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Overview of Sustainable Aviation Fuels with Emission Characteristic and Particles Emission of the Turbine Engine Fueled ATJ Blends with Different Percentages of ATJ Fuel

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Abstract: The following article focuses on sustainable aviation fuels, which include first and second generation biofuels and other non-biomass fuels that meet most of environmental, operational and physicochemical requirements. Several of the requirements for sustainable aviation fuels are discussed in this article. The main focus was on researching the alcohol-to-jet (ATJ) alternative fuel. The tests covered the emission of harmful gaseous compounds with the Semtech DS analyzer, as well as the number and mass concentration of particles of three fuels: reference fuel Jet A-1, a mixture of Jet A-1 and 30% of ATJ fuel, and mixture of Jet A-1 and 50% of ATJ fuel. The number concentration of particles allowed us to calculate, inter alia, the corresponding particle number index and particle mass index. The analysis of the results made it possible to determine the effect of the content of alternative fuel in a mixture with conventional fuel on the emission of harmful exhaust compounds and the concentration of particles. One of the main conclusion is that by using a 50% blend of ATJ and Jet A-1, the total number and mass of particulate matter at high engine loads can be reduced by almost 18% and 53%, respectively, relative to pure Jet A-1 fuel.

Keywords: alcohol-to-jet; alternative fuel; SAF; emission; particles; particulate matter

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1. Introduction

Along with the development of the aviation industry, its share in the emission of environmental pollution has increased. Currently, the aviation industry is responsible for an estimated 2% of global greenhouse gas emissions [1,2]. In 2015, aviation operations generated over 781 million tons of carbon dioxide, and it is expected that by 2050, based on forecasts of air traffic growth, 2700 million tons of carbon dioxide will be generated annually [2]. According to forecasts by Airbus, air traffic doubles every 15 years and the number of flights increased by 80% between 1990 and 2014 [3,4]. The growing number of air connections unfortunately significantly affects environmental pollution and the associated climate change effects. As a result, many aviation organizations and airlines are taking measures to reduce greenhouse gas emissions from the aviation industry, including using alternative fuels. The increase in interest in alternative fuels is caused not only by climate change and the impact of burning conventional fuels on the environment, but also by the depletion of natural resources of crude oil [5], rising oil prices and countries' dependence on their suppliers. The aviation sector wants to ensure security of supply alternative aviation fuels at affordable prices [6]. Alternative fuels obtained from plants or other raw materials would achieve energy independence from Organization of Petroleum Exporting Countries (OPEC) member states, whose political instability is associated with frequent changes in oil prices [7]. For this reason, more and more countries and airlines are investing in research to produce sustainable aviation fuels from alternative sources, e.g., used oil, municipal waste, algae or even plastic. In 2018 the Renewable Energy Directive II (REDII) entered into force, which increased targets for the share of renewable fuels in transport from 10% by

2020, to 14% by 2030 [8]. Also due to REDII savings of greenhouse gas emissions from use of renewable liquid and gaseous fuels made from non-biological origin in transport field shall be at least 70% from the year 2021 [9]. In the aviation field there are currently seven approved technologies for the production of alternative aviation fuels, which include for example hydroprocessed esters, hydroprocessed fermented sugar and alcohols. Alcohols have a huge potential as alternative fuels, because of their liquid nature, production from renewable biomass and high oxygen contents and also high cetane number. Fuels which contain oxygen can reduce the combustion chamber parameters, like temperature, and through this emission of harmful gaseous compounds can be reduced [10]. Therefore, the work below focuses on the study of the concentration of harmful exhaust compounds and particles in the engine exhaust, depending on the degree of mixing of the alternative alcohol-to-jet (ATJ) fuel with conventional Jet A-1 fuel.

2. Sustainable Aviation Fuels

Sustainable aviation fuels (SAF) is the principal term used to refer to non-conventional aviation fuels. Another names are sustainable alternative fuel, biojet or renewable jet fuel [11]. The term sustainable aviation fuels covers not only biofuels, but also fuels produced from raw materials other than biomass, such as waste. Biofuels refer to fuels produced from raw materials of plant or animal origin, and due to their aggregate state, we divide them into solid, liquid and gas [11]. In the aviation industry, biofuels mainly refer to liquid biofuels [2]. In order to qualify as "sustainable" aviation fuels must meet the following criteria [11]:

- Reducing carbon dioxide emissions throughout the life cycle;
- Limited need for fresh water;
- No need for deforestation and no competition with food production for land for cultivation.

Biofuels used in aviation can be divided into first, second and third generation biofuels according to the general division of biofuels. In this analysis of alternative fuels, the 1st generation fuels have been omitted due to the fact that they cannot be called sustainable fuels, as their production uses food crops [12]. Second-generation biofuels are fuels obtained from inedible plants or plant waste, which can be grown on less fertile soils, and even on wastelands [13]. This group includes wood and its waste, which contain lignocellulosic biomass, organic waste and food waste from agri-food processing [14]. They do not compete with food cultivation as they come from a separate biomass, but some biomass still competes with land use, as it grows in the same climate as food crops [15]. Other raw materials, which are not biomass, are currently in the phase of physicochemical research and testing, or test flights are being carried out with their use. Most often it is waste from households and companies. Research on the use of clothes, bottles, leftovers and newspapers has also been started. The use of municipal solid waste (MSW) has a very large potential, due to the use of raw materials that would be stored and would emit carbon dioxide, and thanks to re-use they can drive aircraft engines [13]. These are e.g., fuels produced from municipal waste.

The second-generation raw material is jatropha oil. It is sourced from jatropha seeds, which are poisonous to both humans and animals. 30 to 40% of the seed weight can be obtained from each seed. Jatropha has low soil and climatic requirements, therefore it can be cultivated in difficult conditions, such as dry and undeveloped areas [14]. As a result, it does not compete with food crops for arable land. Jatropha is subjected to the process of oil extraction, which produces bio oil, and then it is treated with hydrogen to obtain a fuel of the hydroprocessed renewable jet (HRJ) type [16]. Another oilseed plant is camellina. It is often cultivated as a crop rotation plant, so like jatropha—it does not compete with food crops for arable land [13]. It occurs mainly in a temperate climate, in Central Europe, Finland and the United States [17]. The latter is also subjected to an oil extraction process and then treated with hydrogen to obtain HRJ fuel.

Vegetable and animal oils, which are already waste and will not be used further in the food industry, can also be considered as second-generation biofuels. Used vegetable oils can be treated with hydrogen to make jet fuel. It is currently one of the most promising raw materials for the production of alternative aviation fuels.

Aviation biofuels are processed differently, depending on the raw material used. The specific group of raw materials and the corresponding transformations are shown in Figure 1. This article focuses on alcohol-to-jet fuel, made from starch and sugar crops.

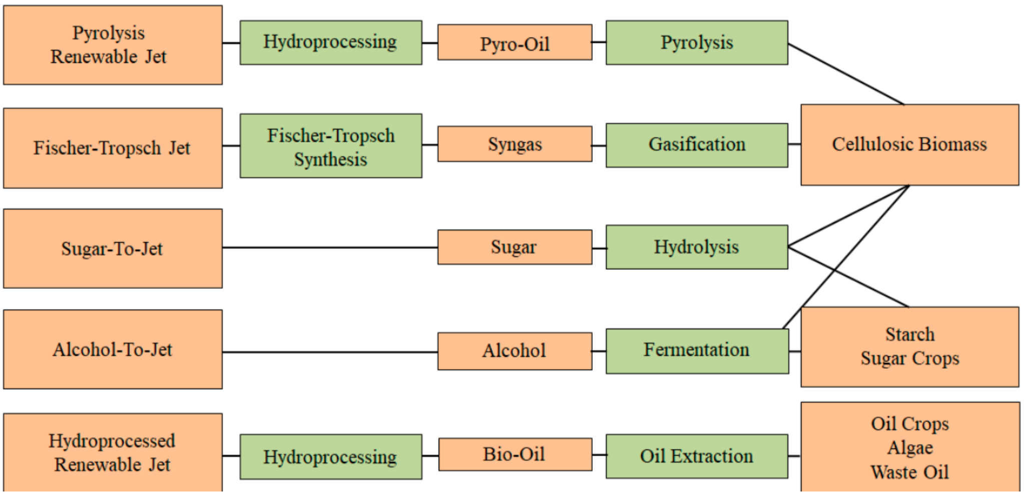


Figure 1. Raw materials used for the production of aviation biofuels and the corresponding processing [17].

