Testing and comparing of portable air cleaners for indoor aerosol particle removal in laboratory environments

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Abstract. This study aims to test the performance of eight commercial portable air cleaner devices (ACDs) (i.e., ACD1-ACD8) in a standard test chamber (STC) to remove aerosols. The test has been performed according to ANSI/AHAM standard AC-1-2020, and also focus on the variation at particle size. In addition, it compares differences in clean air delivery rates (CADR) of three ACDs tested in the STC with results obtained from measurements in a large test chamber (LTC). Both tests were conducted in a controlled STC and LTC with a volume of 28.4 m^3 and 202.0 m^3, respectively. Multiple modes of each ACD were evaluated, with tests repeated three times for each mode. The results show the difference in performance of ACDs in terms of CADR, due to the specific technology used by ACD and the specifications of the system. Some devices were less able to remove the aerosols that were used as contaminant in this research. The results also show that there is an effect of the room size on the CADR performance, with larger effects at lower CADR values. Therefore, theoretical values from the standard should not be assumed as CADR values for performance in practice. The results of this paper are intended to support future experimental studies of aerosol removal using portable ACDs in more realistic situation, such as classrooms, to enable a comparison between theoretical and actual CADR values in practice.

Abbreviations	
ACD	Air cleaner device
AHAM	Association of home appliance manufacturers
APS	Aerosol particle sizer
CADR	Clean air delivery rate
LTC	Large test chamber
STC	Standard test chamber

1 Introduction

Indoor aerosol particles refer to tiny suspended particles (less than 10 micrometres in diameter) in the air within enclosed spaces, often composed of solid or liquid droplets [1-2]. Typical sources include cooking, combustion, smoking, some cleaning activities, and biological contaminants (such as exhaled breath aerosol) [3]. Exposure to these micron-scale particles is one of the most significant environmental risks people face [4]. Elevated indoor aerosol concentrations are associated with increased respiratory and cardiovascular health issues such as coronary artery disease, congestive heart failure, and chronic obstructive pulmonary disease [5], as well as the potential spread of airborne transmission diseases, for instance Chickenpox, Influenza, SARS-CoV-2 [6-7]. The negative impact is further exacerbated in poorly ventilated [8] or poorly air-cleaned indoor environments, where the aerosol particle concentration can accumulate, posing a higher risk to occupants. Therefore, maintaining proper ventilation or/and air cleanliness in indoor environments (such as residences, offices, classrooms, etc.) is crucial for mitigating the adverse effects of elevated aerosol concentrations and ensuring a healthier indoor environment.

In support to room ventilation, portable air cleaner devices (ACDs) can be a potential solution to reduce indoor aerosol concentrations and hence the spread of pathogens. ACDs can easily be introduced in an existing room and operated with flexible time schedules. The removal mechanisms of ACDs include (but are not limited to) filtration, ultraviolet germicidal irradiation, electrostatic precipitation, photocatalytic oxidation, and plasma, depending on the contaminant phase and the design of the system itself [9-10].

In the context of the global spread of COVID-19 disease, ACDs have been given a high level of attention and investment in the past few years. They have been used in many non-residential spaces like classrooms, gyms, and offices, often as a support to insufficient existing ventilation. Accordingly, some ACD manufacturers also aim to produce ACDs with a higher CADR for both residential and non-residential uses. However, little information regarding their performance is available beyond the general claims of the manufacturers.

Standardized test procedures, such as those outlined by the Association of Home Appliance Manufacturers

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(AHAM) [9] to obtain the clean air delivery rate (CADR), are commonly employed by manufacturers and researchers to assess the effectiveness of air cleaners. Previously studies have tested the performance of multiple types of ACDs using the ANSI/AHAM standard [11-12]. However, this standard, using a test chamber with a volume of 28.5 m^3 for assessing the efficiency of ACDs, has established boundaries in terms of measurability, with $CADR_{maximum}$ = 680 m^3/h for dust (with particle size in a range of 0.5-3 µm), 764 m^3/h for cigarette smoke (0.1-1 µm) and for pollen (5-11 µm). The performance of the ACDs may not be accurately evaluated using the chamber employed in the standard [9, 10, 13], if the performance of the ACDs is higher than the $CADR_{maximum}$. A previous study [13] enlarged the test chamber from 30 to 50 m^3 and compared the differences of the CADR values of multiple ACDs obtained by the two test rooms. This study followed the standard of KACA, SPS-KACA002-132 [14], which is different from the ANSI/AHAM standard [9]; and utilized potassium chloride as the particle source, which is different from the human exhaled breath aerosol or similar analogues.

