

New standardized test methods for air cleaners – Influence of measurement instrumentation and test aerosol

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ABSTRACT

In 2024, IEC 63086-2-1 was published as the first international testing standard for evaluating the performance of air cleaners with particulate pollutants. For particles from 0.1–1 µm, the standard requires Optical Particle Size Spectrometers (OPSS), while total number concentrations including ultrafine particles <0.1 µm are measured with Condensation Particle Counters (CPC). However, the standard does not prescribe specific instrument models. It also allows cigarette smoke or potassium chloride (KCl) as interchangeable test aerosols and leaves neutralization of KCl particles optional. The influence of these flexibilities on measurement results has not yet been systematically investigated.

Therefore, in this study three air cleaners with different filter types were therefore examined: an H13 filter according to EN 1822-1, a typical electret filter, and a fully discharged electret filter with pronounced particle size dependence. Measurements followed IEC 63086-2-1 using ten instruments in parallel, including a CPC, five OPSS models, a Mobility Particle Size Spectrometer (MPSS), a Fast Mobility Particle Sizer (FMPS), and two instruments based on unipolar diffusion charging. Tests were conducted with cigarette smoke and with neutralized and non-neutralized KCl particles.

For the integrated size range from 0.3 µm to 1 µm, all OPSS agreed well, typically within 5 % deviation in Clean Air Delivery Rate (CADR). Including particles down to 0.1 µm led to larger differences due to varying counting efficiencies near detection limits. MPSS with bipolar neutralization also proved suitable despite lower time resolution, whereas the FMPS showed notable deviations and unipolar diffusion chargers yielded inconsistent results between manufacturers.

Comparisons between cigarette smoke and KCl revealed partially significant differences, indicating that the aerosols are not fully interchangeable. Unexpectedly, such differences also appeared for the H13 filter, where they should theoretically be negligible. Neutralization of KCl particles showed no significant influence on the derived CADR. These results provide input for the ongoing revision of IEC 63086-2-1 and for studies using different measurement techniques.

KEYWORDS

indoor air cleaners, standardization, ultrafine particles, Clean Air Delivery Rate (CADR), test method

1 Introduction

In 2024, IEC 63086-2-1 was introduced as the first international standard specifying test procedures for evaluating the performance of air cleaners in removing particulate pollutants. The central metric for rating the cleaning performance is the Clean Air Delivery Rate (CADR), which equals the volume of clean air per time interval provided by the air cleaner. It is typically determined as an integrated value for a specific test aerosol in given particle size ranges. For particle measurements in the size range of 0.1 μm to 1 μm , the standard requires the use of Optical Particle Size Spectrometers (OPSS), while total particle number concentrations, including ultrafine particles below 0.1 μm , are determined using Condensation Particle Counters (CPC). However, the standard does not prescribe specific instrument models. In addition, it permits the use of either cigarette smoke or potassium chloride (KCl) as equivalent test aerosols and, in the case of KCl, allows the particles to be tested either with or without prior neutralization. To date, no systematic investigation has been conducted to assess how these choices regarding measurement instruments, test aerosols, and particle neutralization may influence the resulting performance data. Therefore, the objective of the present study was to examine these aspects through a comparative laboratory investigation.

2 Experimental Setup

2.1 Investigated air cleaners

Since the impact of the selected measurement method is expected to depend on the particle size dependence of the air cleaner's filtration efficiency, three filtration scenarios with increasing size selectivity were investigated. An overview about the appliances is listed in Table 1. In the following, the abbreviations A, B and C will be used for the three air cleaners. To preserve anonymity, the manufacturers and specific model names are not reported.

Table 1 *Investigated air cleaners*

Air cleaner	Filter type
A	H13 filter
B	New electret filter
C	Discharged electret filter

As a reference case, an air cleaner equipped with an H13 filter according to EN 1822-1 was tested. Such filters exhibit a minimum filtration efficiency of at least 99.95 % at the most penetrating particle size (MPPS), while the efficiency approaches 100 % for both smaller and larger particles. Consequently, the filtration efficiency is nearly independent of particle size. Under these conditions, any stronger differences observed in the CADR when using different measurement instruments or test aerosols cannot be attributed to variations in filtration efficiency with particle size and must therefore orig-

inate from the measurement approach itself. Conversely, an absence of observed differences would not necessarily demonstrate equivalence of the methods, as potential systematic biases could remain hidden due to the almost uniform filtration efficiency.