A renewable fuel option for aviation is also power-to-liquids (PtL) production pathway, which is based on electricty, water and carbon dioxide. The first step in PtL is electrolysis of water in which hydrogen is producted from renewable electricity. Afterwards carbon dioxide is supplied and and at the last step is synthesis to liquid hydrocarbons with subsequent conversion to refined fuels. Power to liquid can use renewable electricity and $CO_{2,}$ for example from biomass or from the air. What's the most important, PtL fuels can be close to carbon neutral and need less water than several biogenic fuels, for example from jathropha plants, which need a lot of water to grow. Water in Pt: technology is needed as a hydrogen source, but they amount needed is still less than for growing some of the plants used in production of biofuels [18,19].

3. Requirements for Alternative Aviation Fuels

3.1. Operational Requirements

One of the main requirements for alternative aviation fuels is their compatibility with the existing fuel infrastructure. This includes the pipelines through which fuel is transported, refueling systems for the aircraft and the engine structure itself [20]. It is very important that the change of conventional fuel to alternative fuel does not require changes in design and infrastructure, as this would significantly hinder the entry of alternative fuels into the aviation market. Therefore, an ideal sustainable aviation fuel would be 100% compatible in operation with currently used aviation fuels [20,21]. Such fuel is known as "drop-in" [13]. There is an alternative fuel compatibility assessment with existing infrastructure, which assigns a neutral assessment if the fuel is fully compatible and does not require any interference with the existing system, and a negative assessment if the fuel requires a complete system change [20]. For now, only alternative and conventional fuels may be mixed.

3.2. Physicochemical Requirements

Aviation fuels must meet a number of requirements regarding their physicochemical properties in order to be used in aircraft engines. Physicochemical properties of aviation fuels are the main determinant of safe flight performance, therefore they must be strictly observed. The ASTM D1655 standard specifies the specific values of the physicochemical properties of aviation fuels. For alternative aviation fuels was assigned the standard ASTM D7566 [21], shown in Table 1.

Table 1. Physicochemical properties according to ASTM D7566 standard.

No.	Property Name	Unit of Measure	Requirements acc. to ASTM D7566
1	Density at 15 °C	kg/m^3	from 775 to 840
2	Viscosity at −20 °C	mm^2/s	max 8.0
3	Viscosity at −40 °C	mm^2/s	max 12
4	Calorific value	MJ/kg	min 42.8
5	Aroma content	%	min 8, max 25
6	Naphthalene content	%	max 3.0
7	Flash-point	°C	min 38
8	Crystallization temperature	°C	max −47
9	Distillation:		
	Start distillation temperature	°C	-
	10% distils to temperature	°C	max 205
	End distillation temperature	°C	max 300
	Residue	%	max 1.5
	Loss	%	max 1.5
10	Lubricity	mm	max 0.85

This standard specifies the maximum share of alternative fuels in the mixture consisting of conventional and sustainable fuels at the level of 50% in volume terms. At least half of the mixture must be Jet A or Jet A-1 fuel [13]. Alternative fuels that meet the requirements of ASTM D7566 can be used in aircraft engines that require the D1655 aviation fuel standard [22]. The approved aviation fuel production methods are presented in Table 2.

Table 2. Methods of producing alternative fuels approved by the ASTM D7566 standard (own study based on [4,14,23,24]).

Annex	Process	Raw Material	Approval Date	Blending Limit
A1	Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Biomass (wood waste, grass, municipal solid waste)	2009	up to 50%
A2	Hydroprocessed Esters and Fatty Acids (HEFA-SPK)	Oily biomass, e.g., algae, jatropha, camelina	2011	up to 50%
A3	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	Bacterial conversion of sugars into hydrocarbons	2014	10%
A4	FT-SPK with aromatics (FT-SPK/A)	Renewable biomass, i.e., municipal solid waste, agricultural and wood waste	2015	up to 50%
A5	Alcohol-to-jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Agricultural waste (corn shoots, grass, straw), cellulosic biomass	2016	up to 50%
A6	Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)	Vegetable or animal fats, oils and greases	2020	up to 50%
A7	Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK)	Hydrocarbons of biological origin, fatty acid esters, free fatty acids, or a species of *Botryococcus braunia* algae	2020	up to 10%

3.3. Environmental Requirements

One of the main reasons for studying alternative fuels and looking for new solutions to power jet engines is the impact of crude oil and its derivatives on the environment and climate change. Emissions of harmful compounds are related to the physical and chemical properties of fuel [24]. High emissions of carbon dioxide, greenhouse gases and other harmful substances generated during the combustion of conventional aviation fuels, such as carbon oxides, nitrogen oxides, hydrocarbons and particles, increase the interest in alternative fuels. Carbon dioxide absorbed by plants during the growth of biomass is similar to the amount of carbon dioxide emitted during the combustion of fuel from that biomass, which makes it possible to remain neutral in terms of greenhouse gas emissions [13]. Sustainable aviation fuels should enable a significant reduction in greenhouse gas emissions during their combustion, but also, which is crucial, throughout their entire life cycle, from the growth and fertilization of plants and algae, through their transport, processing, distribution, and end use in the engine aviation. Life cycle emissions are mainly related to second and third generation biofuels which are based on plants and algae that need to be grown for use in the aerospace industry.

By using fuel based on wood biomass, 95% of CO_2 can be saved compared to the currently used jet fuel. Wood biomass is one of the lowest carbon dioxide emissions per MJ of fuel, only algae fuel has a greater one, which in a realistic case could be 98% greenhouse gas emissions, and in the best scenario up to 124%, compared to conventional jet fuel. This is due to the fact that during their growth and development, algae absorb large amounts of carbon dioxide, which in the case of their total CO_2 emission, may be below zero. Carbon dioxide emissions for other alternative fuels obtained e.g., from conventional oil, jatropha or animal fuels range from 20% to 90% depending on the raw material used, with the least preferred fuel being from oil plants. The above data is indicative of the fact the specific emission value for each of the analyzed fuels depends on the method used for producing the alternative fuel [25].

4. Experimental

The fuels used during the research were the alternative fuel alcohol to jet synthesized paraffinic kerosene (ATJ-SPK) from isobutanol and the comparative fuel Jet A-1. The alternative fuels supplying the engine during the tests were mixed in the following volume proportions with conventional JetA-1 fuel: 30% ATJ fuel and 50% ATJ fuel. During the tests, the concentration of carbon oxides (CO), carbon dioxide (CO_2), hydrocarbons (HC) and nitrogen oxides (NO_x) was measured, as well as the concentration of the number of particles by particle diameter.

The conventional fuel Jet A-1 is produced during the fractional distillation of crude oil, known as rectification. It is aviation kerosene, i.e., the liquid fraction of distilling crude oil ranging from 130 °C to about 280 °C. Due to the low octane number and simple production technology, it is relatively cheap—cheaper than gasoline or diesel. Jet A-1 is used in civil aviation, and it differs from Jet A mainly in the freezing point, which is −47 °C for Jet A-1 and −40 °C for Jet A [26].

The ATJ alternative fuel can be produced by many different conversion routes, but each starts with a biomass feedstock. The raw materials used to produce ATJ fuel are, for example, sugar cane, sugar beet, cereals or lignocellulosic biomass. ATJ fuel is made by converting alcohols such as methanol, ethanol, butanol and long-chain fatty alcohols. The maximum use of ethanol in the production of ATJ fuel is 10–15%. ATJ fuels currently used in aviation and meeting the requirements of ASTM D7566 are isobutanol- and ethanol-based fuels, however Annex A5 (ATJ-SPK) is ultimately to include the use of any alcohols containing from two to five carbon atoms [25,27–29]. Use of ATJ fuel in an aircraft engine requires a maximum of 50% ATJ blend with conventional fuel. The process of converting alcohol into alcohol-to-jet fuel includes the following processes: isobutanol or ethanol dehydration, oligomerization, hydrogenation and fractionation to obtain a component which is a mixture of hydrocarbon jet fuel (Figure 2) [23].

