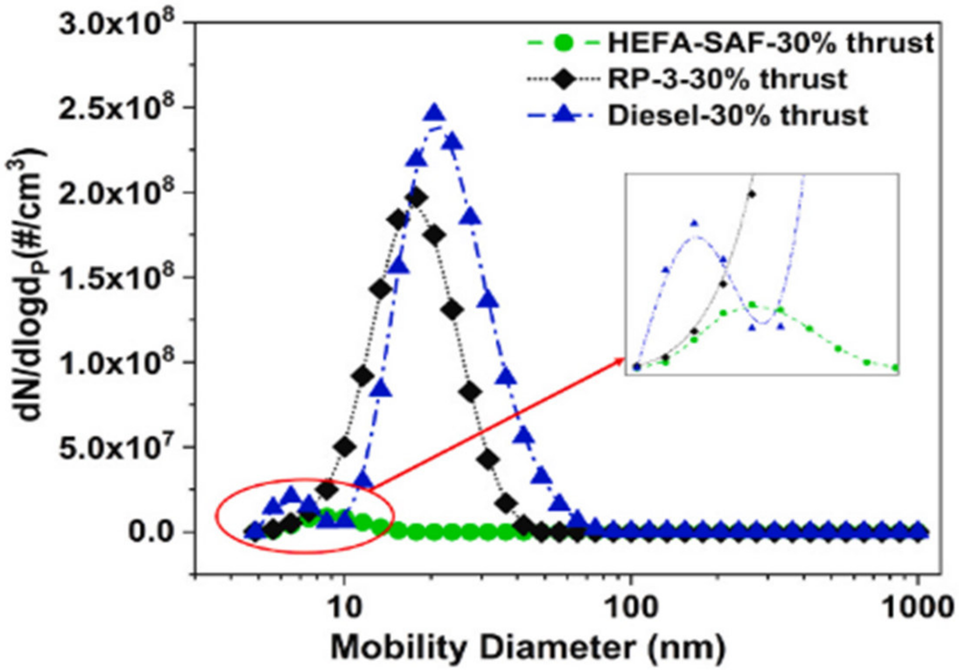
- *More uniform fuel-air mixture formation of HEFA fuel and more complete combustion*

Combustion efficiency

η_{CC}	Jet T	Jet N	HEFA 30	HEFA 50	HEFA
GI	93.94	93.78	93.83	93.85	93.8
LL	98.11	98.03	98.10	98.11	98.3
ML	99.44	99.42	99.47	99.45	99.5
TO	99.58	99.58	99.61	99.61	99.6

4. Emission characteristics of SAF-fueled engines

HEFA-Based aviation fuels



Particle size distribution of particulate matter emitted from a turbofan engine at 30% thrust using HEFA and RP-3 fuels. (Ref. Xu et al.)

HEFA-SPK engine emitted approximately 1.35×10^7 #/cm³ of ~8 nm PM

whereas the RP-3-fueled engine emitted about 1.9×10^8 #/cm³ of ~19.3 nm PM.

