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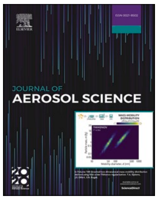

Advancing regulatory aircraft nvPM sampling and measurement practices: Uncertainty quantification and recommendations

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ABSTRACT

Despite recent advancements in regulatory standards for aircraft turbine engines, significant uncertainty remains in accurately quantifying non-volatile particulate matter (nvPM) number and mass emissions due to the complexity of sampling, measurement, and calibration procedures. The transition to new engine technologies and sustainable aviation fuels can also reduce regulatory nvPM levels towards the limit of quantification (LOQ), necessitating better quantification and mitigation of these uncertainties.

This study, initiated by the European Union Aviation Safety Agency (EASA) and funded under the EU Horizon 2020 RAPTOR and SAMPLE IV research programmes, investigated uncertainties in instrument drift, system-to-system variability, nvPM mass LOQ, and system operability within current regulatory nvPM measurement, sampling, and calibration standards. To assess these uncertainties, two comparative tests of the European (EUR) and Swiss (CH) regulatory-compliant reference systems were performed over a twelve-month calibration cycle using a non-proprietary Rich-Quench-Lean (RQL) combustor rig, following prior parallel calibration of identical nvPM number and mass instrument technologies. Additional laboratory experiments using a range of aerosol sources were conducted to evaluate instrumentation and calibration uncertainty independently.

With calibration and instrument-technology uncertainty minimised and enhanced cleanliness protocols applied, the nvPM Emission Index (EI) number showed <1 % systematic difference with 3 % variability between the EUR and CH systems, and the nvPM EI mass showed 3 % bias with 8 % variability. No annual instrument drift was observed in either the nvPM mass or number instruments. However, when directly comparing nvPM measurements across different calibration and instrument technologies, variability increased noticeably: Condensation Particle Counter (CPC) counting efficiency was impacted by particle type and morphology, even within the same CPC models, and a variability of 12 % (with biases up to 33 %) was observed across a range of nvPM mass instruments. In addition, particle shedding from the prescribed 1-μm cyclone was observed during RQL combustor rig exhaust sampling and was found to significantly impact

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nvPM mass measurements at low concentrations, which are typical of modern engine technologies and sustainable aviation fuels. Yet, with improved cleanliness protocols, accurate nvPM mass quantification down to 3 μg/m^3 was achieved. These findings provide critical insight into current regulatory practices and identify areas for improvement towards more accurate characterisation and future reduction of harmful nvPM emissions from aircraft engines.

Abbreviations

Symbol	Definition
AFR	Air to Fuel Ratio
ASTM	American Society for Testing and Materials
AIR	Aerospace Information Report (SAE document)
APC	AVL Particle Counter
ARP	Aerospace Recommended Practice (SAE document)
CAPS	Cavity Attenuated Phase Shift (Aerodyne Research)
CI	Confidence Interval
CH	Swiss
CPC	Condensation Particle Counter
DF_2	Dilution Factor 2 - APC internal dilution factor
DMA	Differential Mobility Analyser
DMS500	Differential Mobility Spectrometer (Cambustion)
D_{50}, D_{90}	Particle diameter at which the CPC achieves 50, 90 % counting efficiency
EC	Elemental Carbon
EEP	Engine Exit Plane
EEPS	Engine Exhaust Particle Sizer (TSI)
EI	Emission Index
EUR	European
GMD	Geometric Mean Diameter
GMR	Geometric Mean Ratio
GSD	Geometric Standard Deviation
ICAO	International Civil Aerospace Organisation
LII 300	Laser Induced Incandescence (Artium Technologies)
LOQ	Limit Of Quantification
L/min	Litres per minute
nvPM	Non-volatile Particulate Matter
NCB	Nebulised Carbon black
NPL	National Physical Laboratory (UK)
NRC	National Research Council of Canada
MSD	Mass-space particle Size Distribution
MSS	Micro-Soot Sensor
N/M	Number to Mass ratio (nvPM)
OC	Organic Carbon
PM	Particulate Matter
PSD	Particle Size Distribution (Number-space)
PSD_B	Particle Size Distribution Bin-by-bin
RF	Radiative Forcing
RQL	Rich-burn, Quick-mix, Lean-burn
RAPTOR	Research of Aviation PM Technologies, mOdelling and Regulation
$R_{N/M}$	Regulatory Number to Mass ratio
SAG	Spark-Ablated Graphite
SAMPLE	Studying, sAmpling and Measuring of aircraft ParticuLate Emission
SI	Supplementary Information
SMPS	Scanning Mobility Particle Sizer
STP	Standard Temperature and Pressure
TC	Total Carbon
TOT	Thermal Optical Transmittance
UHC	Unburnt Hydro-Carbons
VPR	Volatile Particle Remover

1. Introduction

Aircraft turbine engines emit a range of exhaust pollutants that negatively affect local air quality and contribute to global warming. Global aviation has been estimated to cause approximately 74,300 premature deaths annually (Eastham et al., 2024), and accounts for around 3.5 % of total anthropogenic radiative forcing, including contributions from CO_2 and non-CO_2 emissions such as contrails and indirect ozone formation (Lee et al., 2021), (Teoh et al., 2024). This share is expected to grow with increasing aviation demand and traffic, particularly as other sectors reduce their emissions through decarbonisation.

Non-volatile particulate matter (nvPM), which mostly consists of black carbon, is defined as particles present at the aircraft engine exit plane that do not volatilise when heated to 350 °C, and that can persist in the atmosphere for weeks after their emission (Owen et al., 2022). Aircraft turbine engines typically emit nvPM with a geometric mean diameter (GMD) ranging from 10 to 50 nm (Durdina et al., 2024). These ultrafine particles can penetrate deep into the lower airways upon inhalation and are associated with adverse health effects similar to those caused by diesel exhaust particles and other traffic-related emissions (Bendtsen et al., 2021), (Melzi et al., 2024). Accurately quantifying and regulating nvPM emissions from aircraft is therefore essential to fully understand their environmental and health impacts and to develop effective mitigation strategies in line with global net-zero commitments.

The regulation of particulate emissions from aircraft began in the 1980s with the introduction of the Smoke Number standard, aimed at reducing the visible plume produced by civil aviation turbofan and turbojet engines with rated thrust >26.7 kN. In January 2020, a more precise approach to regulating carbonaceous particles was adopted with the International Civil Aerospace Organisation (ICAO) nvPM mass standard. This was further strengthened in January 2023 with the addition of an nvPM number standard (ICAO, 2023). Regulation requires the use of long and complex standardised sampling and measurement systems to afford repeatable measurements of nvPM number and mass concentrations. These systems are composed of a probe that extracts raw exhaust at the engine exit plane (EEP) before diluting, cooling and conditioning prior to measurement by the prescribed calibrated gaseous and nvPM instruments (SAE International, 2024a). Despite regulatory advances, significant uncertainties remain in the reported nvPM number and mass, primarily due to system complexity, difficulty in achieving representative calibration, and the absence of size-dependent particle loss corrections (Durand et al., 2023), (Durand et al., 2020). This study aims to address some of these limitations to support more effective regulation of aircraft particulate emissions.

The uncertainty associated with reported regulatory aircraft nvPM number and mass emissions has not yet been fully established. However, several sources provide indicative values. SAE Aerospace Recommended Practice (ARP) 6481A adopted an expanded uncertainty of ±30 % (k = 2) for both nvPM number and mass when estimating the uncertainty in system loss correction factors (SAE International, 2024b). In addition, ARP6320B specifies a performance accuracy of ±10 % and an applicability of ±16 % for nvPM mass instruments (SAE International, 2024a), which give a relative standard uncertainty of approximately 18.9 % when combined. This is broadly consistent with the expanded uncertainty (k = 2) of 17 % reported by Sipkens et al. (Sipkens et al., 2024) for elemental carbon (EC), which is used for nvPM mass calibration. For nvPM number, Durdina et al. (Durdina et al., 2025) applied a value of 10 % in their nvPM number emission index (EI) uncertainty analysis, reflecting the condensation particle counter (CPC) counting accuracy requirements. Similarly, Lobo et al. (Lobo et al., 2020) reported the theoretical total uncertainties in the nvPM EIs to be ~22 % for mass and ~25 % for number. However, the true uncertainty in regulatory nvPM number and mass EIs is likely to be substantially higher, as the values above do not account for additional contributors such as instrument drift, particle losses, or increased variability near the limit of quantification (LOQ).

Several studies have already experimentally investigated aspects of aircraft nvPM regulatory sampling and measurement uncertainty by comparing reference systems between 2012 and 2018. The A-PRIDE and SAMPLE III projects compared several regulatory-compliant nvPM sampling and measurement systems on CFM56 and PW4000 aircraft engines, reporting average agreement within 15 % for nvPM number EI and 30 % for nvPM mass EI (Lobo et al., 2020), (Lobo et al., 2015). The VARIAnT projects also compared standardised systems on soot from a mini-CAST burner and a J85 turbojet engine burning multiple fuels and reported agreement within 17 % for nvPM mass and 26 % for nvPM number, with better agreement when the mini-CAST results are excluded (Kinsey et al., 2021). Dedicated nvPM mass instrument comparisons on different soot sources were also performed as part of VARIAnT, which found that three mass instrument types (MSS, CAPS PM_{SSA}, and LII 300) exhibited varying response to reference EC ratios depending on the emission source (Giannelli et al., 2024).

Currently, regulation mandates system cleanliness checks prior to an engine test series, primarily to verify system integrity and check for leaks. A cleanliness check is passed if the 30-s averaged measured nvPM mass is less than 1 $\mu g/m^3$ and the nvPM number is fewer than 2 $particles/cm^3$ when sampling a clean compressed gas introduced at the primary dilution stage (Diluter1) (ICAO, 2023). However, this does not address the potential for particle shedding from a regulatory system following a high measured nvPM mass test point or a sudden pressure fluctuation, which could increase the nvPM mass LOQ. While current regulation defines the limit of detection (LOD) for nvPM mass instruments to be $\leq 1\ \mu g/m^3$ and SAE ARP6481 defines the LOQ as three times the LOD, it is acknowledged that "*Future work is required to assess and improve the stated limitation values for mass and number based upon multiple sources of variability*" (Durand et al., 2023), (SAE International, 2024b).

