Testing Portable Air Cleaning Units –Test Methods and Standards: A Critical Review




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Standards and Procedures for Portable Air-cleaning Units

The most effective ways to reduce exposure to indoor air pollutants are to eliminate individual sources of pollution or to reduce their emissions. Another approach is source control i.e. if the outdoor pollution level is low, ventilation reduces the concentration of indoor particles by means of dilution. In addition, research studies show that removal control i.e. air filtration can be an effective supplement to source control and ventilation. Using a portable air cleaner, also known as air purifiers or air sanitizers can help to improve indoor air quality. Portable room air cleaners can clean the air in poorly ventilated spaces such as aged classrooms and offices, prisons, homeless shelters, etc., when continuous and localised air cleaning is needed.

To make an informed choice of a portable air cleaning (PAC) device. the following information is recommended:

- A metric for measuring the performance of residential air purifiers
- Filters: efficiency, size and amount of filter media
- Noise level
- Motor quality
- Safety – no ozone and uses no technology that could introduce contaminants

There are no standard definitions of portable air cleaning (PAC) devices. Sultan et al., [1] defined a PAC as an energy consuming device used to reduce the concentration of airborne pollutants, including but not limited to dusts, particles, environmental tobacco smoke, allergens, micro-organisms (e.g., mould, bacteria, pollen, viruses, and other bioaerosols), fumes, gases or vapours and odorous chemicals from the indoor air of a residential space. PAC technologies include, but are not limited to, mechanical air cleaners (e.g. HEPA filters), electrically charged filters, electrostatic precipitators, ionizers, photocatalytic oxidation, plasma-cluster ion, ozone generators, activated carbon (with and without chemical impregnated compounds) filters and others. PACs include devices of any size used for cleaning the air in a residential room of any size or in a whole house which could be stand-alone devices designed as wall-, floor-, ceiling-, table-, combination- or plug-in types.

There are a wide range of different portable air cleaners marketed for the removal of particles and gases. It is difficult for potential users or purchasers to select one device that is best suited for removing a certain pollutant and what technical information to request, consider and assess during the selection process. It is often difficult for non-experts to comprehend the differences between them or evaluate manufacturer claims.

In several years, the dominated market for portable air cleaner is largely in the U.S. among countries in North America and China in Asia. There are several test methods in the world for use in determining how well an air cleaner works in removing pollutants from indoor air. Majority of these test methods focus mainly on particle removal and estimate the efficiency or effectiveness of an air-cleaning device in removing particles from indoor air and can be used for comparisons among different devices. ISO 29464:2017 [2] is applicable to particulate and gas phase air filters and air cleaners used for the general ventilation of inhabited enclosed spaces.

Summary of the test methods and standards

This summary **Table 1 and 2** are standards and procedures for evaluating the particle and gaseous contaminant removal performance of portable air cleaners (PAC).

Table 1. *Summary of the test methods and standards for particle removal.*

Standard/Protocol (Ref.)	Country	Method	Challenge Particles	Measured Particle Size Range	Performance Index
ANSI/AHAM [3]	US	Pulldown	Environmental tobacco smoke, Arizona road dust, paper mulberry pollen	0.1 to 1.0 µm 0.5 to 3.0 µm 5 to 11 µm	CADR [a]
GB/T-18801 [4]	China	Pulldown	Environmental tobacco smoke, Arizona road dust, paper mulberry pollen	0.1 to 1.0 µm 0.5 to 3.0 µm 5 to 11 µm	CADR
NRC Protocol [5]	Canada	Pulldown	Polydisperse sodium chloride (NaCl)	50 nm to 5 µm	CADR
NCEMBT Procedure [6]	US	Pulldown	Polydisperse potassium chloride (KCl)	0.1 to 11.5 µm	CADR
Lucerne University (2012) [7]	Switzerland	Pulldown	ISO 12103-1 A1 Ultrafine test dust.	0.2 to 5 µm	
JIS C 9615 [8a]	Japan	Singlepass	JIS Z 8901 standard dusts	…	Removal rate
XP B44-200 [9]	France	Singlepass	DEHS, Cat allergens, *Staphylococcus epidermidis* *Aspergillus niger*	0.3 and 5 µm	SPE [b], CADR
ISO 29464:2017 [10a]	International	Singlepass	$PM_1 – PM_{10}$	0.3 and *X* µm	SPE
Nord test method – NT CONS 009 [45]	Nordic	Singlepass	Particles	e. g. 0,3 µm, 0,5 µm, <1 µm	SPE

Notes: (a) CADR: clean air delivery rate; (b) SPE: Single-pass efficiency.

