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Title: Regulatory gaps in nvPM and non-CO2 aviation-emission standard under SAF adoption pathways

Regulatory gaps in nvPM and non-CO2 aviation-emission standard under SAF adoption pathways

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Abstract**—***Non-Volatile Particulate Matter (nvPM) emission requirements in the aviation industry are examined in depth in this dissertation. The research analyses the present available technologies to measure the number concentration as well as the mass of aerosol particles in order to compare it with the aircraft emissions. Equipment's like SMPS, ELPI+ and DMS-500 have been discussed briefly in the dissertation. It also analyses the present regulations and determines if they are still appropriate in light of future developments such as incorporation of upcoming technology and sustainable aviation fuels. Along with regulations, it has also been highlighted that how important it is for the government, policy makers and other stakeholders to come together and deal with the issue of nvPM emissions, its measurement and its reduction. The objective is to learn how these technological advances might be maximized in the aviation industry to reduce nvPM emissions. Technologies like SAFs have been discussed in this paper. This research is a step towards a more ecologically responsible and sustainable aviation sector.*

Index Terms**—***Non-volatile particulate matter (nvPM); aircraft emissions; SMPS; DMS-500; ELPI+; ICAO regulation; sustainable aviation fuels (SAF); aviation environmental policy.*

I. INTRODUCTION

Continued growth in the aviation sector in terms of development and scalability has made it a major topic to be studied closely. Just as other forms of transportation like railways, shipping etc., aviation is one of the most energy intensive sectors in the world, at present (Gossling et.al., 2020). Just as it makes the world more connected by reducing the time required to travel from one place to another, it contributes approximately 11% to the emissions from the transportation sector. With increased efficiency in the aircraft and operations and the resultant lower cost affording unprecedented access and connectivity to more people and even the remote areas. Therefore, these emissions are expected to increase further with a growth of 3-4% each year in the sector (ICAO). For example, in India, the number of passengers has grown from 1.2 billion in 1990 to 4.5 billion in 2019. This is quite significant in a country like India where the domestic air passengers have grown from 7 million in 2000 to over 141 million in 2019, which is twenty-fold increase in less than two decades (DGCA, Aviation ministry, India). However, this trend was disturbed globally with the onset of COVID-19 pandemic. COVID-19, mid 2020, had led to the reduction in the scheduled flights and revenue passenger kilometers (RPK) by 50% (ICAO, 2020). The industry is expected to rebound and return to its original trajectory in the coming times which would lead to the increased emission and conflicts with decarbonization goals (Larsson et.al., 2019). Therefore, there is a need to strike a balance between growth of aviation industry and emissions.

With the increased awareness about the emissions and its harmful environmental and health effects, there has been a demand from the industry to make it into a sustainable industry. Several international platforms such as Kyoto protocol has assigned the emissions limitation responsibility from the aviation sector to the International Civil Aviation Organization (ICAO) (UN, 1998). ICAO Annex 16 deals with international standards recommended practices related to environmental protection in civil aviation where Volume I deal with noise from the aircraft, Volume II includes the Standards and Recommended Practices (SARPs) on HC, CO, NOx, smoke and nvPM and Volume III deals with CO2 emissions.

The impact of Particulate Matter emissions from the aircraft contributes to the concentrations of ultrafine particles in and around airports together with other combustion sources including traffic from roads (Owen et.al., 2022). PM are the tiny particles with mean diameters of less than 0.1 µm and hence a hazard.

This chapter aims at developing an understanding about the fundamentals and formation of PM, its harmful effects on the health and environment, a thorough analysis of the present policies in place and therefore, the need to improve them further.

A. Emissions from the Aircraft Engine

Just like any other engine, which produces energy due to combustion, aircraft engines also produce energy due to combustion. In the whole process, engines emit harmful pollutants into the atmosphere which are harmful for the environment as well as for the human health. The main pollutants emitted are in the form of NOx (NO2 and NO), unburnt hydrocarbons, CO, Sulphur oxides, Particulate Matter and other trace compounds. The pollutant emissions from the aircraft engines are highly influenced by the flame temperature in the primary combustion zone (Liu et.al., 2017). This combustion is influenced by the air-fuel ratio (AFR). When there is rich combustion, solid carbon and emissions of unburnt hydrocarbons, CO and soot is produced. Huge quantities of NOx is produced under stoichiometric conditions where enough air is supplied. Lean combustion happens when huge quantities of air is supplied (Durand, 2019).

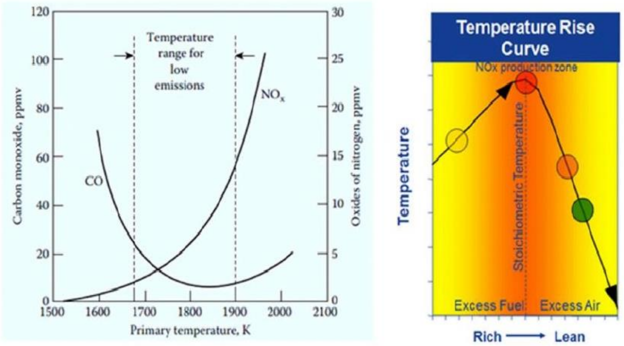


Fig. 1. NOx and CO emissions vs primary temperature and temperature vs AFR. Source: Yize Liu, et.al., 2017.

