Review of international standards describing air cleaner test methods

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ABSTRACT

The offer of air cleaners has increased significantly since the SARS-CoV-2 pandemic. However, it is not clear to what extent they can contribute to indoor air quality. There are multiple standards that describe test methods for air cleaners, but no consensus can be found on how to determine the performance of the air cleaners.
This paper contains a review of test methods for several types of air cleaners, (e.g. photocatalytic devices). This allows to make a holistic analysis of the existing test methods, in order to make recommendations for legislation regarding test methods to be used on the Belgian market.
For this paper, a literature study has been conducted to investigate the similarities and differences between several standards. The investigated documents include, among others, a French standard, ISO standards, ASHRAE standards and AHAM standards.
The literature study results in a structured overview of similarities, knowledge gaps and challenges. The main differences between the standards concern the test apparatus and the pollutants used. Most of the test methods use either a test duct, which measures the single-pass efficiency, or a test chamber, where the decay of the pollutants is measured over a certain period of time. All standards define different pollutants in different concentrations that should be tested. The test pollutants consist of VOCs, aerosols, (synthetic) dust, (acid) gases and microorganisms. They also differ in the type of air cleaners being tested. Several test methods are suited for any type of air cleaner. Other methods can only be used for a specific type of air cleaner, e.g., UV-C lights. In this case the test pollutants, measurements and test apparatus are adapted to the specific kind of air cleaner.
Most standards lack a non-targeted analysis of the treated air, because this is too complicated or expensive to test. However, the by-products can be harmful and are relevant to test.
Overall, the test methods are not suitable to predict the air quality in a room where the air cleaner may be used. They provide a means to compare the performances of different air cleaners to each other, but they do not predict real life performance. Furthermore, most of the test methods do not test the long-term performance of the air cleaners. This is because the test methods are kept as short as possible to reduce the costs.

KEYWORDS

Air cleaners, test methods, literature review, indoor air quality

1 INTRODUCTION

In the context of a study commissioned by the Federal Public Service of Health in Belgium, a review has been conducted on the existing test standards for air cleaners. Since the SARS-CoV-2 pandemic the amount of air cleaners on the Belgian market has increased significantly. All the air cleaners have been tested for efficiency and safety, but many different test methods are used, and it is not known to what extent they are reliable. An extensive literature review has therefore been conducted to investigate the state of the art of the existing test standards. The review includes national and international standards that are now commonly used to test air cleaners. The technical characteristics of the test standards are compared with each other, to see to what extent they resemble or differ from each other. Therefore, this is a more technical and holistic assessment, which differs from previous research, such as the research by Afshari et al. (2022) where they focussed on test methods and standards only for portable air-cleaning units.

2 OVERVIEW OF THE INVESTIGATED STANDARDS

Table 1 gives an overview of the investigated standards, and for which type of air cleaners they are suitable.