Note: A "Pulldown" test method consists of three test periods under full-recirculation mode of the chamber operation: VOC or particle injection period, static period and dynamic period. The injection of known amount of contaminants into the experimental system, followed by a quasi-static period, result in stable initial high concentration levels. The time when the air cleaner is turned on is defined as time zero, at which the dynamic period begins. Using the measured concentration decay rate from the dynamic period, the clean air delivery rate (CADR) of the cleaner can then be calculated for each VOC and different size particles [39].

Note: SPE- Single-pass efficiency (η) represents the fraction of pollutants removed from the airstream as it passes through the air cleaner [39].

EUROPEAN STANDARD

EN ISO 29464:2019 (MAIN)
Cleaning of air and other gases - Terminology (ISO 29464:2017)

This document establishes a terminology for the air filtration industry and comprises terms and definitions only. This document is applicable to particulate and gas phase air filters and air cleaners used for the general ventilation of inhabited enclosed spaces. It is also applicable to air inlet filters for static or seaborne rotary machines and UV-C germicidal devices. It is not applicable to cabin filters for road vehicles or air inlet filters for mobile internal combustion engines for which separate arrangements exist. Dust separators for the purpose of air pollution control are also excluded. This European Standard was approved by CEN on 12 August 2019.

Table 2. *Summary of the test methods and standards for gaseous removal.*

Standard/Protocol (Ref.)	Country	Method	Challenge Gaseous	Measured Gaseous	Performance Index
ANSI/AHAM [3]	US	N/A	N/A	N/A	N/A
GB/T-18801 [11]	China	Pulldown	Single species gas	*e.g.*, Formaldehyde toluene	CADR
GB/T-18801 [11]	China	Singlepass	Single species gas	*e.g.*, Formaldehyde toluene	SPE
NRC Protocol [5]	Canada	N/A	N/A	N/A	N/A
NCEMBT Procedure [6]	US	Pulldown	Eight VOCs mixture [a]	$TVOC_{toluene}$ [b] formaldehyde	CADR
Lucerne University (2012) [7]	Switzerland	N/A	N/A	N/A	N/A
JIS C 9615-2007 [8b]	Japan	Singlepass	NO_2, SO_2	NO_2, SO_2	SPE
JEM 1467-1995 [8b]	Japan	Pulldown	Tobacco smoke	Ammonia, acetaldehyde, and acetic acid	Removal rate
XP B44-200 [9]	France	Singlepass	Four VOCs mixture [c]	Acetone, acetaldehyde, heptane, and tolune	SPE, CADR
ISO 29464:2017 [10b]	International	Singlepass	VOCs, acids, bases, and others	VOCs, acids, and bases, and others	SPE

Notes: (a) The components of the challenge VOC mixture include n-hexane, n-decane, toluene, dichloromethane, tetrachloroethylene, iso-butanol, 2-butanone, and formaldehyde; (b) Total hydrocarbon as toluene equivalent measured by the INNOVA 1312 Photoacoustic Multi-gas Monitor; (c) The components of the challenge VOC mixture include acetone, acetaldehyde, heptane, and toluene.

ANSI/AHAM: This standard is only for PM: dust, cigarette smoke and pollen.

NRC Protocol: This standard is only for PM: NaCl.

Lucerne University (2012): This standard is only for PM: DEHS

EXISTING TEST METHODS FROM THE USA

ANSI/AHAM AC-1: 2020

In the early 1980s, AHAM developed an objective and repeatable performance test method for measuring the ability of portable household electric room air cleaners to reduce particulate matter from a specific size room. The standard, ANSI/AHAM AC-1-2006, Method for Measuring the Performance of Portable Household Electric Room Air Cleaners, is designed to evaluate portable household electric room air cleaners regardless of the particle removal technology utilized.

In 2020, the U.S. Environmental Protection Agency (EPA) updated the referenced test procedure, for use in measuring the cigarette smoke Clean Air Delivery Rate (CADR) and operating power to determine certification for ENERGY STAR Room Air Cleaners i.e. titled ANSI/AHAM AC-1 test method "*Portable Household Electric Room Air Cleaners* ("ANSI/AHAM AC-1-2020"). For the purposes of ENERGY STAR certification, room air cleaners should be tested using ANSI/AHAM AC-1-2020 moving forward. AHAM describes this standard as establishing a uniform, repeatable procedure or standard method for measuring specified product characteristics of household portable air cleaners. The standard methods provide a means to compare and evaluate different brands and models of household portable air cleaners on the basis of characteristics significant to product use [12].