No study to date specifically isolated the impact of the sampling system uncertainty or instrument drift on reported nvPM number and mass values. Furthermore, since the initial development of nvPM sampling and measurement standards, reference systems have seen extensive operational use and have undergone various updates and improvements in both procedure and calibration, while the nvPM measurement instrument hardware have remained unchanged.

Building from the findings of the SAMPLE, VARIAnT and A-PRIDE programmes, this study addresses the following research aims for regulatory nvPM number and mass.

1. Assess and quantify what drives **sampling** uncertainty, and establish its relative importance compared with calibration and instrument uncertainty
2. Assess if **instrument drift** contributes significantly to uncertainty
3. Further assess the factors driving **measurement** uncertainty (e.g. instrumentation, technology, and calibration methodologies)
4. Experimentally quantify the **nvPM mass LOQ**

Aims 1 and 2 were investigated by comparing two regulatory-compliant nvPM sampling and measurement systems at the beginning and end of a 12-month calibration cycle, following a parallel calibration of the nvPM number and mass instruments performed by the manufacturer. Tests were conducted using a small-scale Rich-burn Quick-quench Lean-burn (RQL) combustor rig at Cardiff University's Gas Turbine Research Centre (GTRC). The resulting dataset comprises hundreds of discrete test-points across various combustor conditions, using seven aviation fuels of varying hydrogen and aromatic content, providing a wide range of nvPM number and mass concentrations and particle size distributions representative of those emitted by large civil aviation gas turbines (Harper, 2022). The two RQL combustor test campaigns were conducted using both the Swiss (CH) and European (EUR) nvPM reference systems performing parallel measurements of nvPM number and mass, gases (CO_2, CO, NOx, UHC), and particle size distributions. Aim 3 was addressed by performing dedicated laboratory experiments comparing nvPM number and mass instrumentation, using exhaust from the RQL rig and a range of laboratory-generated aerosol sources including gold, silver, graphite, carbon black, and salt. Measurement uncertainty was also investigated during the main RQL rig testing using ancillary instruments (i.e., APC with dual CPC, LII 300 vs. MSS). Aim 4 was investigated along with aims 1 and 2 by using additional nvPM mass instruments sampling raw exhaust in parallel and by performing cleanliness checks several times during each test.

By comprehensively examining the existing measurement protocols and their associated uncertainties, this study supports the optimisation of regulatory frameworks, ensuring they are both scientifically robust and practically feasible. In doing so, it addresses a critical gap in aviation environmental research and offers insights to support more effective mitigation strategies for aircraft-related emissions. Agreement between systems is quantified using statistical methods that separately assess systematic differences and random variability.

2. Material and methods

2.1. Experimental setup

Two sets of experiments are presented in this study. First, RQL combustor rig tests were conducted to compare the EUR and CH regulatory-compliant nvPM sampling and measurement systems at the beginning and end of a 12-month calibration cycle, after both systems had been calibrated in parallel (repeatability). These tests also included additional nvPM mass instruments sampling raw exhaust in parallel. Second, dedicated laboratory experiments were performed to directly compare different instrument technologies and particle sources in order to investigate specific contributors to nvPM number and mass measurement uncertainty (reproducibility).

2.1.1. RQL combustor rig experiments

Emissions were generated using an updated configuration of a rich-quench-lean (RQL) combustor rig, previously described and utilised to study the effects of alternative fuels on nvPM and gaseous emissions (Harper, 2022). The rig was designed for high repeatability and precise control of fuel and air flows. This was achieved using high-precision Emerson Coriolis mass-flow controllers to regulate three independent air supplies, and a high-precision Bronkhorst CoriFlow magnetically coupled variable-speed gear pump to deliver precise fuel flow. Fuel and air preheat temperatures were independently maintained with water and electric heating systems.

The initial experimental campaign, labelled RQL 1, was conducted in December 2020, with the second campaign, labelled RQL 2, undertaken in December 2021. To enable a wide variation in nvPM mass, number, and size emissions from the RQL combustor rig, a total of seven fuels and eight operating conditions were tested, with additional details provided in both the RAPTOR report (Crayford et al., 2022) and the supplementary information (see Section S1 of the SI). Due to damage sustained during RQL 1 testing, which resulted in a burnout of the combustor liner (see Section S2 of the SI), a nominally identical combustor liner was manufactured for use in RQL 2 testing. To minimise the likelihood of similar damage occurring, the fuel injector design was modified for RQL 2 testing to produce a narrower fuel spray cone angle.

The nvPM and gaseous emission measurements were obtained in accordance with ICAO standards (ICAO, 2023) and SAE ARP6320 (SAE International, 2024a) using both the EUR CH nvPM reference systems, which are described in detail elsewhere (Lobo et al., 2020), (Durand et al., 2021), (Durdina et al., 2019), operating in parallel as depicted in Fig. 1. The aerosol was extracted from the combustor exhaust stream using a 9-point, equal area piccolo emissions probe, coupled with a 160 °C water-cooled heat exchanger (3/8″ internal diameter) before being split between the two nvPM reference systems via a 160 °C heated splitter box (30° angle). As per ICAO regulatory practices, the aerosol was further divided in each systems at Splitter1 between the gas sampling line, Diluter1, and a spill line (SAE International, 2024a). Gaseous emissions (CO_2, CO, NO_x, UHC) were measured in the raw exhaust (gas line), while nvPM emissions were measured downstream of an ejector diluter (Diluter1) to minimise particle coagulation, water condensation, and the formation of volatile particles prior to measurement. CO_2 was also measured downstream of Diluter1 to enable real-time determination of the dilution factor and emission index, though it is omitted from Fig. 1 for simplicity. A 1-μm cyclone was positioned upstream of the nvPM instrumentation, as required by regulation, to remove large non-exhaust particles and debris that could artificially increase measured nvPM mass and risk damaging the instruments.

Each reference system was equipped with an APC fitted with a TSI 3790 CPC for nvPM number measurements and an AVL MSS for nvPM mass measurements. As shown the SI (section S3), the counting efficiencies of both CPCs were within 2 % of each other at 10 nm (77.7 % for EUR vs 79.2 % for CH) and 15 nm (93.0 % for EUR vs 94.9 % for CH). As per the instrument operation procedures, resonance checks for the MSS were systematically performed on RQL combustor exhaust to compensate for an observed zero offset of up to 4 $\mu g/m^3$, relative to checks performed on clean nitrogen.

The main difference between the two systems are the slightly different line lengths, diameters, and designs surrounding Splitter1, Diluter1 and Splitter2 (after the cyclone). The EUR nvPM reference system also included additional nvPM mass (Artium Technologies LII 300) and particle sizing (Cambustion DMS500 M44) instruments, installed on an ancillary sampling port behind the 1-μm cyclone. The CH nvPM reference system was equipped with additional nvPM mass (AVL MSS2) and particle sizing instruments (TSI SMPS Model

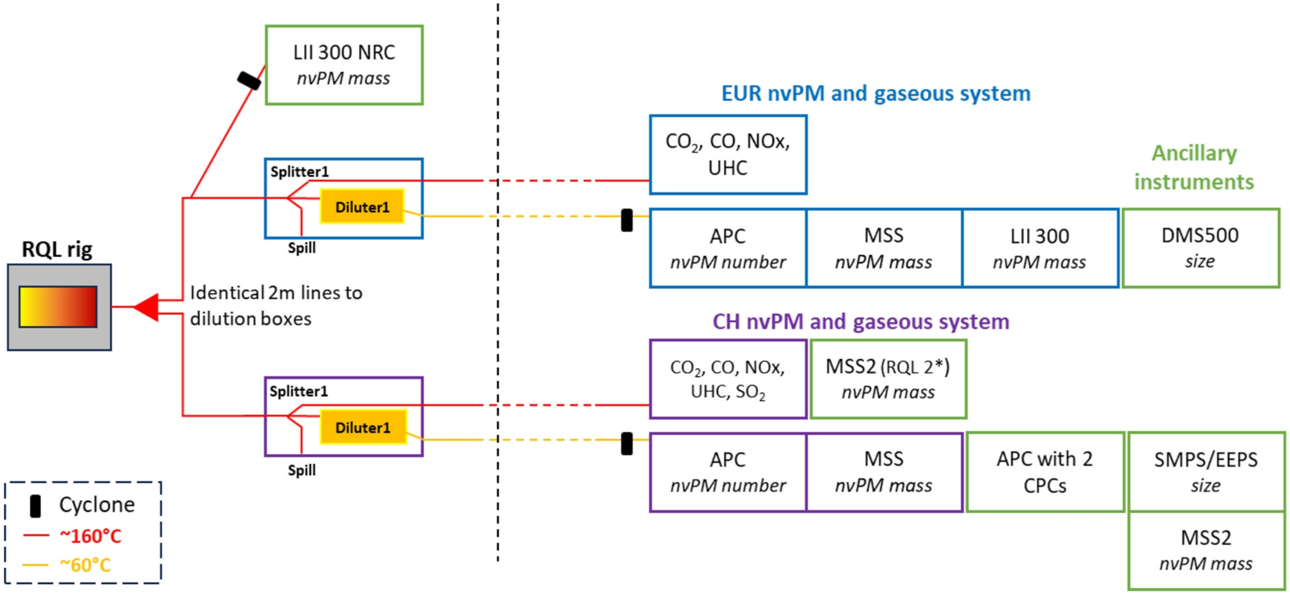

Fig. 1. Simplified diagram of the EUR and CH regulatory system comparison used during RQL 1 and 2 testing (*MSS2 location was changed between experiments).