Table 1: Overview of the test standards

Test standard	Title	Type of air cleaners
AHAM AC-1 (2020)	Method for Measuring Performance of Portable Household Electric Room Air Cleaners	Portable household electric room air cleaners
AHAM AC-4 (2022)	Method of Assessing the Reduction Rate of Chemical Gases by a Room Air Cleaner	Portable household electric room air cleaners
AHAM AC-5 (2022)	Method for Assessing the Reduction Rate of Key Bioaerosols by Portable Air Cleaners Using an Aerobiology Test Chamber	Portable household electric room air cleaners
ASHRAE 52.2 (2017)	Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size	General ventilation Air-Cleaning Devices
ASHRAE 145.1 (2015)	Laboratory Test Method for Assessing the Performance of Gas-Phase Air-Cleaning Systems: Loose Granular Media	Gas-phase air-cleaning systems (tests the loose granular media)
ASHRAE 145.2 (2016)	Laboratory Test Method for assessing the Performance of Gas-Phase Air-Cleaning Systems: Air-Cleaning Devices	In-duct sorptive media gas-phase air-cleaning devices
ASHRAE 185.1 (2020)	Method of Testing UV-C Lights for Use in Air-Handling Units or Air Ducts to Inactivate Airborne Microorganisms	UV-C lights for use in air-handling units or air ducts
ASHRAE 185.2 (2020)	Method of Testing Ultraviolet Lamps for Use in HVAC&R Units or Air Ducts to Inactivate Microorganisms on Irradiated Surfaces	UV-C lights for use in air-handling units or air ducts
IEC 63086-1 (2020)	Household and similar electrical air cleaning appliances – Methods for measuring the performance Part 1: General requirements	electrically powered household and similar air cleaners
EN IS0 10121-3 (2022)	Test methods for assessing the performance of gas-phase air cleaning media and devices for general ventilation - Part 3: Classification system for GPACDs applied to treatment of outdoor air	gas-phase air cleaning devices supplying single pass outdoor air to general ventilation systems
ISO 16000-36 (2021)	Indoor air - part 36: Standard method for assessing the reduction rate of culturable airborne bacteria by air purifiers using a test chamber	Air purifiers commonly used in single room spaces
EN 16846-1 (2017)	Photocatalysis — Measurement of efficiency of photocatalytic devices used for the elimination of VOC and odour in indoor air in active mode. Part 1: Batch mode test method with a closed chamber	Photocatalytic devices or combined systems that include a photocatalytic function
NF B 44-200 (2016)	Independent air purification devices for tertiary sector and residential applications Test methods — Intrinsic performances	Any standalone air purification device

It is clear that most of the test standards only differentiate between portable air cleaners and in-duct air cleaners and not between different technologies. However, there are some exceptions to this, e.g. tests that only apply to UV-C technology. Standard ASHRAE 145.1 (2015) is also an exception, since it does not test the air cleaner itself, but the loose granular sorptive media used in the air cleaner.

3 TEST METHOD

3.1 Test apparatus

A first characteristic of the test methods is the test apparatus that is used. The two most commonly used test set-ups are the test chamber and the test duct.
The test chamber is an air-tight chamber in which the air cleaning device is placed. If the position of the air cleaner in the test standard is specified, it has to be placed in the centre of the chamber, on the floor, on a table or attached to a wall, depending on the type of air cleaner. The size of the chamber is also defined and differs among the different standards. Standard EN 16846-1 (2017) prescribes a test chamber with a minimum volume of 1 m^3, where the ratio of the volume of the device to the volume of the chamber shall be less or equal to 0,10. Most other standards define larger test chambers. ISO 16000-36 (2021) states that the volume of the test chamber should reflect the later application of the air cleaner. It should be 8m^3 or more and is usually between 15m^3 and 30m^3. AHAM AC-1 (2020), AHAM AC-4 (2022), AHAM AC-5 (2022) and IEC 63086-1 (2020) require a volume of around 30m^3. NF B 44-200 (2016) is an exception to the other standards. It uses a test chamber in a test bench, which is a different way of testing than room size test chambers. It does not require a minimum volume of the test chamber, only a minimum dimension for the upstream section of the test chamber. This should at least be three times larger than the air cleaner that overruns into this upstream section.
The test duct is a duct with an air inlet and outlet in which the air cleaner is placed in a manner that the airflow has to pass through the air cleaner. The dimensions of the test duct are clearly defined in each standard. The standards ASHRAE 52.2 (2017), ASHRAE 145.2 (2016), ASHRAE 185.1 (2020), ASHRAE 185.2 (2020) and EN ISO 10121-3 (2022) (that refers to standard EN ISO 10121-2 (2013)) use a test duct for a nominal device of 610 x 610 mm, which corresponds to the dimensions of the duct. Other dimensions are also possible, if the duct is adjusted to it as described in the standards.
As mentioned earlier, standard ASHRAE 145.1 (2015) is a special case. In consequence it does not use a test chamber or test duct, but a test apparatus with a gas-phase air filtration media column, which is comparable to the test duct in terms of test set-up and test method.

