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Evaluating the Impact of Using HEFA Fuel on the Particulate Matter Emissions from a Turbine Engine

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Abstract: The dynamically growing sustainable aviation fuel (SAF) industry and the implemented European policy create the need for conducting research on the actual benefits of using alternative fuels in aviation. The aim of this research was to assess the impact of HEFA (hydroprocessed esters and fatty acids) fuel on the particulate matter emission indicators of an aircraft engine. This article presents the results of the measurements of particle emissions from a jet engine fueled by a blend of aviation kerosene and HEFA fuel (with HEFA content at 5%, 20%, and 30% by volume). A positive effect of HEFA on both the number and mass indices of particles was observed. The use of SAF fuel led to a reduction in the particulate number index by 90% and the particulate mass index by 75%. The Particle Number Emission Index (EI_N) for an engine fueled with Jet A-1 exhibited values ranging from 5.23×10^{16} to 1.33×10^{17} particles per kilogram. The use of HEFA fuel (30% content) allowed for a reduction in the EI_N to the range of 2.83×10^{15} to 1.04×10^{16} particles per kilogram. A detailed analysis of particle size distribution (PSD) for both the number and volume of particles was conducted. It was noted that neither the fuel composition nor the engine operating parameters significantly affected the shape of the PSD, but the use of HEFA fuel distinctly reduced the values of the number-based PSD. It was observed that the volume-based PSD had a bimodal shape, indicating a significant contribution of particles larger than 100 nm, forming the so-called soot mode. Our findings suggest that even a small amount of HEFA fuel yields satisfactory results in reducing particulate matter emissions.

Keywords: HEFA; SAF; emission; particles; particulate matter

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1. Introduction

The issue of climate change necessitates tackling challenges aimed at reducing carbon footprint. One of the main sources of greenhouse gases and air pollution is transportation. In the European Union, aviation is responsible for approximately 14% of carbon dioxide emissions from the transport sector [1]. The aviation industry plays a significant role in global transportation, connecting people and goods across the globe. However, this convenience comes at a cost, with aviation accounting for a notable share of greenhouse gas emissions. In response to the escalating concerns about climate change and environmental sustainability, there has been a growing imperative to develop and adopt alternative fuels in the aviation sector [2]. One such pivotal initiative is the integration of sustainable aviation fuel, a promising solution designed to mitigate the environmental impact of air travel. SAFs include biofuels, such as HEFA fuel, which will be discussed in this work.

SAF, also known as biojet fuel or aviation biofuel, represents a crucial component of the aviation industry's commitment to reducing its carbon footprint. Unlike conventional jet fuels derived from fossil sources, biofuel is produced from sustainable feedstocks such as waste oils, agricultural residues, and non-food crops. This shift toward renewable feedstocks holds the potential to significantly lower the net greenhouse gas emissions associated with aviation, addressing the sector's contribution to climate change [3].

In standard aviation fuel for jet engines, sulfur is present, leading to the emission of sulfur oxides. In addition to the direct emission of sulfur oxides, sulfur also influences the emission of particulate matter. Regarding the non-volatile fraction, a higher sulfur content contributes to increased soot emissions (known as the soot mode). It is essential to note that sulfur oxides are classified as precursors to the volatile fraction of particulate matter. The use of SAF as part of a blend with conventional aviation fuel allows for a reduction in the sulfur content in the mixture, consequently lowering both particulate matter and sulfur oxide emissions [4,5].

Due to increasing concerns about the local air quality impact of ultrafine particulate matter (nvPM) emissions from aviation, the International Civil Aviation Organization's Committee on Aviation Environmental Protection (ICAO CAEP) introduced a regulatory standard for non-volatile particulate matter emissions [6–9]. All currently produced engines with a rated thrust exceeding 26.7 kN are required to adhere to the maximum permissible concentration of nvPM in the exhaust (CAEP/10 nvPM standard) and the specified limits for nvPM mass and number emitted during the standard landing and take-off (LTO) cycle, normalized by thrust (CAEP/11 nvPM standard) [8–10].

Scientific research delves into the multifaceted dimensions of sustainable aviation fuel, examining its production processes, environmental benefits, and economic feasibility, as well as its integration into existing aviation infrastructure. By delving into the scientific intricacies of SAF, we aim to contribute to the ongoing discourse on sustainable aviation practices, offering insights that may further propel the industry toward a more environmentally conscious and sustainable future.