To investigate the influence of particle size-dependent filtration efficiency, a second air cleaner was tested with two versions of the same filter. First, measurements were performed using the original electret filter, representative of the filter technology commonly employed in residential air cleaners. Such filters exhibit a moderate particle-size dependence of typically a few percent in the region of the MPPS. Second, the filter was discharged by exposure to isopropyl alcohol (IPA)-saturated air for 24 h, thereby removing its electrostatic charge. After discharge, particle removal is governed solely by mechanical filtration mechanisms, resulting in both lower overall efficiency and a more pronounced particle size dependence.

Together, these three filtration scenarios – H13 filter, charged electret filter, and discharged electret filter – provide a systematic range from almost size-independent to strongly size-dependent filtration behavior. This allows to access the influence of measurement instrumentation and test aerosol on the determined CADR under ideal, typical and worst-case conditions.

2.2 Investigated measurement instruments

Table 2 provides an overview of all measurement instruments used in this study. To assess the influence of instrument choice within the framework of IEC 63086-2-1, five Optical Particle Size Spectrometers (OPSS) from different leading manufacturers were investigated: Grimm MiniWRAS, Palas welas digital 3000, Palas Fidas Frog, Topas LAP 323, and TSI 3340A. Among these instruments, only the TSI 3340A covers the particle size range specified in IEC 63086-2-1 from 0.1 to 1 μm . The remaining instruments have larger D50 values (particle diameter at 50 % counting efficiency). However, all investigated OPSS cover the alternative size range from 0.3 to 1 μm defined in Annex I of IEC 63086-2-1, which was introduced to accommodate a broader range of commercially available instruments.

For some OPSS, external diluters were required because the instruments are not capable of directly measuring the initial particle concentrations specified in the standard. In addition to the five OPSS, a Condensation Particle Counter (CPC) was used to determine the total particle number concentration in accordance with IEC 63086-2-1. As the primary focus of this study was on the influence of the OPSS, only one representative CPC model, the butanol-based TSI 3776, was employed.

Beyond the measurement techniques specified in the standard, two alternative particle characterization approaches were investigated to evaluate their suitability for CADR determination. The first approach is based on particle classification according to electrical mobility and was represented by a Mobility Particle Size Spectrometer (MPSS; TSI 3080/3081) and a Fast Mobility Particle Sizer (FMPS; TSI 3091). Both instruments are widely used for measuring particles below the size range accessible by optical

methods and may therefore represent potential alternatives for future CADR measurements. Although neither instrument fully covers the upper particle size limit of 1 μm specified in IEC 63086-2-1, the contribution of particles in this size range to the total number concentration of the test aerosols is negligible. Consequently, this limitation is not expected to significantly affect size-integrated CADR values.

A second alternative approach is based on diffusion charging and called in the following Diffusion Charging Aerosol Monitor (DCAM). This type of instruments was investigated using the naneos Partector 2 Pro and the Grimm MiniWRAS, the latter of which also contains an OPSS. Recent studies have shown that diffusion charging instruments can provide reasonably accurate estimates of total particle number concentration and particle size distributions. Like the mobility-based instruments, their inability to measure particles up to 1 μm is not expected to substantially influence the resulting CADR values. Since diffusion charging instruments are typically less expensive and easier to operate than the previously described systems, they may represent a particularly attractive alternative for future CADR measurements.

Table 2 *List of investigated measurement instruments with their basic properties*

Type	Manufacturer	Instrument	Short name	Size range (μm)	Dilution
OPSS	Grimm	MiniWRAS 1371 ^[1]	MINIWRAS	0.253 – 35.15	1:10
OPSS	Palas	welas digital 3000	WELAS	0.2 – 10	none
OPSS	Palas	Fidas Frog	FIDAS	0.178 – 17.8	none
OPSS	Topas	LAP 323	LAP	0.15 – 40	1:10
OPSS	TSI	LAS 3340A	LAS	0.09 – 7.5	1:3.3
CPC	TSI	3776	CPC	>0.0025	none
MPSS	TSI	3080/3081	SMPS	0.011 – 0.478 ^[3]	none
FMPS	TSI	3091	FMPS	0.0056 – 0.56	none
DCAM	Grimm	MiniWRAS ^[2]	MINIWRAS	0.01 – 0.193	1:10
DCAM	naneos	Partector 2 Pro	PARTECTOR	0.01 – 0.3	none