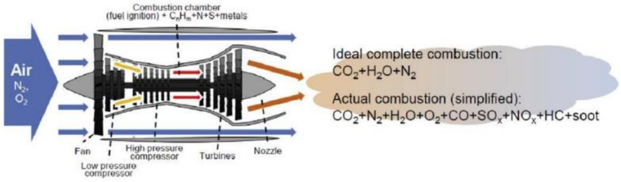


Fig. 2. Aircraft turbofan engine with combustion products. Source: Durand, 2019.

This paper focuses on the Particulate Matter emissions from the gas turbine engine in general which has potential harmful effects on the health and environment. PM emissions from the aircraft engines are the result of incomplete oxidation of soot formed during the combustion of hydrocarbon fuels (Saffaripour et.al., 2020). PM are of different sizes Studies show that PM consists of volatile and non-volatile fraction which are known as elemental carbon and organic carbon, respectively.

The adverse health impacts of PM are those in the range of median aerodynamic diameter <2.5 µm (PM2.5) and <10 µm (PM10). Lower the aerodynamic diameter, adverse the health impacts.

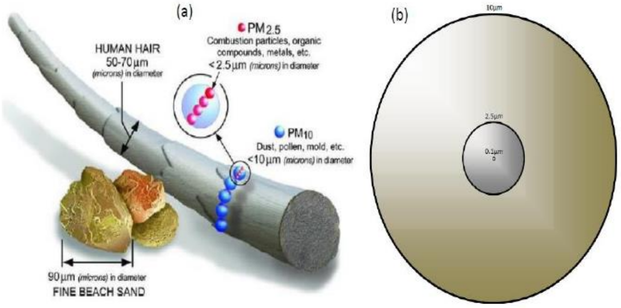


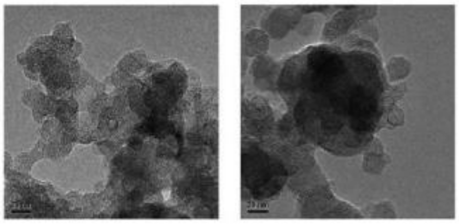
Fig. 3. Illustration of PM size in comparison to human hair (a) and visual representation of major particle sizes used for classification of PM (b). Source: Durand, 2019.

This study focuses on the nvPM emissions in particular due to their small size, which makes it difficult to quantify and thus difficult to regulate. nvPM are the emissions from the aircraft gas exhaust which do not volatilize at 623K and consists mainly soot (ICAO).

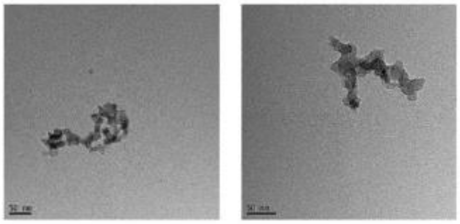
B. The Makeup of Non-Volatile Particulate Matter (nvPM)

As previously mentioned above, nvPM are the emissions which are solid at the engine exit plane and that do no volatilize when heated at higher temperatures like 623K (Saffaripour et.al., 2020). In order to better understand the impacts of nvPM on health and environment, it's important to understand its aggregate structure. When studied through Transmission Electron Microscopy (TEM), nvPM generally consists of branch like fractal aggregates of multiple nearly spherical primary particles.

(a) 4–7% full thrust (b) 100% full thrust



(c) 70 shp (d) 770 shp



(e) 30% full thrust (f) 100% full thrust

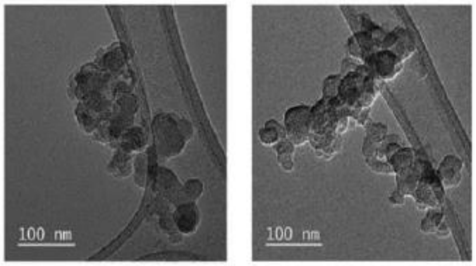


Fig. 4. The aggregate structure of nvPM characterized using TEM imaging for particles emitted at different thrust levels and power settings. Source: Saffaripour et.al., 2020.

Aggregate structure of the nvPM emissions from the engines depends on the power of the engine. Generally, higher engine power promotes the formation of compact aggregates whereas lower engine power leads to the formation of branched aggregates (Marhaba et.al., 2019). These aggregate structures play a major role in determining nvPM’s effect on health and environment.

C. Particulate Matter Impact on Environment

Particulate matter emission from the aircraft gas turbine engines results in the concentration of ultra-fine particles into the atmosphere along with emissions from different sources of traffic, which in turn affects adversely the local air quality of the region. Environmental contamination and exposure of humans to the PM pollution has drastically increased in the last decade (Rai, 2016). This is very much true for the developing countries like India. The presence of PM pollutants in urban areas have made considerable changes in the morphology and chemistry of plants (Agrawal and Agrawal). Not only plants, it also impacts the climate and cloudiness in the region (Owen et.al, 2022).

“Radiative forcing” is used to describe the impact of pollutants from the engine exhaust in terms of positive and negative effect. Positive refers to warming effect and negative refers to the cooling effect (Durand, 2019). Phenomenon like scattering and absorption of solar radiation contributes to the warming and cooling of the atmosphere. Not only PM, but CO2 released into the atmosphere leads to the GHG effect, NOx interacting with oxygen leads to ozone depletion and presence of sulphur leads to acid rain.