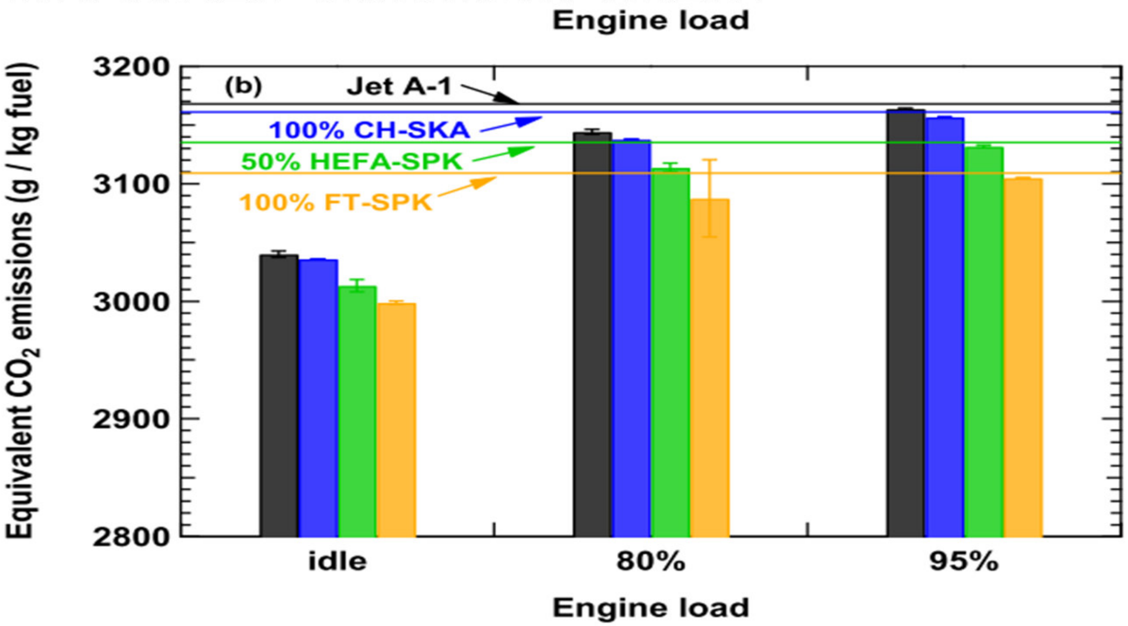
4. Emission characteristics of SAF-fueled engines

HEFA-Based aviation fuels

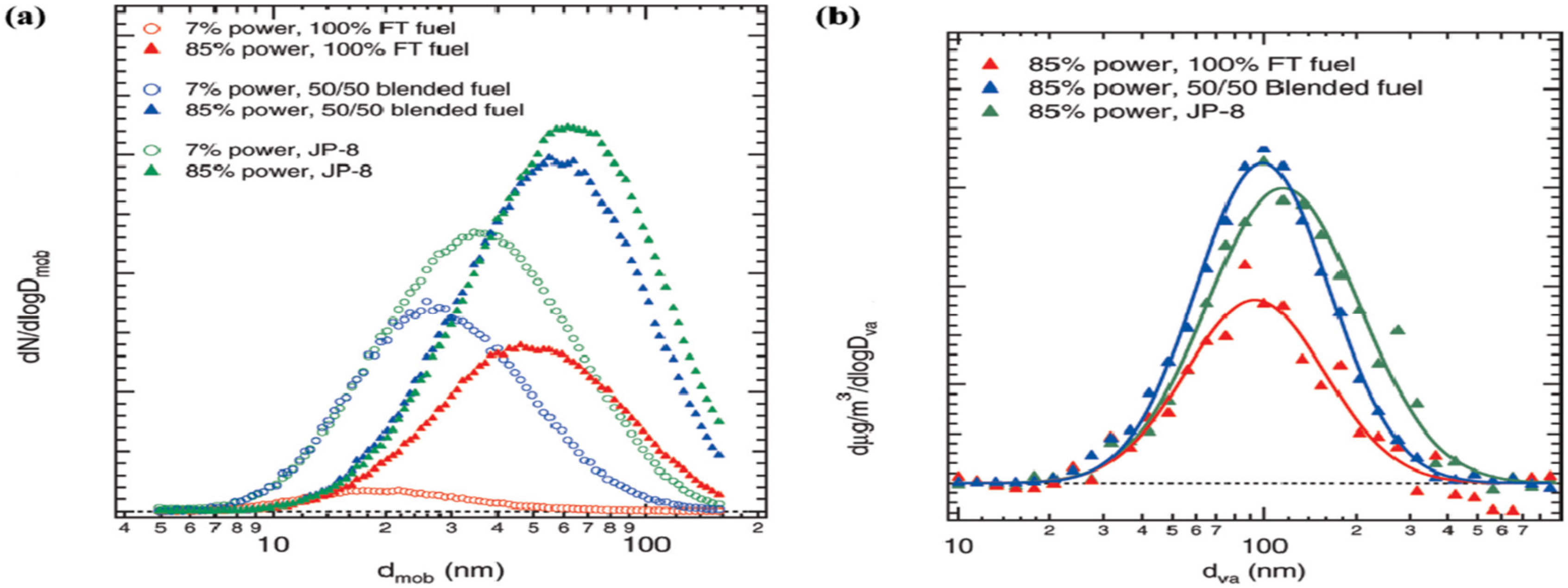
- *The reduced PM emissions from HEFA fuel are primarily attributed to its negligible aromatic and sulfur content, key precursors of particulate matter. Additionally, the hydroprocessing and esterification pathways used in HEFA production yield fuel with more uniform properties, promoting more complete combustion and limiting the formation of volatile and non-volatile particulates.*