^[1] OPSS part ^[2] DCAM part ^[3] for the chosen flow and scan settings

2.3 Test procedure

All measurements were conducted in a test chamber complying with the requirements of IEC 63086-1. The internal dimensions of the chamber are 3.45 m $\times$ 3.40 m $\times$ 2.50 m, corresponding to a volume of 29.32 m³. The chamber walls were lined with antistatic foil to minimize electrostatic particle losses. Prior to each experiment, the background particle concentration was reduced below the limit specified in IEC 63086-2-1. Temperature and relative humidity were adjusted to (23 $\pm$ 3) $^{\circ}\text{C}$ and (50 $\pm$ 10) %RH, respectively, using an air-conditioning system and a portable humidifier. During the actual test period, the secondary air cleaner, air-conditioning system, and humidifier were switched off.

Cigarette smoke was generated by burning a 3R4F reference cigarette in a custom-built smoking generator and introduced into the chamber through a Venturi nozzle until the required initial particle concentration was reached. The aerosol was not neutralized as it is not required by the standard. Additionally, KCl particles were generated from a 50 g L⁻¹ aqueous solution using an atomizer (Palas AGK 2000) and subsequently dried by dilution with dry air. As the standard leaves the flexibility, the KCl aerosol was either neutralized using an ⁸⁵Kr neutralizer (TSI 3012A) or directly introduced into the chamber without charge neutralization.

Following aerosol generation, the test aerosol was mixed for 1 min using a centrally mounted ceiling fan and subsequently homogenized for additional 3 min using a wall-mounted recirculation fan. In accordance with IEC 63086-2-1, the recirculation fan remained in operation throughout the entire test period.

After homogeneous mixing of the test aerosol had been achieved, either the air cleaner under investigation was switched on and the resulting concentration decay was monitored (total decay test), or the concentration evolution was measured without operation of the air cleaner to determine the natural decay rate (natural decay test). The measurement instruments were located either directly inside the chamber or externally with sampling lines extending into the chamber. In both cases, comparable sampling locations were used for all instruments. Natural and total decay curves were recorded for 60 min, exceeding the maximum test duration of 20 min specified in IEC 63086-2-1, to obtain additional information on the long-term decay behavior.

2.3 Data base and evaluation

For each test aerosol (non-neutralized cigarette smoke, neutralized KCl, and non-neutralized KCl), at least three natural decay measurements were performed. For air cleaners A and C, at least three repeated CADR measurements were conducted using non-neutralized cigarette smoke and KCl particles. Additional measurements with neutralized KCl particles were performed only for air cleaner B, as the influence of particle charge is expected to be most pronounced for electret-based filtration. Details on the number of measurements conducted under each test condition are provided in Table 3.

Table 3 *Test runs for the different configurations*

Test aerosol	Natural decay	Air cleaner A	Air cleaner B	Air cleaner C
KCl neutralized	3	6	5	3
KCl not neutralized	3		3	
Smoke not neutralized	4	3	4	4

In total, the experimental design comprised 38 individual test runs, which ideally corresponded to 380 decay curves recorded by the ten measurement instruments. Owing to occasional technical issues, such as connectivity failures or data acquisition errors,

only 339 complete decay curves were available for evaluation, corresponding to a data completeness of 89 %.

The temporal evolution of the particle number concentration $C(t)$ was fitted using an exponential decay model

$$C(t) = C_o e^{-kt}$$

where C_o is the initial particle concentration and k is the decay rate constant. Depending on the test condition, the fitted decay rate represents either the total decay rate k_{tot} or the natural decay rate k_{nat} . The CADR was subsequently calculated from the difference between the total and natural decay rates according to

$$CADR = (k_{tot} - k_{nat}) \cdot V$$

where V denotes the volume of the test chamber.