CADR – Clean Air Delivery Rate

The most used parameter for understanding the effectiveness of portable air cleaners is the clean air delivery rate (CADR). Clean Air Delivery Rate or CADR is a rating system that can help determine the effectiveness of an air purifier based on how many cubic meters per hour (m^3/h) of particulate matter it can filter. A higher CADR relative to the room size increases the effectiveness of a portable air cleaner i.e. the higher the CADR value, the faster the air purifier is at processing air. According to the Association of Home Appliance Manufacturers, an air purifier should have a CADR rating of at least two-thirds of your room's square footage. A CADR can theoretically be generated for either gases or particles; however, the current test standards only rate CADRs for particle removal [13]. CADR is a method for testing the capacity to reduce smoke, dust and pollen particles in the 0.10 to 11 µm size range from the air.

A factor that CADR does not account for is an air purifiers' long-term efficiency. Air purifiers start declining in efficiency after only one hour of usage, the extremely

short twenty-minute CADR test will not accurately reflect a purifiers' performance in the long term. CADR also does not test for air purifiers' performance against ultrafine particles. The three contaminants that CADR tests for (dust, pollen, and smoke) are on the larger side of the spectrum of airborne contaminants that are commonly filtered, ultrafine particles smaller than 0.1 microns make up 90% of the particles found in the air and harmful biological aerosols typically come in these sizes. It is important to note that the CADR system has its limitations, and it is in the best interest of the consumer not to base their decision in getting an air purifier solely on its CADR rating alone.

ASHRAE Standard 52-2 (1992)

ASHRAE Standard 52-2 (1992), provides for filter efficiency ratings by evaluating the fractional efficiencies in three particle size ranges i.e. 0.3 to 1.0 µm, 1.0 to 0 3 µm and 3.0 to 10 µm. The filter efficiency ratings are designated by Minimum Efficiency Reporting Value (MERV) between 1 and 20. For the test, a standard synthetic dust is fed into the air cleaner and the proportion (by weight) of the dust trapped on the filter is determined. Because the particles in the standard dust are relatively large, the weight arrestance test is of limited value in assessing the removal of smaller, respirable-size particles from indoor air [14].

EXISTING TEST METHODS FROM NORDIC COUNTRIES

Nord test method – NT CONS 009 Approved 1985-02

This NORDTEST method is used to test the technical performance of room air cleaners which are provided with fibrous or electrostatic filters. The air cleaners designed for public and industrial rooms are excluded. It contains tests for: Filtration efficiency of the filter, Air volume flow through the equipment, Equivalent clean air production which can be determined instead of the removal efficiency and volume flow, Outflow profile of the equipment and Noise properties of the equipment.

For measuring the performance of a room air cleaner, the following test methods are used: 1) The filtration efficiency of the filter determined by measuring the test particle concentrations in the inflow and outflow of the equipment. 2) The volume flow through the equipment is determined by using a measuring bag of a known volume and an auxiliary blower. 3) The equivalent clean air production is determined by measuring the decrease of the particle concentrations in the test room as a function of time and by calculating the product "filtration efficiency x volume flow" from the curve of the measured values. 4) The outflow profile is determined by feeding smoke to the outflow part of the equipment and by photographing the outflow profile. The critical flow velocity can be measured by an anemometer. 5) The noise properties (sound power level) are determined in an anechoic chamber with the precision method (ISO 3745) and 6) The ozone production of the equipment is determined by measuring the outflow and inflow ozone content of the air cleaner.

EXISTING TEST METHODS FROM CHINA

NATIONAL STANDARD OF THE PEOPLE'S REPUBLIC OF CHINA GB/T 18801—2015, AIR CLEANER

This standard is drafted according to the regulations published in GB/T 1.1-2009 [4]. This standard replaces GB/T 18801-2008 "Air cleaner". This standard stipulates the terminology, definition, model and nomination, requirements, test methods, inspection rules, labels, user instructions, packing, shipping and storage of the air cleaner. This standard applies to air cleaner for household use and similar use. This standard applies to, but is not limited to air cleaner of the following operating principle: filter type, absorption type, molecular complex locking type, chemistry catalytic type, photo catalytic type, static electricity type, plasma type and combination type, etc. With combination type means that the air cleaner uses two or more than two above-mentioned purifying technologies, and it can remove one or more than one kind of air pollutants.