3.2 Test conditions

The tests are performed under different conditions. The temperature and relative humidity of the air are prescribed and do not differ much among most of the standards. Most of the standards require a temperature from 20°C to 25°C with a deviation of 0.5 to 3°C. Two of the investigated standards are an exception to this; ASHRAE 52.2 (2017) requires a temperature between 10°C and 38°C and ASHRAE 185.2 (2020) requires to test at three different temperatures: 12.8°C, 23.9°C and 48.9°C ± 2.2°C. The required humidity of all standards is between 40% and 50% with a deviation of 1 to 10%.
For tests using test chambers, the air inside the test chamber has to meet these requirements prior to the test, but the air is not conditioned anymore once the test starts. In the case of test ducts, the supply air should be conditioned.
The tests using test chambers state that the incoming air has to be clean, which is defined as a maximum pollutant concentration that is allowed. Filters are used to clean the air that enters the test chamber. Standards using test ducts also address the background concentration of the test air. This can be done by imposing a limit for the background concentration, as e.g. standard ASHRAE 145.1 (2015) does. Here, the influent air cannot contain more than 1% of the challenge concentration of each challenge gas. Another way to handle the background concentration is filtering the influent air and measuring the background concentration, which is taken into account in the calculations of the performance. (ASHRAE 52.2 (2017))

3.3 Operational mode of the air cleaner/flow rate through the air cleaner

To test the air cleaning device in a test chamber, the air cleaner has to be turned on in a certain operational mode. Depending on this, the air cleaner has a different efficiency. Standard NF B 44-200 (2016) defines that the test sponsor shall determine the speed for the tests. The AHAM AC-1 (2020), AHAM AC-4 (2022) and AHAM AC-5 (2022) standards define that the air cleaners are tested at the highest operating mode. The last two standards also mention that it is possible to test additional modes, if this is included in the test report. IEC 63086-1 (2020) requires testing in the maximum operational mode, except if the device only has an automatic mode, then it should be tested according to the manufacturer's instructions. ISO 16000-36 (2021) requires testing for multiple operation modes. The results then have to be checked on validity (e.g. the decay rate in step one has to remain below 50%). Only valid results are taken into account. Standard EN 16846-1 (2017) does not mention an operation mode.
If a test duct is used to test the air cleaner, an airflow rate in the test duct must be specified. Standard ASHRAE 52.2 (2017) specifies that the airflow rate should be at the upper limit of the air cleaner's application range. If this has not been specified an airflow rate corresponding to 2.50 m/s is used, which is rather low for large air groups. EN ISO 10121-3 (2022) states that the rated airflow of the air cleaner should be used. If this information is not given, a face velocity of 2.54 m/s shall be used. Standard ASHRAE 185.1 (2020) and ASHRAE 185.2 (2020) prescribe a fixed air velocity of 2.54 m/s, which corresponds to an airflow rate of 3400 cmh. ASHRAE 145.1 (2015) tests at an airflow rate to achieve a residence time of 0.10 ± 0.01s. A formula to calculate this is given in the standard.

4 DEFINITION OF PERFORMANCE

4.1 Performance when using a test chamber (CADR)

When a test chamber is used, test pollutants are usually added to the air until a certain concentration is reached. Then the supply of test pollutants stops, and the decay rate is measured. A common way of expressing the performance using this test method is the Clean Air Delivery Rate (CADR), that can be calculated by multiplying the volume (m^3) of the test chamber with the decay rate (h^{-1}) of the pollutant measured in the test chamber. As an exception, standard NF B 44-200 (2016) has a continuous supply of pollutants, since the test setup consists of a combination of a test duct and a test chamber. As a consequence, the CADR is calculated by multiplying the air flow rate of the air cleaning device with its purification efficiency.
As standard IEC 63086-1 (2020) explains, the reduction rate must be due to the operation of the air cleaner. This standard does not specify this further, but other standards do take this into account. The standards AHAM AC-1 (2020), AHAM AC-4 (2022) and AHAM AC-5 (2022) calculate the decay rate as the difference between the total decay rate with operating the air cleaner and the natural decay rate without operating the air cleaner. Standard NF B 44-200 (2016) uses a correction factor on the purification efficiency calculation to take the natural decay rate into account.
Standard ISO 16000-36 (2021) is an exception, as it uses a test chamber but only calculates the reduction rate of bacteria, without converting it into a CADR.

