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Paula KURZAWSKA-PIETROWICZ
Marta MACIEJEWSKA
Remigiusz JASIŃSKI

Combustion Engines
Polish Scientific Society of Combustion Engines

Exhaust emissions from a jet engine powered by sustainable aviation fuel calculated at various cruising altitudes

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The article focuses on emission analysis of non-CO_2 pollutions from aircraft engines on different flight levels: FL240, FL300 and FL350. The calculation was made based on the A320 flight from Berlin to Lisbon at flight level 350, which was the reference flight level in the analysis. Four sustainable aviation fuels have been taken into consideration: biofuel from jatropha and biofuel from camelina, which are used in different percentages of fuel: 20% of CSPK and JSPK and 40% of CSPK and JSPK. The results showed that the lowest emission of carbon monoxide is on the lowest tested flight level for flight on biofuel, and the lowest emission of nitrogen oxides is for Jet A-1 on the lowest tested flight level. Emission of every toxic gas compound has been compared to conventional jet fuel on flight level 350 to show the differences between flight levels.

Key words: *aviation, sustainable aviation fuel, emission, flight level, jatropha, camelina, biofuel*

1. Introduction

The aviation sector was responsible for 2% of global CO_2 emission from human activities and 12% of global transport-related CO_2 emission in 2019 and is forecast to be growing in the future years [14]. Aviation organizations have been trying to solve the problem of growing CO_2 emissions from the aviation sector for years. Greenhouse gases are not the only pollutants emitted by aircrafts, there are also pollutants such as nitrogen oxides, carbon monoxide, hydrocarbon, sulfur oxides, particulate matter and others [12, 18]. There are many solutions to reduce the impact of the aviation sector on the environment, for example, the development of electric propulsion, changes in the construction of the engines to reduce noise, more sustainable flight routes, and more ecological taxiing [7]. As one of the main aims for aviation is to reach net zero GHG emissions in the future, a lot of new technologies have to be developed as a more ecological solution. One of the most promising and mid-term solution is usage of Sustainable Aviation Fuels (SAF). According to European Aviation Environment Report 2019, Sustainable aviation fuel can reduce GHG emission by even 94% compared to conventional aviation fuel [9]. Sustainable aviation fuel can also reduce the emission of particulate matter by 50–70%, depending on the used fuel [17]. Regarding to Carbon Offsetting Reduction Scheme for International Aviation (CORSIA), sustainable aviation fuel (described as CORSIA eligible fuel) should be used in the aviation sector more often due to the offsetting requirements. CORSIA is a global offsetting scheme under which airlines and other aircraft operators offset any increase in CO_2 emission above 2019 levels. This means that net aviation CO_2 emissions will be stabilized while implementing other emissions reduction measures, such as technology, SAF, operational and infrastructure options [20].

This article focuses on the analysis of the emission of carbon monoxide, hydrocarbons, and nitrogen oxides depending on the flight level and also depending on the percentage usage of sustainable aviation fuels, which are, in this particular research, Camelina bio-synthetic paraffinic kerosene and Jatropha bio-synthetic paraffinic kerosene. The purpose of the article is to analyze the differences in harmful exhaust compounds depending on the flight level and to determine which flight level would have the least ecological impact. The primary focus of most analyses is on greenhouse gases, while toxic compounds are specifically examined only during the LTO test and in close proximity to the airport. Other exhaust compounds, like for example nitrogen oxides or sulfur oxides affect the radiative forcing and can indirectly contribute to the climate change [13].

The emission indexes for the Landing and Take-off cycle were obtained from the work of Biasco [3], and based on these indexes, emission indexes for the cruise phase were calculated using a trend line. That allowed to calculate emission of toxic exhaust compounds on different flight levels, based on formulas, that take into account changes in atmospheric parameters at different flight altitudes. The limitation of this approach is that the changes in aircraft weight were not taken into account in the calculations.

2. Sustainable aviation fuels

2.1. Requirements and production pathways

Alternative aviation fuel to be considered as ‘sustainable’ should meet a few requirements [11]:

- Reduce GHG emission through the life cycle by at least 10% compared to conventional aviation fuel
- Raw materials used in production of sustainable fuel should do not compete with food crops for land
- Raw materials used in the production of sustainable fuel should have limited demands on drinking water.