3938 and TSI EEPS Model 3090).

During the RQL 1 campaign, an additional customised APC featuring two CPCs (TSI 3790E and AVL CPC 10 nm 488) was operated in parallel to the prescribed APC nvPM number instrument within the CH system. In the RQL 2 campaign, the EUR system incorporated an additional Artium LII 300 from NRC, installed on the raw line and sampling at 160 °C behind a 1-μm cyclone. Similarly, an AVL MSS2 was used in the CH system either on the raw line sampling at 60 °C or in parallel with the MSS to facilitate direct comparisons with the prescribed diluted nvPM mass measurements. Additionally, an Aerodyne CAPS PM_{ssa}, operating at a wavelength of 660 nm and using a mass absorption cross-section of 6.3 m^2/g (Kinsey et al., 2021), was used during the laboratory intercomparison experiments but is not reported for RQL testing. During RQL testing, the instrument was installed in the CH system near the MSS, but suffered from mirror contamination and excessive noise levels, which were attributed to pressure changes in the system resulting from valve switching and cyclone cleaning operations.

Cleanliness, leak and ambient background system checks were regularly performed in accordance with SAE ARP6320B to ensure data integrity.

2.1.2. *Laboratory intercomparison experiments*

The dedicated nvPM number and mass comparison experiments were performed using various particle types from different sources. Spark-ablated graphite (SAG) and gold nanoparticles were produced using a VSP-G1 nanoparticle generator from VSparticle, while silver nanoparticles were generated using Catalytic Instrument's Silver Particle Generator (SPG). Nebulised carbon black (NCB) colloids and salt nanoparticles were produced with a Topas ATM 226 aerosol generator. These diverse aerosol generation techniques, described in detail elsewhere (Johnson et al., 2025), provided different particle types/morphologies encompassing a size range from 7 to 70 nm GMD.

The experimental setup for laboratory instrument comparison, as illustrated in Fig. 2, comprised three main sections.

- (1) **Particle generation section**: For nvPM mass comparison, particles were generated using the RQL combustor (soot), VSP-G1 (SAG) and ATM 226 (NCB). For nvPM number comparison, particles were generated using VSP-G1 (SAG and gold), SPG (silver), or ATM 226 (salt and NCB).
- (2) **Particle conditioning section**: This section included vents to minimise pressure effects, a PALAS VKL-10ED to dry the sample, mix the aerosol, and ensure sufficient flow, and a Grimm flow splitter 5483 to evenly distribute the aerosol to the instruments while minimising particle losses.
- (3) **Measurement section**: Various nvPM number (EUR and CH APCs) and nvPM mass (EUR LII 300, NRC LII 300, EUR MSS, CH MSS, MSS2 and CAPS) instruments were compared in succession, as shown in Fig. 2(a) and (b). Additional particle size measurements were performed in parallel to the nvPM instrument comparison using the EUR DMS500 and the CH SMPS.

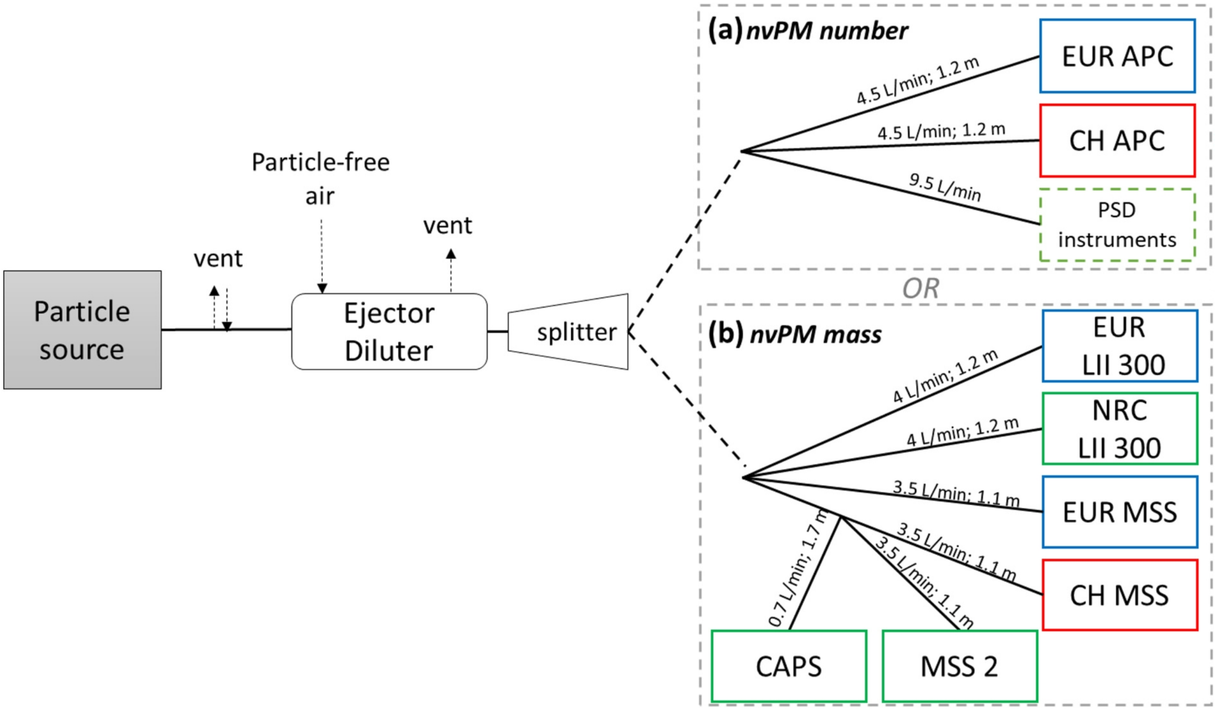

Fig. 2. Diagram of the dedicated nvPM number (a) and subsequent mass (b) instrument intercomparison experiments (particle source includes RQL combustor, nanoparticle generators and nebuliser).

2.2. Data processing and analysis

2.2.1. Calibration data

In order to assess Aims 1 and 2, the EUR and CH nvPM number instruments (i.e., APC) were calibrated in parallel on the same source, as were the mass instruments (AVL MSS, calibrated using a mini-CAST). All calibrations were conducted by the instrument manufacturer prior to RQL 1 testing, in compliance with regulatory requirements (ICAO, 2023), (SAE International, 2024a), with the calibration certificates provided in the SI (section S3).

In contrast, to address Aim 3, the MSS2, EUR LII 300, and NRC LII 300 were calibrated separately, at different times and using different nvPM sources: The EUR LII 300 was calibrated on a Rolls-Royce legacy helicopter engine in March 2020 (calibration factor of 0.98 - filters analysed by NRC) and again in November 2021 (calibration factor of 0.87 - filters analysed by NPL) with no servicing or adjustments performed between calibrations. The difference between the calibrations performed twenty months apart on the same instrument at two different laboratories is less than the 17% uncertainty associated with the determination of EC (Sipkens et al., 2024). The NRC LII 300 was calibrated on the same helicopter engine in March 2020 (calibration factor of 0.72 - filters analysed by NRC). The MSS2 was calibrated by AVL in November 2021, just before RQL 2, using the same procedure as for the EUR and CH MSSs (mini-CAST). The CAPS instrument was not calibrated for aircraft nvPM; however, it was manually corrected to standard temperature and pressure (STP - 273.15 K and 101.325 kPa) conditions (correction factor ~1.09) to enable direct comparison with the other nvPM mass analysers, which all reported data at STP.

2.2.2. nvPM emission calculations

Each data point presented in this study is an average value determined from 1 Hz measurements taken over a minimum of 1 min at a stable rig and sampling condition (defined as a raw CO_2 fluctuation within ±0.1 %) and including at least two 30-s SMPS scans. Additional long 30-min test points were obtained at some conditions to assess low mass conditions. All nvPM data is reported at STP.

The reported nvPM EIs, a measure of the nvPM emitted per unit mass of fuel consumed, were calculated from measured nvPM number and mass taken from the EUR and CH AVL MSSs and APCs using the simplified equations as defined in the relevant aerospace practice (SAE ARP6320B (SAE International, 2024a)). The EI equations include a diluted CO_2 term. Although each system had its own CO_2 analyser, they were both calibrated and regularly checked using the same zero and span cylinders to ensure consistency across systems. The use of simplified EIs was deemed appropriate given the relatively low measured UHC (0 – 18 ppm) and CO (11 – 712 ppm) witnessed across all the RQL 1 and RQL 2 campaigns, resulting in an absolute difference <1 % when compared to EIs calculated using the full equation. Particle size measurements were used to derive GMDs, with the GMD from the EUR DMS500 reported in this study. The EUR DMS500 was calibrated and processed using the monomodal aggregate inversion matrix. It is noted that the EUR DMS500 and the CH SMPS agreed on average within 0.6 ± 0.9 nm ($k = 1$) in GMD over the range observed on the RQL combustor rig (12-60 nm).

Since the EUR and CH systems sampled from the same probe and were therefore subject to similar particle losses in the collection section, thermophoretic loss correction (k_{thermo}) was not applied. Similarly, because this study focused on regulatory aircraft nvPM sampling uncertainty (excluding probe), and size-dependent system loss corrections are not currently prescribed, they were also not applied.

2.2.3. Agreement metrics and statistical analysis

Previous intercomparisons of regulatory-compliant nvPM sampling and measurement systems have typically reported agreement using percentage deviations (arithmetic mean ratio) and linear regressions between systems on an arithmetic scale (e.g., (Lobo et al., 2020), (Giannelli et al., 2024)). The regression slope reflects proportional scaling between systems but is dominated by high-concentration points. The arithmetic mean ratio provides an average point-to-point difference, although opposite-signed percentage deviations can partly cancel when averaged. These approaches therefore characterise overall variability rather than explicitly separating systematic inter-system differences from random point-to-point scatter.