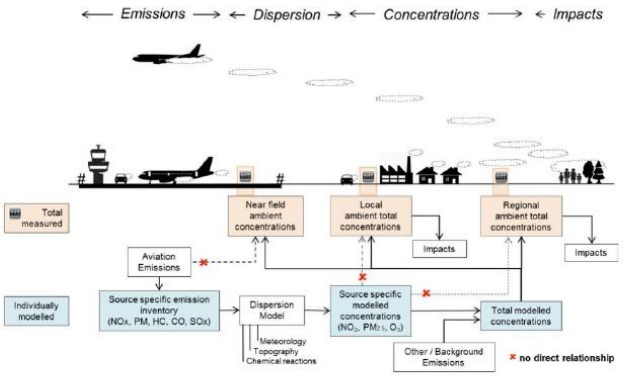


Fig. 5. Schematic presentation of emissions, dispersion, concentrations and impacts with their interaction at airport level. Source: ICAO environmental report (2016).

Morphological characters of the PM particles determine its impact on the atmosphere (Durand, 2019). For example, freshly generated soot particles consist of hydrophobic spherical primary carbonaceous particles forming fractal aggregates (Durand, 2019). On the other hand, with time, volatile matter condenses into soot which increases their hygroscopicity and thereby, increases their ability to act as a cloud condensation nucleus (Surawski et.al., 2012).

D. Impact of PM on Health

The adverse health impacts of nvPM including PM2.5 and PM10 are of concern for the national and international government, organizations and various communities. Clinical and epidemiological studies have shown that short- and long-term exposure to the PM with a diameter of <10µm leads to increased respiratory problems, pulmonary diseases and cardiovascular diseases (Byeong-Jae Lee et.al, 2014).

Particles of different sizes get deposited at different areas of the body. For example, particles ranging between 10-100 nm gets deposited at alveolar part of the lungs (Nemmar et.al, 2002). Most importantly, fine and ultra-fine particles, PM0.1, can have severe effects as they can enter directly into the systemic circulation.

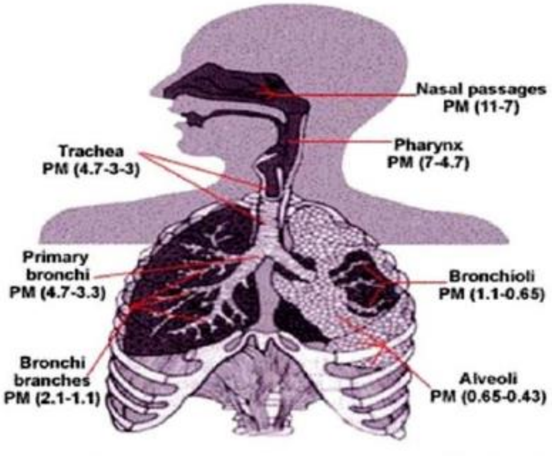


Fig. 6. Deposition potential for particles of varying sizes. Source: Londahl et.al., 2006.

It has been reported that 3.7 million deaths in 2012 were due to the ambient air pollution (WHO), representing 6.7% of total deaths worldwide and was the cause of 11% of chronic obstructive pulmonary disease related death, 16% of lung cancer deaths, 29% of heart disease and stroke and approximately 13% deaths due to respiratory infection (B.-J. Lee et.al., 2014).

As per the 2005 guideline level of WHO, annual mean air quality guideline for PM2.5 was 10µg/m3. This has now been updated in 2021 to 5g/m3 in response to the increases in the quality and quantity of evidence air pollution impacts (Pollution action note, UNEP, 2023). This paper further understands the need to study the regulations in place for Particulate Matter (PM) as they have serious impacts on the ecology as a whole.

E. International PM Regulation

International Civil Aviation Organisation (ICAO) has been assigned the responsibility to limit the emissions from the aviation sector at the global level. It develops policies and standards, undertakes compliance audits, performs analysis and studies, and builds aviation capacity through many other activities in cooperation with its member states and stakeholders. Currently, ICAO has 193 member states out of which 36 member states form the governing council. United Kingdom is one of the members of ICAO. A technical committee known as Committee on Aviation Environmental Protection (CAEP) has been established by ICAO to develop international standards and improving the methods of regulating PM emissions (Durand, 2019). CAEP came into force since the beginning of 1990s and the last 3 years cycle came up in 2019. ICAO, Annex 16 prescribes with international standards recommended practices related to environmental protection in civil aviation. It has three volumes:

- Volume I: details with aircraft noise
- Volume II: details with emissions from the engine. It includes the Standards and Recommended Practices (SARPs) on HC, CO, NOx, smoke and nvPM. It focuses on emissions below 3000 feet in order to manage the Local Air Quality (LAQ) near the airports.
- Volume III: describes aeroplane CO2 emissions

Therefore, current regulations and recommended practices for the emissions from the aircraft gas turbine can be found in Volume II of Annex 16, ICAO. Due to the presence of hostile conditions in the exhaust of aircraft gas turbine, measurement of nvPM is very difficult. The particles from the exhaust need to be diluted, cooled down and conditioned appropriately to be analyzed by the instruments. In this whole process, there is significant loss of nvPM particles which makes it necessary to have standardized sampling system to keep a track of nvPM emissions from the aircraft.