Sustainable aviation fuel should be a “drop in” fuel, which means that it can be used directly in aircraft engine, without any changes in engine construction, fuel infrastructure and fuel distribution systems.

The standard for alternative aviation fuel is ASTM D7566, which describes what physicochemical properties the fuel should meet to be safely used in aircraft engines. The ASTM D7566 standard describes also certified pathways for production of SAF. Currently there are 8 certified pathways, which are [5, 16, 22, 25]:

1. Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), approved in 2009. Raw material in this pathway is mostly biomass (wood waste, grass) but also Municipal Solid Wastes
2. Hydroprocessed Esters and Fatty Acids (HEFA-SPK), approved in 2011. Raw material in this pathway is oily biomass (jatropha, camelina)
3. Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP), approved in 2014. Raw material used in this pathway are sugars, which are converted into hydrocarbons in bacterial conversion
4. Fischer-Tropsch Synthetic Paraffinic Kerosene with aromatics (FT-SPK/A), approved in 2015. Raw material used in this pathway is renewable biomass (Municipal Solid Waste, agricultural and wood waste)
5. Alcohol-to-jet Synthetic Paraffinic Kerosene (ATJ-SPK), approved in 2016. The raw material used in this pathway is a feedstock that can be converted into alcohol, like agricultural wastes (corn shoots, grass, cellulosic biomass)
6. Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK or CHJ), approved in 2020. Feedstock in this pathway is vegetable and animal fats, oils and greases
7. Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK), approved in 2020
8. Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA), approved in 2023. Feedstock in this pathway is similar to ATJ-SPK, which is for example cellulosic biomass. The blending limit is 50%.

There are also 3 co-processed pathways which are described in the ASTM D1655 standard with a blending limit of up to 5%. Co-processed pathways are: co-processed HEFA, which is co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery; co-processed FT, which is co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery; co-processed biomass, which is co-hydroprocessing of biomass [15].

As the physicochemical parameters of fuel depend on the percentage volume of SAF in blend with Jet A-1, the selected physicochemical parameters required in ASTM D1655 standard are shown in Table 1. Every sustainable aviation fuel certified in ASTM D7566 standard has to meet the requirements described in ASTM D1655 [16].

Table 1. Selected physicochemical properties of ASTM D1655 standard [16]

Property	Unit	ASTM D1655
Density at 15°C	kg/m^3	775–840
Viscosity at –20°C	mm^2/s	max 8,0
Viscosity at –40°C	mm^2/s	–
Flash point	°C	min 38
Calorific value	MJ/kg	min 42.8
Aroma content	%	max 25
Naphthalene content	%	max 3.0
Crystallization temperature	°C	max –47

2.2. Second generation of biofuels

Sustainable aviation fuels are produced from different raw materials, as described in section 2.1. Aviation biofuels, which are produced from biomass, can be divided in three generations [4, 6]:

1. First generation, which contains food crops and edible plants, like sunflower and corn. First generation of biofuels can’t be called as ‘sustainable’ as it doesn’t meet the basic SAF requirements
2. Second generation, which contains inedible plants or wastes, like agricultural and forestry residues. Second generation doesn’t compete with food crops for land use and doesn’t have huge demands for water use so it can be described as sustainable
3. Third generation, which contain algae.

This article focuses on the emission indexes of alternative aviation fuel made from jatropha and camelina. Both of these plants are in the second generation of biofuels, and both are rich in oil. Jatropha and camelina are inedible and can be grown in difficult areas, so they do not compete with food crops for land, and they do not require a lot of water for cultivation. These features allow it to be classified as a sustainable raw material for the production of aviation fuel [2]. Jatropha oil is perceived as safe for use in aviation and as a raw material for sustainable aviation fuels, it may reduce CO_2 emissions [10].