In this work, agreement between the EUR and CH systems is quantified using the geometric mean ratio (GMR), which provides a measure of the systematic multiplicative difference between systems, consistent with metrological guidance for separating trueness (systematic bias) from precision (random scatter) (ISO 5725 (ISO 5725)). For the datasets considered here, the geometric and arithmetic mean ratios were found to be similar, enabling appropriate comparison with previous studies while adopting a more robust statistical framework. Inter-measurement variability is characterised using the geometric standard deviation (GSD), which quantifies the variability and typical magnitude of inter-system differences independently of sign. Together, these provide a more robust description of agreement, particularly when only the four standard ground operating conditions used for regulatory engine certification (idle, approach, climb-out, take-off) are considered (ICAO, 2023). The 95 % confidence interval (95% CI) is also reported to represent the uncertainty in the estimated GMR. These statistics are distinct from the GMD and GSD used to describe particle size distributions.

3. Results and discussions

3.1. Repeatability of regulatory nvPM measurements (aims 1 & 2)

The repeatability of regulatory nvPM number and mass measurements was assessed by comparing the EUR and CH reference systems during parallel sampling of RQL combustor exhaust shortly after parallel calibration (RQL 1) and again twelve months later (RQL 2). This setup minimised calibration and instrument-technology uncertainty, enabling direct evaluation of sampling-related variability and long-term instrument stability within a regulatory configuration.

3.1.1. nvPM number system-to-system variability and drift

Fig. 3 presents the nvPM EI number agreement for RQL 1 and RQL 2. During RQL 1, a 6 % systematic nvPM EI number difference and a 7 % variability was observed (GMR = 1.06; 95 % CI = 1.05-1.08; GSD = 1.07), with the CH system generally reporting lower values. At the lowest concentrations and smallest particle sizes, this difference increased significantly, up to ~45 % (Fig. 3b). It is suspected that the increased bias <20 nm GMD was due to the presence of small metallic particles, generated unintentionally as a result of combustor liner degradation at high thermal powers, as discussed in Section S2 of the SI (see example PSD in Fig. S2). These particles may have affected the counting efficiencies of the EUR and CH CPCs differently, as even instruments that are virtually identical in design can exhibit variations due to internal settings such as the saturator to condenser temperature ratio, resulting in differing efficiencies and associated particle losses. Alternatively, it is possible that the observed bias was driven by differences in particle loss within the two sampling systems. It is noted that differences in VPR losses and CPC counting efficiency, as indicated by the AVL calibration (see Section S3 of the SI), do not explain the size-dependent differences observed during RQL 1. When disregarding the test points with small metallic particles, the systematic difference in nvPM EI number reduced to 3 % with a variability of 3 %.

When the RQL 2 comparison was performed a year later, following improvements informed by lessons learned during the RQL 1 test, no metallic particles were present. The instruments showed negligible systematic difference in nvPM EI number (GMR = 1.00; 95 % CI = 0.99-1.01) and reduced variability of 3 % (GSD = 1.003). No apparent dependency on particle size or number concentration was observed (Fig. 3 - blue). This also suggests that neither APC experienced significant drift over the 12-month period, despite extensive transport and use.

The notably better level of agreement observed here, compared with previous reference nvPM system intercomparison studies (Lobo et al., 2020), (Lobo et al., 2015), (Kinsey et al., 2021), is largely attributed to the EUR and CH nvPM number instruments being of the same technology and calibrated in parallel at the same time. This highlights that calibration is likely a significant contributor to overall regulatory nvPM number uncertainty. However, it is also important to note that calibration and sampling protocols have improved since the earlier studies conducted between 2012 and 2018. For example, the APC VPR AVL calibration rig was upgraded in 2018 from thermally treating CAST soot using a 350 °C evaporation tube to thermally treating AVL APG soot using a 370 °C catalytic stripper, which led to an increase in calibrated VPR penetration of ~10 % at 15 nm, and ~2-5 % at larger sizes (Durand et al., 2025).

3.1.2. nvPM mass system-to-system variability and drift

Fig. 4 presents the nvPM EI mass agreement for RQL 1 and RQL 2. During RQL 1, a 13 % systematic nvPM EI mass difference and a 19 % variability was observed (GMR = 0.87; 95 % CI = 0.84–0.89; GSD = 1.19), with the EUR system reporting lower values. This difference remained approximately consistent across the range of nvPM number, mass, and size investigated, and did not correlate with the metallic peak (see Section S2 of the SI). Given that both the EUR and CH AVL MSS instruments were calibrated by the manufacturer on the same source in parallel and agreed within 1 μg/m^3 during side-by-side measurements (see Fig. 8), it is hypothesised that the observed 13% difference during RQL 1 arose from a flow imbalance at the initial two-way splitter, caused by the coupling of unequal spill-line resistances (the EUR spill was narrower than the CH spill). As a result, the CH branch experienced a higher flowrate, resulting in asymmetric flow conditions at the splitter which may have caused additional inertial loss of larger particles along the lower-flow EUR branch and/or additional thermophoretic loss due to the different temperature profiles up to Diluter1 caused by the different flows. This hypothesis is further supported by inter-system mass comparisons, which showed good agreement between different nvPM mass instruments used within the CH and EUR systems when sampling next to each other (see Fig. 6).

It is also noted that increased scatter was observed during RQL 1 testing at mass loadings <10 mg/kg$_{\text{fuel}}$ (i.e., <30 μg/m^3 measured), as highlighted in Fig. 4b, likely due to shedding interference and increased measurement uncertainty near the instrument's LOD, as further discussed in Section 3.3.1, and reported in the literature (Lobo et al., 2020), (Giannelli et al., 2024), (Crayford et al., 2022), (Durand, 2019).

To further assess these uncertainties, more regular cleanliness checks and cyclone pot cleaning were implemented during RQL 2 testing, in addition to the decoupling the Splitter1 spill exhaust connections between the EUR and CH systems. This led to a reduction in system-to-system differences, with the systematic nvPM EI mass offset decreasing to 3 % (GMR = 0.97; 95 % CI = 0.94–0.99) and the variability to 8 % (GSD = 1.08), confirming that the RQL 1 13 % bias was primarily due to the coupled spill lines. Although the EUR system continued to report slightly lower values, the improved maintenance protocols also significantly reduced data scatter at low mass concentrations compared to RQL (Fig. 4b). Consistent with the findings for the nvPM number instruments, these results further suggest that neither of the AVL MSSs experienced significant drift over the 12-month period, despite extensive use and transport.

The level of agreement for nvPM EI mass during RQL 2 testing is notably better than that reported in previous reference nvPM system intercomparison studies (Lobo et al., 2020), (Lobo et al., 2015), (Kinsey et al., 2021), largely due to the use of the same instrument technologies, parallel calibration, and improved cleanliness protocols. This indicates that calibration and system cleanliness are primary contributors to regulatory nvPM mass uncertainty.

3.2. Instrument-technology and calibration-driven variability (Aim 3)

While excellent agreement of nvPM EI number and mass was achieved between the CH and EUR reference systems during RQL testing, they both employed the identical instrument technologies calibrated in parallel. Other regulatory-compliant systems may use different instrument technologies as current requirements are performance-based. To assess these effects, additional comparisons were

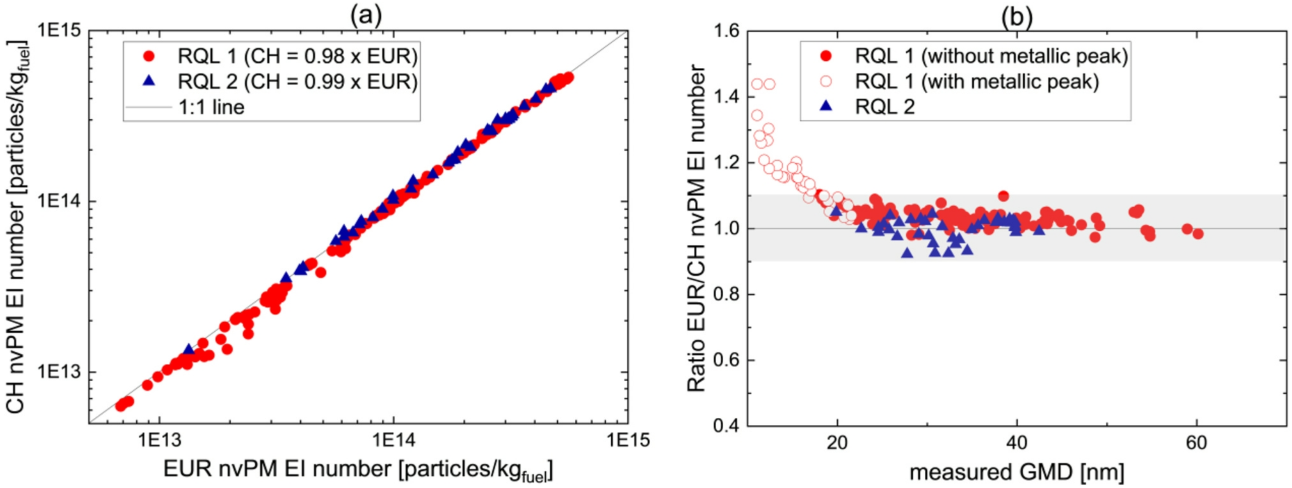

Fig. 3. EUR and CH nvPM EI numbers measured in parallel on RQL-combustor exhaust (a) and their ratio against measured GMD (b).