Political actions aimed at mitigating the impact of aviation on climate include initiatives such as ReFuel EU, a plan that is part of the broader FitFor55 package. On 9 October 2023, the Council of the European Union adopted the ReFuel EU program, the main goals of which will increase the supply and reduce the cost of sustainable aviation fuel. Through this plan, the EU seeks to create a conducive environment for SAF producers and users, fostering the development of this innovative aviation fuel [11].

The European Union is actively engaged in scientific research, technological development, and the promotion of collaboration between the public and private sectors in the field of SAF. Supported research projects aim to enhance the efficiency of SAF production and advance technologies based on renewable resources. The political plans are highly ambitious and envision that the share of sustainable aviation fuels (including synthetic fuels) should be 2% by 2025, 6% by 2030, and 70% by 2050. Starting from 2030, synthetic fuels must constitute 1.2%, reaching a level of 35% by 2050 [11].

In the literature, the positive impact of SAF on the carbon footprint has been confirmed. The positive impact of SAF on air quality, particularly in airport areas and their vicinity, should be considered separately [12–14]. Currently, one of the major issues of air pollution is particulate matter. Scientific studies indicate that airport areas are contaminated with nanoparticles [15,16], similar to airport terminals [17]. This poses a threat primarily to airport workers. Particulate matter, consisting of tiny particles suspended in the air, poses health and environmental concerns when emitted into the atmosphere [18]. In the context of aviation, these particles can result from the combustion of jet fuels and are associated with adverse respiratory effects and environmental damage. SAF's cleaner combustion profile, attributed to its renewable feedstocks and advanced production processes, leads to a notable reduction in particulate matter emissions compared to conventional aviation fuels. This positive environmental impact aligns with global efforts to enhance air quality and mitigate the adverse health effects associated with particulate matter exposure [19].

The objective of the research presented in this article was to conduct a quantitative comparative assessment of particulate matter emissions from a jet engine powered by conventional aviation kerosene and its blend with SAF. The analysis was based on emission indices and particle size distributions. The study was conducted on a full-scale, dual-flow jet engine. Such studies are expensive, which is why they are not as commonly performed. The conducted research provides empirical data used to assess the impact of HEFA fuel on particulate matter emission parameters. The analysis of particulate matter emissions relates to the engine's operational parameters. The presented analysis provides data that can be used for a comprehensive assessment of the benefits of the widespread use of SAF.

2. Materials and Methods

2.1. Fuels, Test Engine, and Operating Schedule

In this research, HEFA fuel was used. This is a type of sustainable aviation fuel that holds significant promise in reducing the carbon footprint of aviation. Derived from renewable feedstocks such as vegetable oils and animal fats, HEFA undergoes a hydroprocessing treatment to produce a high-quality, low-emission alternative to traditional jet fuels. This process ensures that HEFA meets stringent aviation fuel standards. The HEFA method became the second ASTM-approved conversion process, obtaining certification in 2011. A notable benefit of this approach is its seamless integration into an oil refinery with just one extra step. This is why it stands out as the most economically feasible choice for sustainable aviation fuel (SAF), having fueled more than 95% of all SAF flights until now. Due to the aforementioned fact, the decision was made to choose HEFA fuel for the research [20]. One of the key advantages of HEFA is its compatibility with existing aircraft and infrastructure, requiring no modifications to current engines or fueling systems [13,21]. The HEFA fuel used in this research was produced from used cooking oil and meets the ASTM D7566 standard. The prepared blends were tested in terms of different factors such as density at 15 °C, viscosity at −20 °C and −40 °C, calorific value, the aromatic and naphthalene content, flash point, crystallization temperature, non-smoking smoke point, and distillation. The physicochemical parameters of the fuel have been presented in a previous publication [14].

As the reference fuel, Jet A-1 was utilized, and experiments were conducted on blends of Jet A-1 and HEFA with sustainable aviation fuel content at 5%, 20%, and 30% of volume.

The engine used in this research was DGEN 380 [22,23]. This is a two-spool unmixed flow turbofan engine with a high bypass ratio equal to 7.6. It has six modules, namely an axial fan module, a gearbox module with a planetary gearbox, a low-pressure module with a radial compressor, a high-pressure module with an embedded starter–generator, a central module hosting the fan and HP rotor, and a combustion and primary exhaust module with the annular combustion chamber, as well as an oil and fuel control unit. The engine core consists of a radial compressor and two axial turbines. The planetary gearbox with a reduction ratio of 3.32 connects the low-pressure spool and the fan. The basic technical parameters of the engine are presented in Table 1 [24].

Table 1. Technical specification of the DGEN 380 turbofan.