The exponential decay model was applied either to individual size channels or to particle number concentrations integrated over selected size ranges:

- **Standard fine particle size range (0.1 μm – 1 μm):** LAS, SMPS, FMPS, MINIWRAS, and PARTECTOR. Except for the LAS, the instruments do not fully cover the upper limit of 1 μm . However, as discussed above, the resulting bias is expected to be negligible because particle number concentrations in this size range are very low.
- **Alternative fine particle size range (0.3 μm – 1 μm):** All instruments except PARTECTOR and CPC. Again, the incomplete coverage up to 1 μm for some instruments is not expected to significantly affect the results due to the negligible contribution of particles near the upper size limit.
- **Total particle number concentration:** CPC, SMPS, FMPS, MINIWRAS, and PARTECTOR. Although the CPC covers a wider particle size range than the other instruments, the influence on the integrated concentration is expected to be small because particle number concentrations are low at both extremes of the size distribution.

3 Results

3.1 Decay curves

Figure 1 shows exemplary decay curves measured for neutralized KCl particles during operation of air cleaner A for the three integrated size ranges investigated. The decay curves for the other air cleaners show in principle the same behavior with different overall decay rates. For the 0.1 μm – 1 μm size range, the initial particle number concentrations are in good agreement across all instruments. A similarly good agreement is observed for the 0.3 μm – 1 μm size range, except for the FMPS, which reports

substantially lower concentrations. This deviation can be attributed to an underestimation of particle concentrations in the size range between 0.1 μm and 0.3 μm .