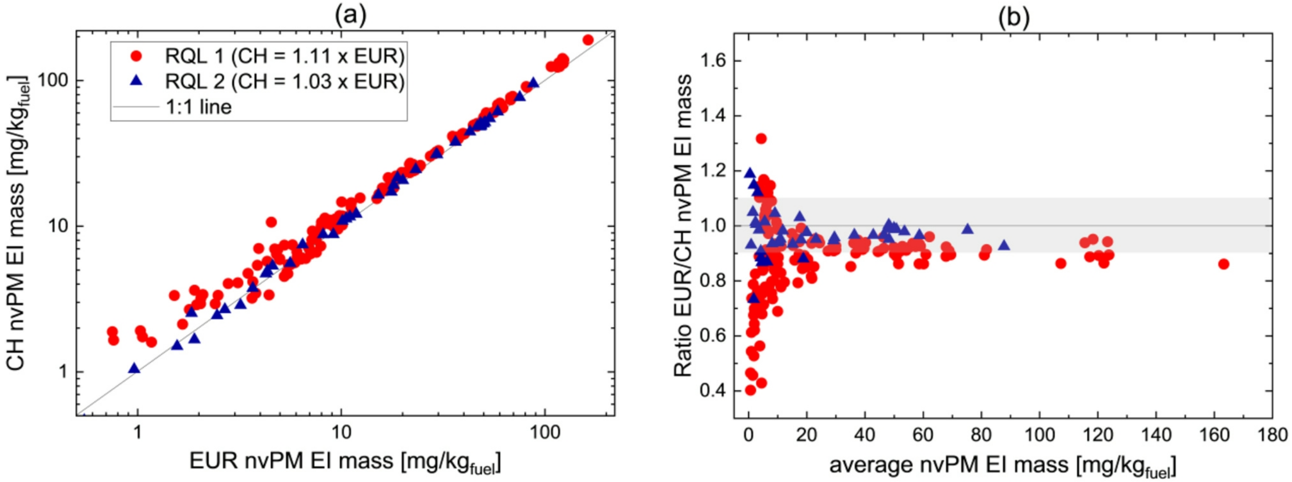

Fig. 4. EUR and CH nvPM EI mass measured in parallel on RQL-combustor exhaust (a) and their ratio over the average mass (b).

performed during RQL testing and through dedicated laboratory intercomparisons to isolate instrument-technology and calibration-driven variability.

For nvPM number, butanol-based CPCs are prescribed by regulation, so uncertainty is primarily driven by VPR design and CPC performance. For nvPM mass, both the LII 300 and MSS have been shown to meet regulatory performance specifications, but their differing measurement principles can introduce additional variability, particularly with changes in particle morphology or operating condition.

3.2.1. *nvPM EI number reproducibility: intra-system and laboratory comparisons*

During RQL 1 testing, the previously hypothesised dependence between CPC counting efficiency and particle type/morphology was further assessed by comparing two regulatory-compliant CPCs ($D_{90} > 15$ nm and $D_{50} > 10$ nm (ICAO, 2023)) from different manufacturers (TSI and AVL) fitted within the same APC and sampling RQL combustor exhaust behind the same dilution and VPR, with the results shown in Fig. 5.

When sampling soot exclusively, and for GMDs down to 12 nm, the systematic number difference between the two CPCs was <1 % (GMR = 1.00; 95 % CI = 0.996–1.004), with a variability of 2% (GSD = 1.02). It is noted that this agreement was achieved by applying the k-factor to correct for counting accuracy (i.e., linearity) from their respective calibration certificates, which is not a requirement of the current ICAO regulations. Higher discrepancies of up to ~20 % were observed again (GMR = 1.07; 95% CI = 1.05-1.08; GSD = 1.02) when condensed metallic particles, generated during combustor liner damage at high thermal powers, dominated the sampled aerosol (see Section S2 of the SI), as seen in Fig. 5b. These findings further highlight that CPC counting efficiency may vary with particle morphology and surface properties, particularly in the presence of metallic particles. This is consistent with previous studies reporting that particle morphology can influence the condensation behaviour of the CPC's working fluid (Giechaskiel et al., 2011), (Kangasluoma et al., 2014), (Wlasits et al., 2020). The observed discrepancies underscore the importance of specifying the particle type used when calibrating CPC counting efficiency to ensure consistent measurements (current regulation specifies the use of Emery oil (ICAO, 2023)). In the context of aircraft engine certification testing, where sub-15 nm metallic nanoparticles are not expected, using particles with properties more representative of aircraft soot, as discussed in the literature (Kangasluoma et al., 2014), or prescribing a lower D_{50} and D_{90} threshold for regulatory nvPM number measurements (e.g., $D_{50} > 4$ nm instead of the current 10 nm), could help reduce this source of uncertainty.

Additionally, a direct laboratory comparison of the CH and EUR APCs was carried out at the start of RQL 2 across a range of particle types, sizes, and concentrations, as shown in Fig. 6. Close agreement was achieved for GMD >20 nm and >2000 particles/cm^3 (<5 % difference), particularly for carbonaceous SAG and NCB. However, more significant discrepancies were noted in the cases of gold and silver particles, with larger offsets observed at lower particle size and number concentrations. These differences cannot be attributed to variability in calibrated VPR losses (EUR VPR > CH VPR by less than 3 %), CPC counting accuracy (linearity effects corrected) and counting efficiency (EUR CPC < CH CPC by less than 2 %), as these parameters were consistent.

As previously discussed with Figs. 3 and 5, this comparison suggests that CPC performance is influenced by particle morphology and surface properties, and reflects variability with specific internal settings, which impacts counting efficiency at the smallest particle sizes. It is noted that the trends observed between the EUR and CH APCs in Fig. 6 for gold and silver particles are opposite to those previously reported in Fig. 3 for combustor liner metallic particles. This discrepancy likely reflects differences in the measurement configuration, as combustor emissions measurements were conducted downstream of the CH and EUR sampling systems, where additional size-dependent particle losses may have occurred at the initial two-way splitter during RQL 1 as discussed with Fig. 4. In contrast, the gold and silver particle measurements were performed without such sampling systems (see Fig. 2).

It is noted that the APC internal dilution factors (DF_2) were also varied from the minimum (~70) to the maximum (~1100) on given sources to understand the impact of APC internal dilution on uncertainty. For the DF_2 settings typically used during engine certification testing (i.e., <~370), the APCs agreement was consistent. However, agreement between the APCs decreased at higher DF_2 of ~370, ~750 and ~1100 (up to 12.5 % uncertainty), thought to be driven by the internal dilution correction uncertainty (see section S5 in the SI).

3.2.2. *nvPM EI mass reproducibility: intra-system and laboratory comparisons*

Instrument reproducibility for nvPM EI mass was first assessed by comparing the MSS and MSS2 within the CH system and the MSS and EUR LII 300 within the EUR system, with the results shown in Fig. 7. During RQL 2, the EUR LII 300 data were processed using the two available calibration factors from 2020 to 2021 to assess laboratory-to-laboratory calibration uncertainty, as no service had been performed during the calibrations and no significant drift was anticipated.

Within the CH system (Fig. 7a), and after applying suitable particle loss corrections to account for the different sample line supplying the MSS2 (estimated to introduce up to 7 % additional loss using the PSD_B method (Durand et al., 2023)), the MSS and MSS2 showed good agreement. During RQL 1, the systematic difference was 3 % with 8 % variability (GMR = 0.97; 95 % CI = 0.96–0.98; GSD = 1.08). During RQL 2, the difference slightly increased to 6 % with 9 % variability (GMR = 0.95; 95 % CI = 0.91-0.98; GSD = 1.09), likely due to the MSS2 being re-calibrated prior to the campaign and to the more limited RQL 2 dataset which contained a higher proportion of low-mass datapoints when compared to RQL 1.

Within the EUR system (Fig. 7b), the systematic difference between the EUR MSS and LII 300 was 3 % with 30 % variability during RQL 1 (GMR = 1.03; 95 % CI = 0.98–1.08; GSD = 1.30) when using the applicable LII 300 calibration factor from 2020 (0.98). During RQL 2, the offset increased to 11 % with a decreased 8 % variability (GMR = 1.11; 95 % CI = 1.08–1.14; GSD = 1.09) when applying the same 2020 calibration factor. Applying the 2021-issued calibration factor (0.87) shifted the RQL 2 GMR from 1.11 to 0.99, consistent with the change in calibration factor, highlighting laboratory-to-laboratory variability as a significant contributor to nvPM

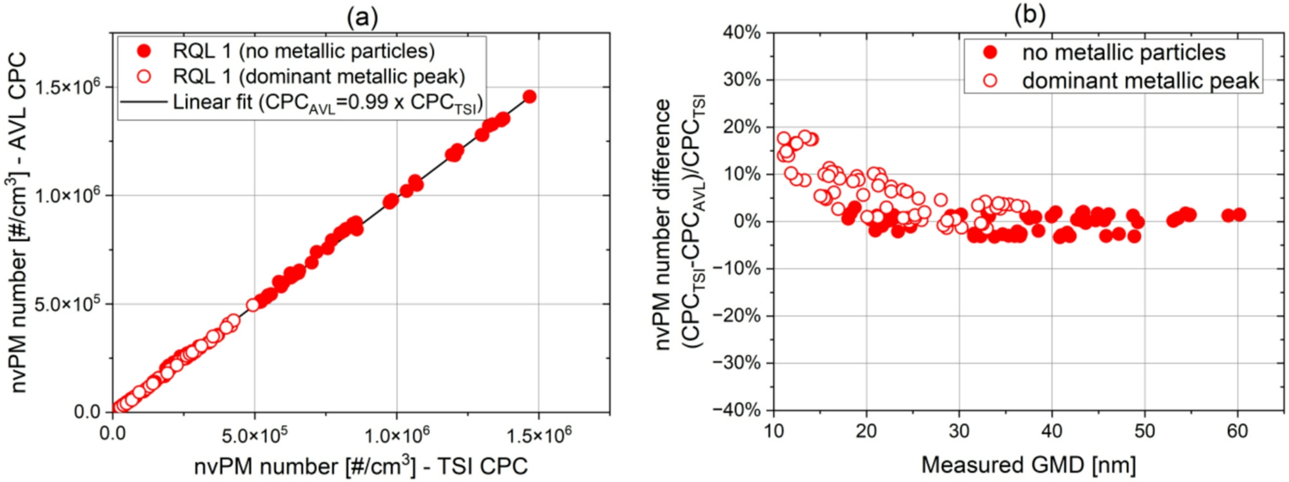

Fig. 5. nvPM number measured by the TSI CPC and AVL CPC within the same APC (a) and percent difference plotted against measured GMD (b) when sampling RQL 1 exhaust.