Parameter	Value
Maximum thrust	255 daN
Specific fuel consumption (for maximum thrust)	12.4 g/kN·s
Bypass ratio	7.6
Weight	85 kg
Lifetime	3600 h

In Table 2, the setup parameters of the conducted tests on the engine are presented. The atmospheric conditions during measurements were an ambient temperature of 13 °C and an atmospheric pressure of 1010 hPa. According to [6], adding HEFA fuel results in slight thrust changes, and these changes are within the specified ±2% (Table 2). It was therefore possible to obtain the same relative thrust and fuel flow despite the changes in the fuel mixture.

Table 2. Engine test matrix.

Fuel Type	Average Sample Gas Temperature (°C) ± 0.1	Fuel Flow Rate (kg/h) ± 1.5 kg	Tested Percent Rated Thrust Settings (%) ± 2% Value
Jet A-1	15.4	26, 31, 35, 40, 55, 70, 89, 118	10, 13, 20, 26, 40, 56, 72, 97
HEFA 5%	15.8	26, 31, 35, 40, 55, 70, 89, 118	10, 13, 20, 26, 40, 56, 72, 97
HEFA 20%	16.0	26, 31, 35, 40, 55, 70, 89, 118	10, 13, 20, 26, 40, 56, 72, 97
HEFA 20%	15.8	26, 31, 35, 40, 55, 70, 89, 118	10, 13, 20, 26, 40, 56, 72, 97
HEFA 30%	15.9	26, 31, 35, 40, 55, 70, 89, 118	10, 13, 20, 26, 40, 56, 72, 97
HEFA 30%	16.0	26, 31, 35, 40, 55, 70, 89, 118	10, 13, 20, 26, 40, 56, 72, 97

2.2. Apparatus and Procedures

Selected online instrumentation was mounted in a 3-m-long sampling system to measure particle size distribution (PSD). The sampling probe was made of stainless steel, which is non-reactive in high temperatures, and the cyclone was used in accordance with ICAO recommendations. The cyclone functions by removing large particles, preventing counting errors, and keeping the instrument clean. It removes large particles and fibers that can cause excessive noise on one or more channels and are not the effect of jet engine operation.

The apparatus used for PSD measurements was TSI 3090 EEPS (Engine Exhaust Particle Sizer, TSI Inc., Shoreview, MA, USA). It enabled the measurement of a discrete range of particle diameters (5.6–560 nm) on the basis of their differing speeds. The degree of the electric mobility of particulate matter changed exponentially, and measurement of their size was performed at a frequency of 10 Hz. Photographs of the measurement setup, equipment, and the experimental schematic diagram have been presented in previous publications [4,14].

2.3. Data Analyses

The data acquired with TSI 3090 EEPS provided particle number concentrations and particle size distribution from the tested engine for different fuel mixtures. The differential number-based particle size distribution, dCN/d logDp, at a specified fuel flow rate (thrust) was obtained by averaging the particle numbers recorded under the same engine operating condition from the same instrument particle size bins. The PM mass emissions were determined by converting the PM number concentration data obtained from the EEPS, assuming unit density for the particles. The particles were assumed to have a spherical shape, and their density was distributed according to a specific model [25]. The density change curve, determined empirically for particulates from an aircraft jet engine, was considered. Subsequently, the averaged particle number and mass concentrations were utilized to compute the emission indices (EI_N, EI_V, and EI_M) based on the specified pollutant and test parameters.

The Particle Number Emission Index (EI_N) defines the number of particles emitted by the engine per unit mass of fuel. In this study, it was used in relation to the fuel flow (dependent on thrust) and the size of particles, thereby illustrating the size distribution of particles based on engine operating parameters. The Particulate Mass Emission Index (EI_M) determines the mass of particles emitted by the engine per unit mass of fuel. It was used in relation to the fuel flow. The Particle Volume Emission Index (EI_V) specifies the volume of particles emitted by the engine per unit mass of fuel. It was assumed that the particles had a spherical shape. The index was used in relation to the size of particles, indicating the particle size distribution (PSD).

3. Results

3.1. Particle Number and Mass Emission Indices

The average values of the Particle Number Emission Index (EI_N) along with error bars are presented in Figure 1. In the case of the engine fueled with Jet A-1, a significant increase (5.23×10^{16} to 1.08×10^{17} particles per kilogram of Jet A-1 fuel) in the EI_N was observed in the range from the minimum to approximately 40 kg/h of fuel flow rate. A further increase in the fuel flow resulted in fluctuations of the EI_N, reaching a maximum value of 1.33×10^{17} particles per kilogram at a fuel flow of approximately 90 kg/h (around 70% of maximum thrust). A continued increase in thrust (fuel flow) led to a reduction in the EI_N values, reaching a value of 1.04×10^{17} particles per kilogram at maximum thrust.