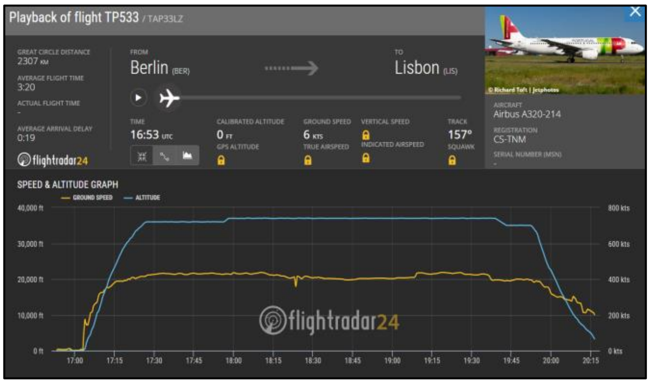
Jatropha contains 27 to 40% of oil in seed mass. The seeds are inedible for human and animals. Jatropha has low requirements for water use and land use and can be grown in infertile soils and in difficult conditions. The plant is well adapted to tropical, semi-arid regions and marginal sites [1]. To be highly productive, jatropha needs from 4 to 5 years [1]. Oil made from jatropha seeds can be directly used in diesel engines due to parameters similar to those of fossil diesel fuel. Jatropha oil also has high stability in low temperatures, which makes it useful for jet engines [1]. Jatropha as a feedstock for sustainable aviation fuel and CORSIA eligible fuel has to reduce CO_2 emission during life cycle. A full-grown tree of jatropha absorbs around 8 kg of CO_2 per year. According to research, fuel made from jatropha can reduce 80% of CO_2 and 100% of SO_2 than fossil diesel [1].

Camelina is another plant in the second generation of biofuels, which can be a sustainable raw material for the production of SAF. Camelina is a short-season crop, from 85 to 100 days. As jatropha it can be cultivated in difficult areas, even in very cold regions, as it germinates at low temperatures and is frost tolerant [23]. It doesn’t require a lot of water, can be cultivated in marginal lands and in drought stress conditions [23]. Camelina can be cultivated in temperate and tropical climates and has low demand in nutrition [8]. It doesn’t compete with food crops for land and for water, so it can also be described as sustainable.

3. Calculation methods

The calculations were made for a flight of Airbus A320 from Berlin to Lisbon. Figure 1 shows the flight profile of the selected flight. The cruise phase was on an altitude from 36,000 to 37,000 ft; for calculation, the FL 350 has been chosen as the reference flight level. Calculations were made for three selected flight levels: FL260, FL300, and FL350.

The duration of flight remained consistent at each of the examined altitudes, enabling a comparison solely of emission variations based on flight altitude for different types of fuel. The ascent and descent times were not factored in, which would undoubtedly impact the overall flight duration at a specific altitude.



Playback of flight TP533 / TAP33LZ

GREAT CIRCLE DISTANCE 2307 KM

AVERAGE FLIGHT TIME 3:20

ACTUAL FLIGHT TIME -

AVERAGE ARRIVAL DELAY 0:19

FROM Berlin (BER)

TO Lisbon (LIS)

TIME 16:53 UTC

CALIBRATED ALTITUDE 0 FT

GROUND SPEED 6 KTS

TRACK 157°

AIRCRAFT Airbus A320-214

REGISTRATION CS-TNM

SERIAL NUMBER (MSN) -

Fig. 1. Flight profile of the selected route

Based on the equations described in researches [11, 19, 24] emission for different altitudes has been calculated, based on the changes in emission indexes depends on flight level and used fuel. Changes in aircraft weight were not taken into account in the calculations.