Fig. 7. From smoke number standard to the new nvPM standard. Source: ICAO environmental report, 2016.

Figure 7 shows that until 2020, the level of smoke from the engine exhaust was based on the reflectance on the filter paper (smoke number). This technique gives no indication of PM size, number or mass. Therefore, standardized regulations should be in place in order to quantify the nvPM and thereby, try to reduce them.

The first proposal for the ICAO particulate standard were made in 2008 and got agreed in CAEP 8th meeting. It is with the efforts of swiss company, SR Technics, NASA led Aviation Alternative Fuels Experiment -II (AAFEX-II) that the tests were conducted and got published in Aerospace Information Report (AIR 6241) in 2013 (ICAO, Environmental report). AIR 6241 report specifies the standards for the nvPM sampling and measurement system.

ICAO in its 10th CAEP meeting introduced Standard and Recommended Practices (SARPs) for nvPM sampling and measurement standards in terms of mass and number for the aircraft with maximum thrust >26.7 kN (Corbin et.al., 2022). CAEP/10 nvPM standard mandates the reporting of following:

- The fuel flow at each thrust setting of the certification land and take-off cycle (LTO) (i.e. thrust).
- The nvPM mass and number emission indices for the four LTO points.
- Maximum nvPM EI mass
- Maximum nvPM EI number
- Maximum nvPM mass concentration.

It should be noted that we do not have any established SARPs for volatile Particulate Matter or total PM, which also have significant environmental impacts.

F. Research Motivation

PM emissions from the aircraft engines contributes negatively to the environment and health. As per the ICAO regulations, there is a need to standardize the sampling and measurement methodology in order to determine the number concentration and mass concentrations. This is due to the fact that while measuring the PM there is a lot of loss of particles which hampers the accuracy of number and mass concentrations.

The main motivation is to analyze the available technologies and understand why there is a need to come up with the better technologies. Along with that, it is also important to examine the policy frameworks in place and scope of future technologies such as SAFs. Therefore, it is important to reduce the emissions with a mix of policies, regulations and technologies.

II. OBJECTIVES OF THE STUDY

1) Critically assess existing regulatory requirements for nvPM (non-volatile Particulate Matter) to determine where there are strengths, flaws, and gaps in the aviation industry.
2) Technology Compatibility and Future Prospects Examine how well existing regulations mesh with new developments in the field, such as lean burn methods and innovative approaches to lowering emissions.
3) Instrumentation for Measuring Emissions To identify best practices and opportunities for development in nvPM emissions evaluation, compare and contrast the various emission measuring instruments.

III. METHODOLOGY

A. Laboratory Facilities

Research based facilities in the Cardiff University were used to conduct the tests for this project. This chapter discusses the instruments and sampling systems available to measure the nvPM from the aircraft engines.

B. Overview of ICAO-Compliant nvPM Measurement System

ICAO has standardized the nvPM sampling and measurement system for accurate reporting and comparison from aircraft engines. This project briefly discusses about the EASA reference system which consists of five sections. Figure 8 shows that section 1 consists of collection part which consists of sampling probe and short sampling lines with length ≤8 m. Section 2 to section 4 is the transfer section. This section includes a diluter to dilute the sample, a 25 m long stainless steel or carbon loaded electrically grounded polytetrafuoroethylene (PTFE) tube and a cyclone as separator (M. Saffaripour et.al., 2020). Commonly used diluters use synthetic air or nitrogen. There are various reasons why dilution is important. Those are i) to avoid the collection of particles ii) cool down the aerosol particles while avoiding the thermophoretic losses iii) keeping the aerosol particles dry so that they do not condense into particles and iv) ensures missing of particles. The major usage of cyclone is to separate the particles greater than 1 µm. Section 5 consists of instruments to measure the mass and number of nvPM. Measurement section is briefly described below.

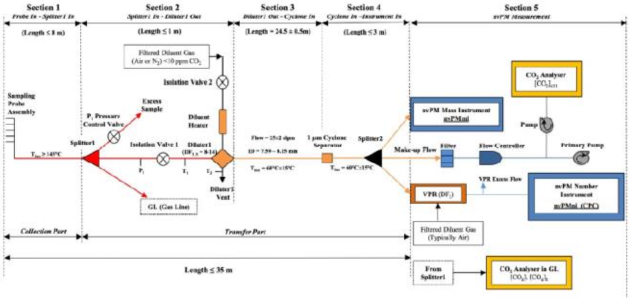


Fig. 8. Overview schematic of an nvPM sampling and measurement system. Source: ICAO nvPM annex 16.

nvPM Number Measurement

The ICAO complaint apparatus for measuring number consists of Volatile Particle Remover (VPR) and n-butanol Condensation Particle Counter (CPC) in series. Since it's not possible to completely eliminate the volatile particles from the sample, therefore, VPRs are used. The temperature for heating is maintained at 350° C ± 15° C so that the volatile particles are evaporated. The dilution helps in maintaining the particle number concentration within the CPC count mode (Durand, 2019).

There are multiple ways by which the samples can be lost such as diffusion, thermophoresis, inertial deposition etc.

nvPM Mass Measurement

nvPM mass is defined as equivalent to the elemental carbon as per the standardized measurement system of ICAO. Thermal Optical Transmittance (TOT) method is to be used as the measurement reference method when it comes to measuring mass of nvPM (ICAO). It needs to be insensitive to the volatile PM.