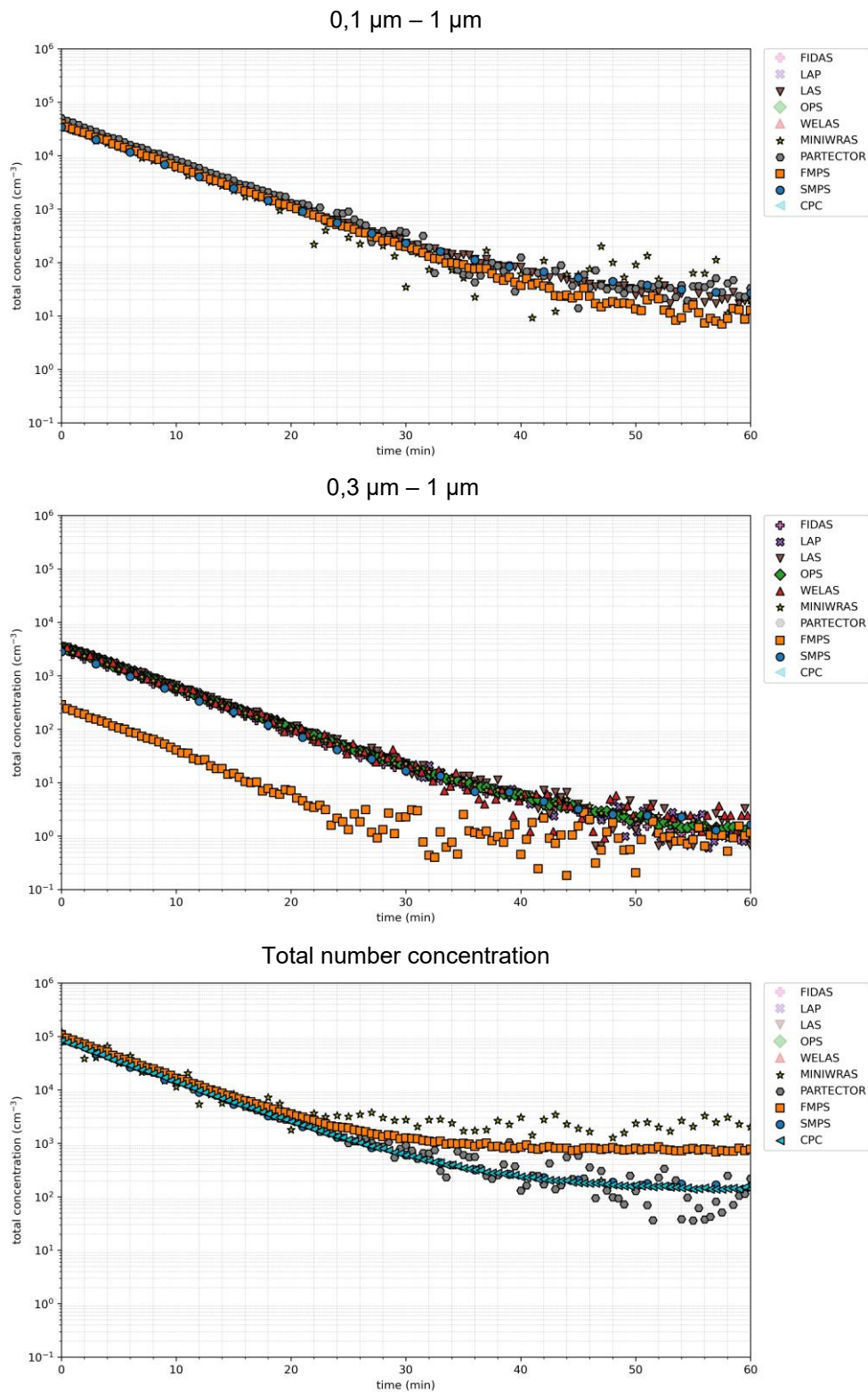


Figure 1 Exemplary individual decay curves for the three different integrated size ranges measured in parallel with different measurement instruments.

More pronounced differences become apparent after approximately 20 min, when particle concentrations have decreased substantially. For all instruments, deviations from the ideal exponential decay behavior are observed. In the logarithmic representation, a purely exponential decay would appear as a straight line. Instead, the decay curves gradually level off and approach an apparent equilibrium concentration. This behavior suggests the presence of a weak particle source within the system. Possible explanations include particle ingress from outside the test chamber or particle emissions from the air cleaner itself.

The effect is particularly pronounced for the FMPS and the diffusion-charging channel of the MINIWRRAS, both of which reach higher apparent equilibrium concentrations than the other instruments. It can be explained by a small offset in the measured electrometer current, resulting in an artificial residual particle size distribution even at very low particle concentrations. In principle, such artefacts could be reduced by appropriate background correction procedures.

Overall, these results support the specification of a maximum test duration of 20 min in IEC 63086-2-1. Extending the exponential fit to longer measurement durations may increase the influence of instrumental artefacts and non-ideal decay behavior, potentially resulting in poorer fit quality and an underestimation of the CADR.

3.2 Size-dependent CADR

Figure 2 shows the size-resolved CADR of the three air cleaners. The reported values were obtained by averaging all equivalent test runs and using the mean natural decay rate. The shaded areas indicate the range between the minimum and maximum CADR values obtained from the individual measurements. Artefacts at the smallest and largest particle sizes, originating from low particle counts in these size ranges, have not yet been removed.

A pronounced decrease in CADR towards the smallest investigated particle sizes is observed for both air cleaners A and B. This is surprising for air cleaner A, which is equipped with an H13 filter and would therefore be expected to exhibit almost no particle size dependence. The origin of this effect is currently unclear. One possible explanation is the presence of small internal leakages or bypass flows that introduce a particle size dependence independent of the filter efficiency itself. For air cleaner B, a certain particle size dependence is expected due to the use of an electret filter. To further investigate this hypothesis, the fractional filtration efficiency curve of the filter will be measured in a dedicated test rig according to ISO 11155-1 and compared with the observed CADR curve. Air cleaner C exhibits a more pronounced size dependence with the MPPS around $0,2\ \mu\text{m}$, which is generally consistent with the behavior expected for a discharged electret filter.