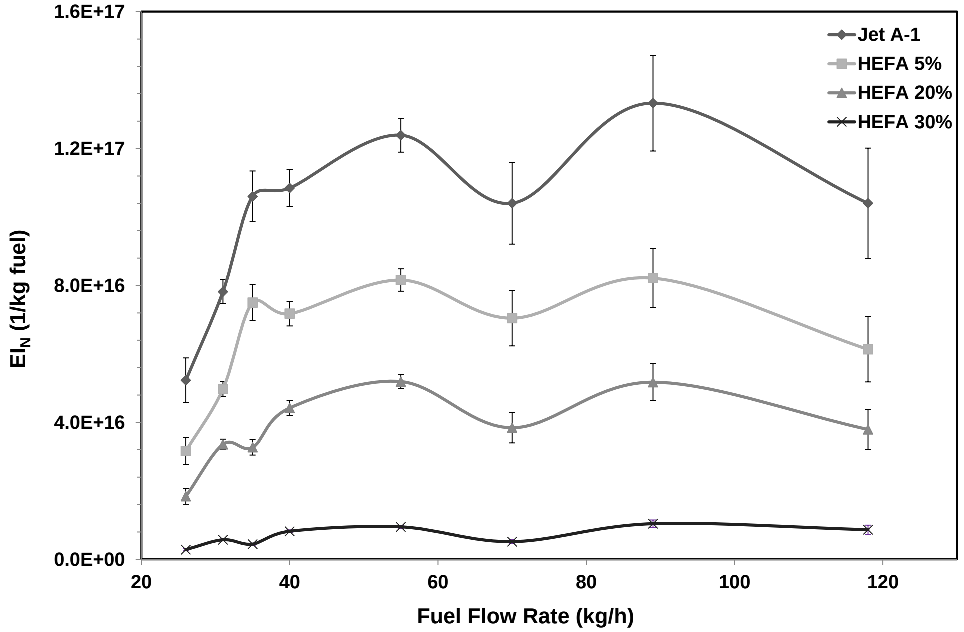


Figure 1. Particle Number Emission Index (EI_N) versus DGEN 380 fuel flow. Error bars represent one standard deviation.

The figure also shows that, in comparison to the other fuels tested, Jet A-1 had the highest EI_N values over the entire range of engine thrust (fuel flow rate). The EI_N values for HEFA 30% were the lowest among the four fuels tested. The EI_N curves for HEFA 5% and HEFA 20% fuels closely resemble the profile of Jet A-1 fuel. It is noteworthy that even a small proportion of SAF, such as 5%, led to a significant reduction in the EI_N.

The use of a 30% HEFA blend resulted in a significant reduction in the EI_N (by approximately 90%). Throughout the engine operating range, the EI_N value fluctuated around the mean (6.86×10^{15} particles per kilogram), reaching its minimum (2.83×10^{15} particles per kilogram) and maximum (1.04×10^{16} particles per kilogram) values for fuel flow rate values of 26 kg/h (10% of maximum thrust) and 89 kg/h (70% of maximum thrust), respectively.

The emission indices for PM mass (EI_M) were computed based on the EEPS measurements across different testing scenarios. Figure 2 illustrates how the EI_M is influenced by both the fuel blend and its flow rate (as well as thrust). The use of SAF fuel resulted in a reduction in the EI_M throughout the engine's operating range compared to the results obtained when the engine was fueled with Jet A-1.

In the case of the engine fueled with Jet A-1, a significant increase (from 62.2 mg to 150.2 mg per kilogram of Jet A-1 fuel) was observed in the EI_M in the range from the minimum to approximately 55 kg/h of fuel flow rate (40% of maximum thrust). The maximum EI_M value was obtained at a fuel flow rate of 89 kg/h, equal to 184.5 mg/kg. A continued increase in thrust (fuel flow) led to a reduction in the EI_M values, reaching a value of 149.9 mg/kg at maximum thrust.