C. Testing Apparatus

The apparatus includes the following instruments:

1) Aerosol Generator ATM 226 (TOPAS):

For the purpose of this report, an aerosol generator is used as an alternative to PM particles from gas turbine engine from aircraft. Its purpose is to generate nanoparticle aerosols from the liquid as per the international standards. The size of aerosol particles generated from ATM 226 range from 5 and 30 nm, which makes it suitable for laboratory experiments. The aerosol generation technique used in this report is nebulization of a solution. Nebulization necessitates atomization of liquid solution containing solid nanoparticles (Durand. 2019). A nebulizer, also known as an atomizer, creates tiny droplets that contain particles that evaporate quickly in a "dry" carrier gas, causing the particles to be carried in the gas flow. Evaporation can be done by furnace, a membrane drier, or by keeping the carrier gas below its saturation point for the respective liquid used as a solvent.

2) HEPA (High Efficiency Particulate Air) Filter (CAPSULE):

HEPA filter is used to filter the air to be used for the experiment. The filter used had maximum operating pressure of 3.4 bar and 21° C. Along with that, it had maximum operating temperature of 88° C.

3) Splitter:

It separates the sample into three to be transported to the different instruments such as DMS 500, Grimm SMPS and ELPI+. It is to be noted that the particle loss for the instruments after splitter is negligible in the measurement set up. This is because the length of the silicon tube (carbon coated) is almost the same. Also, the initial transfer is done via stainless steel pathway which acts as a very good conductor of electricity.

4) Three Instruments: DMS 500, Grimm SMPS, ELPI+:

Size measurements were carried out using these three instruments. DMS 500 and SMPS work on the basis of electric mobility diameter whereas ELPI + is based on the aerodynamic diameter.

D. DMS 500 and Grimm SMPS

DMS stands for Differential Mobility Spectrometer which permits the measurement of particles ranging from 5 nanometers to 2.5 microns with 200 ms response time with a frequency of 10 Hz. It combines electrical mobility classification of particles with sensitive electrometer detectors giving output of particle size and number distributions in real time. DMS 500 has a cyclone and a restrictor. Cyclone is present at its inlet prevents the micron size particles from contaminating the readings. Restrictor, on the other hand, controls and optimizes the sample flow and particle size selection.

DMS 500 measures the particles on the basis of electrical mobility theory. Particles are classified on the basis of differing electric mobility when placed in electric field. Aerosol particles pass through electric field and acquire charge which is directly proportional to their surface area. Particles are moved towards the classifier section which is positively charged high voltage electrode at the center. Since particles are already positively charged, they are repelled and moved towards the electrode rings which are known as detectors. Smaller particles get collected on the initial rings whereas larger particles move further and gets collected towards the later rings' detectors (Bokor et.al., 2020). Each detector measures the charge of total particles collided to it. Therefore, 22 detector rings together form a size distribution of the sample aerosol particles through a calibration inversion.

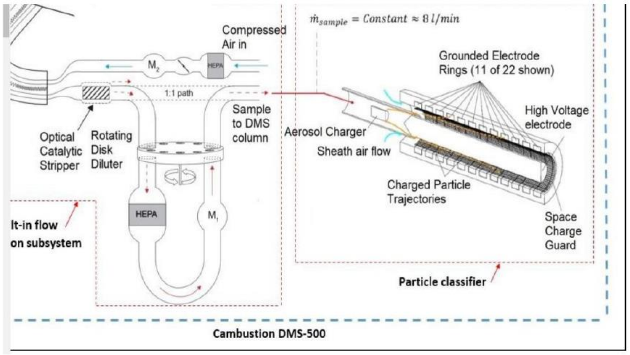
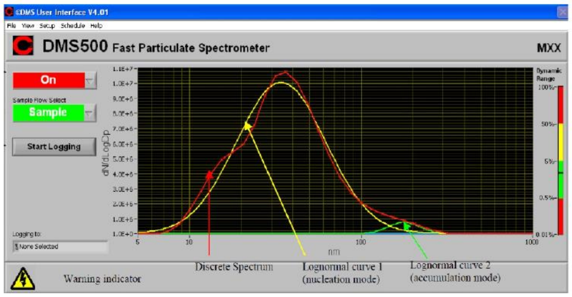


Fig. 9. Cambustion DMS-500. Source: B Rohani et.al., 2021.

DMS 500 measures the sample of aerosol particles and outputs the size distribution and number concentration along with GMD and GSD derived from dN/dlogdp.



Sample Flow Select: Sample

Logging to: None Selected

Fig. 10. Screenshot of the DMS-500 user interface displaying the measurement of a bi modal size distribution. Source: Durand, 2019.

SMPS stands for Scanning Mobility Particle Sizers. It is designed to measure the aerosol particles of size 5 – 1110 nm. It consists of Condensation Particle Counter (CPC) and Differential Mobility Analyzer (DMA).

Particles of different sizes are classified with a DMA. Larger particles are removed by an impactor at the inlet of the DMA. Electric field is created between the inner and the outer electrodes of DMA.