4. Emission characteristics of SAF-fueled engines

FT-SPK-Based aviation fuels



CO2 equivalent emissions from the four fuels at the three steady engine load conditions with theoretical equivalent CO2 for each fuel (Ref. Chan et al.)

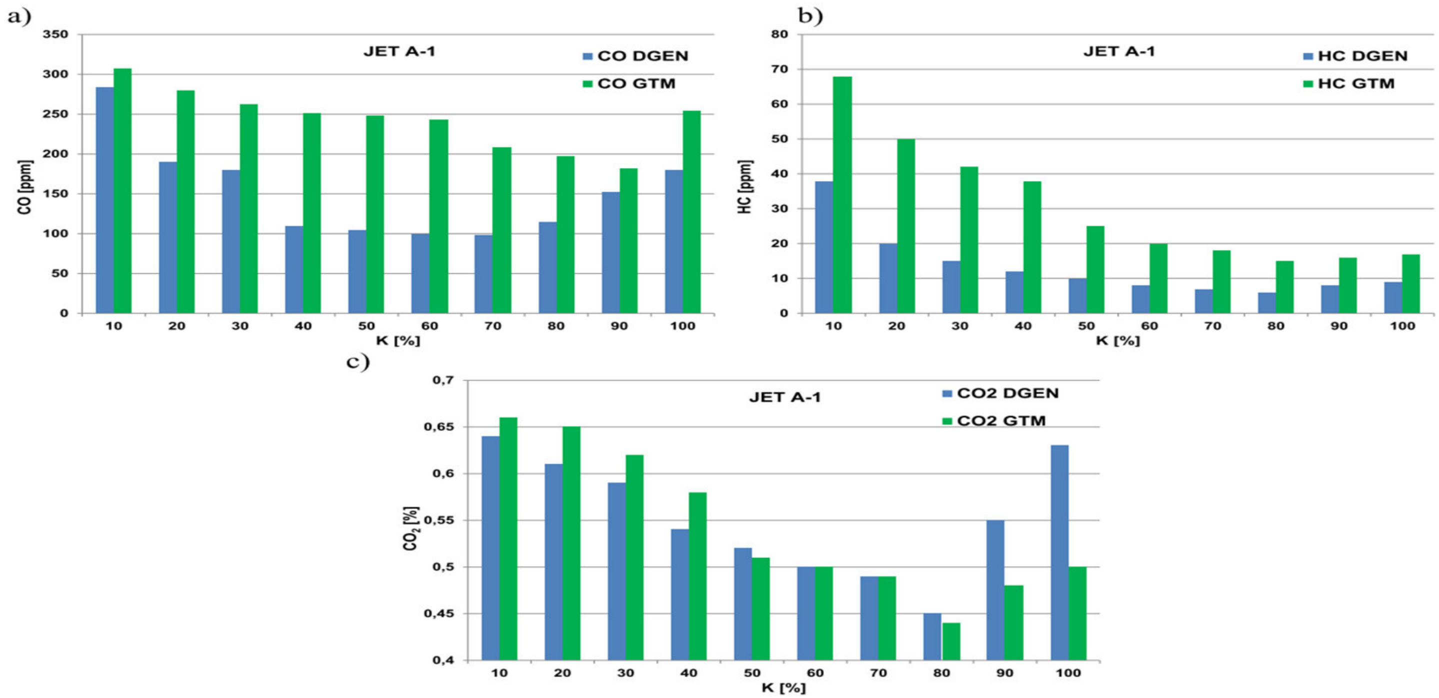


Particle size distribution from engines fueled with 50% and 100% FT-SPK, as well as JP-8: (a) size-resolved PM number density measured by a scanning mobility particle sizer at 7% idle and 85% climbout power; (b) size-resolved volatile PM mass measured by an aerosol mass spectrometer at 85% power. (Ref. Timko et al.)