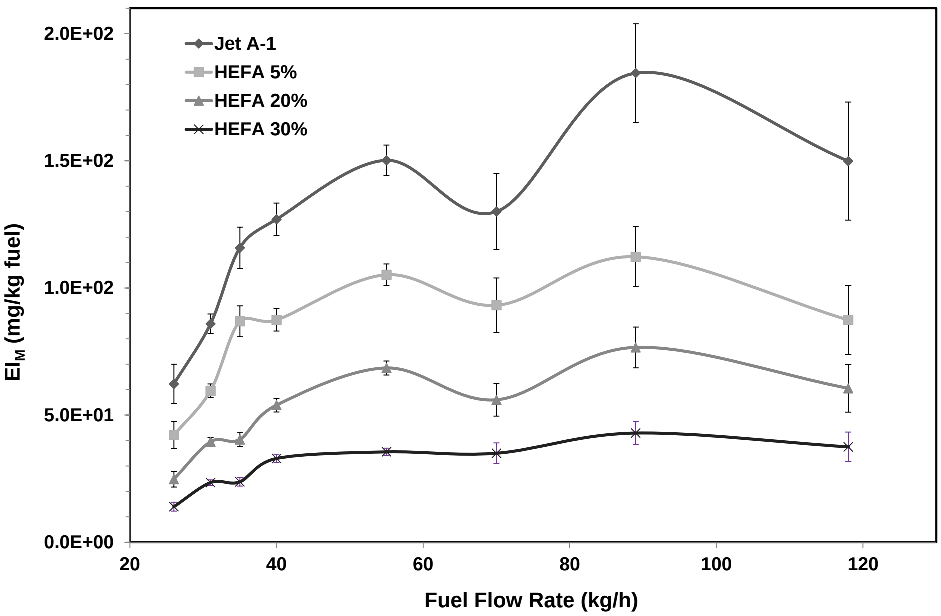


Figure 2. Particulate Mass Emission Index (EI_M) versus DGEN 380 fuel flow. Error bars represent one standard deviation.

The figure further indicates that, when compared to the other fuels examined, Jet A-1 exhibited the highest EI_M values across the entire spectrum of engine thrust (fuel flow rate). Among the four fuels tested, HEFA 30% displayed the lowest EI_N values. The EI_N curves for HEFA 5% and HEFA 20% closely mirrored the pattern observed for Jet A-1 fuel.

Utilizing a 30% HEFA blend led to a substantial decrease in the EI_M, amounting to around a 75% reduction. Across the entire range of engine operation, the EI_M varied around the average value, with the minimum (14.0 mg/kg) and maximum (42.9 mg/kg) values occurring at fuel flow rates of 26 kg/h (10% of maximum thrust) and 89 kg/h (70% of maximum thrust), respectively.

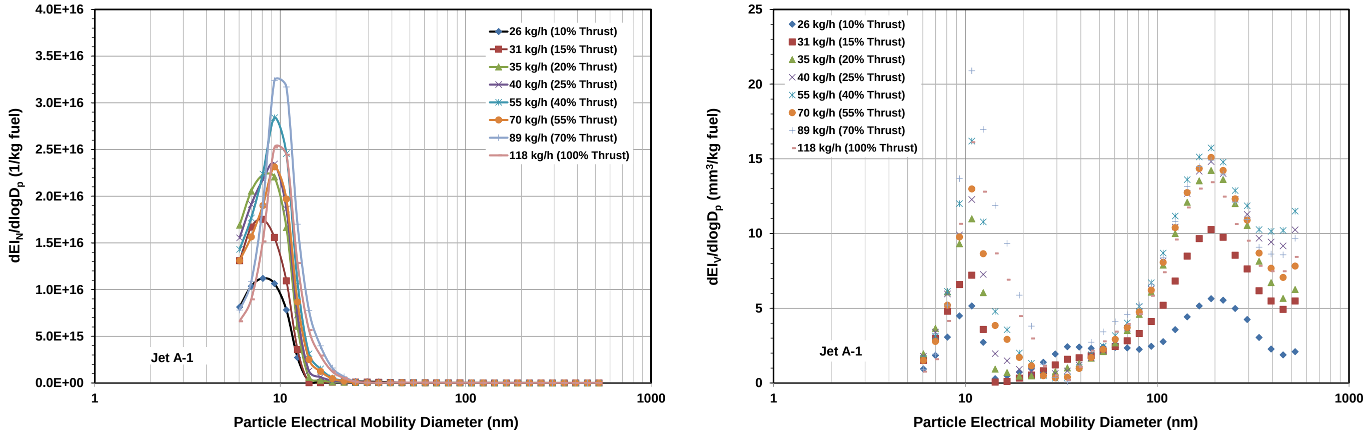
The shape of the characteristics presented in Figures 1 and 2 (specifically the decrease in the EI_N and EI_M indices for a fuel flow rate of 70 kg/h) is related to the engine's operating characteristics. Thus, a wavy shape is observed regardless of the type of fuel used. The authors attribute the reason for this similarity to the characteristics of the compressor's operation.