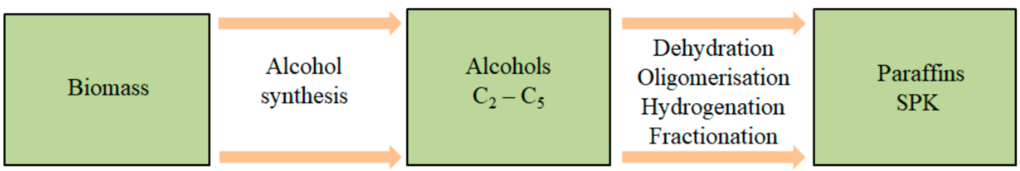


Figure 2. Simplified diagram of the ATJ-SPK process [30].

According to the European Aviation Environmental Report 2019 prepared by the European Union Aviation Safety Agency (EASA), thanks to the use of ATJ fuel, the percentage reduction in greenhouse gas emissions compared to the use of conventional fuel ranges from 26 to 74%, depending on the raw material used in the production. These estimates do not take into account the greenhouse gas emissions in the raw material growth phase. In the case of ATJ aviation fuel based on isobutanol, the lowest percentage reduction can be achieved by using maize grain as a raw material (54%), and the highest by using forest residues (74%). On the other hand, in the case of ATJ fuel obtained from ethanol, the lowest reduction in greenhouse gas emissions can be obtained by using corn kernel as a raw material (26%), and the highest—sugar cane (69%). Table 3 presents the physicochemical properties of the tested fuels [4].

Table 3. Physicochemical properties of tested fuels [own study based on [31,32].

Property	Jet A-1 [According to ASTM D1655 Standard]	ATJ-SPK	50/50% v ATJ-SPK and Jet A-1
Crystallization temperature [°C]	−47	−61	−54
Flash point [°C]	min 38	48	min 38
Calorific value [MJ/kg]	42.8	43.2	43.8
Total sulfur content [%]	max 0.3	<0.01	0.02
Aromas content [%]	17.3	0	8.8

The tests were carried out on a GTM-120 miniature turbine engine, made of a centrifugal compressor, diffuser, annular combustion chamber with pre-vaporising tubes, turbine nozzle, turbine wheel and nozzle cone. The engine is started by a starter. The technical parameters of the described engine are presented in Table 4.

Table 4. Technical parameters of the GTM-120 engine.

Maximum thrust [N]	100
Fuel consumption (for maximum thrust) [g/min]	520
Length [mm]	340
Width [mm]	115
Weight [kg]	1.5

The Semtech DS analyzer from Sensors Company (city, state abbrev if USA, country) was used to measure the concentration of gaseous exhaust compounds. This analyzer measures the concentration of nitrogen oxides, hydrocarbons, carbon monoxide and carbon dioxide. The exhaust gases from the GTM-120 engine were fed to the analyzer via a probe placed 3 cm from the outlet nozzle and a cable with a temperature of 191 °C, required to measure the concentration of hydrocarbons in the flame ionization analyzer. Then after cooling the exhaust gases to the temperature of 4 °C, measurements of the concentrations of carbon monoxide, carbon dioxide and nitrogen oxides were carried out. The Semtech DS analyzer includes the following measurement modules [32]:

- A flame ionization detector (FID), which uses the change of electric potential resulting from the ionization of molecules in the flame; it is used to determine the total concentration of hydrocarbons,
- A non-dispersive ultraviolet (NDUV) analyzer that uses ultraviolet radiation to measure the concentration of nitrogen oxide and dioxide
- A non-dispersive infrared (NDIR) analyzer using radiation infrared to measure the concentration of carbon monoxide and dioxide, and
- An electrochemical analyzer for determining the oxygen concentration in the exhaust gas.

At the same time, the particle number concentration was measured using an EEPS 3090 (Engine Exhaust Particulate Sizer™ spectrometer) analyzer from TSI Incorporated (city, state abbrev if USA, country). This analyzer measures the discrete range of particle diameters from 5.6 nm to 560 nm [32,33]. The exhaust gas was directed to the analyzer through a dilution system, where the total flow was 10 l/min, including the exhaust gas flow 0.3 l/min, so the exhaust gas in the tested sample accounted for 3%. Technical data of the EEPS 3090 analyzer are presented in Table 5.

Table 5. Technical data of the EEPS 3090 analyzer [33].

Parameters	Value
Diameter of the measured particles	5.6–560 nm
Number of measurement channels	16 channels per decade
Resolution	10 Hz
Exhaust sample volume flow rate	0.6 m^3/h
Compressed air volume flow rate	2.4 m^3/h
Input sample temperature	10–52 °C

The measuring range was from 10 to 100 N, and the measurements were made every 10 N. In order to clearly present the results, after the measurements, the measuring range was reduced to the following three ranges: low engine operation load from 10 to 30 N, medium engine operation load from 40 to 60 N and high engine operation load ranging from 70 to 100 N (Table 6). Measurement results were averaged in each of the examined areas.

Table 6. Measurement ranges for engine operation load and their values.

Range Name	Engine Operation Load Range [N]	
	Up	To
Low	10	30
Medium	40	60
High	70	100

5. Results and Discussion

5.1. Concentration of Harmful Exhaust Gas Compounds

The results were grouped for easier comparison by reference to the fuel composition and the engine load range. During the measurements, the focus was on the concentration of harmful exhaust gas compounds, such as CO_2, CO, HC and NO_x. The measurement results of the tested exhaust gas compounds are shown in Figure 3. It is worth underlining that the maximum thrust power of the GTM 120 engine, amounting to 100 N, was achieved only with the use of pure conventional Jet A-1 fuel. For a fuel containing 30% and 50% ATJ fuel the maximum load was about 90 N. Carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides are the main products of combustion. Emissions of these harmful gaseous exhaust compounds depend on the engine load, so also on flight mode. Basically, emission of carbon dioxide is proportional to fuel consumption. Emission of carbon monoxide is high for low engine load, for example for idling and taxiing, and decreases when engine load is increasing. The opposite situation is true for nitrogen oxides. NOx emissions increase with increasing engine load, so they are high for climbing and take-off. Nitrogen oxides and unburned hydrocarbons are formed, inter alia, depending on the temperature and pressure in the engine [34,35].