At the 7% power setting, the particle sizes for the 50% FT-SPK, 100% FT-SPK, and JP-8 cases were approximately 69.8 nm, 45.1 nm and 89.1 nm, respectively. At the 85% power setting, the corresponding particle sizes were about 136.2 nm, 114.1 nm, and 140.6 nm.

4. Emission characteristics of SAF-fueled engines

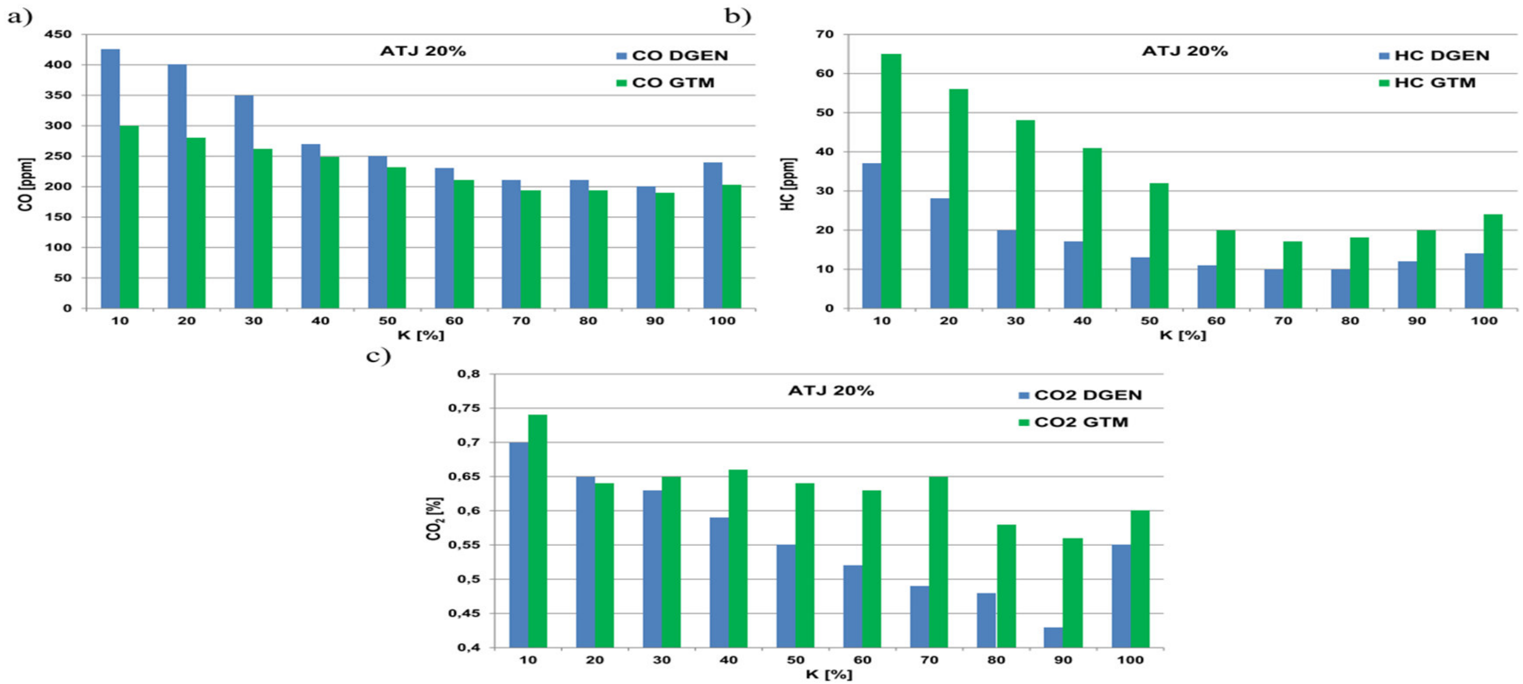
- **ATJ-SPK-Based aviation fuels**



Exhaust concentrations of CO, HC, and CO_2 from the Jet A-1-fueled DGEN 380 and GTM-120 engines. (Ref. Merkisz et al.)