4.2 Performance when using a test duct

Test standards using a test duct usually have a continuous supply of pollutants for the first tests, where for e.g. the removal efficiency can be measured. Afterwards, the supply of pollutants stops, and other parameters will be measured, such as the desorption. Consequently, the performance is not expressed with a CADR. E.g. standards ASHRAE 145.1 (2015) and

ASHRAE 145.2 (2016) calculate the removal efficiency at a specific time, the penetration at a specific time and the capacity for removal for a time interval, all expressed as a percentage. From these values, other important factors can be calculated, such as the time to reach 50% breakthrough, which is the percentage of the challenge concentration that is reached at the outlet of the filter and is seen as an easy and useful indicator of air-cleaner performance (ASHRAE 145.2, 2016). Besides that, also performance curves that plot different performance parameters against the time are used. Standard EN ISO 10121-3 (2022) does not differ much from these ASHRAE standards. It calculates the (initial) removal efficiency and plots a removal efficiency versus capacity curve to define the efficiency of the air cleaner.

Standard ASHRAE 52.2 (2017) provides an extra way to express the efficiency; the Minimum Efficiency Reporting Value (MERV) for air cleaners. First the minimum particle size removal efficiency (PSE) is calculated for twelve size ranges of particles. The data points of the curves are then averaged per size range, and there are three different size ranges. The MERV value is then based on these three composite average PSE points. In this way only one value is needed to report the efficiency, instead of a curve with the removal efficiency per particle size. The MERV value should always be reported together with the test airflow rate, as it depends on it. Next to this, e.g. also the dust holding capacity of the air cleaner should be calculated. This method of expressing the efficiency is quite similar to the method used in standard EN ISO 16890-1 (2017), which is the basic standard to test in-duct filters for particulate matter. In this standard the particulate matter efficiencies (ePM) are calculated for three size ranges, based on the average fractional efficiencies and the standardized particle size distribution.

Standard ASHRAE 185.1 (2020) measures the efficiency of UV-C lights and thus has a slightly different approach. Since no filter is used, the efficiency will not differ much by time. Hence, only the single-pass bioaerosol inactivation efficiency is calculated, which is then corrected with the no-light transmission rate, where the inactivation of organisms is measured with the UV-C light turned off.

Lastly standard ASHRAE 185.2 (2020) forms an exception to the other standards. It tests UV-C lamps to inactivate microorganisms, but it has a different approach. The tests are not done with microorganisms, but the intensity of ultraviolet lamps on irradiated surfaces is measured. Hence the efficiency is expressed as the UV-C irradiance levels measured.

5 DURATION OF THE TEST

All the standards have their own practicalities, and there are also differences in measurement time. The duration of the test is often expressed in a similar way for tests using a test chamber. The following will discuss the duration from reaching and measuring the initial concentration to the end of the natural or total decay test. Some standards have a shorter measurement time, for e.g. standards AHAM AC-1 (2020), AHAM AC-4 (2022), AHAM AC-5 (2022) and ISO 16000-36 (2021) have a test time that ranges from ten minutes to an hour. The differences in measurement time are due to a faster or slower decay rate of the pollutants, characteristics of the measurement device or characteristics of the air cleaner. Standard EN 16846-1 (2017) describes a longer test duration: the test will run until 90% of the volatile organic compounds (VOCs) are removed, with a maximum test time up to 24 hours. Standard IEC 63086-1 (2020) is an exception that does not mention a test duration. This is because the standard only specifies general requirements to measure the performance, without providing a test method.

For the test methods using a test duct there is a greater difference in expressing the duration of the test. Some standards clearly specify a test duration. E.g. Standard ASHRAE 145.2 (2016) lets the standard initial performance test run for one hour, or until the penetration reaches 0.95%. The standard capacity test runs for four hours, or until a breakthrough of 95% is achieved. Then the challenge gas is removed, and desorption is monitored for 30 minutes or until the contaminant reaches 10% of the test challenge concentration.