Air purifier long-term performance: CCM (Cumulate clean mass)

Cumulative clean mass (CCM) measures the efficiency of an air purifier based on its ability to filter out particulate matter and formaldehyde. The cumulative total of purified particles is calculated when the CADR is degraded to half its original value through a series of tests deliberately made to wear out the air purifier's filter.

The tests conducted to reduce CADR to half its initial value include sealing it off in a chamber, lighting 100 to 200 cigarettes for the filter to clean, and exposing it to formaldehyde and other volatile organic compounds to wear out filtration media such as activated carbon filters. The purpose of this rigorous testing is to simulate how much volume of particular matter, odours, and formaldehyde an air purifier can process before its overall efficiency starts to diminish over time.

The final CCM rating indicates the continuing efficiency of an air purifier to clean indoor air even after long and heavy usage. CCM is tested for particle pollution as follows (per the GB/T 18801-2015 standard):

EXISTING TEST METHODS FROM JAPAN

There are two standard methods for assessing the performance of air-cleaning appliances in Japan, JIS C 9615 (Japanese Industrial Standards Committee [JISC] 2007) and JEM 1467 (Japan Electrical Manufacturers' Association [JEMA] 2015). These two test methods were standardized to examine the removal efficiency of (mainly) particles and odours; however, other chemical substances, such as HCHO and volatile organic compounds (VOCs), were not considered.

JEM 1467 (Japan Electrical Manufacturers' Association)

JEM 1476 test method applies to air cleaners designed to be used at home, offices, etc which are able to reduce odours and particulate levels indoors [4]. The JEMA describes a method to measure the performance at the initial stage and after loading phases on gas and particulate pollutants. In this method, tobacco smoke is employed as the challenge gas, and ammonia, acetaldehyde, and acetic acid are the test pollutants. The air cleaner is installed within an airtight small chamber (1 m^3) whose air is polluted by burning cigarettes, and after operating the air cleaner for 30 min, the removal efficiency is assessed by estimating the reduction rate of the pollutant concentrations [15].

JIS C 9615 (Japanese Industrial Standards Committee [JISC] 2007)

In this method, NO_2 and SO_2 are supplied as challenge gases, and the removal efficiency is calculated by measuring their concentrations at the inlet and outlet of the air cleaner after 10 min of operation in an airtight chamber; however, the chamber volume is not specified [16].

EXISTING TEST METHODS FROM KOREA

Korea Association of Cleaning Air (CA) certificated air cleaners which had been commercially available in Korea from 2003 to 2015 were analysed. Among the test parameters such as flow rate, particle collection efficiency, clean air delivery rate (CADR), ozone emission, odour removal efficiency and noise level, noise level and CADR are correlated with flow rates. [17].

EXISTING TEST METHODS FROM FRANCE

The standardization process began in France with the official creation by AFNOR in 2007 of a working group "Air cleaners". The experimental standard XP B44-200 was published in May 2011.

This test method applies to assess the air cleaning efficiency but also the harmlessness of residential air cleaners. It considers the various kind of contaminants i.e., particles, gas, allergens, and microorganisms at concentration that are representative of typical concentration levels found in indoor settings. The basis of this test method has been used to develop a new standard in France. For particles the fraction efficiency (by particle size) of the air cleaner under test is measured on DEHS (between 0.3 and 5 µm). For gases a mixture of acetone, acetaldehyde, heptane, and toluene. For allergen, it was used cat allergens Felis domesticus. For microorganisms, it was used Staphylococcus (bacteria) and Aspergillus Niger (fungi). The test rig is mainly composed of a chamber (1.5 m × 1.5 m × 1.5 m) divided to parts. With an upstream and downstream duct respectively [18].

EXISTING TEST METHODS FROM CANADA

This protocol establishes a test procedure for evaluating the performance of portable air cleaning (PAC) devices intended primarily for residential environments. This protocol describes a method for evaluating the particle and gaseous contaminant removal performance of portable air cleaners used primarily in residential settings with mixing-type ventilation systems. For the IAQ performance, PACs are evaluated for their emissions and by-product formation as well as particle and VOC removal. A standard emissions test performed under steady state conditions are used to determine the PACs emissions of selected pollutants and their by-product formation. For PAC particle and VOC removal, a "pulldown" method will be used to conduct the test (AHAM, 2006).