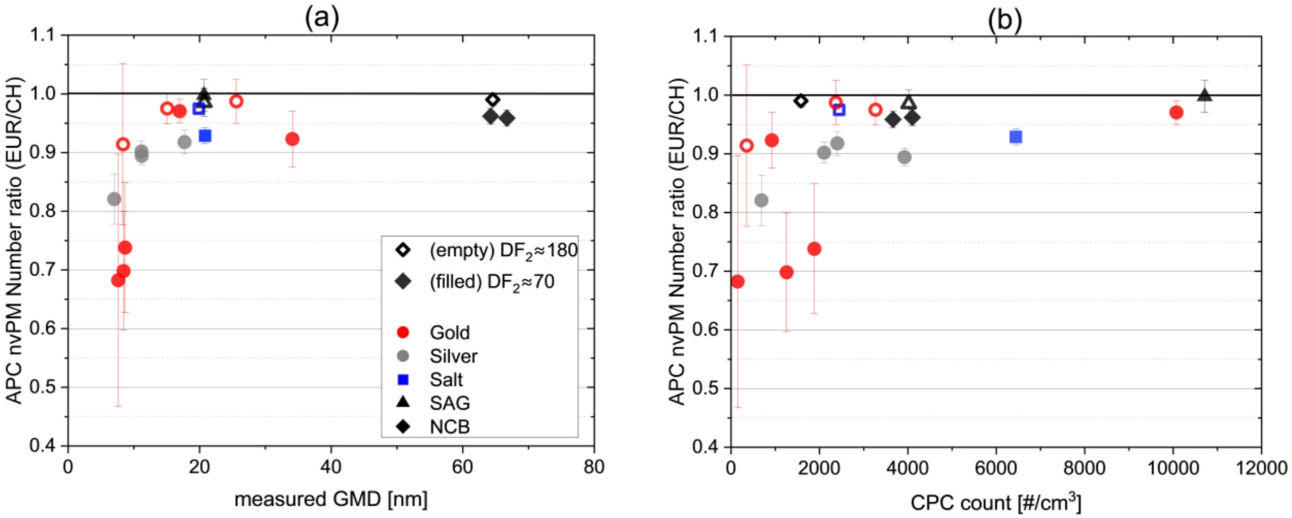

Fig. 6. Ratio of the CH and EUR APCs against GMD (a) and EUR APC total CPC count (b); the error bars represent ±1 standard deviation of the 1-min average.

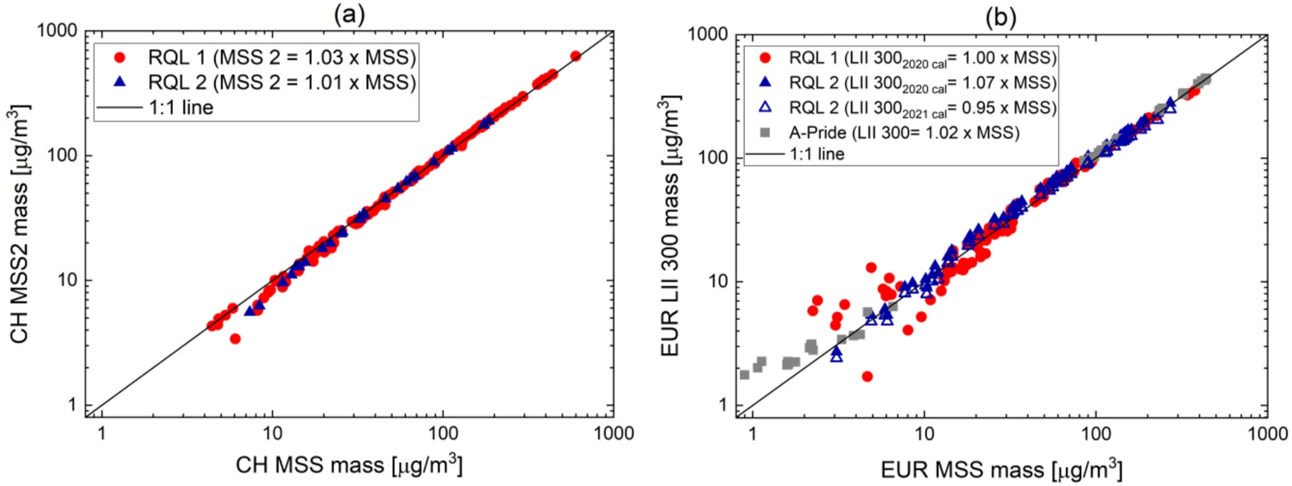

Fig. 7. nvPM mass measured by an MSS and MSS2 within the CH system (a) and nvPM mass measured by an MSS and LII300 in the EUR system (b) during different campaigns.

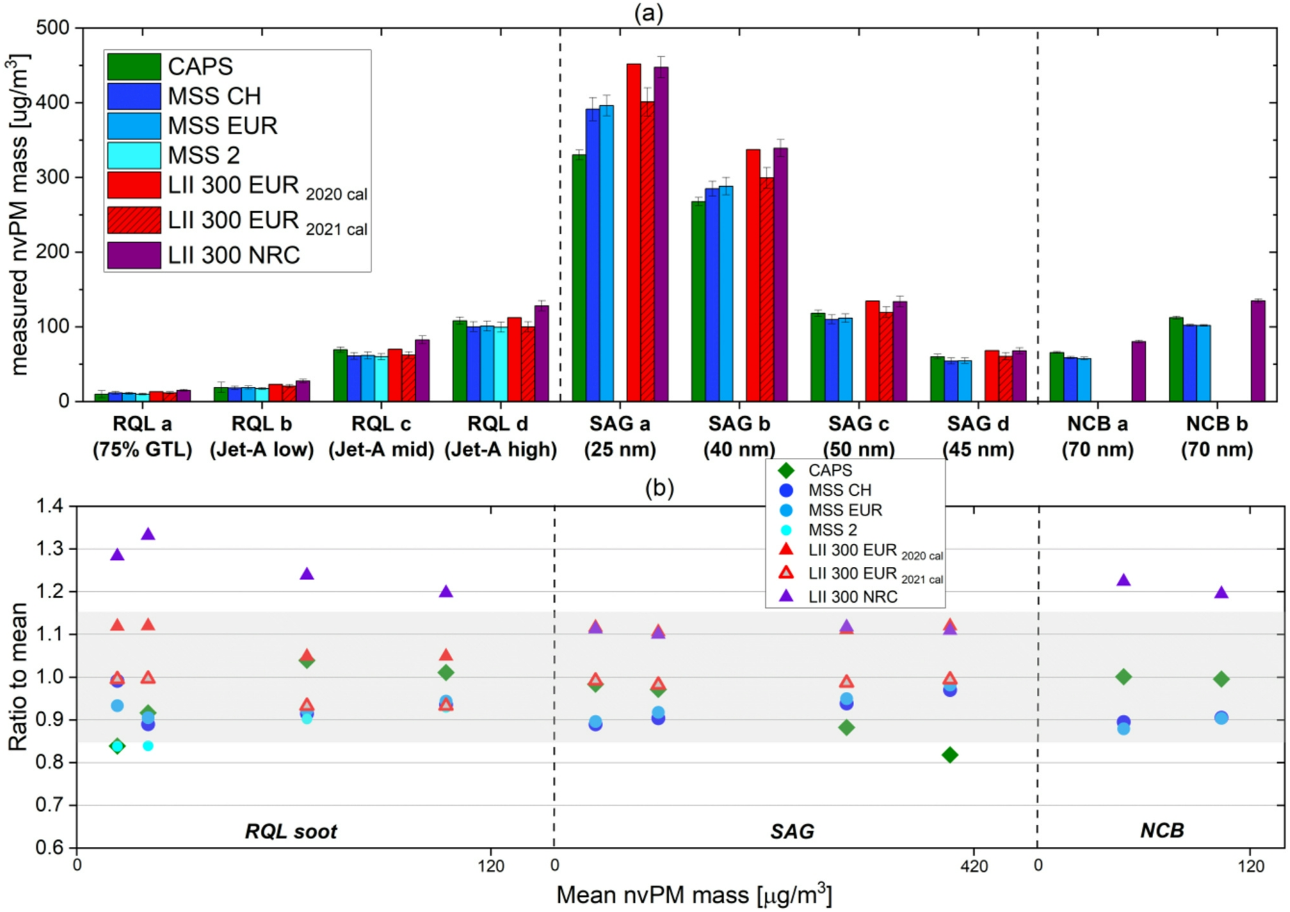

Fig. 8. Measured RQL exhaust nvPM mass for different analysers (a) and ratio to the mean plotted against the mean nvPM mass (b); the error bars represent ±1 standard deviation of the average.

mass calibration uncertainty, in line with the literature (Sipkens et al., 2024). Generally, these results show systematic differences between the EUR MSS and LII 300 consistently below 15 %, in agreement with published A-PRIDE 5 data (GMR = 1.18; 95 % CI = 1.08-1.30; GSD = 1.35) collected on a large turbofan engine using the same instruments in 2013 (Lobo et al., 2020), and with the wider literature (Kinsey et al., 2021), (Giannelli et al., 2024), (Corbin et al., 2022). Differences in GMR across campaigns are attributed to variations in nvPM mass concentration and the observed non-linearity between the MSS and LII 300 (see Fig. S3 in Section S4). The reduced variability during RQL 2 compared to RQL 1 and A-PRIDE 5 is attributed to improved cleanliness protocols, as witnessed in Fig. 4b and discussed in more detail in section 3.3.