The formulas used for the calculations [19]:

$$E_{CO} = EI_{CO} \cdot 10^{-3} \cdot K \cdot SFC \cdot t \cdot l \tag{1}$$

$$E_{NOx} = EI_{NOx} \cdot 10^{-3} \cdot K \cdot SFC \cdot t \cdot l \tag{2}$$

$$E_{HC} = EI_{HC} \cdot 10^{-3} \cdot K \cdot SFC \cdot t \cdot l \tag{3}$$

where: E_{CO}, E_{NOx}, E_{HC} – emission of particular exhaust gas compounds [kg], EI_{CO}, EI_{NOx}, EI_{HC} – emission indexes for particular substances, depended on the type of engine and the range of its run [g/kg], K – engine thrust [N], SFC – specific fuel consumption [kg/(N·h)], t – engine run time at a given thrust [h], l – number of engines.

$$EI_{CO} = EI_{COLTO} \cdot \frac{\theta^{3.3}}{\delta^{1.02}} \tag{4}$$

$$EI_{HC} = EI_{HCLTO} \cdot \frac{\theta^{3.3}}{\delta^{1.02}} \tag{5}$$

$$EI_{NOx} = EI_{NOxLTO} \cdot \sqrt{\frac{\theta^{3.3}}{\delta^{1.02}}} \cdot e^{h} \tag{6}$$

where: EI_{CO}, EI_{HC}, EI_{NOx} – CO, HC and NO_x emission indexes at a given altitude [g/kg], EI_{COLTO}, EI_{HCLTO}, EI_{NOxLTO} –emission indexes measured for LTO parameters [g/kg], θ – temperature change coefficient [–]:

$$\theta = \frac{T_c}{288.15\ K} \tag{7}$$

δ – pressure change coefficient [-]:

$$\delta = \frac{p_c}{101325\ Pa} \tag{8}$$

e – Euler number (e = 2.72), h – air humidity factor depended on the altitude [-]

$$h = -19 \cdot (\omega - 0.00634) \tag{9}$$

ω – specific humidity,

where

$$\omega = 10^{-3} \cdot e^{-0{,}0001426 \cdot (H-12900)} \tag{10}$$

where H – cruising altitude [ft].

The fuel taken into analysis were Jet A-1 as reference fuel, and different mixtures of Camelina bio-synthetic paraffinic kerosene (CSPK) and Jatropha bio-synthetic paraffinic kerosene (JSPK) in the percentage use of: 20% of CSPK, 40% of CSPK, 20% of JSPK and 40% of JSPK. Every sustainable aviation fuel have been mixed with conventional aviation fuel. The maximum volume of SAF fuel in the fuel blend with Jet A-1 is described in the ASTM D7566 standard and is equal to 50%. All calculations have been done for engine CFM56-5A4 based on the results of the Landing and take-off (LTO) test in research of Biasco R. [3] for chosen fuels. Also, the fuel flow has been taken into calculation. Analyzes conducted by Biasco [3] allowed for the expansion of the ICAO database regarding emission indexes for individual engines with indexes for selected alternative fuels. The analyzes were carried out based on correction factors for given fuels and using the COPERT model, which enabled the calculation of emission factors from Jet A-1 for other fuels, taking into account their physicochemical properties. The emission indexes for LTO test obtained by Biasco R. [3] has been shown in Table 2.

Table 2. Emission indexes for CFM56-5A4 engine obtained by Biasco [3]

	Jet A-1	20% CSPK	40% CSPK	20% JSPK	40% JSPK
		EI_{CO} [g/kg]			
Taxi	20.3	19.8128	19.3256	19,9752	19.6504
Approach	3.1	2.9946	2.8892	3.0132	2.9326
Climb out	1.1	1.0978	1.0956	1.0736	1.0472
Take off	1.1	1.1484	1.1968	1.0088	1.1018
		EI_{HC} [g/kg]			
Taxi	1.75	1.75	1.75	1.75	1.75
Approach	0.5	0.5	0.5	0.5	0.5
Climb out	0.23	0.23	0.23	0.23	0.23
Take off	0.23	0.23	0.23	0.23	0.23
		EI_{NOx} [g/kg]			
Taxi	4.04	4.3923	4.7446	4.2258	4.117
Approach	8.51	9.1057	9.7014	8.8334	9.1568
Climb out	19.11	20.2566	21.4032	19.7139	20.3178
Take off	22.64	23.5909	24.5418	23.0837	23.5275

Emission indexes for the cruise phase were calculated using a trend line based on the emission indexes obtained by Biasco [3] for the LTO cycle. This method is subject to errors, but due to the lack of appropriate field tests, it was decided to use it. R-squared for CO was equal to 0.99, R-squared for HC was equal to 0.994, and R-squared for NO_x was equal to 1. Emission indexes for the cruise phase were calculated based on the research [3] and are presented in Table 3.