4. Emission characteristics of SAF-fueled engines

- **ATJ-SPK-Based aviation fuels**



Exhaust concentrations of CO, HC, and CO2 from the ATJ-SPK-fueled DGEN 380 and GTM-120 engines. (Ref. Merkisz et al.)

4. Emission characteristics of SAF-fueled engines

- **ATJ-SPK-Based aviation fuels**

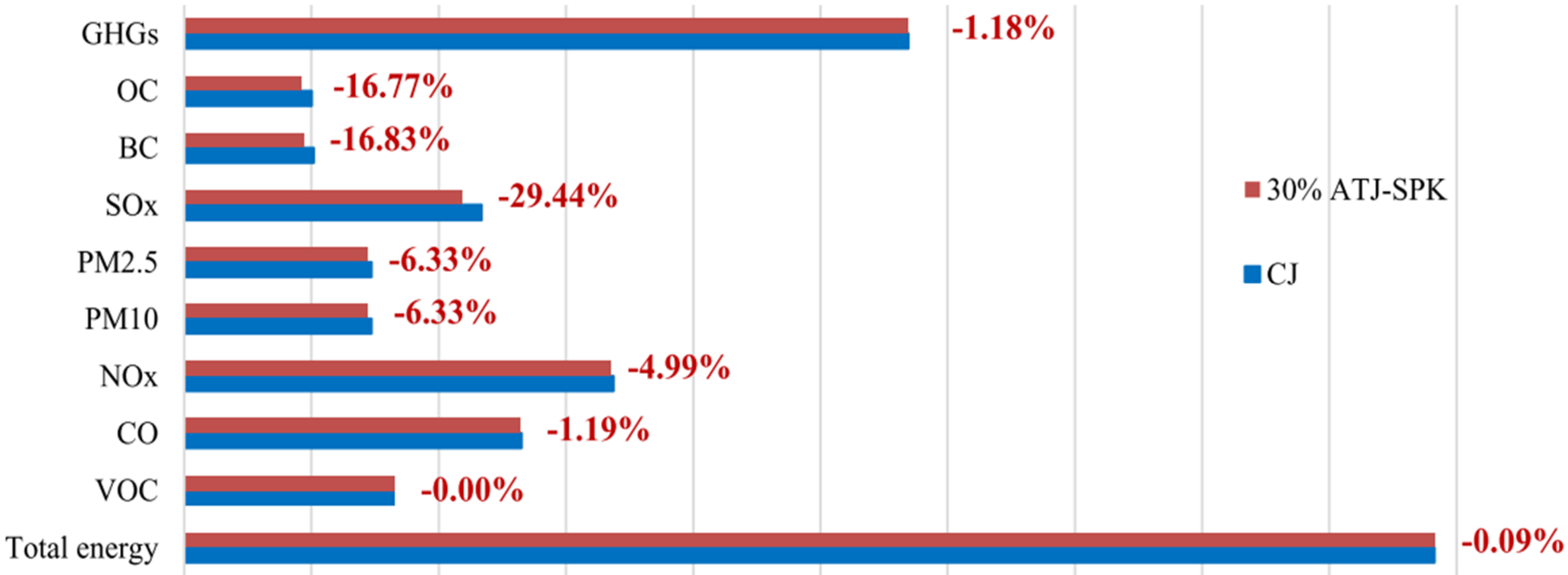
The highest CO emission observed for the ATJ-SPK-fueled engine was 51.03% higher than that of Jet A-1, which is likely attributable to differences in combustion efficiency.

Overall, HC emissions from ATJ-SPK-fueled engines were generally higher than those from Jet A-1, with the maximum HC emission being 40.26% higher for ATJ-SPK.

The ATJ-SPK-fueled GTM-120 turbine engine exhibited higher CO2 emissions than the Jet A-1-fueled GTM-120 turbine engine, with a maximum increase of 35.42% for ATJ-SPK.