A broader assessment of nvPM EI mass reproducibility was conducted at the start of RQL 2 through a multi-instrument intercomparison involving regulatory-compliant mass analysers calibrated at different times and in different laboratories and tested using multiple aerosol sources. This assessment included instruments not specifically calibrated to aircraft nvPM (CAPS) and others that were beyond their recommended 12-month calibration periods (EUR LII 300 with the 2020 calibration factor, NRC LII 300), although no significant drift was anticipated for these instruments. The instruments were compared across RQL exhaust, SAG (excluding MSS2 due to instrument issues), and NCB (excluding the EUR LII 300 for the same reason), with results shown in Fig. 8.

Across all tested particle types, with nvPM mass concentrations ranging from 10 to 450 μg/m^3 (Fig. 8a), the CH and EUR MSS showed excellent agreement with a systematic difference <1 % and a variability of 2 % (GMR = 1.00; 95 % CI = 0.98–1.02; GSD = 1.02), again indicating no measurable drift twelve months after their parallel AVL calibration on mini-CAST soot prior to RQL 1. Similarly, the MSS2, which was calibrated independently by AVL just before this intercomparison, showed good agreement with the both the CH and EUR MSSs (GMR = 1.06; 95 % CI = 1.01–1.11; GSD = 1.06), consistent with intra-comparison results shown in Fig. 7a. This level of agreement is well within the reported expanded uncertainty for EC reproducibility of 17 % (Sipkens et al., 2024), which also noted that EC uncertainty mostly arises from inter-laboratory variability. It is also noted that the MSS2, while employing the same measurement cell design as the legacy MSS, uses different signal processing hardware.

The EUR and NRC LII 300 instruments, both calibrated on the same helicopter engine exhaust at the same time in 2020, showed a systematic difference of 14 % when measuring RQL soot and agreed within 1 % on SAG. However, when applying the more recent calibration factor to the EUR LII 300 derived by a different laboratory, the systematic difference increased to 24 % on RQL soot and 11 % on SAG, further highlighting the contribution of laboratory-to-laboratory variability to overall nvPM mass calibration uncertainty.

A comparison of all instruments against the mean, as shown in Fig. 8b, indicates a global variability of 12 % (GSD = 1.12) across all particle types and mass ranges. Exceptions were the NRC LII 300 on RQL soot and NCB, and the CAPS on SAG, which showed larger deviations from the mean. Although some of the variability between sources (RQL soot vs SAG vs NCB) may be attributed to differences in particle morphology and surface properties, with the LII 300 fluence optimised on aircraft soot, this does not account for the bias of up to 33 % observed on RQL soot at ~20 μg/m^3. This discrepancy is most likely attributable to laboratory-to-laboratory nvPM mass calibration uncertainty, as discussed previously. It is noted that while the MSS includes a partial in-field check (absorber window check), there are currently no in-field performance checks for LII 300 instruments. In this context, NCB particles may offer a simple and low-cost option for pre-test nvPM mass verification.

The poorer agreement observed with CAPS PM$_{SSA}$ on SAG is likely due to the higher nvPM mass concentrations witnessed, approaching or exceeding the instrument's quoted measurement range of 0–1000 Mm^{-1}, equivalent to approximately 150 μg/m^3 for black carbon, beyond which saturation and optical limitations may occur (Onasch et al., 2015). It is also noted that it hadn't been specifically calibrated for aircraft nvPM.

Overall, this level of agreement aligns with the literature, where different instrument types often exhibit varying BC-to-EC ratios, depending on calibration procedures and emission sources (Giannelli et al., 2024), (Corbin et al., 2022). It is noted that the error bars, which reflect the stability of the source over the testing period, suggest no single shedding event occurred that disproportionately impacted one instrument over the others.

3.3. Regulatory nvPM mass measurements at low concentrations (Aim 4)

The increased variability observed at low measured nvPM mass (see Fig. 4b) was further investigated by comparing measurements from the raw and diluted sampling lines, where the concentrations are typically ten times lower, within both the EUR and CH reference systems. This approach enabled evaluation of the lower operational measurement limit and the influence of sampling system cleanliness, including particle shedding from the prescribed 1-μm cyclone, on nvPM mass quantification at low concentrations.

3.3.1. Impact of cyclone particle shedding and system cleanliness

The impact of system shedding on measured nvPM mass was assessed by conducting cleanliness checks more frequently during RQL 2 testing than regulation specifies (i.e., once prior to an engine test series). On a failed cleanliness check, the 1-μm cyclone collection pots were cleaned with isopropanol and cleaning tissue. Fig. 9a illustrates a measured nvPM mass timeseries between two test points whilst performing a zero check (i.e., sampling Nitrogen from the primary diluter), showing that carbonaceous particle shedding from the cyclone led to biased nvPM mass readings prior to cleaning, with an observed zero offset of ~3 μg/m^3. This effect was consistently observed by both the EUR and CH systems, particularly after a high-mass test points (~> 150 μg/m^3 measured) and/or a sudden rig pressure change. As previously discussed with Figs. 4b and 7b, the more frequent cleanliness checks and cyclone pot cleaning during RQL 2 also reduced nvPM EI mass scatter observed <30 μg/m^3 compared to RQL 1. In contrast, Gianelli et al. (Giannelli et al., 2024) found no evidence of particle shedding from the cyclone or other parts of their reference sampling system when sampling from a LGT-60 start cart and J85GE-5 turbojet engine, although their methodology only included daily pre-test zero checks. In explaining this apparent difference in observations, it is noted that more frequent shedding events were experienced from this small-scale

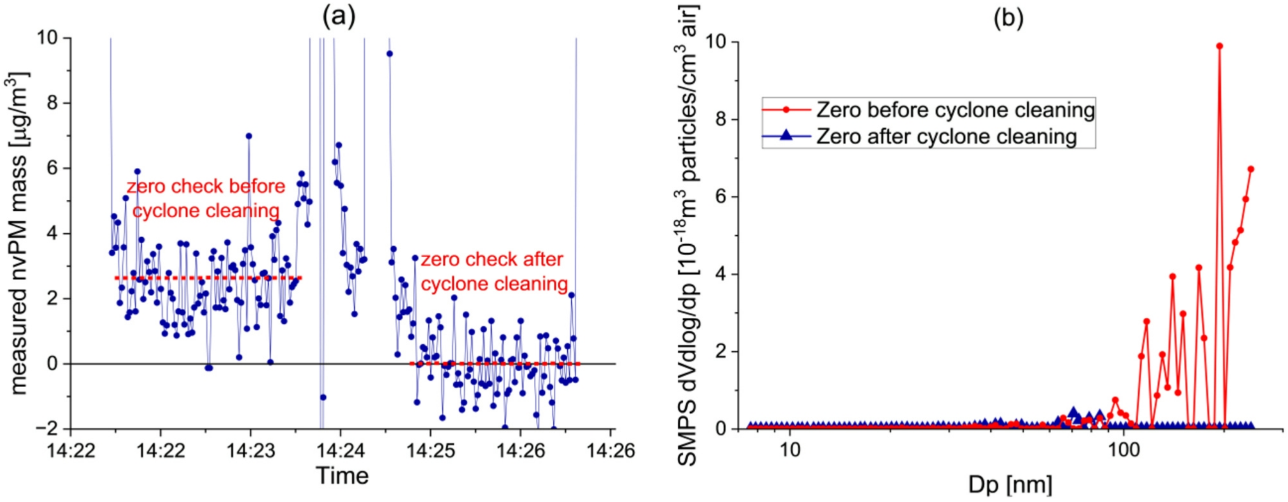

Fig. 9. Measured MSS nvPM mass against time between a cyclone cleaning period (a) and volume-space particle size distribution measured before and after cyclone cleaning (b).

non-proprietary RQL combustor rig following soot build-up on the combustor walls. Although shedding from the cyclone has been previously observed in the CH system during certification-like emissions measurement of commercial turbofan engines, nvPM concentrations are typically much more stable on engines compared to this combustor rig.

As would be expected, particle shedding was seen to impact only nvPM mass, as only small numbers of relatively large particles (>100 nm) were shed form the cyclone pot. This is evidenced by the volume-based SMPS size distributions which were measured behind the 1-μm cyclone before and after cleaning, with an example shown in Fig. 9b. It is noted that shedding occurs not only from the 1-μm cyclone but also from the sample lines, splitters, ejector diluter and probe, all of which require cleaning when a cleanliness check fails and cannot be resolved by cleaning the cyclone alone.

These findings highlight that more frequent cleanliness checks, not just prior to an engine test, should be considered to reduce regulatory nvPM mass uncertainty, particularly for low mass concentration test points following high-mass conditions (e.g., >150 μg/m^3). Alternatively, the cyclone design could be improved to minimise re-entrainment of captured large particles.

3.3.2. Limit of quantification (LOQ) for regulatory nvPM mass measurements

During RQL 2 testing, the regulatory nvPM mass LOQ was assessed by placing an additional NRC LII 300 on the raw gas sampling line of the EUR system for the entire campaign. Similarly, an additional MSS2 was installed on the CH system's raw line, but only during dedicated low-mass comparison tests. The measured nvPM mass was intentionally reduced towards the instrument LOD by controlling the air-to-fuel ratio (AFR) and by using a higher hydrogen content fuel within the RQL combustor. To afford a more accurate comparison, in addition to dilution correction, differences in system losses between the nvPM mass instruments located on the raw and diluted lines were corrected using method PSD_B (Durand et al., 2023). Notably, the NRC LII 300 was equipped with a 1-μm cyclone at its inlet, while the MSS2 was not.

Fig. 10 shows a 1 % systematic difference and 7 % variability between the diluted EUR MSS and raw-corrected NRC LII 300 (GMR = 0.99; 95 % CI = 0.96–1.02; GSD = 1.07). For measurements below 20 μg/m^3, raw-corrected and diluted nvPM mass measurements also agreed in both the EUR (MSS vs LII 300) and CH (MSS vs MSS2) systems (GMR = 0.94 and 0.98; variability = 7 % and 6 %, respectively), provided cleanliness checks were maintained. These findings confirm an nvPM mass LOQ of ≤3 μg/m^3 under improved cleanliness protocols and demonstrate the feasibility of undiluted-line mass measurements near the LOQ.