Table 3. Emission indexes in cruise phase for selected fuels

	EI_{CO} [g/kg]	EI_{HC} [g/kg]	EI_{NOx} [g/kg]
Jet A-1	2.08	0.36	12.49
20% CSPK	2.09	0.36	13.21
40% CSPK	2.09	0.36	13.93
20% JSPK	1.99	0.36	12.86
40% JSPK	2.02	0.36	13.23

4. Results and discussion

Results show that the emission of hydrocarbon is the same for all used fuels because the emission index is the same for every tested fuel. Changes can be seen in the emission for different flight levels, which increases with flight altitude. For hydrocarbons, the lowest possible flight level will be the most ecological. The results are shown in Fig. 2.

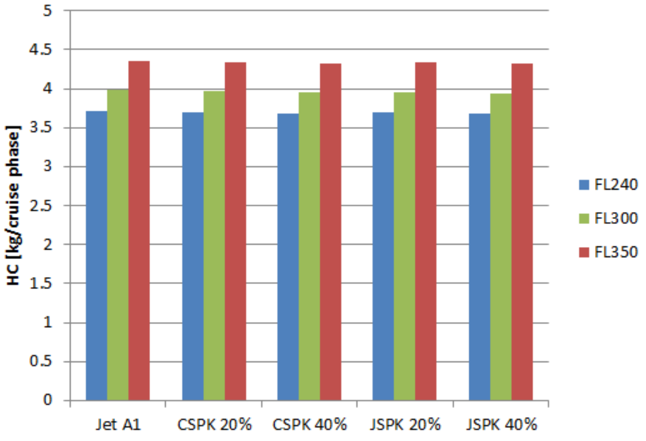


Fig. 2. Emission of hydrocarbons for selected fuels on different flight levels

The emission of carbon monoxide depends on the used fuel (Fig. 3). The lowest CO emission is for 20% JSPK, where reduction is 5% compared to Jet A-1 on every tested flight level. Emission reduction in CO is also for 40% JSPK and is equal to 4% compared to Jet A-1. Similar to hydrocarbons, the higher the flight level, the higher the emission of carbon oxides. For CSPK, the CO emission was almost the same as that of the Jet A-1 at every flight level.

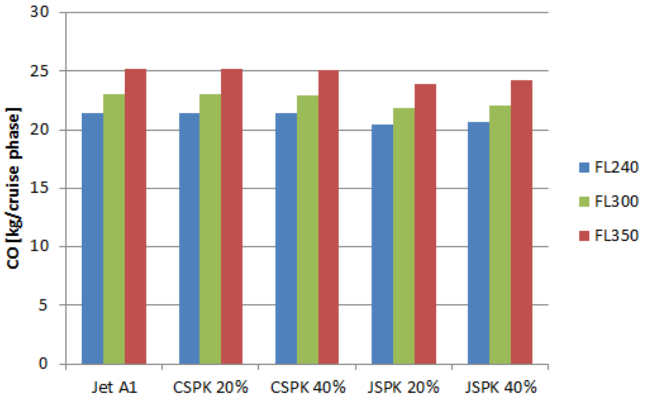


Fig. 3. Emission of carbon monoxide for selected fuels on different flight levels

The emission of nitrogen oxides grows with the increase of biofuel for CSPK and JSPK for every flight level (Fig. 4). The lowest emission of nitrogen oxides is for Jet A-1 on the highest calculated altitude. The changes in NO_x emission is different than in CO and HC and decrease with the increase of flight level.