Therefore, the present study aims (i) to gain further insight into the technical properties of commercial ACDs in the current market; (ii) to evaluate the performance of eight ACDs in reducing the concentration of aerosol particles similar to human exhaled breath aerosol particles, also as function of particle size; (iii) to compare the difference of CADR of the ACDs tested in a standard test chamber (STC) following the ANSI/AHAM AC-1-2020 standard [9] and in a large test chamber (LTC). The tests were conducted in a controlled STC with a volume of 28.4 m^3 and a controlled LTC with a volume of 202.0 m^3. The effectiveness is quantified by particle size resolved CADR.

2 Description of tested ACDs

Table 1 provides the technical properties of the eight ACDs tested in this study. These ACDs were provided by the manufacturers based on the assumption of application in a classroom. The ACDs are sorted based on the dimensions first, then type of air cleaning technologies, power consumption, and noise level. Note that some of the columns have "NA" values, indicating that no information is available for that particular specification. All the eight ACDs employ filtration as the main technology with two-layer or three-layer filters (up till HEPA). A HEPA grade of H14 is used in ACD1, ACD3, and ACD8. The grade of HEPA filters used in ACD2, ACD6, and ACD7 is not provided by the manufacturers.

All the eight ACDs have a minimum of two modes and a maximum of eight operational modes, depending on the type of the ACDs. All the ACDs used in the tests are newly produced. The only prior usage of the devices is for checkout.

Table 1. Technical properties of the commercial ACDs tested in this study.

ACD type	Dimensions (L×W×H) [m^3]	Type of air cleaning technologies	Power consum-ption [W]	Noise level [dB]
ACD1	0.63 × 0.29 × 1.05	1, 2	240	NA
ACD2	0.508 × 0.533 × 0.228	1, 3, 4,	5-100	38- 67
ACD3	0.703 × 0.59 × 1.36	1, 2	440	NA
ACD4	0.44 × 0.33 × 0.768	1, 5, 6, 7, 8	68	55
ACD5	0.44 × 0.33 × 0.80	1, 6, 7, 8, 9	68	NA
ACD6	0.69 × 0.57 × 1.17	1, 3, 4	88	48
ACD7	0.435 × 0.40 × 0.835	1, 3, 4	6-170	11-57
ACD8	0.69 × 0.63 × 1.30	1, 2	140-750	29-50

ACD technology：1. Pre-filter; 2. HEPA 14 filter; 3. HEPA filter: High efficiency particulate air filter; 4. Activated carbon filter; 5. Ultraviolet sterilization; 6. Anti-allergy filter; 7. Deodorization-filter; 8. Ultrafine particle free filter; 9. Ionizing

NA: Not available

3 Measurement tests in the STC

3.1 Measurement setup

Measurements were conducted in a standard test chamber (STC) with dimensions of 3.2 × 2.4 × 3.7 m (volume of 28.4 m^3), in line with [9]. Fig. 1 shows the schematic view and photos of the measurement setup. One ACD was placed in the middle of the room. Three electric fans were located in the three corners of the STC for air-aerosol mixing purposes. Two sensor stations (Fig. 2) were placed on the tables positioned at the two short sites of the room at 1.0 m above the ground. Each sensor station included a Grimm 11D aerosol particle sizer (APSs) [15] with a measurement range of about 0.25-30 µm and an air temperature and relative humidity sensor (Fig. 2). Two artificial aerosol generators were placed on a table at 0.8 m above the ground and each bottle was filled with a filtered mixture of 97% distilled water, 2% glycerol, and 1% NaCl at room temperature (Fig. 3). The mixture spraying generated a large number of artificial saliva aerosol particles in the size range 0.5-2.5 µm.