3.2. Particle Size Distribution

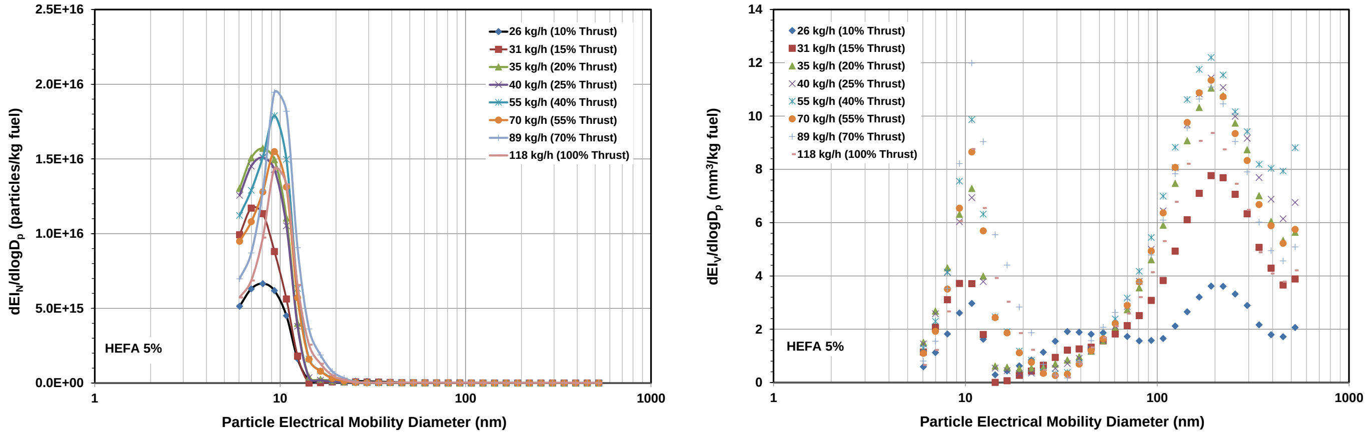
The data collected using the EEPS were averaged for identical fuel flow rate settings and then converted into differential number-based ($dEI_N/d\,logD_p$) and differential volume-based ($dEI_V/d\,logD_p$) particle size distributions. Figure 3 illustrates the representative plots of $dEI_N/d\,logD_p$ and $dEI_V/d\,logD_p$ for various fuel flow rates (with thrust additionally indicated) using the DGEN 380 engine while burning Jet A-1 (Figure 3a,b), HEFA 5%–Jet A-1 blend (Figure 3c,d), HEFA 20%–Jet A-1 blend (Figure 3e,f), and HEFA 30%–Jet A-1 blend (Figure 3g,h). The particles generated through the nucleation mechanism predominantly contribute to PM emissions. Consequently, number-based PSDs exhibit a single-mode log-normal distribution.

Particle size distributions indicate that, for all examined fuels, the majority of the particles were in the range of 5–30 nm. PSDs did not indicate the presence of particles larger than 100 nm. Increasing fuel flow did not significantly affect the diameter of formed particles; however, it did influence the number of emitted particles. In most cases, increasing engine thrust resulted in the generation of a greater number of particles. It was observed that increasing the proportion of HEFA fuel helped reduce the emission of particulate matter. This suggests that HEFA fuel has a positive impact on the emission parameters of particulate matter.