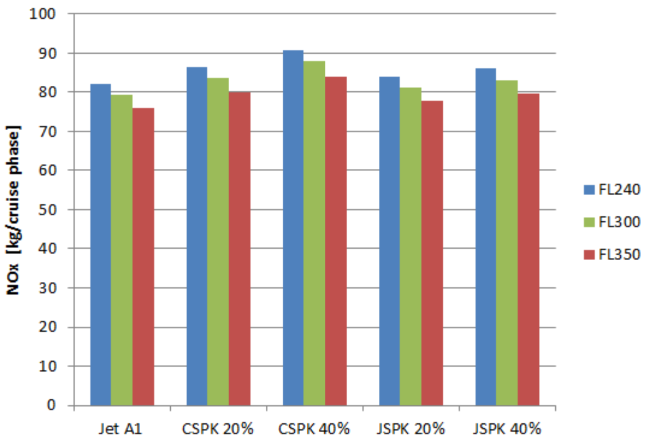


Fig. 4. Emission of carbon monoxide for selected fuels on different flight levels

Changes in the emission of particular toxic gas compounds of selected fuel are shown in Fig. 5. The changes are accurate for every calculated flight level. The biggest changes are for 40%CSPK for NO_x compared to Jet A-1, which is equal to 11%. The addition of JSPK has a positive impact on the emission of carbon monoxide and can reduce this emission by 4–5% compared to Jet A-1.

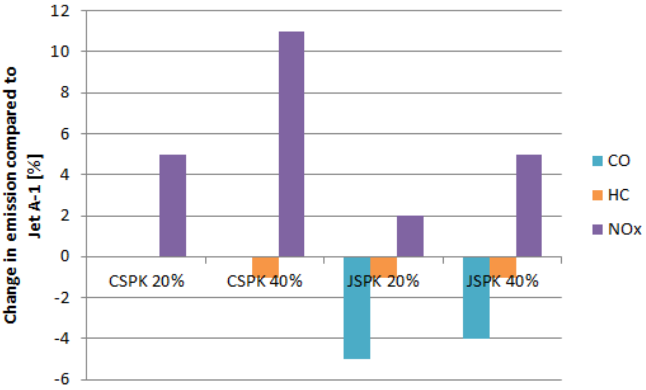


Fig. 5. Differences in emission of particular toxic gas compounds of selected fuels compared to Jet A-1

To analyze changes for different flight level and selected fuel, the Jet A-1 on the FL350 has been set us as reference values. Percentage changes has been shown in Table 4.

Table 4. Percentage differences in emission of particular pollutant depending on the flight level and used fuel, compared to flight on Jet A-1 on the FL350

	Jet A-1	20% CSPK	40% CSPK	20% JSPK	40% JSPK
			CO		
FL240	–14.8%	–14.8%	–15%	–18.9%	–18.1%
FL300	–.6%	–8.6%	–8.9%	–13.1%	–12.2%
FL350	0%	0%	–0.3%	–4.9%	–3.9%
			HC		
FL240	–14.8%	–15.2%	–15.4%	–15.3%	–16.6%
FL300	–8.6%	–9.1%	–9.3%	–9.2%	–9.6%
FL350	0%	–0.5%	–0.8%	–0.6%	–1%
			NO_x		
FL240	8.1%	13.8%	19.6%	10.6%	13.3%
FL300	4.5%	10%	15.7%	7%	9.6%
FL350	0%	5.2%	10.7%	2.3%	4.8%

It can be seen that the flight on the lowest tested altitude can reduce CO emission by almost 15% on Jet A-1, and with 20% of JSPK and 40% of JSPK, it can reduce CO emission by approximately 18,9% and 18,1%. Flight on 20% and 40% of CSPK has almost the same reduction of about 15% compared to Jet A-1. Emission of HC can be reduced also on the lowest flight level by almost 15% on Jet A-1, and by 16.6% with 40% of JSPK fuel. Emission of nitrogen oxides is the lowest for Jet A-1 on the FL350 of all compared flight levels and biofuels.

5. Conclusions

As not only CO_2 affects climate change, it is important to also address other harmful compounds that are emitted by aircraft engines, such as NO_x, HC and CO. Some of the toxic compounds contained in exhaust gases affect radiative forcing, for example, NO_x emissions have warming and cooling effect: NO_x emissions contribute to the generation of ozone, which is a greenhouse gas; the cooling effect is related to methane removal from the atmosphere, while the breakdown of the NO_x gases results in increased OH content, which helps shorten the life of methane [3, 13].