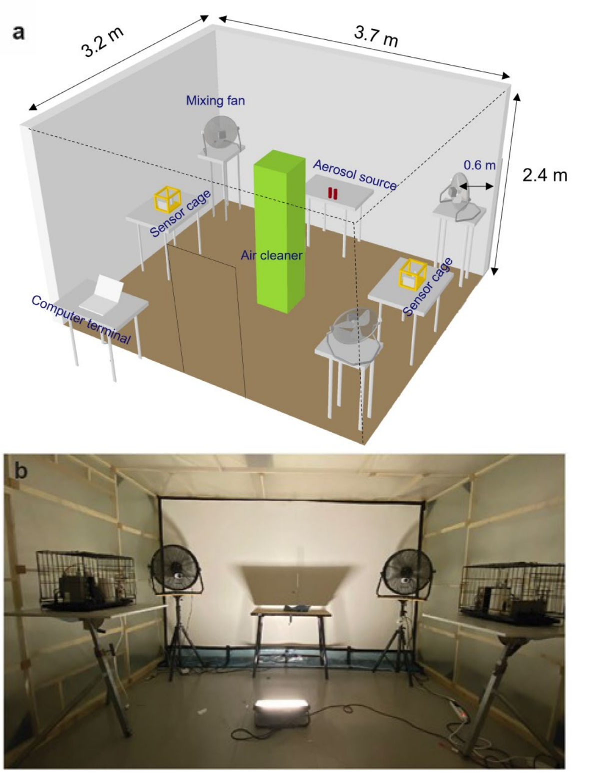

Fig. 1. (a) Schematic view and (b) photo of the measurement setup in the STC. Dimensions are reported in meter.

Fig. 2. Photo of the sensor station used in the STC.

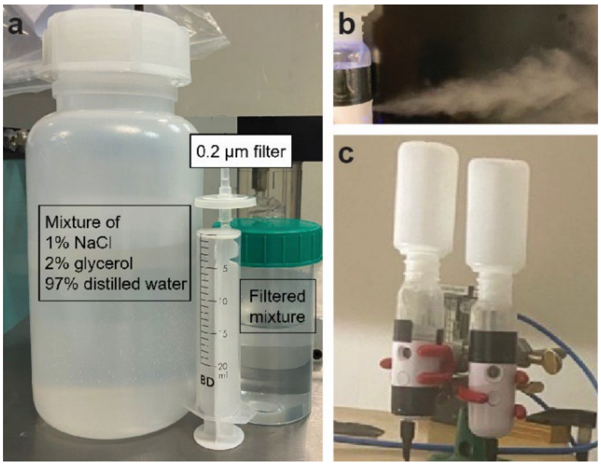

Fig. 3 Photos of (a) the aerosol source and (b-c) artificial aerosol generators used in the STC.

3.2 Measurement protocol

Before the start of the aerosol measurement campaign, additional tests were conducted to control the background air velocity close to the position of the ACD at about 0.2 m/s (satisfying the standard requirements of no more than 0.5 m/s). During the aerosol measurement, all of the eight ACDs were tested. Three modes of ACD1-ACD8 were evaluated with all tests repeated three times for each mode of each ACD.

Firstly, the natural decay of aerosol particles, i.e., when the ACD was nonoperational, was measured three times for a duration of about 23 minutes each. The filtered mixture was sprayed inside the room for about one minute until the initial aerosol concentration was in a range of 200-400 particles/cm^3 [9]. After two minutes of mixing and waiting, the two APSs kept measuring the aerosol particles for about 20 minutes. Then the tests with eight ACDs in operation were conducted one by one to test the decay of aerosol particles. Similar to the natural decay tests, here the measurements started with the mixture release for about one minute, to arrive at the required concentration (200-400 particles/m^3). After two minutes of mixing and waiting, the ACD was turned on and the two APSs kept measuring the aerosol particles for about 20 minutes. Note that before each test, a portable HEPA filter was used to bring the aerosol particle concentration in the room to the background level. The results of the measurements conducted in the room are presented in Section 5.

4 Measurement tests in a LTC

4.1 Measurement setup

Aerosol measurements were also conducted in a LTC with dimensions of 9.9 × 6.8 × 3.0 m (volume of 202.0 m^3). As shown in Fig. 4, one ACD was placed in the middle of the room. Four electric fans were placed on the tables in the four corners of the LTC and another two were placed in the middle of the two long sides of the LTC. Six sensor stations on the tables were placed symmetrically along the two long sides of the LTC (1.0 m above the ground). In total, 12 artificial aerosol generators were used with six in the middle of each short side of the LTC. The same aerosol materials as those used in the STC measurements were used here.

4.2 Measurement protocol

The background air velocity close to the position of the ACD was controlled in a range of 0.11-0.35 m/s before the start of the aerosol measurement campaign. The performance of the six mixing fans in air-aerosol mixing was also evaluated and the results of this evaluation are presented in Section 5.