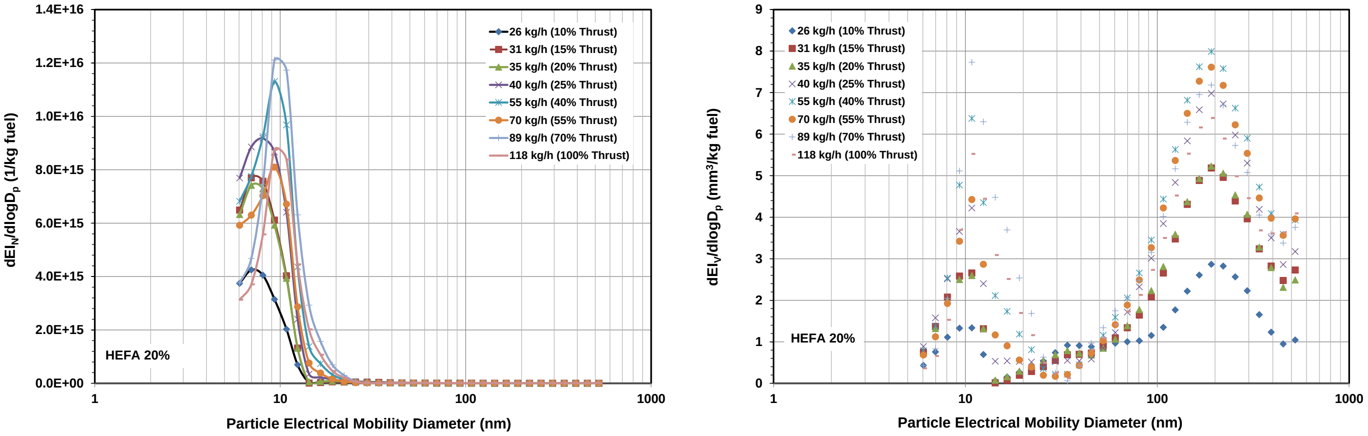
An analysis of volume-based PSDs indicated that particles with diameters above 100 nm had a noticeable impact on the emitted volume of particles. Although these particles constituted a very small number (not visible in EI_N PSDs), their larger size significantly affected the total volume. Volume distributions exhibited a bimodal character, with characteristic diameters around 10 nm and 200 nm. There was no clear influence of engine thrust on EI_V PSDs. For all the examined cases, the shape of the characteristics was similar, differing only in amplitude and maximum values, suggesting that increasing the proportion of HEFA fuel led to a reduction in the EI_V values in each studied scenario.



(**a**) EIN PSD for Jet A-1 (**b**) EIv PSD for Jet A-1

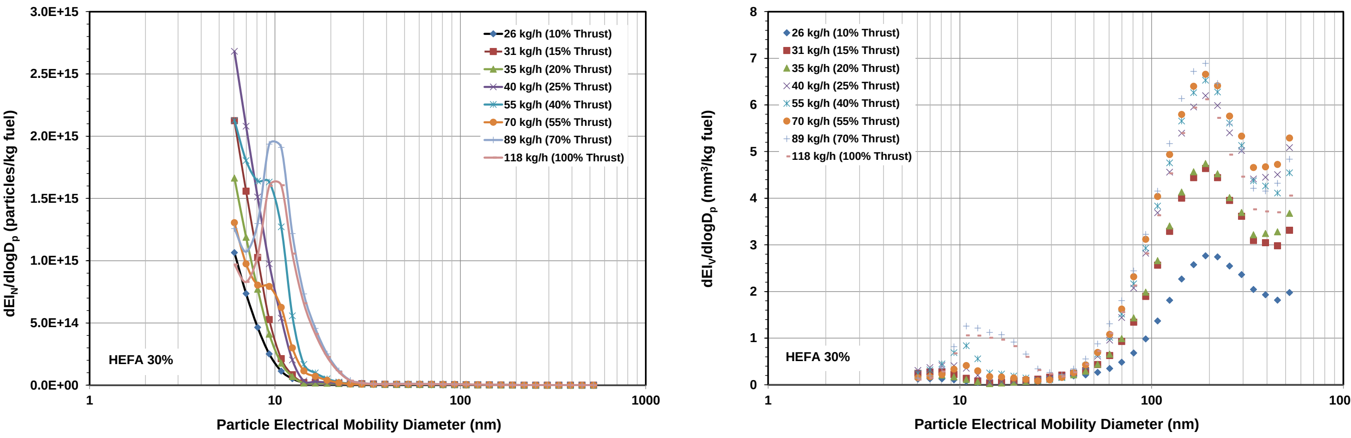


(**c**) EIN PSD for HEFA 5%–Jet A-1 blend (**d**) EIv PSD for HEFA 5%–Jet A-1 blend



(**e**) EIN PSD for HEFA 20%–Jet A-1 blend (**f**) EIV PSD for HEFA 20%–Jet A-1 blend

Figure 3. *Cont.*



(**g**) EI$_N$ PSD for HEFA 30%–Jet A-1 blend (**h**) EI$_V$ PSD for HEFA 30%–Jet A-1 blend

Figure 3. Differential Particle Number Emission Index (EI$_N$) and differential Particle Volume Emission Index (EI$_V$) PSDs for DGEN 380 burning Jet A-1 (**a**,**b**), HEFA5%–Jet A-1 blend (**c**,**d**), HEFA20%–Jet A-1 blend (**e**,**f**), and HEFA30%–Jet A-1 blend (**g**,**h**). Engine operating point is expressed as both fuel flow and percent rated thrust.