This article focused on the calculation of CO, HC, and NO_x from Airbus A320 on selected flight routes to compare the usage of sustainable aviation fuel with conventional aviation fuel on different flight levels. The flight time at each of the analyzed levels was the same to compare only changes in emissions depending on flight altitude for different fuels. The time of climb and descent was not taken into account, which would obviously affect the flight time at a given flight level.

The calculation showed that for CO and HC, the lowest emission is on the lowest flight level, and the reduction in CO emission is almost 15% for Jet A-1 compared to flight level 350, which was the reference flight level. Flight on the lowest analyzed flight level on the 20% of Jatropha bio-synthetic paraffinic kerosene can reduce CO emission by almost 19% compared to Jet A-1 on the FL350 and by 5% compared to Jet A-1 at FL240. For the emission of nitrogen oxides, the reference flight on FL350 on Jet A-1 fuel has the lowest NO_x emission from all analyzed flight levels and fuels. The calculated results show that changes in flight level have a significant impact on emission due to changes in ambient conditions and atmospheric parameters at different altitudes at which the engine operates. CO and HC emissions increased with increasing altitude, and NO_x emissions decreased with increasing altitude. One of the main environmental factors influencing HC, CO and NO_x emissions may be atmospheric pressure. This is also confirmed by tests conducted on a diesel engine at high altitudes [21].

There are very few analyzes for emissions of harmful compounds at cruising altitude, such as CO, HC and NO_x. Most analyzes concern strictly GHG and toxic compounds are analyzed only in the LTO test and in the close vicinity of the airport. Upon comparing the calculated emissions with findings from other studies, it becomes apparent that the results obtained hold significance. However, due to the scarcity of similar articles, a more detailed examination of the results is not feasible at this time. Pawlak et al. [19] made related calculations for different flight altitudes, but the change in the aircraft's weight during the flight and changes in thrust force at individual altitudes were also taken into account, so the relationships between flight levels are different than in the presented analysis. However, alternative fuels were not taken into account in this paper, therefore it is not possible to compare the SAF blend emission results at different flight levels with other studies.

Due to the fact that the physicochemical properties of various SAF fuel blends depend on the volume share of SAF in the blend, it is difficult to assess at this stage of the analysis how individual properties affect the emission of toxic compounds at a given altitude. This topic should be developed and supplemented with an analysis of the physicochemical properties of various concentrations of SAF fuel with Jet A-1 and an attempt to assess the relationship between individual properties and emissions at a given altitude.

When comparing sustainable aviation fuels with conventional fuel, it is crucial to compare its life cycle emission, not only the combustion of the fuel in aircraft engines. That shows how many factors should be considered to fly more ecologically and that reduction in emission of one pollutant can grow emission of another pollutant.

Nomenclature

ATJ-SPK	alcohol-to-jet synthetic paraffinic kerosene
CHJ	catalytic hydrothermolysis jet fuel
CH-SK	catalytic hydrothermolysis synthesized kerosene
CO	carbon monoxide
CO_2	carbon dioxide
CSPK	camelina bio-synthetic paraffinic kerosene
FT-SPK	Fischer-Tropsch synthetic paraffinic kerosene
FT-SPK/A	Fischer-Tropsch synthetic paraffinic kerosene with aromatics
GHG	greenhouse gases
HC	hydrocarbons
HEFA	hydroprocessed esterts and fatty acids
HFS-SIP	hydroprocessed fermented sugars to synthetic isoparaffins
HHC-SPK	hydroprocessed hydrocarbons, esters and fatty acids synthetic paraffinic kerosene
JSPK	jatropha bio-synthetic paraffinic kerosene
NO_x	nitrogen oxides
SAF	sustainable aviation fuels

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Paula Kurzawska-Pietrowicz, MEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology.

e-mail: *paula.kurzawska@put.poznan.pl*

Marta Maciejewska, DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology.

e-mail: *marta.maciejewska@put.poznan.pl*

Remigiusz Jasiński, DSc., DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology.

e-mail: *remigiusz.jasinski@put.poznan.pl*