It is also possible to test until a certain breakthrough is reached. Standard ASHRAE 145.1 (2015) runs the test until a 50% breakthrough of the initial challenge concentration is reached.

There are also other ways to express a measurement time. Standard EN ISO 10121-3 (2022), that partly refers to EN ISO 10121-2 (2013), defines measurement frequencies. For the initial removal efficiency the measurement frequency is less than 2 minutes, and the test normally takes 3 hours or less. The removal efficiency versus dose test has a measurement frequency ranging from 5 min to 12 hours. The test ends when the desired end point is reached and is stable for 10 min. Lastly a retentivity determination is performed without any challenge compounds. The test runs until the downstream concentration reaches 5%, with a maximum of 6 hours. Standard ASHRAE 185.2 (2020) requires to record a one-minute average of irradiance from the sensor per grid-point location for the sensor. Standard ASHRAE 52.2 (2017) states that the number of samples and sample time are determined by a number of data quality requirements.

For standard NF B 44-200 (2016), the test time depends on the pollutant tested. For gases it has a duration of 45 minutes, for inert particulate matter, a count cycle with 15 metering steps is defined for a 30 to 60-second count-per-count window and for allergens and microorganisms no duration is defined. Standard ASHRAE 185.1 (2020) also does not specify a test duration.

6 TEST POLLUTANTS

Depending on the test, different test pollutants are used. Some standards test for a broader range of pollutants, for e.g. standard NF B 44-200 (2016) uses a test gas, microorganisms, an allergen and aerosol. Other standards have a more limited scope of test pollutants. For e.g. standard ISO 16000-36 (2021) only tests for two bacteria. An overview of the test pollutants used in the different standards can be found in Table 2.

Table 2: Test pollutants

Test standard	Pollutants	Concentration
AHAM AC-1 (2020)	Cigarette smoke with particle sizes detected from 0.10 μ m to 1.0 μm diameter	24000 to 35000 particles/cc
	Commercially available test dust with particle sizes detected from 0.5 μm to 3.0 μm	200 to 400 particles/cc
	Paper Mulberry Pollen (non-defatted) with a particle size range of 5 μm to 11 μm, including fragments	4 to 9 particles/cc
AHAM AC-4 (2022)	Formaldehyde, n-Heptane, Toluene, d-Limonene, Nitrogen Dioxide, Ammonia	400 μg m^{-3} (+20 %) 800 μg m^{-3} (+20 %) 700 μg m^{-3} (+20 %)
AHAM AC-5 (2022)	Bacteria: Gram-Positive (Staphylococcus epidermidis), Gram-Negative (Acinetobacter baumannii) and bacterial endospores (Geobacillus stearothermophilus) Virus: more than one bacteriophage as surrogate for human pathogenic viruses, preferred one: MS2 (with host Escherichia coli) Mold: mold spore (Aspergillus brasiliensis) Alternate microbes can also be used (should be listed in the test report): Staphylococcus aureus, Escherichia coli, Klebsiella pneumoniae, Bacillus subtilis, Phi X-174 (with host Escherichia coli), T1(with host Escherichia coli), Phi 6 (with host Pseudomonas syringae), Penicillium citrinum, Aspergillus fumigatus, Penicillium chrysogenum, Penicillium rubens, Stachybotrys chartarum. Other microbes can also be used for specific questions.	The minimum initial concentration can vary (it depends on the microbe and the required log reduction), but will be between $5.0*10^6$ colony forming units (CFU) and $2.1*10^9$ CFU