4. Summary and conclusions

Building upon previous system and instrument comparisons, such as SAMPLE, VARIAnT and A-PRIDE (Lobo et al., 2020), (Lobo et al., 2015), (Kinsey et al., 2021), this study identified and quantified uncertainties in regulated aircraft engine nvPM number and mass emissions. To achieve this, the nvPM number and mass measured by two regulatory-compliant systems were compared immediately after a parallel calibration and again twelve months later. The primary experiments were performed on exhaust from a non-proprietary RQL combustor, which produced nvPM sizes and concentrations representative of the commercial aircraft fleet. Laboratory intercomparison experiments were also undertaken on various sources.

Shortly after parallel calibration of identical instrument technologies, a 6 % systematic difference with 7 % variability for nvPM EI number and a 13 % bias with 19 % variability for nvPM EI mass were observed (RQL 1). Twelve months later, improved sampling and cleanliness protocols reduced these differences to <1 % with 3 % variability for nvPM EI number and 3 % bias with 8 % variability (RQL 2). These results demonstrate that calibration, instrumentation, and cleanliness practices are major contributors to uncertainty in current regulatory nvPM measurements.

No observable drift was detected within the recommended twelve-month calibration interval for either nvPM number or mass instrument, despite extensive and different usage and transportation of both reference systems between RQL 1 and RQL 2 testing. This was further supported by post-RQL 2 as-found verifications of the CH and EUR APCs, which showed differences of <3 % in counting accuracy and <1 % in counting efficiency at 10 nm compared to their original 2020 calibration prior to RQL 1. These findings demonstrate that both nvPM mass and number instruments can maintain measurement accuracy beyond the prescribed calibration interval. However, in-field performance checks prior to testing remain essential to ensure continued reliability. It is noted that CPCs within aviation regulatory nvPM systems generally have lower usage compared to those used in automotive regulation or atmospheric research, where high usage, continuous operation and relatively higher levels of volatile particles may result in more significant drift (Giechaskiel & Bergmann, 2011).

Larger discrepancies of up to ~45 % were witnessed between the EUR and CH nvPM number instruments when sampling non-soot particles at or below the regulatory-specified 50 % CPC counting efficiency (10 nm), even though they were virtually identical instruments calibrated in parallel. These results imply that the particle morphology and surface properties needs to be considered when defining CPC calibration protocols. Using aviation representative nvPM particle type during CPC calibration and/or prescribing a lower CPC D_{50} and D_{90} (e.g., $D_{50} > 4$ nm instead or the current 10 nm) would help reduce this uncertainty. Also, larger discrepancies (+2 %) would have been reported between the EUR and CH measured nvPM EI numbers if CPC counting accuracies derived from calibration had not been corrected via the k-factor. Although current regulations require CPC counting accuracy within ±10 % from 2000 particles/cm^3 to the upper limit of single particle count mode against a traceable standard, they do not mandate corrections for these discrepancies. While some instruments, such as APCs, apply k-factor corrections automatically, others may not. Therefore, a systematic application of the counting accuracy is recommended. It is also noted that the VPRs used in this study were of the same type and exhibited similar particle losses. Greater discrepancies would be expected if different VPR types were used, as particle loss differences of up to 25 % have been reported between designs (Durand et al., 2025).

Laboratory and intra-system nvPM mass comparisons showed 12 % variability and biases up to 33 %, likely driven by calibration-

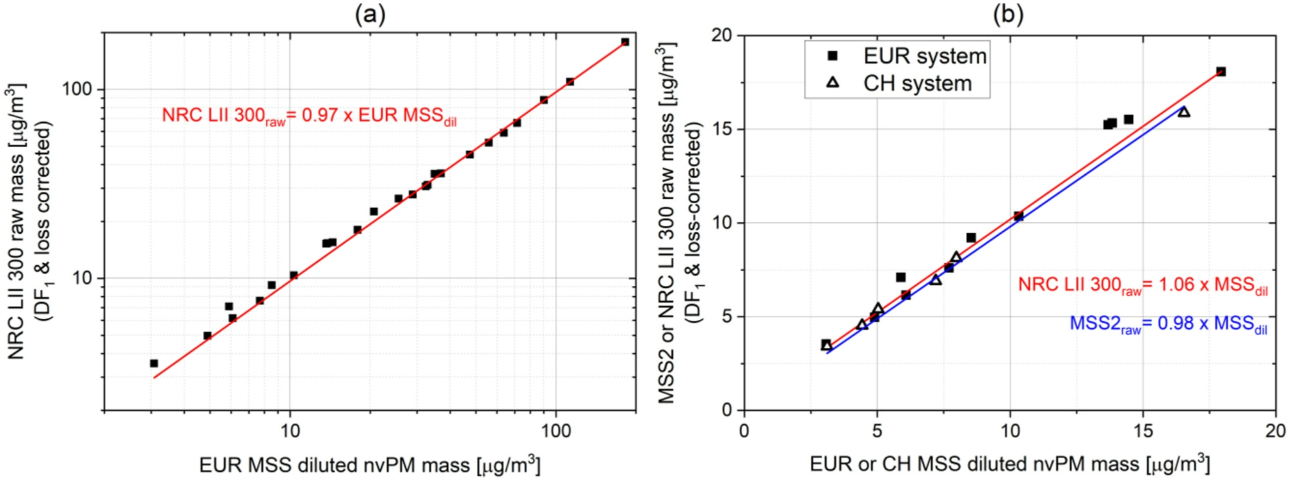

Fig. 10. Diluted vs raw-corrected nvPM mass measured in the EUR and CH system over different mass ranges ((a) EUR system 3–200 μg/m^3; (b) EUR and CH systems <20 μg/m^3).

factor uncertainty (laboratory-to-laboratory variability). Current regulation specifies a filter-based thermal optical transmittance calibration method against EC, which has known reproducibility limitations (17% (Sipkens et al., 2024)), and differs in definition from nvPM. Operator procedures and sampling protocols can also significantly influence results (Durand et al., 2025). Additionally, differing responses of mass instruments to various nvPM types and morphologies further increase measurement uncertainty.

Investigations into nvPM mass LOQ and sampling system cleanliness confirmed that regulatory nvPM mass can be accurately measured down to $\leq$3 μg/m^3 when improved sampling and cleanliness protocols are applied. Without such measures, increased variability was observed below ~30 μg/m^3 measured nvPM mass, consistent with previous studies (Lobo et al., 2020), (Giannelli et al., 2024), with particle shedding from the prescribed 1-μm cyclone collection pot contributing to this uncertainty. However, it is noted that these observations are made on a small-scale research combustor rig, which is more prone to soot buildup and instabilities that cause shedding, rather than on a full-scale commercial engine. This study also demonstrated the feasibility of performing nvPM mass measurements directly on the raw line. While current regulations mandate only a single cleanliness check prior to testing, our findings indicate that more frequent cleanliness checks should be considered, particularly when measuring low nvPM emission levels typical of modern engines and sustainable aviation fuels. These results informed recent updates in ARP6320B (SAE International, 2024a), which now includes guidance for increased cyclone cleaning frequency.

The key findings and recommendations from this study are as follows.

- Calibration and instrument-technology uncertainty are the dominant to current regulatory nvPM number and mass uncertainty, while sampling uncertainty is comparatively minor (**Aim 1**).
  - Mandating CPC counting accuracy correction using the calibration-derived k-factor, consistent with the recent Automotive PMP guidance (UN Regulation No), would reduce regulatory nvPM number measurement uncertainty (**Aim 3**).
  - Further consideration of the calibration material used for CPC calibration is warranted, as small metallic particles have been shown to cause discrepancies between identical CPC models calibrated in parallel using Emery oil. Using a calibration particle type that better represents real-world aircraft nvPM provides a more accurate basis for CPC counting efficiency. Alternatively, reducing the CPC D_{50} and D_{90} thresholds (e.g., adopting a $D_{50} > 4$ nm instead of the current 10 nm) for a given calibration material could help ensure near-100% counting efficiency for aircraft nvPM sampling, thereby reducing associated uncertainty (**Aim 3**).
- No measurable instrument drift was observed over the twelve-month calibration period for either nvPM number or mass instruments (**Aim 2**).
- The regulatory measured nvPM mass LOQ is $\leq$ 3 μg/m^3 (**Aim 4**). However, particle shedding can significantly bias nvPM mass measurements near this threshold. Cleanliness checks should be performed more frequently, particularly following high mass concentration testing or significant pressure changes in the sampling system.

This study highlights that the current uncertainty associated with the sampling and measurement of regulatory nvPM number and mass is in the order of tens of percent. However, it is important to note that size-dependent system loss correction introduces substantially greater uncertainty when regulating engine-exit representative nvPM emissions, with correction factors of up to 7.8 (680% increase) for number and 2.5 (150% increase) for mass reported in the literature (Durand et al., 2023). These corrections, while currently recommended for reporting, are not mandated and represent a key area for future regulatory development.

CRediT authorship contribution statement

Eliot Durand: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lukas Durdina:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joseph Harper:** Writing – review & editing, Investigation, Data curation. **Curdin Spirig:** Investigation. **Manuel Roth:** Investigation. **Greg Smallwood:** Writing – review & editing, Methodology, Investigation, Data curation. **Mark Johnson:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fergus O.N. Lidstone-Lane:** Writing – review & editing, Visualization, Investigation. **Paul I. Williams:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Andrew Crayford:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaerosci.2026.106789.

Data availability

The data used in this manuscript is available as an attachment (Excel spreadsheet “RAPTOR paper Figures data_V2”) and online (https://doi.org/10.5281/zenodo.19096201). Additional data and information can be provided upon request.

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