Based on the results tested in the STC, ACD3, ACD5, and ACD6 were selected and tested again in the LTC. Medium and maximum modes of ACD3 were tested. For ACD5 and ACD6, the minimum, medium, and maximum modes were tested. The same testing process as in the STC was used for both the tests of the natural decay of aerosol particles and the decay of aerosol particles when the three ACDs were operational one by one. The results of the measurements conducted in the room are presented in Section 5.

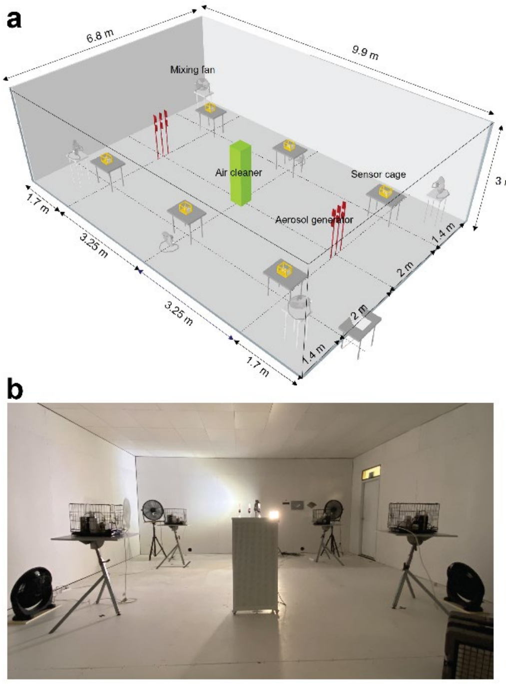

Fig. 4. (a) Schematic view and (b) photo of the measurement setup in the LTC. Dimensions are reported in meter.

5 Results

5.1 CADR of ACDs in the STC

Table 2 shows the overview of the CADR of the eight ACDs in various modes tested in the STC (i.e., CADR$_{STC}$), for six different aerosol particle size ranges: ANSI(0.5-3 µm), PM0.25, PM0.25-PM0.5, PM0.5-PM1, PM1-PM2.5, PM2.5-PM10. ANSI(0.5-3 µm) means the size is in a range of 0.5-3 µm, based on the definition of dust in the ANSI/AHAM standard [9].
The following observations are made:

- A significant difference in CADR$_{STC}$ is observed among the eight ACDs, ranging from 28 m^3/h to 2500 m^3/h, depending on the specific technology and system size used. It highlights the large variation in CADR$_{STC}$ available for ACDs on the market.
- For the same ACD, the CADR$_{STC}$ values show some differences across aerosol particle size ranges, which shows the different removal performances for different aerosol particle sizes. For the smallest aerosol particle (i.e., PM0.25) removal, all the ACDs have a relatively lower performance compared to their performance for large aerosol particle removal. For instance, the CADR$_{STC}$ of PM2.5-PM10 of ACD2 is 158 m^3/h in mode I, while it is only 95 m^3/h for PM0.25.

Table 2 CADR values calculated for eight ACDs tested in STC (i.e., CADR$_{STC}$) for each fraction of aerosol particles.