ASHRAE 52.2 (2017)	Test aerosol: Polydisperse solid-phase (dry) potassium chloride (KCl) particles Synthetic loading dust: 72% ISO 12103-1, A2 Fine Test Dust, 23% powdered carbon, and 5% milled cotton linters	Is determined by initial efficiency tests, so that the total concentration level does not overload the particle counters
ASHRAE 145.1 (2015)	Challenge gases are selected from the following groups: VOC challenge gases: toluene, acetaldehyde, hexane, 2-butanone, isobutanol, dichloromethane, tetrachloroethylene Acid challenge gases: sulfur dioxide, nitrogen dioxide, nitric oxide, hydrogen sulfide, chlorine Other (common) challenge gases: formaldehyde, ozone, ammonia…	100 ± 10 parts per million by volume (ppmv) 100 ± 10 ppmv To be determined based on use application and safety considerations
ASHRAE 145.2 (2016)	A VOC: **toluene**, 2-butanone, acetone, benzene, cyclohexane, cyclopentane, dichloromethane, ethanol, hexane, iso-butanol, isopropanol, tetrachloroethene, m-Xylene, o-Xylene, p-Xylene An acid gas: **sulfur dioxide**, hydrogen chloride, hydrogen sulfide, NO2+ Another gas: formaldehyde, acetaldehyde, hexanal, **ammonia**, methylpyrrolidone, **ozone**, **DMMP**, chlorine, carbon monoxide, carbon dioxide Or another gas that is more applicable to the use of the air cleaner (Required chemicals are indicated in bold)	Low concentration: 400 parts per billion (ppb), high concentration ranging from 20 to 65 parts per million (ppm) Low concentration: ranging from 50 to 100 ppb, high concentration ranging from 5 to 35 ppm Low concentration: ranging from 75 to 100 ppb, high concentration ranging from 0.5 to 75 ppm (exception: CO_2: 400 ppb to 5000 ppm)
ASHRAE 185.1 (2020)	Mycobacterium parafortuitum (ATCC® 19686) Aspergillus sydowii (ATCC® 36542)	Sufficient concentration to allow measurement to show 99% inactivation
ASHRAE 185.2 (2020)	No test pollutants (only the intensity of UV-C lamps on irradiated surfaces is measured).	/
IEC 63086-1 (2020)	Only mentions that the target pollutant is a specific air pollutant with defined components, including the main categories microorganisms, gaseous pollutants and particulate matter	Not mentioned
EN IS0 10121-3 (2022)	Ozone, sulphur dioxide, nitrogen dioxide, toluene	150 ppb(v) and 3 ppm(v) 450 ppb(v) and 9 ppm(v) 900 ppb(v) and 9 ppm(v) (Values respectively for the initial efficiency determination and the efficiency vs. dose determination)
ISO 16000-36 (2021)	Bacteria: Staphylococcus aureus and Micrococcus luteus (other bacteria may be used for specific questions, but this should be listed in the test report.	Between $1.0*10^4$ cfu/m³ and $3.2*10^4$ cfu/m³
EN 16846-1 (2017)	VOC mixture: acetone, acetaldehyde, formaldehyde, heptane, toluene	Test is run at two concentrations: (50 ± 25%) ppbv per compound and (1000 ± 10%) ppbv per compound
NF B 44-200 (2016)	Test gas: mixture of acetone, acetaldehyde, formaldehyde, heptane, toluene A bacterium: Staphylococcus epidermidis and a fungus: Aspergillus niger	50 ppbv to 150 ppbv 10³ to 104 CFU/m³.

	Allergen: Major cat allergen Fel d 1 (*Felis domesticus* 1)	10 ng/m³ to 150 ng/m³
	Aerosol (inert particulate matter range 0,3 - 5 µm): Particulate suspension of DEHS (DiEthylHexyl Sebacate)	Dependent on the manufacturer's requirements of the optical particle counter