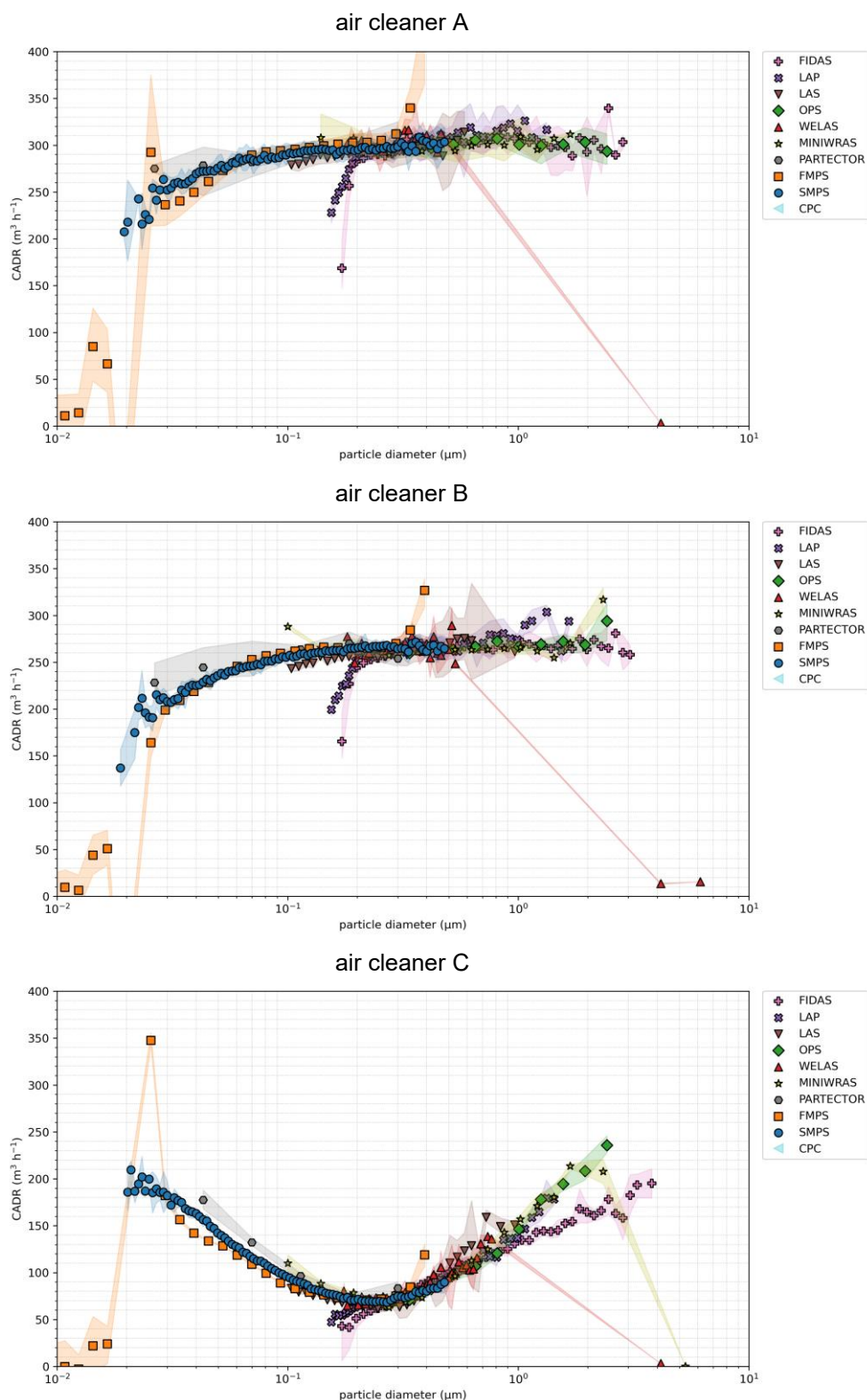


Figure 2 Size-dependent CADR of the three air cleaners after subtraction of the natural decay, here exemplarily shown for neutralized KCl particles.

A second noteworthy observation is the substantial decrease in CADR below approximately 0.2 μm for the LAP and FIDAS instruments. Although the counting efficiency of these instruments is known to decrease significantly in this size range, this alone should not affect the calculated CADR, provided that the counting efficiency remains

independent of particle concentration. The observed behavior therefore suggests the presence of additional effects, such as concentration-dependent counting efficiencies or other measurement artefacts. Further investigations are required to identify the underlying cause.

3.3 Size-integrated CADR

The evaluation of the integrated CADR values for the different particle size ranges is still ongoing. In the following, preliminary results are presented for the size range from $0.3\ \mu\text{m}$ to $1\ \mu\text{m}$, which is covered by most of the investigated measurement instruments. Figure 3 provides an overview of the results obtained for the seven investigated combinations of air cleaners and test aerosols. Overall, the different measurement techniques show good agreement, with deviations typically remaining within $\pm 5\%$. The only notable exception is the FMPS, which in some cases yields substantially different CADR values. This may be related to the previously mentioned background artefacts and could potentially be improved by applying an instrument-specific background correction. However, such a correction would require additional measurements under particle-free conditions for each test run. Consequently, the FMPS appears less suitable for routine CADR measurements. In contrast, the SMPS, which is currently not included as an alternative measurement technique in IEC 63086-2-1, yields CADR values that are highly consistent with those obtained from the OPSS instruments.