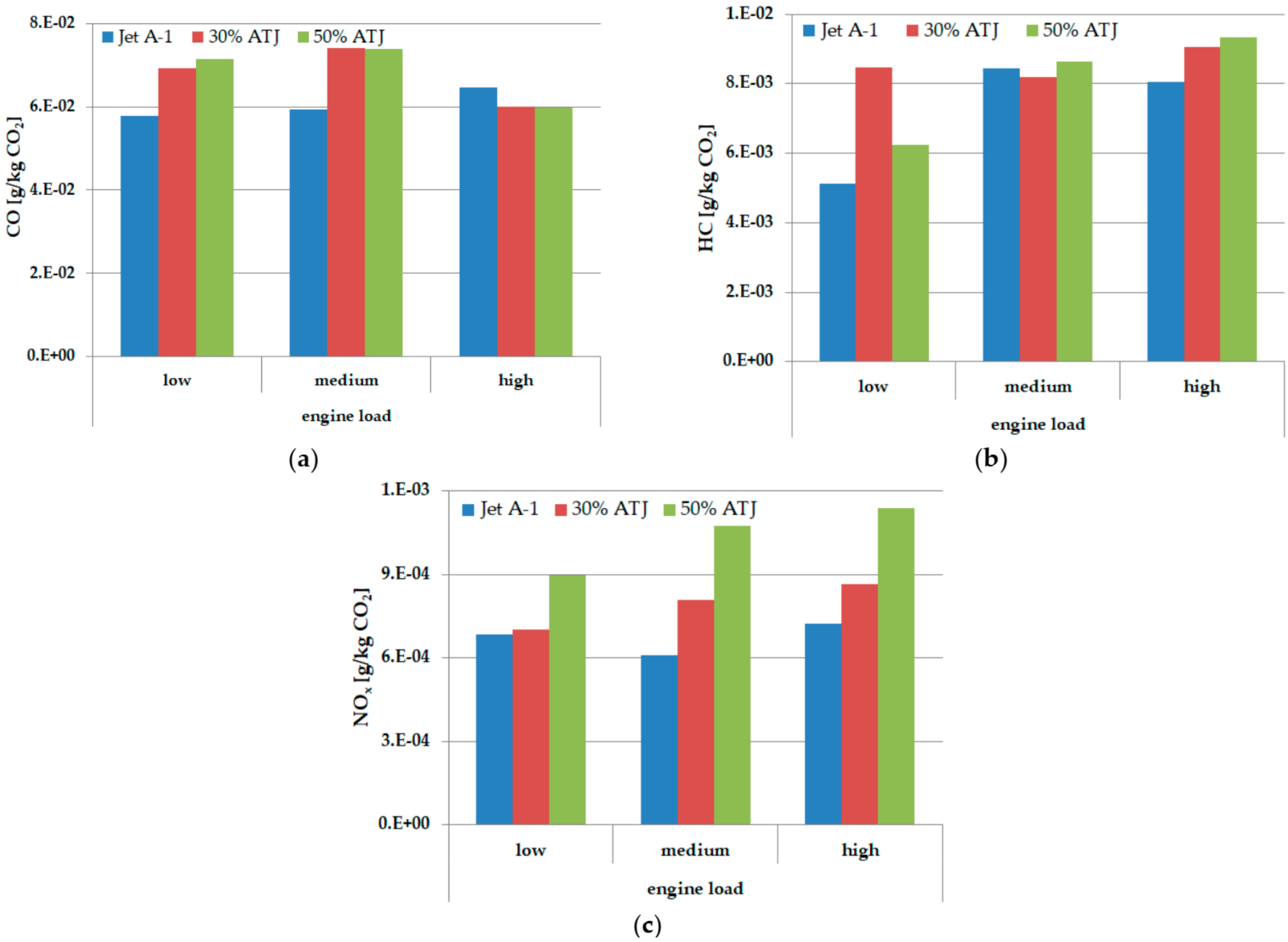


Figure 3. Emission index for (**a**) carbon monoxide; (**b**) hydrocarbons; (**c**) nitrogen oxides.

The emission of harmful gaseous compounds was presented in the form of emission factors related to the emission of carbon dioxide during each measurement. Comparing the emissions of carbon monoxide (Figure 3a) with CO_2 emissions at low and medium engine operation load, it was found that it is the lowest for pure Jet A-1 fuel, while in the case of high engine operation load for Jet A-1 fuel it is the highest, compared to other tested fuels. Carbon monoxide emissions for between 30% and 50% ATJ fuel do not differ significantly over the entire operating range of the engine. The difference between Jet A-1 and 50% ATJ for low engine operation load is 23% and for medium engine operation load it is 25%, when the emission was higher for 50% ATJ. In turn comparing high engine operation load, emissions of CO related to CO_2 were the lowest for 50% ATJ and about 8% lower than for Jet A-1.

On the other hand, in the case of hydrocarbon emissions (Figure 3b), for low engine operation load, the highest HC emission is shown for fuel with 30% ATJ content, while at medium and high engine operation load it is for fuel with 50% ATJ content. For low engine operation load the difference between 30% ATJ and Jet A-1 is 40% and between 30% ATJ and 50% ATJ is 36%. In turn for high engine operation load difference between the highest emission for 50% ATJ and Jet A-1 is 16% in favor of the Jet A-1 fuel.

Comparing the emission of nitrogen oxides (Figure 3c), it was found that the lowest emissions occur for the pure conventional fuel Jet A-1 in the entire engine operation range, while the highest carbon oxide emission per CO_2 emission occurs for the fuel with 50% ATJ content in the entire engine operation range. The differences between Jet A-1 and 50% ATJ are respectively 31% for low load engine operation, 76% for medium load and 57% for high load engine operation. In this case, increasing the content of alternative fuel Alcohol-to-Jet in the mixture of Jet A-1 and ATJ is expected to increase the emission of nitrogen oxides.

5.2. Particles Concentration

Based on the obtained data for the particle number concentration, the characteristics of the mass concentration of particles depending on their diameter were calculated. For the calculation the solids density characteristic was used (Figure 4), which decreases with increasing particle diameter. The particle density function was determined empirically on the basis of the CFM56-7B26/3 aviation engine [36–38]. Knowing the diameter of particles, it was possible to calculate the mass of particulate matter by using the density and volume of the particles.

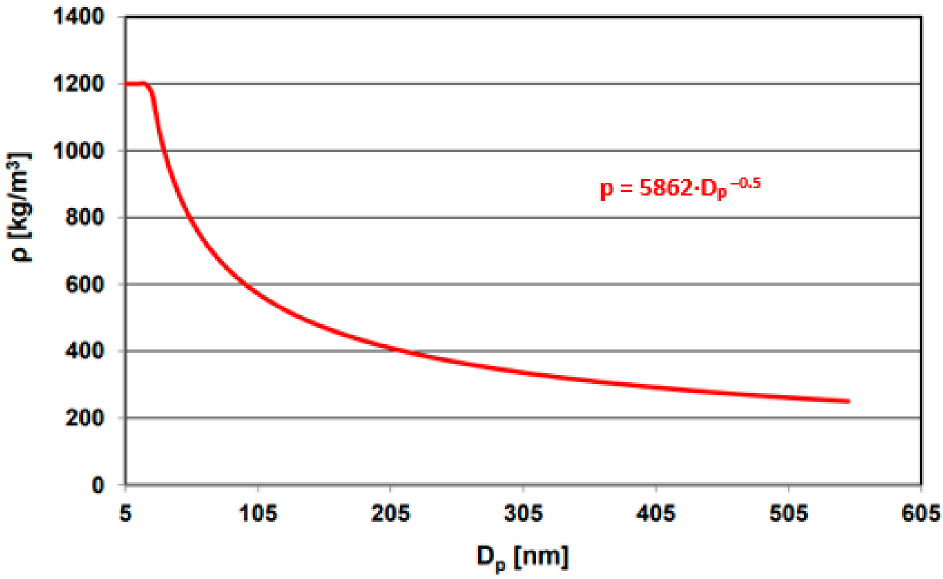


Figure 4. Density of solid particles depending on their diameter [32].

5.2.1. Low Engine Load

Figure 5 shows the number and mass concentration of particles depending on their diameter (first column) and cumulative values of the relative particle number and relative mass of particulate matter (second column) for low load engine operation fueled Jet A-1 (first row), 30% ATJ (second row) and 50% ATJ (third row). The cumulative curves were determined by standardizing the obtained data for the number and mass of particulate matter to the value 1 and using the connection between the quotient of the number of particles and the maximum number of particles as well as the quotient of the mass of particles and the maximum mass of particles.

In the case of particles in the exhaust of an engine running on clean fuel Jet A-1 (Figure 5a), for low engine operation load, particles with 25.5–124.1 nm diameter dominated. The characteristic diameter, i.e., the highest number of particles, of the discussed number concentration characteristic was about 60.4 nm. Based on the characteristics of the mass concentration of particulate matter for Jet A-1 fuel at low engine operation load, the vast majority of the mass of particulate matter was due to particles with a diameter of 25.5–220.7 nm. The remainder of the particulate mass results from the emission of a very small amount of particulate matter with diameters in the 294.3–523.3 nm range. At low engine operation load fueled Jet A-1 (Figure 5b) the cumulative values of the relative particles number and relative mass of particulate matter show that 90% of the relative number of all particles emitted corresponds to 60% of their relative mass. About 90% of all particles are less than 100 nm in diameter.