ACD type		**CADR$_{STC}$ (m^3/h)**		
		Mode I	**Mode II**	**Mode III**
ACD1	ANSI(0.5-3 µm)	165	742	1265
	PM2.5-PM10	202	874	1176
	PM1-PM2.5	144	732	1249
	PM0.5-PM1	162	740	1266
	PM0.25-PM0.5	172	698	1211
	PM0.25	163	607	1085
ACD2	ANSI(0.5-3 µm)	99	187	353
	PM2.5-PM10	158	242	422
	PM1-PM2.5	92	180	346
	PM0.5-PM1	97	185	350
	PM0.25-PM0.5	98	186	352
	PM0.25	95	184	347
ACD3	ANSI(0.5-3 µm)	647	1452	2500
	PM2.5-PM10	692	1578	2686
	PM1-PM2.5	637	1451	2491
	PM0.5-PM1	644	1448	2513
	PM0.25-PM0.5	641	1429	2489
	PM0.25	630	1399	2438
ACD4	ANSI(0.5-3 µm)	125	432	692
	PM2.5-PM10	144	433	779
	PM1-PM2.5	104	418	671
	PM0.5-PM1	122	431	693
	PM0.25-PM0.5	135	432	690
	PM0.25	134	423	647
ACD5	ANSI(0.5-3 µm)	173	179	581
	PM2.5-PM10	215	229	700
	PM1-PM2.5	156	168	568
	PM0.5-PM1	171	177	579
	PM0.25-PM0.5	178	180	575
	PM0.25	176	178	551
ACD6	ANSI(0.5-3 µm)	420	533	697
	PM2.5-PM10	449	587	733
	PM1-PM2.5	396	514	670
	PM0.5-PM1	419	532	695
	PM0.25-PM0.5	423	534	696
	PM0.25	400	517	670
ACD7	ANSI(0.5-3 µm)	26	204	497
	PM2.5-PM10	62	272	542
	PM1-PM2.5	17	199	490
	PM0.5-PM1	24	202	496
	PM0.25-PM0.5	27	203	492
	PM0.25	27	197	480
ACD8	ANSI(0.5-3 µm)	430	772	1721
	PM2.5-PM10	460	806	1931
	PM1-PM2.5	404	749	1699
	PM0.5-PM1	427	770	1714
	PM0.25-PM0.5	443	779	1736
	PM0.25	428	767	1727

- For mode II and mode III of the ACD3 and ACD8, the $CADR_{STC}$ among all the aerosol particle sizes are over 680 m^3/h (the maximum CADR value suited in the ANSI/AHAM standard [9]), with the minimum CADR of PM0.25 = 1399 m^3/h for ACD3 in Mode II and 767 m^3/h for ACD8 in Mode II.
- For mode I of ACD3 and mode III of ACD4-ACD6, the $CADR_{STC}$ is over 680 m^3/h for the large aerosol particle size such as PM2.5-PM10, while it is below 680 m^3/h for the small aerosol particles such as PM0.25.

5.2 CADR of ACDs in the LTC

Firstly, the performance of the six electric fans used for air-aerosol mixing is presented in Fig. 5. It shows the plots of the natural decay rate of aerosols with six different aerosol particle size ranges from the three natural decay tests in the LTC. Each dot in the figure presents the natural decay rate, for each test, in one position of the sensor station (in Fig. 4a). Despite the small differences found for the size range of 10-2.5 µm, for the other aerosol particle size ranges a very similar natural decay rate is observed among the six positions of the sensor stations in the three natural decay tests. It shows that a well-mixed condition of air and aerosol particles is achieved with the use of the six electric fans, and it shows the repeatability of the measurement.

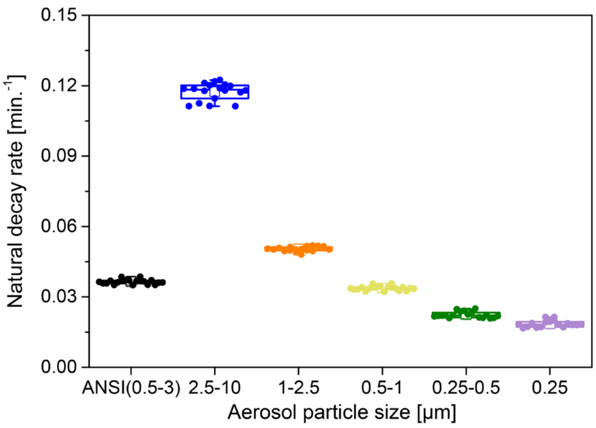

Fig. 5. Plots of natural decay rate of aerosols in various particle sizes from the three natural decay tests in the LTC.

Table 3 shows the CADR of the ACD3 in mode II and mode III, ACD5, and ACD6 in mode I to mode III tested in the LTC (i.e., $CADR_{LTC}$), for six different aerosol particle size ranges: ANSI(0.5-3 µm), PM0.25, PM0.25-PM0.5, PM0.5-PM1, PM1-PM2.5, PM2.5-PM10. Note that in ACD5, the CADR of PM2.5-PM10 in mode I and mode II is not listed due to some uncertain factors.

The following observations are made:

- ACD3 demonstrates a comparable performance in both Mode II and Mode III across all aerosol particle size ranges. A gradual increase in $CADR_{LTC}$ is observed as the aerosol particle size escalates from PM0.25 to PM2.5-PM10. This ACD refers to relatively large $CADR_{LTC}$ values.
- ACD5 in mode III shows effective air cleaning across various particle sizes. A larger $CADR_{LTC}$ (511 m^3/h) for small particles (PM0.25) is observed compared to the $CADR_{LTC}$ (459 m^3/h) for larger particles (PM2.5-PM10).
- ACD6 shows an increasing trend in $CADR_{LTC}$ values as aerosol particle size decreases, with higher values in Mode III.