4. Emission characteristics of SAF-fueled engines

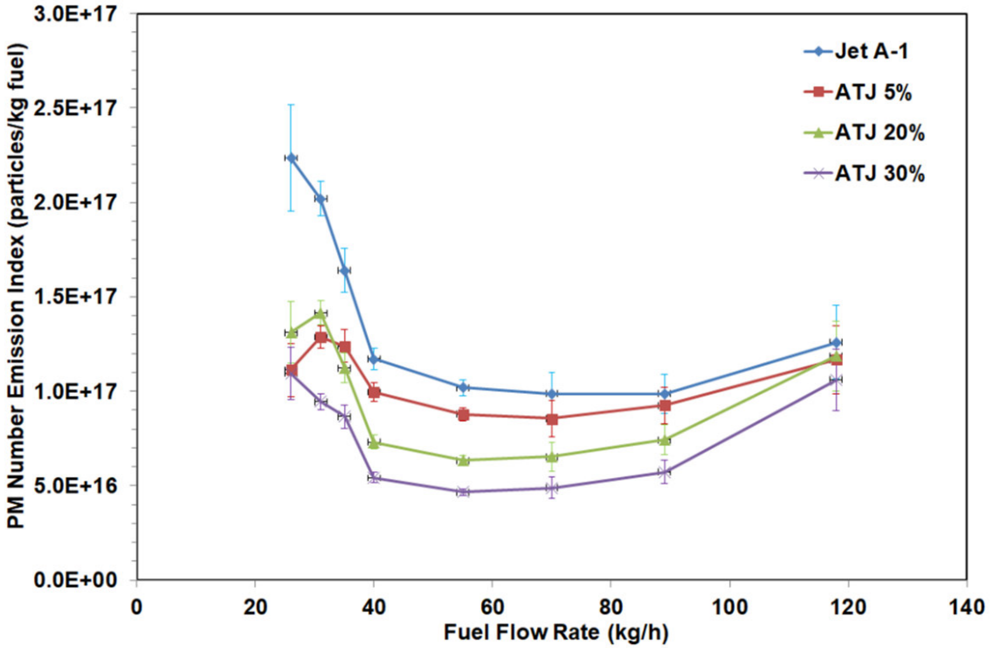
- **ATJ-SPK-Based aviation fuels**



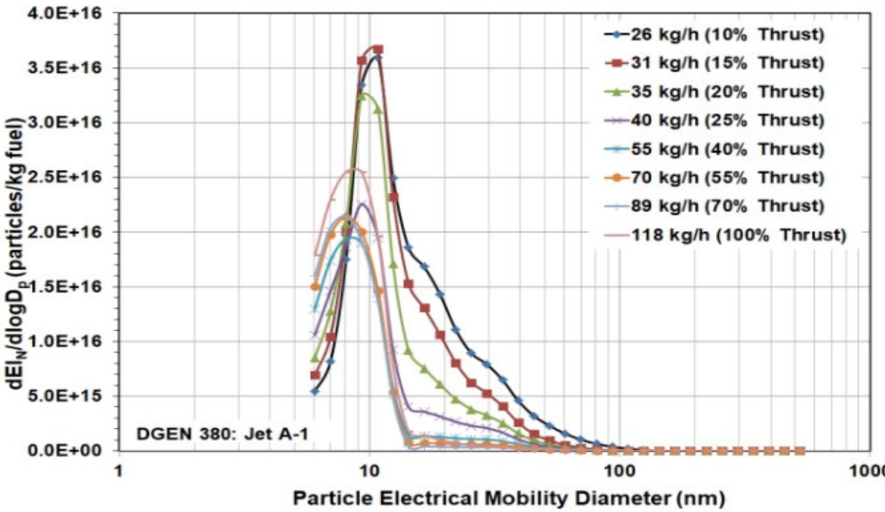
Operational phase emissions (grams/PL-km) and energy consumption (J/PL-km) comparison between 30% ATJ-SPK and conventional jet fuel for their use in a STA passenger aircraft (Ref. Swapnil et al.)