In the case of low engine operation loads ranging from 10 N to 30 N for the fuel with 30% ATJ content (Figure 5c), the particle diameters of 25.5–107.5 nm dominated, and the majority were the particles with a diameter of 52.3 nm. Compared to the total particles concentration for Jet A-1, the 30% ATJ fuel had a slight reduction in total particle count. The main part of the emitted mass was particulate matter with diameters in the range 34.0–165.5 nm. The remainder of the particulate mass results from the emission of a very small number of particulate matter with diameters in the range 294.3–523.3 nm. Cumulative values of the relative number and relative mass of particles for a 30% ATJ fuel (Figure 5d) shows, that 90% of the relative number of all particles emitted is about 55% of their relative mass. About 90% of all particulate matter is less than 80 nm in diameter.

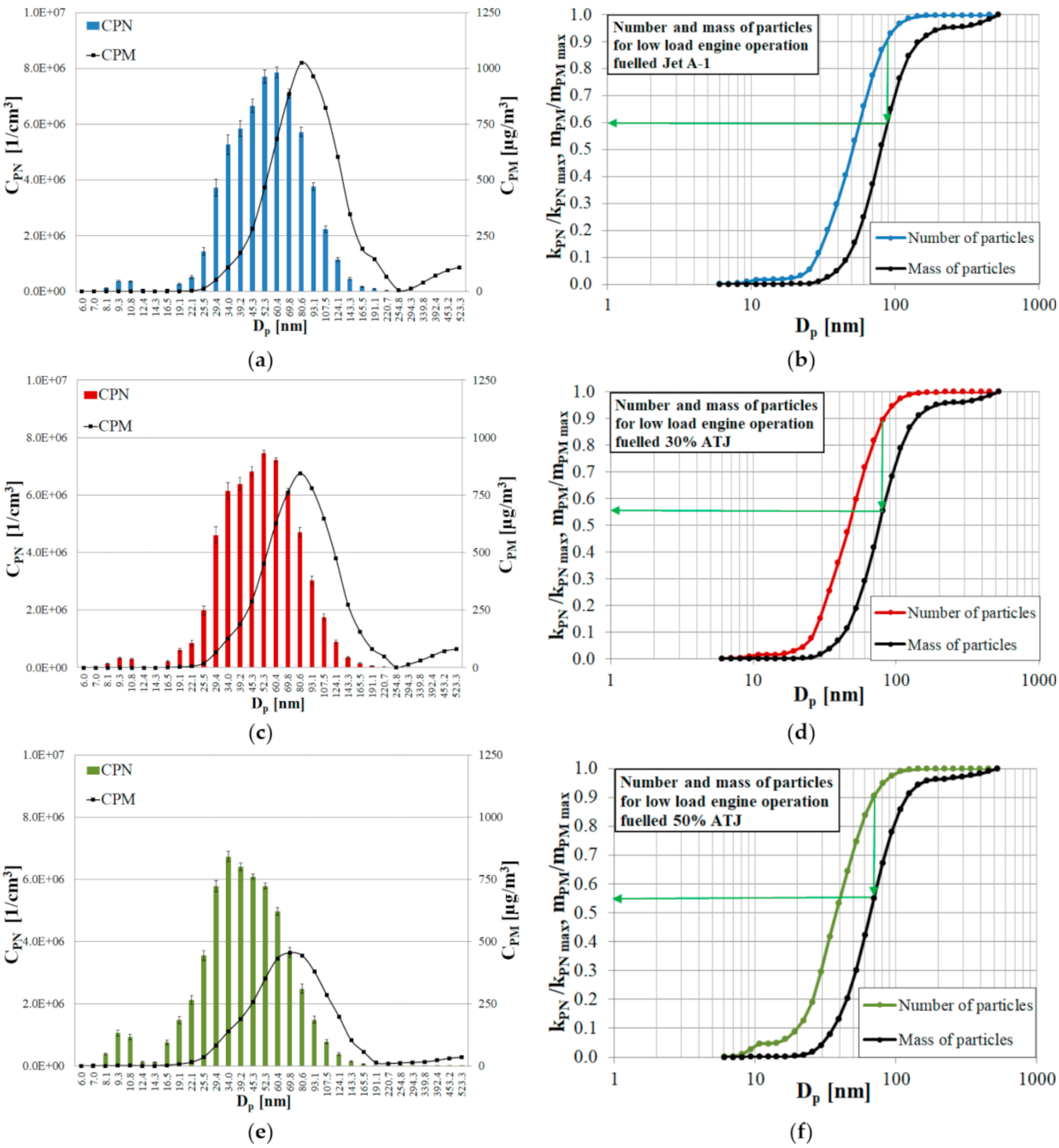


Figure 5. Number and mass concentration of particles depending on their diameter (**a**,**c**,**e**) and cumulative values of the relative particles number and relative mass of particulate matter (**b**,**d**,**f**) for low engine operation load fueled Jet A-1 (**a**,**b**), 30% ATJ (**c**,**d**) and 50% ATJ (**e**,**f**).

On the other hand, for the fuel containing 50% ATJ in the range of low engine operation load, the range of dominant particle diameters for low engine loads was 19.1–93.1 nm, and most of the particles had a diameter of 34.0 nm (Figure 5e). However, the concentration of the total number of particles in this case was the lowest compared to other tested fuels. The difference is approximately 10% compared to the total particles concentration for conventional Jet A-1. In the case of mass concentration of particulate matter, depending on their diameter, the main part of the emitted mass of particulate matter were particles with a diameter of 25.5–165.5 nm. The remainder of the particulate mass results from the emission of a very small number of particulate matter with diameters ranging from 254.8–523.3 nm. The total particulate mass concentration for the fuel containing 50% ATJ was 51% lower than the total particulate mass concentration for the Jet A-1 fuel in the discussed engine operating range. For a fuel containing 50% ATJ (Figure 5f), cumulative values of the relative number and relative mass of particles shows that 90% of the relative number of all particulate matter emitted is about 55% of their relative mass. About 90% of all particulate matter is less than 70 nm in diameter.

5.2.2. Medium Engine Load

Figure 6 shows number and mass concentration of particles depending on their diameter (first column) and cumulative values of the relative particles number and relative mass of particulate matter (second column) for medium engine operation load fueled Jet A-1 (first row), 30% ATJ (second row) and 50% ATJ (third row). In the case of medium load engine operation in the range of 40–70 N, for the conventional fuel Jet A-1, particles with a diameter of 25.5–107.5 nm were dominant, and the characteristic diameter was 52.3 nm (Figure 6a). Particles with a diameter of 29.4–165.5 nm accounted for the main share in the emitted mass of particles. The remainder of the particulate mass is due to the emission of a very small number of particles with diameters in the range 339.8–523.3 nm. Cumulative values of the relative number and relative mass of particles (Figure 6b) show that 90% of the relative number of all emitted particles is 60% of their relative mass. About 90% of all particulate matter is less than 80 nm in diameter.

For the fuel with 30% ATJ content, the particles with a diameter of 22.1–93.1 nm dominated for medium engine operation load, and the particles with a diameter of 34.0 nm were the most numerous (Figure 6c). As with the low engine operation load, the total particle concentration was lower than that of Jet A-1. In the case of mass concentration of particles, depending on their diameter, particles with a diameter of 25.5–124.1 nm accounted for the main share in the emitted particulate matter mass.

The remainder of the particulate mass results from the emission of a very small number of particles with diameters in the range 294.3–523.3 nm. Cumulative values of the relative number and relative mass of particles (Figure 6d) show that 90% of the relative number of all emitted particles is 60% of their relative mass. About 90% of all particulate matter is less than 70 nm in diameter.