4. Discussion

The provided data indicate a decrease in PM emissions with the utilization of the biocomponent. To assess the extent of change for both the EI$_N$ and EI$_M$, the average percentage change was calculated concerning Jet A-1 fuel, as illustrated in Tables 3 and 4. The median values for each fuel type, determined across all engine thrust levels, were also computed. As depicted in Tables 3 and 4, the reduction amount is influenced by both the proportion of the biocomponent and the engine's thrust.

Table 3. The average change in emission index relative to Jet A-1 at different engine thrusts for particle number. Also shown are the median values.

Fuel Type	Thrust (%)								Median
	10	15	20	25	40	55	70	100	
HEFA 5%	−0.396	−0.364	−0.292	−0.338	−0.341	−0.322	−0.384	−0.410	−0.352
HEFA 20%	−0.648	−0.570	−0.691	−0.592	−0.581	−0.630	−0.612	−0.635	−0.621
HEFA 30%	−0.946	−0.927	−0.958	−0.924	−0.923	−0.950	−0.922	−0.917	−0.926

Table 4. The average change in emission index relative to Jet A-1 at different engine thrusts for particulate mass. Also shown are the median values.

Fuel Type	Thrust (%)								Median
	10	15	20	25	40	55	70	100	
HEFA 5%	−0.323	−0.306	−0.249	−0.312	−0.300	−0.283	−0.391	−0.417	−0.309
HEFA 20%	−0.602	−0.540	−0.651	−0.576	−0.544	−0.569	−0.585	−0.596	−0.580
HEFA 30%	−0.775	−0.727	−0.795	−0.741	−0.763	−0.731	−0.767	−0.750	−0.757

The use of HEFA fuel had a positive impact on particle emissions. In the case of the particle number index, even a 5% share of HEFA fuel in the blend with aviation kerosene led to a reduction in the EI$_N$ by up to 40% (the median result for the entire engine operating range was −35%). Increasing the share of SAF to 30% resulted in over a 90% reduction in the EI$_N$ index, which is a remarkable result. Similar effects were observed for the particulate mass index. The use of 5% HEFA yielded excellent results, reducing the EI$_M$ by up to 40% (median result −30%). A higher proportion of SAF further contributed to the engine's ecological properties. In the case of using HFA30% fuel, a reduction of over 70% in the EI_M was achieved compared to an engine fueled with aviation kerosene.

Other publications have also demonstrated a positive impact on the emission indices of particulate matter from aircraft engines fueled by HEFA [26,27]. Based on the information presented in Tables 3 and 4, it can be inferred that the decline in both the number and mass of particles becomes more significant with an increasing proportion of SAF. This correlation has been previously documented in experiments in a diffusion flame of a burner [28] and for real engines [29,30]. The alterations in non-volatile EI_N and EI_M are attributed to the decrease in sulfur content and aromatic compounds within the blend. Additionally, the rise in the hydrogen proportion in the fuel plays a role in diminishing particulate matter formation in the soot mode. A reduction in the aromatic content leads to an elevation in the H/C ratio [31–33]. This research indicates that the use of SAF allows for a significant reduction in soot emissions, which is crucial in terms of the EI_M. Some fuels excel in this regard, with examples being HEFA and FT-SPK [30,34].

The presented research pertains to the non-volatile fraction of particulate matter. SAF is an excellent solution for reducing particle emissions. However, it is essential to consider the volatile fraction of particulate matter in the case of aircraft engines. There are analytical models available for estimating the vPM, but they are based on emissions from engines fueled with aviation kerosene [35]. As the authors, we believe that further research on emissions from aircraft engines powered by SAF is necessary to collect data that facilitate the improvement or development of new models for vPM emissions.

5. Conclusions

In light of ongoing climate change and the adverse impact of transportation on air quality, activities that mitigate the environmental impact of aviation are recommended. One way to enhance the ecological properties of aircraft is through the use of SAF. The introduction of SAF is strongly supported and even mandated by the European Union's policies, exemplified by initiatives like the Refuel EU program. The presented research results lead to the following conclusions:

- HEFA fuel significantly reduced particle emissions from the jet engine; a 5% share of SAF in a blend with aviation kerosene yielded distinct positive effects on both the number and mass of particles.
- Future research directions should focus on exploring the relationships between physicochemical parameters and exhaust emission. This exploration can facilitate the optimization of SAF production with a focus on minimizing exhaust emissions.
- The empirical data collected during SAF experiments can be utilized to develop analytical models for estimating the volatile fraction of particulate matter emissions.

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Conflicts of Interest: The authors declare no conflicts of interest.

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