Table 3 CADR values calculated for eight ACDs tested in LTC (i.e., $CADR_{LTC}$) for each fraction of aerosol particles.

ACD type		$CADR_{LTC}$ (m^3/h)		
		Mode I	Mode II	Mode III
ACD3	ANSI(0.5-3 µm)	-	1341	2816
	PM2.5-PM10	-	1457	3074
	PM1-PM2.5	-	1424	2944
	PM0.5-PM1	-	1346	2814
	PM0.25-PM0.5	-	1321	2770
	PM0.25	-	1322	2768
ACD5	ANSI(0.5-3 µm)	74	85	506
	PM2.5-PM10	-	-	459
	PM1-PM2.5	87	125	533
	PM0.5-PM1	83	93	513
	PM0.25-PM0.5	81	74	506
	PM0.25	89	81	511
ACD6	ANSI(0.5-3 µm)	367	456	625
	PM2.5-PM10	238	370	546
	PM1-PM2.5	371	464	633
	PM0.5-PM1	374	464	633
	PM0.25-PM0.5	380	469	640
	PM0.25	382	474	645

5.3 Comparison of the CADR from STC and LTC

Fig.6 compares the CADR of ACD3, ACD5, and ACD6 tested in STC and LTC. Different colors and marker shapes present the six different aerosol particle sizes and modes of ACDs, respectively.

The following observations are made:

- Fig. 6a shows overall a reasonable agreement between the CADR of ACD3 tested in the STC and in the LTC among all the aerosol particle sizes, with an average deviation of 6.2% (lower in LTC) for mode II and 13.7% (higher in LTC) for mode III ($CADR_{STC}$ in the order of 1500-2500 m^3/h). It suggests that while the performance of ACD3 in mode II surpasses the stipulated ANSI/AHAM standard scope [9], the divergent sizes of the test chambers do not significantly impact the test outcomes of ACD3, especially in mode II.

- Fig. 6b shows a clear difference between the CADR of ACD5 in mode I and mode II tested in the STC and in the LTC among all the aerosol particle sizes, with an average deviation of 51.4% and 47.8% for mode I and mode II, respectively. A much lower CADR for all the aerosol particle sizes in LTC is observed, compared to those in STC in these two modes. This means the divergent sizes of the test chambers significantly impact the test outcomes of ACD5 in mode I and II ($CADR_{STC}$ in the order of 200 m^3/h). On the other hand, an average deviation of 15.4% is observed between the CADR of aerosol particle sizes in mode III tested in the STC and in the LTC ($CADR_{STC}$ in the order of 500 m^3/h). This means that the sensitivity of the room size to the outcome is CADR dependent.
- Fig. 6c shows that the deviations of the CADR of ACD6 in all three modes tested in the STC and in the LTC are all below 15% among all the aerosol particle sizes, except for PM2.5-PM10 ($CADR_{STC}$ in the order of 400-700 m^3/h). In this size range, the CADR in LTC is consistently lower than that in STC across all three modes.

6 Discussion and Conclusions

The present study provides valuable insights into the performance of eight portable ACDs in reducing aerosol particle concentrations. The effectiveness was quantified by particle size-resolved (six different aerosol particle size ranges) CADR. The difference of CADR of three ACDs tested in the standard and large test chamber are also compared.

The main limitations of this study are listed below:

- The air temperature and relative humidity were within the scope of ANSI during the measurements in LTC. In STC, the relative humidity was in the range of 55%-70% during the measurement period, which is above the standard values (35%-45%). The air temperature in STC was in the range of the ANSI requirements.
- This study only presents aerosol particle concentration and its removal, but it is not targeted to directly investigate the performance in the removal of, e.g., pathogenic microorganisms.

Despite the aforementioned limitations, some important conclusions can be drawn:

- The different performance of ACDs on the market in terms of CADR as observed, is partly due to the specific technology used by individual ACDs in combination with the type of particle (aerosols) applied.