In the case of the fuel with 50% ATJ content, for medium engine operation load, particles with a diameter of 16.5–80.6 nm dominated, however, particles with a diameter of 9.31 and 10.8 nm also appeared in a greater number (Figure 6e). The characteristic diameter was 34.0 nm. As with the low engine operation load, the total particles concentration was lowest for the fuel containing 50% ATJ compared to the fuel containing 30% ATJ and Jet A-1 fuel. The difference between Jet A-1 and 50% ATJ is less than 14%. Particles with a diameter of 25.5–124.1 nm were the main share in the emitted mass of particulate matter. The total particulate mass concentration was also the lowest compared to previous fuels in this engine load range and was about 40% of the total mass concentration of Jet A-1 for medium operation load. Cumulative values of the relative number and relative mass of particles (Figure 6f) show that 90% of the relative number of all emitted particles is also 60% of their relative mass. About 90% of all particles is less than 60 nm in diameter, so for medium load engine operation, when the fuel contained more ATJ alternative fuel, the diameter of 90% of all particles was smaller: for pure Jet A-1 it was 80 nm, for 30% ATJ—70 nm, and for the highest content of alternative fuel which was 50%, it was 60 nm.

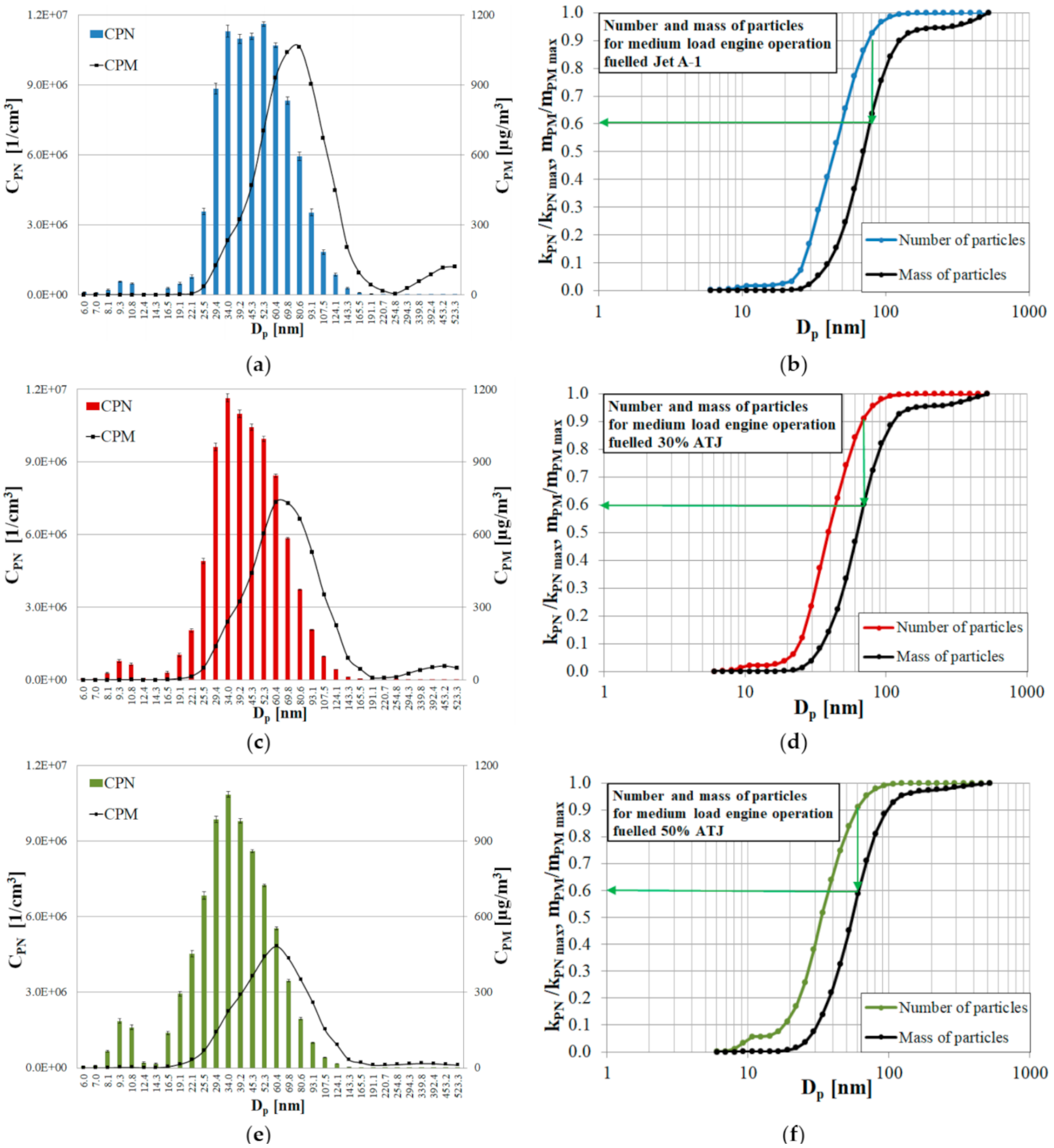


Figure 6. Number and mass concentration of particles depending on their diameter (**a**,**c**,**e**) and cumulative values of the relative particles number and relative mass of particulate matter (**b**,**d**,**f**) for medium engine operation load fueled Jet A-1 (**a**,**b**), 30% ATJ (**c**,**d**) and 50% ATJ (**e**,**f**).

5.2.3. High Engine Load

At high engine operation load (Figure 7), for each of the tested fuel, an increase in the concentration of the total number of particles was found. In the case of Jet A-1 fuel, particles with a diameter of 16.5–107.5 nm dominated for high engine load (Figure 7a). As can be seen, with increasing engine load, the diameter of the dominant particles decreased. For low and medium engine operation load, the most were particles with a diameter of 60.4 nm, while for high engine operation load, the most were particles with a diameter of 34.0 nm. However, the total number of particles is incomparably the highest at high engine operation load. On the other hand, the main part of the emitted mass of particulate matter were particles with diameters of 25.5–143.3 nm, and the remaining part of the mass of particulate matter results from the emission of a very small number of particles with diameters in the range of 294.3–523.3 nm. Cumulative values of the relative number and relative mass of particles (Figure 7b) show that 90% of the relative number of all emitted particles is also 60% of their relative mass. About 90% of all particles is less than 70 nm in diameter.