For acoustic measurements, the experiments are conducted in a reverberant test chamber that conforms to the requirements of the ISO 3743-1 method (ISO, 1999). The comparison procedure for determining the sound power of a test source to an 'engineering' grade of precision described in ISO 3743-1 is adopted. This requires the comparison of measurements of the PAC source with those of a reference sound source, such as the ILG reference sound source. The reference source is calibrated to a 'precision' grade according to ISO 3741 and must meet all of the requirements in ISO 6926 for reference sound sources. The electrical power measurements are conducted under PAC running and standby modes [19].

ANSI/UL. UL standard 867:

This Standard addresses the safety of portable and fixed (including duct-connected) electrostatic air cleaning equipment. Standard UL 867 is also used to evaluate portable and fixed ion generators. This standard deals with electrostatic air cleaners rated at 600 volts or less, intended to remove dust and other particles from the air and intended for use in accordance with the National Electrical Code, ANSI/NFPA 70 [20]

CSA. CSA Standard 187:

This Standard applies to electrostatic air cleaners intended to remove dust and dirt from the air and intended for general indoor residential and commercial use, air ionizer type air cleaners, other similar ionizing equipment, duct-mounted type electrostatic air cleaners, air ionizers, and other similar ionizing equipment intended for general indoor residential use. This Standard applies to equipment for commercial use that intentionally produces ozone in a temporarily unoccupied space. This Standard applies to cord-connected and permanently-connected equipment operating at nominal supply voltages up to 600 V, single-phase or polyphase, that is intended to be installed or used in accordance with CSA C22.1, Canadian Electrical Code, Part I. This Standard applies to portable and duct-mounted air-cleaning devices that incorporate a UV (ultraviolet) lamp that emits UV radiation between 100 and 280 nm (UVC) [21]

ANSI/ASHRAE. ANSI/ASHRAE Standard 52.2.:

This standard describes a method of laboratory testing to measure the performance of general ventilation air-cleaning devices. The method of testing measures the performance of air cleaning devices in removing particles of specific diameters as the devices become loaded by standardized loading dust fed at intervals to simulate accumulation of particles during service life. The standard defines procedures for generating the aerosols required for conducting the test. The standard also provides a method for counting airborne particles of 0.30 to 10 µm in diameter upstream and downstream of the air-cleaning device in order to calculate removal efficiency by particle size. 2.3 This standard also establishes performance specifications for the equipment required to conduct the tests, defines methods of calculating and reporting the results obtained from the test data, and establishes a minimum efficiency reporting system that can be applied to air-cleaning devices covered by this standard [22].

Discussion

Particle Removal

Afshari et al., (2020) [23] carried out a literature review, taking into account, among other things, the existing test methods for PAC, with focus on particle removal. The authors described that the Pulldown test method is the most used in standards or protocols for assessing the removal of particles in the air using PACs. Standards or protocols using this method include the ANSI/AHAM AC-1 standard [3], National Research Council Canada (NRC) protocol [24], National Center for Energy Management and Building Technologies (NCEMBT) method [25], China standard [11], and the Swiss standard [26]. The Pulldown test method is applied to all technologies (e.g., Electrostatic Precipitators media filtration and photocatalytic technology). The Pulldown test method typically involves particles being dosed into a chamber containing the PAC to be tested and observing the first-order decay of particle concentrations with and without the PAC in operation. The difference in particle decay is used to determine the performance of the PAC.

Standards or protocols differ in terms of particles being used as challenge aerosols and an index to characterize PAC performance. In the former, challenge aerosols may provide consumers with information on PAC performance in removing certain types of particles. The challenge aerosols can provide information on the PAC performance in removing particles of different sizes. For instance, considering that ESP technology has been promoted as being efficient for the removal of UFPs, only a few standards consider UFP removal performance. In terms of the performance index, the most commonly used is the device clean air delivery rate (CADR) values measured in cubic feet per minute (cf/m) or cubic meters per hour (cm/h). Depending on the challenge particles, the CADR values are reported for the removal of particle types or particle sizes. The Swiss, Chinese, and Japanese standards used the concept of the half-life to report the performance of PACs for particle removal. The AHAM, China, and NRC standards relate the CADR performance obtained in chamber settings to actual service conditions by recommending room sizes to achieve an 80% indoor particle concentration reduction under steady-state conditions. The NRC protocol developed a minimum efficiency reporting value-like particle removal rating to rate the PACs. Details on particle challenges and performance index differences are summarized in **Table 1**.