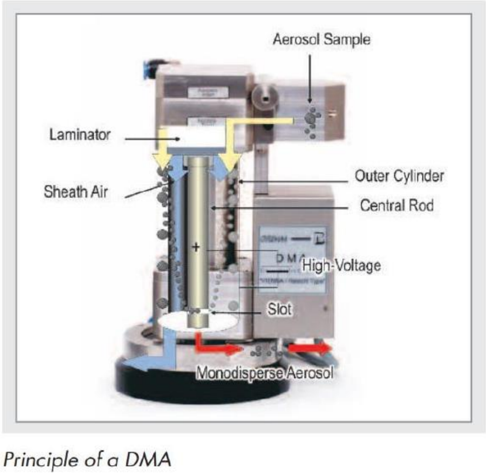
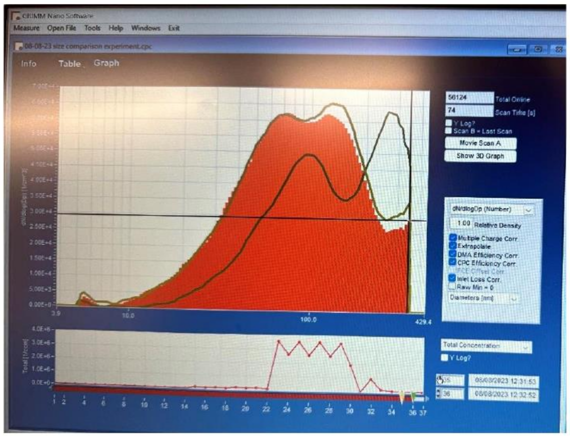


Fig. 11. Principle of a Differential Mobility Analyzer (DMA).

When the positive voltage is applied on inner electrode, negatively charged particles in the air drift towards the inner electrode. Since smaller particles have higher mobility, they travel further than the larger particles. Therefore, different sized particles reach at different length. The final size distribution of particles can be measured by a step wise change of the DMA voltage.



56124 Total Online
74 Scan Time [s]
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35 08/08/2023 12:31:53
36 08/08/2023 12:32:52

Fig. 12. Shows the number and size concentration from Y and X axis respectively.

E. Dekati ELPI+

ELPI stands for Electrical Low Pressure Impactor. It measures the size distribution and concentration of aerosol particles within the aerodynamic size range of 6 nm to 10µm with a sampling rate of 10 Hz.

In ELPI+, particles are classified into 14 size fractions in a cascade impactor. Its operating priniciple can be divided into three stages: i) particle charging ii) inertial size classification in the cascade impactor iii) electrical detection of particle charge with sensitive electrometers. The size of the particles is according to their aerodynamic diameter. Larger particles get collected at the upper stages whereas the smaller particles get collected at the lower stages of the impactor. All the stages of impactor are insulated from each other, along with that, each impactor is connected to the electrometers where the charges are detected.

The measured current signal is directly related to the number of particles. Therefore, enables the ELPI+ to measure the aerosol particle number size distribution and concentration in real time.

F. Test Points for the Experimental Set Up

This report has considered 5 test points for each instrument (DMS 500, SMPS & ELPI+). Those are described below:

- Test point 1: it is taken as zero and all the test point are in reference to test point 1.
- Test point 2: water was added to the nebulizer and readings were recorded on the three instruments.
- Test point 3: NaCl was added to the nebulized water. It can be used as a test aerosol as polydisperse aerosols which have electric charges. Thus, can be passed through membrane dryer where the moisture from water is removed from aerosol stream by the process called atomization (Leung, 2022). NaCl produces cuboid nanoparticles.
- Test point 4: DEHS (Di-Ethyl-Hexyl-Sebacat) was used in the nebulizer for this test point. DEHS is convenient to use in the experiment as the droplets have low vapor pressure. Due to which, they take longer lifetime. DEHS produces spherical nanoparticles which is useful for the measurements between 10-100 nm bracket.
- Test point 5: DEHS was used in the nebulizer and the flow was increased.

Readings from all the instruments were collected at the same time to allow the right comparison of the data.

IV. RESULTS AND ANALYSIS

A. Results from DMS 500 and SMPS

For all the test points, the DMS 500 and SMPS reported values Geometric Mean Diameter (GMD), Geometric Standard Deviation (GSD) and number concentration (Ntot) for the purpose of this report. This section aims to compare the readings from the two instruments and analyze the variation, if any.

TABLE I. READINGS FROM 5 TEST POINTS FOR SMPS AND DMS-500

TP	Particle Type	SMPS GMD	SMPS GSD	SMPS Ntot	DMS GMD	DMS GSD	DMS Ntot
TP1	Zero	0	0	0	0	0	0
TP2	Nebulised water	15.5	1.61	9.33E+04	12.3	1.46	1.37E+04
TP3	Nebulised NaCl	35.0	2.02	2.39E+06	32.7	2.13	3.21E+06
TP4	Nebulised DEHS (low flow)	126.1	2.00	3.35E+05	130.2	2.19	8.22E+05
TP5	Nebulised DEHS (high flow)	120.2	2.09	3.84E+04	133.3	2.24	7.71E+04

Table I shows that there is a huge variation between the GMD derived from the two instruments when nothing is placed in the nebulizer. At the same time, the point was supposedly zero as a way to check zero. So that next test points are calculated with reference to this point. This seems like a discrepancy in the experimental setup or the instruments' readings.

Discussion: this discrepancy can be due to the presence of the particles from the last experiment conducted. Therefore, we clean the se up and measure again until it comes as zero.