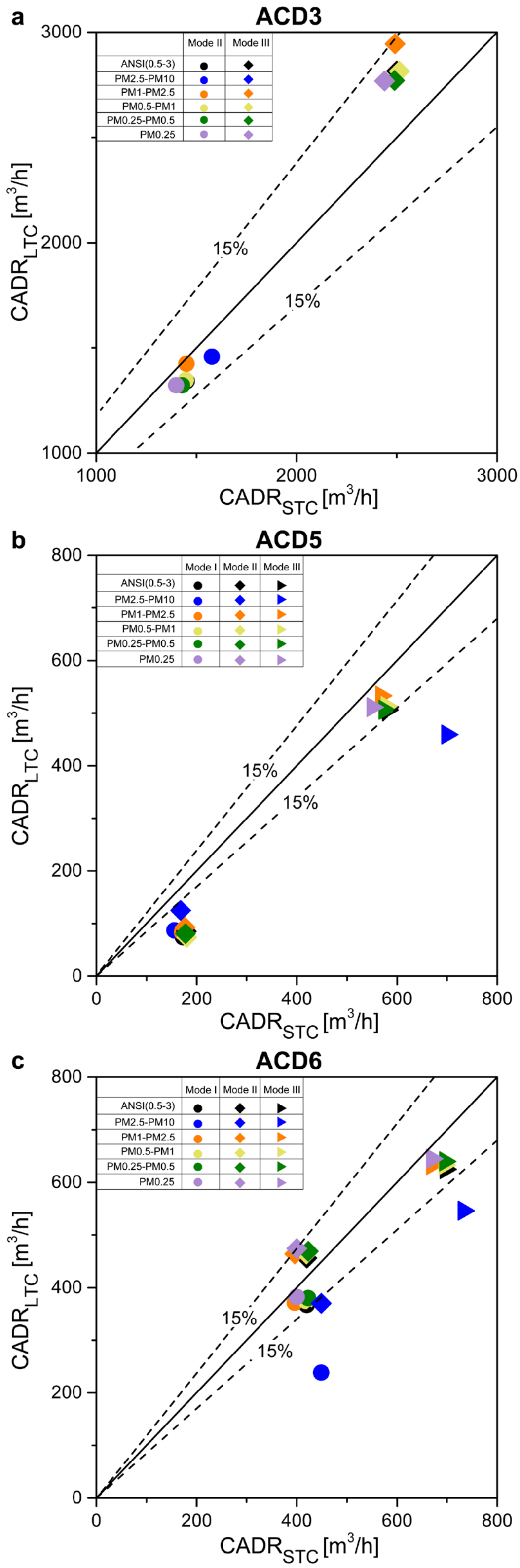

Fig. 6. Comparison of the CADR of (a) ACD3, (b) ACD5, and (c) ACD6 tested in STC and LTC.

- The CADR values vary across aerosol particle size ranges. In general, the $CADR_{STC}$ of small particles (i.e., PM0.25) is lower than that of large particles (i.e., PM2.5-PM10). For the latter, this may be partly explained by the efficiency difference of the two-layer or three-layer filters used in the ACDs in removing different aerosol particle sizes.
- A reasonable agreement is observed between the CADR of ACD3 tested in the STC and in the LTC among all the aerosol particle sizes, followed by ACD6 and ACD5. An effect of the actual $CADR_{STC}$ of the system tested on the outcomes for the LTC appears present. The performance of ACDs with CADR lower than 300 m^3/h seem to be affected significantly for application in a larger room. CADR results should, therefore, not be extrapolated to other rooms and application conditions without consideration. Similarly, the previous study [13] showed that for all the six tested ACDs, the experimental CADR decreased as the size of the test chamber increased from 30 m^3 to 50 m^3 and the deviation of CADR in the two different size chambers was in a range of 14.6%-32.6% depending on the specific ACD evaluated.

There may be a need for an update or new standard for the effectiveness test of ACD for large space usage. Additionally, the noise level due to the long-term operation in some environments, where quietness is required such as classrooms and libraries, can be evaluated in a further study. The present performance evaluation is mainly based on particle-removal; harmful gas-removal-and pathogenic-microorganisms-removal can be taken into account in the future. Energy consumption together with the performance of the ACDs can be evaluated in further studies as well.
The results of the present study are intended to support future measurement studies of aerosol removal using ACDs in a more realistic lab environment (classroom mockup) and in real classrooms, to enable a further comparison between theoretical CADR values from the ANSI/AHAM standard and actual performance in practice.

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