The other method for assessing PAC performance is the Single-pass efficiency test method, which is an approach similar to the ASHRAE standard 52.2 method for testing media filters in a test rig. The French standard, XP B44-200 [9], measures upstream and downstream concentrations of di-ethyl-hexyl-sebacat (DEHS) (between 0.3 and 5 µm) particles, cat allergens, Staphylococcus epidermidis, and Aspergillus niger in a special chamber for PACs. The removal efficiencies and CADR of the particles are given. Although the Pulldown test method and Single-pass efficiency method are theoretically related, air mixing, portable air cleaning, and/or chamber short-circuiting may violate the relationship [27]. The Japanese standard also employs a Single-pass test using a special chamber [28]. Upstream and downstream filters of light transmittances are used to evaluate the removal rates of standardized challenge particles.

The AHAM AC-3 standard [29], JIS 9615 standard [8], China standard [4], and Swiss procedure [29] are the only published standards available that evaluate long-term PAC particle removal performance. In these standards, known amounts of particles are artificially loaded into PACs in a chamber dedicated to simulating long-term operation under a "standard" condition. Upon loading, the PACs are subjected to an initial performance evaluation [3]. The JIS standard includes a particle capacity test by determining the total particle amounts following an 80% flow reduction or determining whether the removal rate decreased by 85%.

Gaseous contaminant removal

The performance test procedures of PACs for gaseous contaminant removal are very similar to those for particle removal, and are often included in the same standard. For example, GB/T-18801 [11] and NCEMBT Procedure [6] used same Pulldown test for particle removal to obtain CADR for gaseous contaminant. Different from particle removal, the Single-pass test method is the most used in standards or protocols for assessing the gaseous contaminant removal efficiency of PACs. Standards or protocols using this method include China standard [11], Japan standard [8b], France standard [9], and ISO standard [10b]. Nevertheless, the performance index of SPE and CADR can be converted to each other.

The most significant difference between the different standards is the challenged and measured gas.

The JEM 1467-1995 [8b] standard, which was released as a voluntary restraint, described a procedure to evaluate the removal rate of PACs for ammonia, acetaldehyde, and acetic acid. For each gas, the removal efficiency is calculated based on the initial gas concentration and the gas concentration measured after 30-min use in a 1-m^3 air tight chamber. And the overall efficiency is defined as the weighted sum of the different gas filtration efficiencies. The XP B44-200 [9] standard and NCEMBT Procedure [6] also used VOCs mixture as challenging gas. Possible VOCs generation methods include placing liquid phased contaminants in a stainless-steel container and heat the container with regulated temperature [9]. For formaldehyde generation, solid paraformaldehyde is an option instead [6]. Besides, JIS C 9615-2007 [8b] standard tested the SPE for inorganic gaseous contaminant (NO_2 and SO_2), and the international standard [10b] considered almost all kinds of gases, including VOCs (*e. g.*, toluene), acids (*e. g.*, SO_2), bases (*e. g.*, NH_3), and other gases (*e.g.*, CO_2) [10b]. GB/T-18801 [11] standard also considered all kinds of gases, but each gas should be tested separately.

Since adsorbent for gas removal would have limited capacity [40], and catalyst for gas decomposition may be poisoned during the working period [41], the long-term performance of PACs for gaseous contaminant should be carefully considered. Though, the long-term performance is now only available in limited published standards [8b][9-11]. Besides, the interference between particles and gaseous contaminants in indoor air should also be carefully considered. For example, PACs may remove some particles adsorbed with organic compounds and then re-emit VOCs or by-products from the collecting media [42,43]. And using ozone to remove some specific VOCs may result in by-products and significant secondary ultra-fine particle formation, which are harmful for human beings [44]. Until now, only JEM 1467-1995 [8b] standard combined the particle and gaseous contaminant removal in a single test, but the challenge pollutant is tobacco smoke, which has limited types of VOCs. In the future, standards are expected to provide reliable test methods for the synergistic removal of particles and gaseous contaminants, which is consistent with the actual working conditions.