4. Emission characteristics of SAF-fueled engines

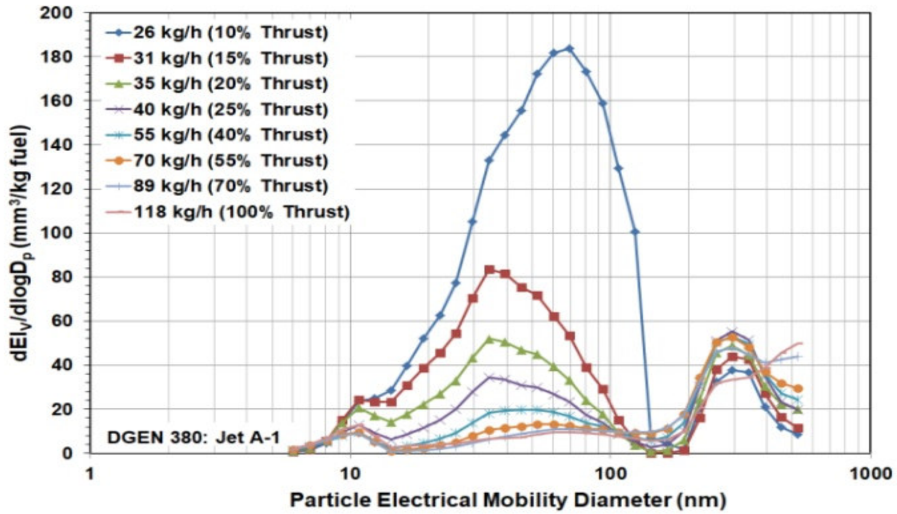
- **ATJ-SPK-Based aviation fuels**



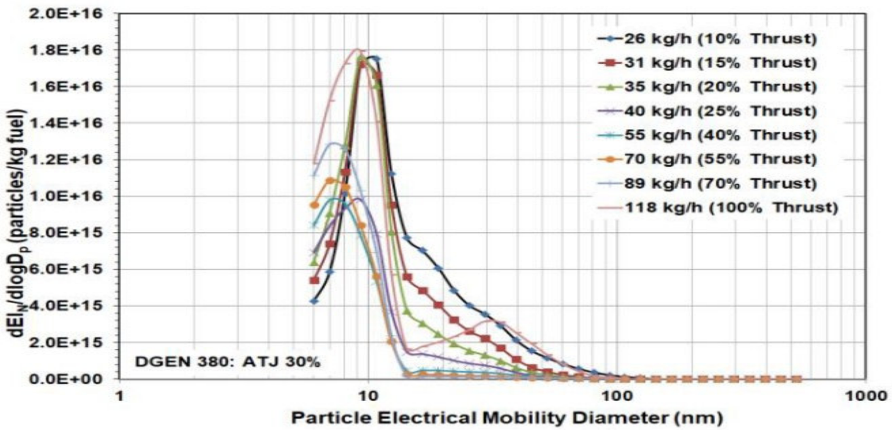
- *PM number emission indices were measured for 5%, 20%, and 30% ATJ-SPK/Jet A-1 blends and neat Jet A-1 fuel in a DGEN 380 turbofan engine. (Ref. Jasinski et al.)*