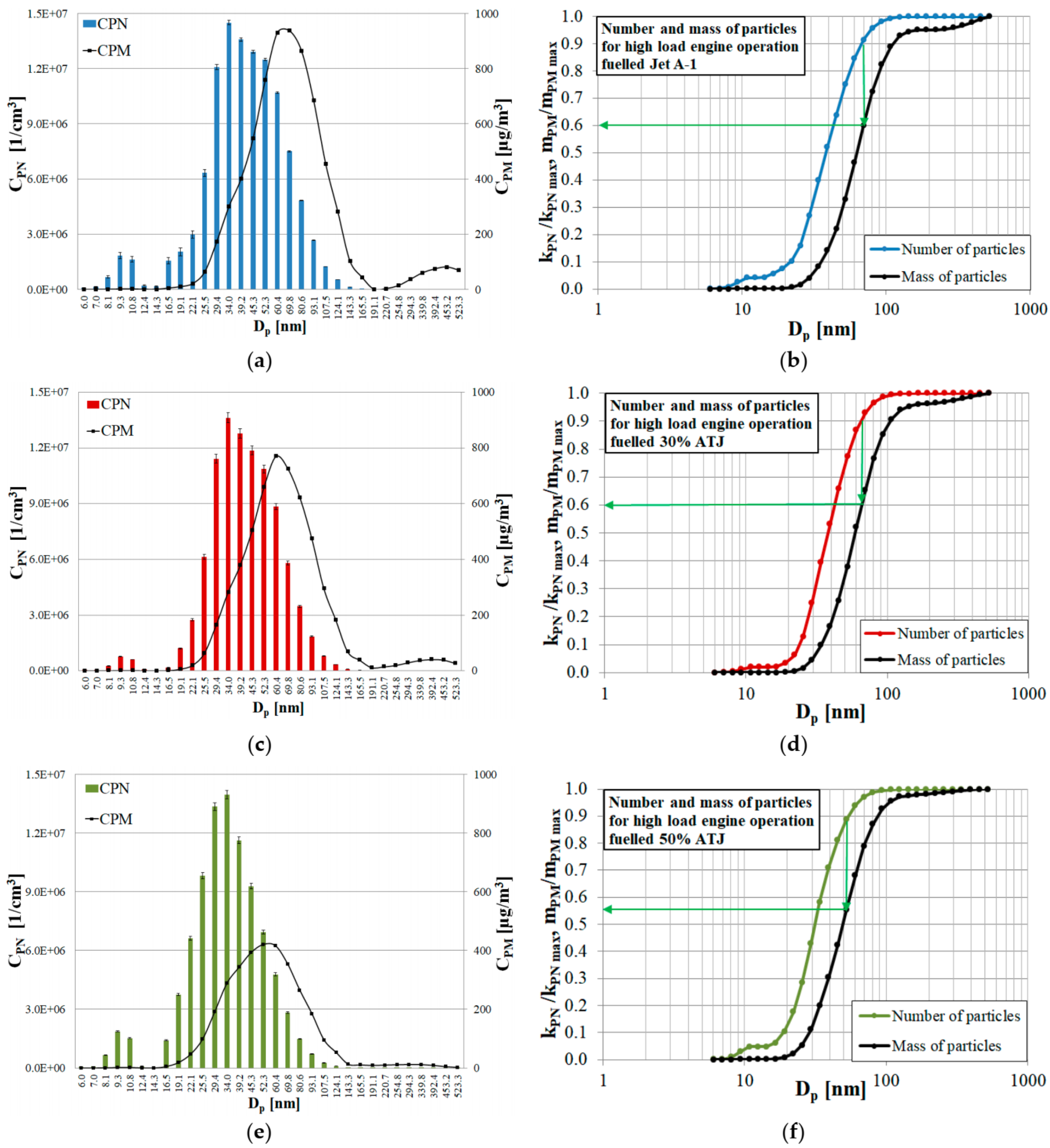


Figure 7. Number and mass concentration of particles depending on their diameter (**a**,**c**,**e**) and cumulative values of the relative particles number and relative mass of particulate matter (**b**,**d**,**f**) for high engine operation load fueled Jet A-1 (**a**,**b**), 30% ATJ (**c**,**d**) and 50% ATJ (**e**,**f**).

For the fuel with 30% ATJ fuel content, particles with a diameter of 22.1–93.1 nm dominated at high engine operation load (Figure 7c), and the most were particles with a diameter of 34.0 nm, similar to the medium engine operation load. In the case of the particulate matter mass concentration, depending on their diameter, the main fraction of the emitted particulate matter mass were particles with a diameter of 25.5–143.3 nm. The remainder of the particulate matter mass results from the emission of a very small number of particles with diameters in the 254.8–523.3 nm range. Cumulative values of the relative number and relative mass of particles (Figure 7d) show that 90% of the relative number of all emitted particles is also 60% of their relative mass. About 90% of all particles is also less than 70 nm in diameter.

On the other hand, when analyzing the numerical and mass concentration of particles for a 50% mixture of ATJ and Jet A-1 fuel (Figure 7e), it was found that in this case the numerical distribution of particles depending on the particle diameter in the entire engine operating range differs the most compared to the previous fuels. The range of diameters of the dominant particles for high loads was 16.5–80.6 nm, but there were also more particles with a diameter of 9.31 and 10.8 nm. The characteristic particle diameter was 34.0 nm. The total particle number concentration was approximately 18% lower than the total particle number concentration for conventional Jet A-1 fuel in the described engine operating range. In turn, the main part of the emitted mass of particulate matter were particles with a diameter of 22.1–124.1 nm. The total particulate mass concentration was 51% of the total Jet A-1 fuel mass concentration at the high engine operation load. Cumulative values of the relative number and relative mass of particles (Figure 7f) show that 90% of the relative number of all emitted particles is also 60% of their relative mass. About 90% of all particles is less than 55 nm in diameter.

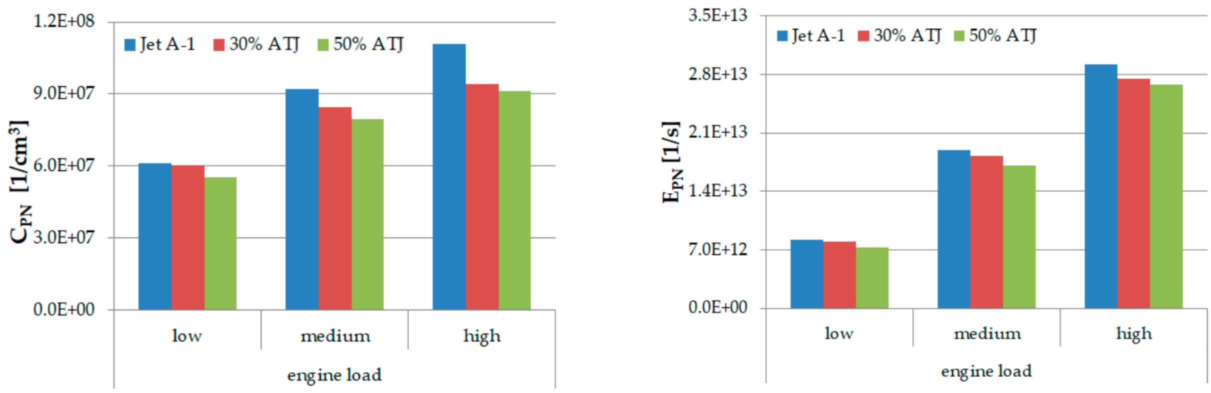
5.2.4. Analysis of the Results

All main results from each tested fuel for different engine operation load have been summarized in Table 6. Dominant diameters in particle number are the smallest for 50% ATJ for every engine operation load. The same conclusion is reached concerning the range of dominant diameters in the particulate matter mass. To compare the cumulative values of the relative number and relative mass of particles for tested fuels, it was found that due to increasing the engine operation load, the diameter of 90% of the relative number of particles for each of the tested fuels decreases. The same happens when the content of the alternative fuel in tested fuels is higher, so the diameter of 90% of relative number of particles was the smallest for high load engine operation fueled 50% ATJ. The differences between the fuels and engine operation load in diameter of 90% of the relative number of particles shows last rows of Table 7.

Table 7. Main results from researches depending on tested fuel and engine operation load.

Engine Operation Load	Tested Fuel		
	Jet A-1	**30% ATJ**	**50% ATJ**
	Range of dominant diameters in particles number [nm]		
low	25.5–124.1	25.5–107.5	19.1–93.1
medium	25.5–107.5	22.1–93.1	16.5–80.6
high	16.5–107.5	22.1–93.1	16.5–80.6
	Range of dominant diameters in particulate matter mass [nm]		
low	25.5–220.7	34.0–165.6	25.5–165.6
medium	29.4–165.5	25.5–124.1	25.5–124.1
high	25.5–143.3	25.5–143.3	22.1–124.1
	The most dominant diameter [nm]		
low	60.4	52.3	34.0
medium	52.3	34.0	34.0
high	34.0	34.0	34.0
	90% of relative number particles is less than [nm]:		
low	100	80	70
medium	80	70	60
high	70	70	55

On the basis of the obtained data, the intensity of the number of particles E_{PN} was determined for the analyzed engine operation load ranges, using the measured numerical concentration of particles C_{PN} for a given engine load and the volumetric flow rate of exhaust gases for individual fuels. The intensity of the emission of particulate matter E_{PM} was also determined in the tested ranges of the engine operation load, based on the mass concentration of the particulate matter of the C_{PM} and the volumetric flow rate of exhaust gases for tested fuels. The intensity of the number and emission of particles was compared between the tested fuels and the analyzed engine load areas (Figure 8).