Safety (Ozone Production)

Two methods assess ozone production from PACs: 1) measuring the concentration and 2) determining the generation rate. For the concentration measurement method, an ozone production test standard procedure is included in the US Underwriters Laboratory (UL) standard 867 [30]. According to the UL standard, the ozone concentration should not exceed 0.05 ppm after 24 h of continuous operation of a cleaner in an enclosed chamber of 31.1 m^3, and the interior surface must be made of stainless steel or other nonporous and nonreactive material. The UL standard 867 specifies that the ozone must be measured at 50 mm downstream of the product air outlet, which is primarily a measure of the outlet concentration instead of the chamber concentration. As a result, the actual ozone generation rate of the air cleaner and its influence on the room ozone concentration depends on the airflow rate of the air cleaner. In addition, the size of a typical bedroom can be smaller or larger than the size specified, and the actual indoor surface materials can be different from those in the UL standard test chamber. It may be a concern that an ESP-based air cleaner that has passed the UL standard test may still pose an ozone exposure hazard to occupants because of differences in room sizes and deposition velocities associated with different interior surfaces.

According to the CSA C-187 Cl. 7.4 [31] standard, the 8-h time-weighted average (TWA) ozone concentration from ESPs measured for 24 h should not exceed 0.05 ppm, and this measure was updated to 0.02 ppm in 2016. This standard requires measurements in a chamber similar in size to that of the standard UL 867 but performed under static conditions.

Other standards or procedures have been proposed with a method to calculate the ozone generation rate, which is an intrinsic property of ESP. The methods involved use a well-mixed and positive-pressured chamber supplied with air filtered for particles and ozone. Typically, two tests are made for measuring ozone generations, first with PAC powered on and the second with PAC powered off to obtain deposition loss to surfaces. From the measured data, the ozone generation rate of the PAC is calculated and then modelled to determine the predicted indoor ozone concentration in actual buildings. The NCEMBT procedure [32] calculates ozone generation rates (in milligrams/hour) of PACs using the measured ozone concentration in a 55 m^3 stainless steel chamber but does not provide guidance for the PAC on expected ozone concentrations in actual residences. The NRC protocol [33] measures the ozone generation rates of PACs from a steady-state ozone concentration in a chamber similar to that used in the NCEMBT procedure and suggests that PACs may or may not exceed the indoor ozone concentration set by the Health Canada guideline of 50 ppb based on a "typical" Canadian residential bedroom.

Running noise

Portable air cleaners use different technologies to remove airborne particulates and gaseous pollutants and noise is a significant issue with many portable air cleaners. Portable air cleaner performance ratings are determined at maximum airflow and therefore typically maximum noise levels. It means that the higher the airflow rate the higher the CADR will be, but it will also be higher noise production. Therefore, there is a risk that occupants may turn them off to avoid the noise. However, at lower airflow settings, an air cleaner may have lower noise production, but it will also be less effective at pollutant removal. Some intervention studies involving the use of

portable air cleaners have noted that portable air-cleaning units were used less frequently over time. Fewer operating hours reduces their effectiveness and, therefore, their potentially positive effect on indoor air quality and health outcomes [34] (EPA, 2018). Peck et al. 2016 [35] reported that association between the noise level and CADR of 5 air cleaners. CADR values were determined with diesel particles while operating on maximum and minimum speeds. The results showed that the total sound pressure Levels (A-Weighted) were between 26.6 dBA and 35.5 dBA at lowest speeds and between 45.4 dBA and 53.4 dBA at highest speed. It means that the measured sound pressure levels were above the EPA indoor activity interference and annoyance level (45 dBA) [36]. In addition, exposure to noise has several negative health impacts i.e., immediate effect by changing the time we spend in certain sleep stages [37], short-term effect is shown as a result of the potential consequences of sleep disruption (Halperin, 2014), and long-term effect is shown as high blood pressure, heart disease, etc [38].

Possibility and limits of CADR

The CADR is a good way to keep from being misled in marketing messages. The advantage of the CADR rating is that it gives the consumer a way to compare air purifiers that consider both air flow and filter efficiency. CADR is given in cubic meters per hour. It's the volume of air flow through the filters on the highest fan speed.