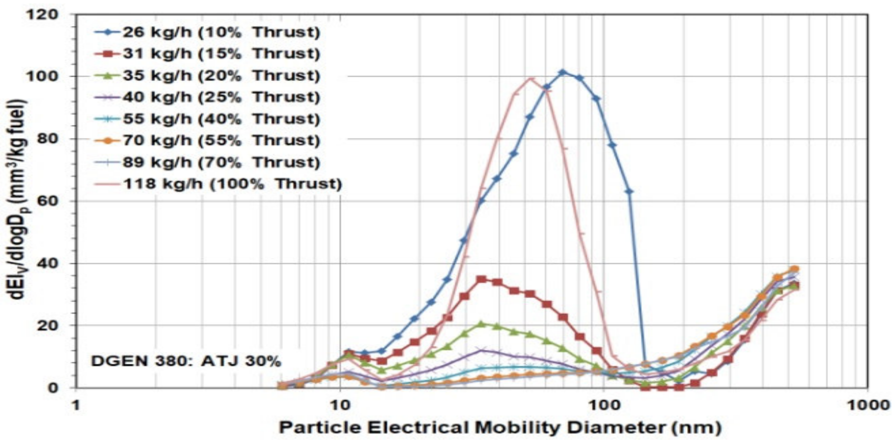
EIN PSD for Jet A-1



EIV PSD for Jet A-1



EIN PSD for ATJ 30%/Jet A-1 blend



EIV PSD for ATJ 30%/Jet A-1 blend

Differential particle number emission index (EI_N) and differential particle volume emission index (EI_V) PSDs for neat Jet A-1 and a 30% ATJ-SPK/Jet A-1 blend in a DGEN 380 turbofan engine. (Ref. Jasinski et al.)

Conclusion

1. The HEFA-fueled engine exhibited stable thrust performance compared with conventional fossil-based aviation fuel, with values occasionally 1.09-7.48% lower or 11.20-28.00% higher than those of Jet A-1, depending on the blend ratios, feedstocks, engine types, and operating conditions. For the FT-SPK-fueled engine, the thrust was 7.27-8.18% higher than that of the conventional fuel, primarily due to its slightly higher lower heating value (approximately 44.6 MJ/kg for 100% FT-SPK compared to 43.1 MJ/kg for Jet A-1), which enables greater thrust generation for the same fuel quantity. In addition, the ATJ-SPK exhibited a 2.07% increase in thrust, owing to the same reason as the FT-SPK fuel.

Conclusion

- 2 . The TSFC of the HEFA-fueled engine was 1.60-17.80% lower than that of Jet A-1, particularly under low-thrust operating conditions, due to the higher heating value of HEFA fuel. For the FT-SPK-fueled engine, the TSFC was 0.9%-9.6% lower than that of conventional aviation fuels, primarily due to the higher hydrogen content (i.e., lower C/H ratio) of FT-SPK, which increases its heating value. In addition, the lower viscosity of FT-SPK fuel, which promotes better fuel evaporation and increases fuel efficiency, could be another contributing factor. The ATJ-SPK-fueled engine showed a 1-2% reduction in SFC relative to Jet A-1, due to the same factors influencing the performance of HEFA fuels.

Conclusion

- 3 . CO emissions from the HEFA-fueled engine were reduced by 3.23-16.13%, owing to the superior fuel-air mixture formation, which promoted more complete combustion and thereby lowered CO emissions. CO emissions from the FT-SPK-fueled engine decreased by 5.01-12.21%, primarily due to the lower viscosity and density of FT-SPK, which improved fuel droplet atomization and evaporation characteristics. CO emissions from the ATJ-SPK-fueled engine were generally 10.26-55.56% higher than those from Jet A-1 and JP-8. However, in a few cases, reductions of 1.19-8% were observed, attributable to differences in combustion efficiency. CO_2 emissions from the HEFA- and FT-SPK-fueled engines were generally 1-3% and 0.34-4.26% lower, respectively, than those from conventional aviation fuel. This reduction is attributed to the higher heating value of SAF, which requires less fuel to achieve the same thrust, thereby lowering CO_2 emissions. In contrast, CO_2 emissions from the ATJ-SPK-fueled engine exhibited considerable variation, showing both higher and lower values relative to Jet A-1.

Conclusion

- 3 . PM number emissions from HEFA-fueled engines were 5.4-82.0% lower than those from Jet A-1. For FT-SPK-fueled engines, reductions in PM number and PM size were 52.2-95% and 72.22%, respectively. In addition, PM mass emissions from ATJ-SPK-fueled engines decreased by 45.45-52.9%, and PM number emissions were reduced by 16.7-51.36%. However, at high thrust levels, PM mass emissions were 133.3% higher than those of Jet A-1. The reductions in PM emissions from SAFs were primarily attributed to their near absence of aromatics, higher hydrogen content, and lower sulfur and naphthalene contents.

Thank You For Your Attention