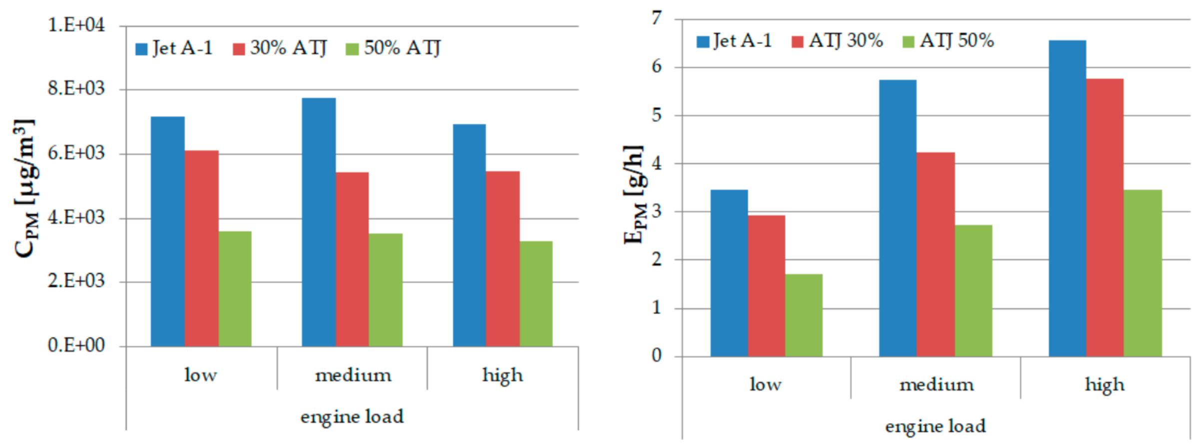


(**a**) (**b**)

Figure 8. The number concentration C_{PN} (**a**) and intensity of the particles number emission E_{PN} (**b**) for tested fuels in three ranges of engine operation.

The number concentration of C_{PN} particles and the intensity of the number of particles E_{PN} increases with increasing engine load for all analyzed fuels. In all engine operating ranges, the particles number and number concentration are the highest for conventional Jet A-1 fuel and the lowest for fuel containing 50% of the alternative fuel.

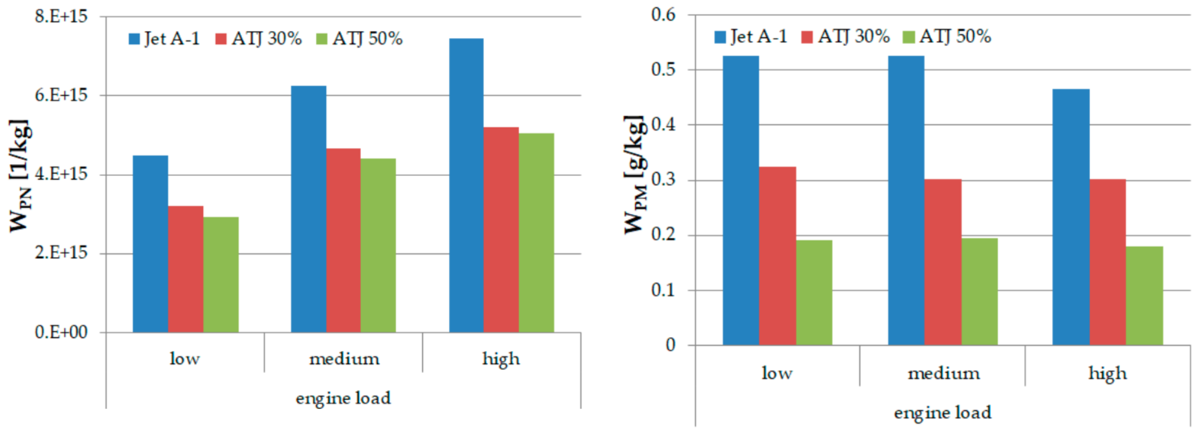
The mass concentration of C_{PM} particulate matter decreased with increasing engine operation load in the case of fuels containing alternative fuel and was the highest at the medium engine load for Jet A-1 fuel (Figure 9). On the other hand, the intensity of E_{PM} particulate matter emission increased with increasing engine operation load for all tested fuels and was the highest for high engine load in the case of Jet A-1 fuel. The lowest particulate matter emission intensity was found for the fuel containing 50% ATJ fuel, which for particular engine operation load accounted for about 53% of the particulate emission intensity for Jet A-1 fuel.



(**a**) (**b**)

Figure 9. Mass concentration C_{PM} (**a**) and emission intensity of particulate matter E_{PM} (**b**) for tested fuels in three engine operation ranges.

The W_{PN} and W_{PM} coefficients were also determined, which determine the number and mass of particles, respectively, formed from one kilogram of fuel consumed by the engine. The values of the discussed coefficients are shown in Figure 10. Based on the charts below, it was found that the highest average number of particles is generated when the engine is fueled with conventional Jet A-1 fuel and at high engine operation load it amounts to 7.45×10^{15} units (Figure 10a). On the other hand, for high engine load the lowest average number of particles per kilogram of fuel used is for fuel containing 50% ATJ fuel and it amounts to 5.05×10^{15} units, thus it is about 32% lower than for Jet A-1. In the case of the particulate matter mass coefficient (Figure 10b), the highest mean value of the coefficient was equal to 0.53 for Jet A-1 fuel for medium engine loads, and the lowest for fuel containing 50% ATJ for high engine loads. The largest difference between the average value of the particulate matter mass factor, amounting to 63%, was found at the medium engine operation load between Jet A-1 fuel and the fuel containing 50% ATJ.



(**a**) (**b**)

Figure 10. Particle number index W_{PN} (**a**) and particle mass index W_{PM} (**b**) for tested fuels in three engine load ranges.

6. Conclusions

Given the problems that the aviation industry is currently facing, the development of alternative fuels to power aircraft is inevitable. Over the past 10 years, over 200,000 flights have already been made using alternative fuels. Thanks to constant research and new solutions, the biofuels and sustainable fuels sector is constantly developing. In relation to the research carried out, using alternative fuel based on alcohol which is ATJ fuel, can have positive impact on the concentration of number and mass of particles compared to Jet A-1, but also negative impact on the emission of harmful gaseous compounds. It is crucial that the maximum engine load for a mixture of 30% ATJ and Jet A-1 and 50% ATJ and Jet A-1 was about 90% of maximum engine load for pure Jet A-1. Thus when comparing the emission of gaseous compound and particulate matter, attention should also be paid to the maximum achievable engine load for a given fuel mixture. For nitrogen oxides, hydrocarbons and carbon monoxide increasing the content of ATJ fuel in mixture of Jet A-1 and ATJ results in an increase of emission of these gaseous compounds in almost every engine operation load situation that was analyzed. As shown in the graphs of cumulative values of the relative particles number and relative mass of particulate matter for tested fuels, it was found that due to the increasing engine operation load, the diameter of 90% of the relative number of particles for each of the tested fuels decreases. The same happens when the content of the alternative fuel in tested fuels is higher, so the diameter of 90% of relative number of particles was the smallest for high load engine operation fueled by mixture of 50% ATJ and Jet A-1. Due to studies it is found out that the highest average number of particles is generated when the engine is fueled with conventional Jet A-1 fuel and the lowest average number of particles per kilogram of fuel used is for fuel containing

50% ATJ fuel. Thus, it can be concluded that the addition of ATJ has a positive effect on the number and mass concentration of particles.

The aim and the main conclusion of the above comprehensive analysis in the field of exhaust gas emissions from biofuels is that the emission of gaseous compounds is not necessarily lower than with the use of conventional Jet A-1 fuel, but in terms of the entire life cycle of biofuels, they are still less harmful to environment than conventional fuels. On the other hand, the emissions of particulate matter, in contrast to toxic compounds, is better when using a mixture of conventional fuel and biofuel than when using pure conventional fuel. Further recommendation is to maximize the proportion of biofuels, as far as possible and with all the safety and technical aspects of the engine, because they give measurable effects in the form of reduced particulate emissions.

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