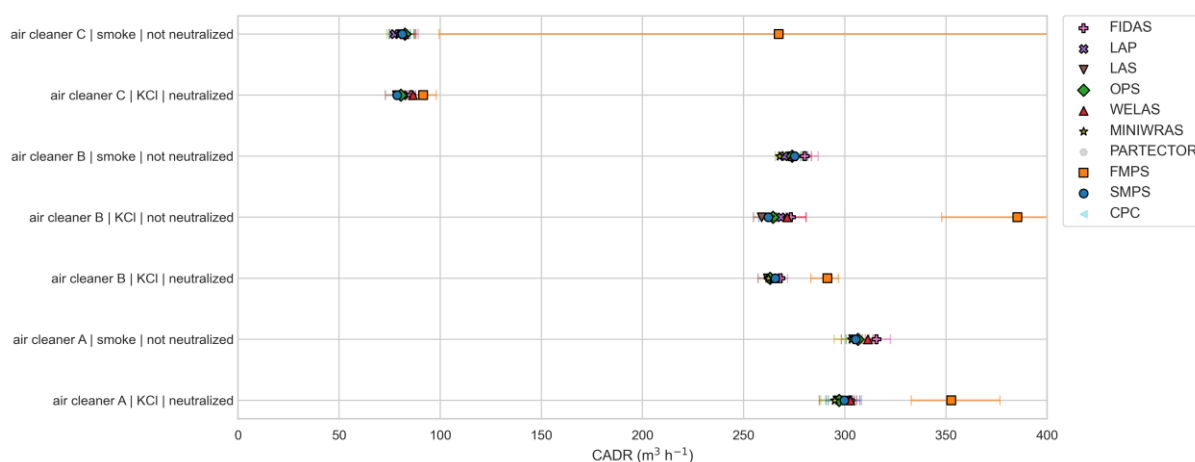


Figure 3 Integrated CADR values for the size range from $0.3\ \mu\text{m}$ to $1\ \mu\text{m}$ for the different investigated combinations of air cleaner and test aerosol measured with different instruments.

A comparison of the different test aerosols reveals significant differences between KCl and cigarette smoke for air cleaners A and B, whereas no comparable effect is observed for air cleaner C. The results for air cleaner A are particularly unexpected, as the H13 filter should exhibit a filtration efficiency close to 100 % across the investigated particle size range and therefore be largely insensitive to differences in aerosol properties. The underlying cause remains unclear and requires further investigation. Conversely, the absence of significant differences for air cleaner C, despite its pronounced

particle size dependence, may be explained by the position of the test aerosol size distributions relative to the most penetrating particle size (MPPS). A more detailed analysis is required to verify this hypothesis.

The comparison between neutralized and non-neutralized KCl particles for air cleaner B did not reveal any systematic differences in the resulting CADR values. However, a larger scatter was observed for the non-neutralized particles. These findings suggest that the optional use of particle neutralization in IEC 63086-2-1 does not introduce a significant systematic bias. Nevertheless, particle neutralization appears advantageous, as it improves the reproducibility of measurements.

4 Summary and outlook

This study investigated the influence of measurement instrumentation, test aerosol, and particle neutralization on CADR determination according to IEC 63086-2-1. Three air cleaners representing different filtration technologies were tested using ten particle measurement instruments for different aerosols and charge stages. For the integrated particle size range from 0.3 μm to 1 μm , the investigated OPSS showed good agreement, with CADR deviations typically below 5 %. An MPSS provided comparable results, whereas the FMPS and diffusion-charging-based instruments exhibited larger deviations. Significant differences were observed between cigarette smoke and KCl aerosols for some air cleaners, indicating that the two test aerosols are not fully interchangeable. In contrast, particle neutralization had no systematic effect on the determined CADR values, although it improved measurement reproducibility. The results contribute to a better understanding of the uncertainties associated with CADR measurements and provide valuable input for the further development and application of IEC 63086-2-1.