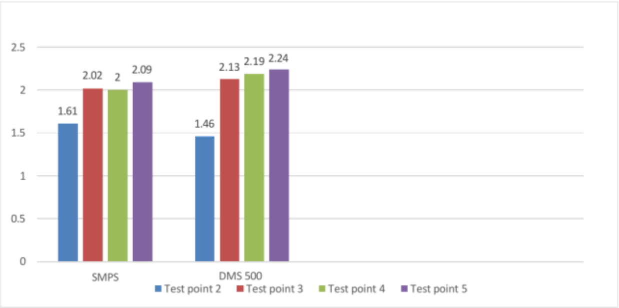

Fig. 13. Comparison between GSD of different test points.

Figure 13 shows that for the rest of the four points the values of SMPS and DMS 500 are quite similar. However, DMS-500's values show more GSD than the SMPS for all the test points.

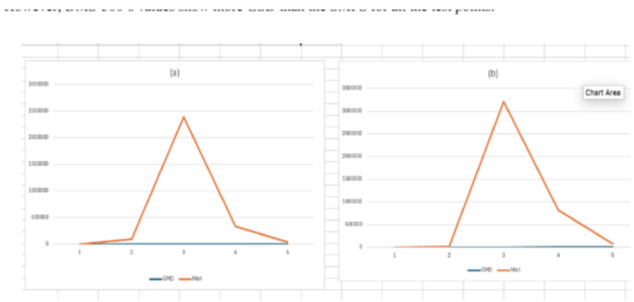

Fig. 14. GMD (nm) vs Number concentration for SMPS (a) and DMS-500 (b).

Figure 14 shows the relation between GMD and Ntot for SMPS and DMS-500. The figure shows there is a correlation between GMD and Ntot in both the instruments. Therefore, with the increase in GMD there is an increase in Ntot. This figure also indicates that DMS is more suitable to measure particle size much larger in size as compared to SMPS. However, they both are not suitable to measure the particle size beyond certain limits.

B. Number Concentration vs Mobility Diameter

Test point 1: zero point (reference point) wherein no solution was added for the test.

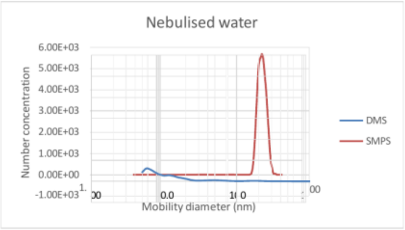

Fig. 15. Number concentration vs mobility diameter for nebulized water.

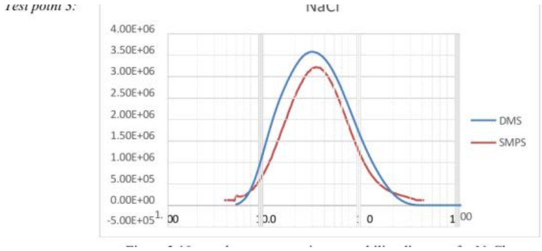

Fig. 16. Number concentration vs mobility diameter for NaCl.

Test Point 4 & 5:

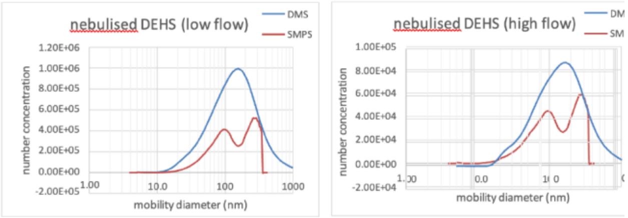

Fig. 17. Number concentration vs mobility diameter for DEHS at low flow rate and high flow rate.

C. Number Concentration in Real Time Using ELPI+ Across 5 Test Points

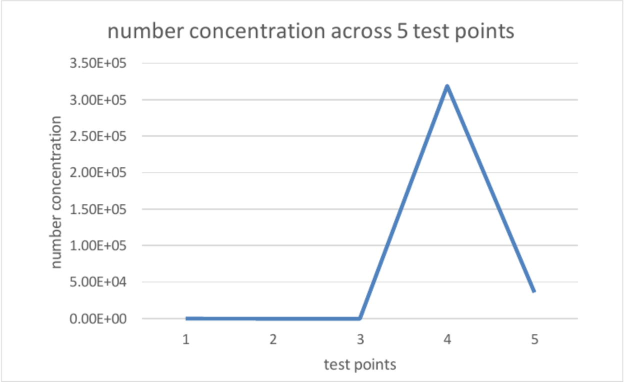

Fig. 18. Number concentration across all 5 test points (ELPI+).

Analysis

Figure 13 represents the GSD from four different test points. First test point has been ignored as no sample has been taken at test point 1.

Test point 2 (Figure 13) contains nebulized water. SMPS shows GSD of 1.61 whereas DMS-500 shows GSD of 1.46. however, the different is not major (0.15 GSD). It has been noted that the overall values from both the instruments are much lower as compared to other samples.

Test point 3 (Figure 13) contains NaCl. The GSD for NaCl in SMPS is 2.02 whereas in DMS-500 is 2.13. However, the test point shows the difference of 0.11 GSD for the same solution.

Test point 4 (Figure 13) contains DEHS solution to test for the aerosol particles at low pressure. Value for GSD for DEHS sample is 2 whereas from DMS-500 is 2.19. the difference between the GSD readings is 0.19.