How CADR is tested

- The CADR is measured with the air purifier run on the highest fan speed. If you will not be running the air purifier on a lower fan speed, then the CADR that you will realize will be lower.
- The CADR is tested with a new, clean filter so it does not reflect the performance of the air purifier over time. A small, thin filter may test well in the

CADR test but soon after show a large drop in performance. To better understand this our suggestion is to find out how much filter media is in the filters. In addition, the size of the air filters will factor into the expected performance over time. A large filter with a lot of filter media will perform much better than a smaller, thinner filter. You may want to watch out if the manufacturer does not provide this information.

- The CADR rating does not factor in noise level.
- The CADR is not a safety test, so it does not measure ozone production, motor reliability or energy usage.
- There are two types of CADR specified in the national standard for air purifiers: CADR (PM2.5, dust, etc.) and formaldehyde CADR. The two parameters represent two aspects, which are also presented separately in the test report.

There are a few issues with the CADR rating:

- If you run the air purifier on a lower fan speed your CADR will be lower, and the testing does not report these values.
- Higher efficiency filters have a higher air flow resistance so it's harder to push air through the filters. This results in lower CADR values. So, if you use higher efficiency filters you can remove the most dangerous particles which is better for your health. But you get a lower CADR because it is so much harder to push the air through a better filter.
- It does not measure the air filter performance over time.
- It is only based on removing airborne particles sized 0.3 microns and larger. This represents dust and larger particulates. It does not measure the smaller particles and gases. These smaller airborne particles make up 90% of all particulates and cause most health issues. So, if you have the best true HEPA air purifier on the market you do not get credit in removing the smallest particles since they are not part of the test.
- The CADR rating is only valid for a given filter as used in a specific equipment design, and when the filter is brand new. The rating is based on a 20-minute test.
- The CADR is an approximate and heavily simplified method that assumes air is well-mixed and does not consider location of the unit, entrainment of the air, or many other complexities, but does provide a simple way of comparing devices.
- Due to the measurement process, the CADR rating is intended for use only with equipment designed for residential spaces. Clean rooms, hospitals, and airplanes use high-efficiency HEPA filters and do not use a CADR rating, but instead may use MERV ratings.

CCM

According to the international definition, CCM, cumulate clean mass, refers to the total quality of cleaning the target pollutants when the CADR of the air purifier reduces to 50%. The particle CCM is divided into four levels P1-P4 and the formaldehyde CCM F1-F4. The higher the level, the bigger the CCM value, which means a longer period of replacing or cleaning the filter screen. CCM (cumulative purification, in mg) is another important parameter in the new standard for air purifiers, which specifies the amount of particulate matter or formaldehyde that can be eliminated before the filter is "discarded".

How CMM is tested

- Measure the CADR of the purifier in normal settings to get an initial value.
- Light up a cigarette in a three square-meter chamber and blow the smoke around briefly with a fan.
- Turn on the fan that's in the room, too, and seal off the chamber.
- Light 50(!) cigarettes one after another (not at the same time!) in the chamber and wait for the purifier to get the particulate concentration below 0.035 milligrams per cubic meter (mg/m³).
- Turn off the purifier and let it sit in the chamber for another 30 minutes before taking it out.
- Repeat these steps for 100 cigarettes, 150, 200, and beyond until the CADR is less than half of that initial value you got in step 1.

Particulate Matter		Formaldehyde	
P1	3000 – 5 000 mg	F1	300 -600 mg
P2	5 000 – 8 000 mg	F2	600 – 1 000 mg
P3	8 000 – 12 000 mg	F3	1 000 – 1 500 mg
P4	>12 000 mg	F4	>1 500 mg

Conclusions

As the portable air cleaners are becoming more common in our buildings and the range of products on offer is growing, it's becoming more difficult for the ordinary consumer to make the right choice. Manufacturers make claims about efficiency and safety and may promote their products for labelled uses, but the lack of a uniform and easily understood way of declaring capacity and performance makes it difficult to compare the products on the market.

The present review shows that four key information are important in choosing an air cleaner i.e., the size of the room and how many air changes per hour is recommended in different space, CADR rating for the room size, clean cumulative mass (CCM) grade for an air cleaner's long-term performance and formaldehyde, and noise level. In addition, it is also important to consider the filter life to make sure the filter will work well over time. If you have an air ionizer or any other electronic device, you run the potential risk of generating some levels of ozone.

More studies are needed to investigate the long-term performance of portable air cleaner devices and integrate performance data of air cleaners into building system design in conjunction with source control and ventilation strategies for better IAQ. ■

References

Please see the full list of references in the HTML version of this article on rehva.eu