Test point 5 (Figure 13), contains DEHS solution at high pressure to test for aerosol particles. Value for GSD from SMPS is 2.09 whereas from DMS-500 is 2.24. The difference between the readings is 0.15.

Both the instruments show the difference in the readings when measured for the same solution. Also, its difficult to predict which one shows the correct value in order to reduce the emissions. For the DEHS solution, there is a difference of 0.04 GSD between the low flow and high flow. This is can be due to the fact that there is more uncertainty at low flow (Durand, 2019).

Figure 14 shows that with increase in GMD there is an increase in GSD. There has been a sharp increase in GMD from test point 3 to four. This can be due to the difference between particle size and shape. For instance, NaCl particles are cuboid in shape where as DEHS particles are spherical in shape. This results in the difference in mobility diameter and hence, GSD. From test point 4 to 5 in SMPS, there has been a reduction in mobility diameter. However, DMS-500 shows something else that is, an increase in GMD with high flow rate. Therefore, it’s difficult to predict the accuracy of these instruments when tested for different aerosol particles.

Figure 15, shows the number concentration vs mobility diameter for nebulized water. There is major difference between the number concentrations that both the instruments show.

Figure 16, shows the number concentration vs mobility diameter for NaCl solution. The readings from both the instruments seem to be in sync. This shows that these instruments are likely to give accurate results when measured for the square aerosol particles for calculating the number and mobility diameter.

Figure 17, shows the number concentration vs mobility diameter for DEHS solution. When measured at low flow, DMS-500 shows that there are a greater number of particles at low flow as compared to high flow rate. With SMPS, there are two peaks in between the number concentrations around 100 nm and 500 nm for both the high flow rate and low flow rate. It implies that at there are greater number of particles which are of size 100 nm and 500 nm. After 500 nm, SMPS could not detect any particles in the solution. DMS-500 on the other hand, could measure the particles until 1000 nm at both the flow rates.

Figure 18, shows the number concentration across all the 5 test points. It shows zero number concentration across all the first three test points. It is may be because the particle size is not suited for the ELPI+ measurement system. The number concentration started to increase from test point 3 and goes up to point 5. These are test points where DEHS solution is used. It can be concluded that ELPI+ is suited for measuring the number of spherical aerosol particles.

V. CONCLUSION AND FUTURE DIRECTIONS

The major discoveries, ramifications, and contributions of the study done for this dissertation are outlined in this concluding chapter. It also identifies prospective directions for further investigation and action in the area of lowering non-volatile particulate matter (nvPM) emissions in the aviation sector.

A. Summary of Major Results

The conclusion of this thorough analysis highlights major findings that highlight the opportunity for considerable advancements in lowering non-volatile particulate matter (nvPM) emissions within the aviation industry. By displaying emission reductions and highlighting the practical viability of greener alternatives, the integration of cutting-edge technologies and sustainable aviation fuels has produced a tangible impact. The study offers a comprehensive knowledge of the issues underlying nvPM emissions and the potential pathways for efficient reduction through the balanced synthesis of quantitative data and qualitative observations (Matthes et al., 2022). This multi-faceted strategy not only confirms the effectiveness of particular tactics but also emphasizes the need for a comprehensive framework that integrates technical advancement with legal requirements and cross-industry cooperation. The combination of these findings not only makes a significant contribution to the subject but also paves the way for informed policy changes, industrial transformations, and a more environmentally conscious aviation sector on a worldwide scale.

B. Limitations and Future Research Directions

The reduction of non-volatile particulate matter (nvPM) emissions in aircraft has been better understood thanks in large part to this work, although it has limitations that should be acknowledged. The generalizability of findings across the whole aviation industry may be constrained by the reliance on specialized case studies and surveys, despite these sources of useful insights (Swinnen, & Vos, 2021).

Furthermore, it is possible that some data will eventually become out-of-date due to the fast-paced evolution of both technology and the legal environment. However, these restrictions set the stage for new lines of inquiry. Research could go in a number of different directions, including complete assessments of the socio-economic effects of emission reduction measures, long-term performance evaluations of implemented technology, deeper analyses of regional variances in regulatory frameworks, and so on. By addressing these issues, the industry would continue to move towards higher sustainability and promote a thorough grasp of the complexities of nvPM emissions reduction.

C. Industry Action Recommendations

A set of achievable recommendations for the sector to follow in order to reduce non-volatile particulate matter (nvPM) emissions effectively emerge from the research's thorough findings. A culture of continual development should be promoted and solutions relevant to different engine types should be adopted, but industry stakeholders should first and foremost proactively embrace novel technologies (Kolada et al., 2022). In order to hasten the adoption of new technologies and improve business practices, collaborative collaborations between airlines, manufacturers, and regulatory organizations should be encouraged.

Furthermore, the use of sustainable aviation fuels should be promoted as a practical and effective way to reduce emissions, necessitating more funding for research, infrastructure development, and other related activities. In order to develop a workforce that is knowledgeable about complicated emission reduction technology, industry engagement with educational institutions is essential. The aviation industry will ultimately be guided towards a greener and more sustainable future through industry-wide discussions, international cooperation, and an unshakable dedication to environmentally sound practices (Maddikunta et al., 2022).

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