The choice of the test pollutants is often based on one of the following criteria: it are commonly used test materials for air cleaners/filters, e.g. the allergen and the aerosol of standard NF B 44-200 (2016) are chosen based on this criterium, or they represent typical pollutants of indoor/outdoor air, e.g. the test gases and the microorganisms of standard NF B 44-200 (2016) are common indoor air pollutants and standard EN ISO 10121-3 (2022) uses typical outdoor air pollutants. Another possible selection criterion is mentioned in ASHRAE 185.1 (2020): the used organisms cover the range of reasonable interest for UV-C device applications.
For tests using test chambers (except for standard NF B 44-200 (2016)), the concentration given in the table above is the initial concentration before the air cleaner is turned on. The concentration is not kept constant during the test, since the decay rate is measured.
The concentration can depend on the preconditions. For e.g. standard EN 16846-1 (2017) performs a test at two different concentrations. The test with the lowest concentration searches for reaction by-products, the test with the highest concentration is to demonstrate the photocatalytic activity with monitoring of the mineralization of VOCs into CO_2. For Standard ASHRAE 52.2 (2017) and standard NF B 44-200 (2016), the concentration depends on the characteristics of the particle counters.
As mentioned before, standard IEC 63086-1 (2020) is an exception, as it only specifies the general requirements to measure the performance. As a consequence, it does not specify the test pollutants and concentration to be used. Standard ASHRAE 185.2 (2020) is also an exception, since it only measures the intensity of the UV-C lamps as performance characteristic.

7 KNOWLEDGE GAPS AND CHALLENGES

7.1 By-products

Only two of the investigated standards explicitly address the testing of by-products. Standard NF B 44-200 (2016) states that the test method can be used to measure any by-products downstream of the air cleaner. Further, the test also prescribes to measure four reaction intermediates with a corresponding limit of detection: ozone (0.5 ppbv), carbon monoxide (1 ppmv), nitrogen monoxide (0.5 ppbv) and nitrogen dioxide (0.5 ppbv). This is measured before the pollutants are added to the test air and during the test with the gas-mixture. Purpose-engineered methods should be used to measure it. Standard EN 16846-1 includes a detection procedure to measure reaction by-products and ozone. A separate test is done with a concentration of 50 ppbv per compound (aldehydes, VOC, ozone), or with a higher concentration if needed. The by-products then have to be analysed according to ISO 16000-3 and ISO 16000-6. In addition, standards AHAM AC-1 (2020), AHAM AC-4 (2022) and AHAM AC-5 (2022) refer, among others, to standard UL 867 (Standard for Electrostatic Air Cleaners), which includes a test method for ozone generation levels (AHAM AC-5, 2022).
However, as Collins (Collins, 2021) points out, air cleaners can introduce several unintended by-products in the air, such as ozone, but also other oxidants for e.g. that can be harmful to health as well. Hence, this is an important topic to address when testing air cleaners and a proper testing method for a non-targeted analysis should be set up.

7.2 Real life performance

The air cleaners are tested in a specific test chamber or test duct. The test conditions and test pollutants are pre-defined, as described in paragraph 3.2 and paragraph 6, and this does not necessarily reflect the real-life conditions in which the air cleaner will be used. As standard ASHRAE 52.2 (2017) and ASHRAE 185.1 (2020) state, the outcome of the tests should help the user to compare the performance of different devices, not predict real-life performance. The tests try to simulate the real-life operation, but field conditions are not duplicated in the test. This would also be hard since field conditions vary from location to location. As a consequence, the cleanliness of a space where the air cleaner is used, or the service life of the device cannot be predicted. Standard ASHRAE 52.2 (2017) also indicates that the synthetic dust that is used as test material is not representative for all atmospheric particulates, which may affect the test results compared to real use situations. Standard ASHRAE 145.1 (2015) further adds that performing tests at low concentrations would probably more accurately predict the performance at actual use conditions, but this would be prohibitively expensive. It is also easier to generate, analyse and control higher gas concentrations than lower concentrations.

Another characteristic of the tests that is not representative for the real use conditions, is the size of the test chamber. As declared in paragraph 3.1, the size of the test chambers typically ranges from $1m^3$ to $30m^3$, which does not necessarily represent the real use conditions. Standard ISO 16000-36 (2021) imposes that the size of the test chamber should reflect the later application of the air cleaner, but this is the only standard that does so. The manner in which the performance is measured when using a test chamber is also not very realistic, as pollutants are not continuously introduced during the test, except in standard NF B 44-200 (2016).

7.3 Long-term performance

As described before, the tests are carried out over a limited period of time. However, as standard ASHRAE 145.2 (2016) mentions, breakthrough in real life conditions may take weeks or months. Therefore, the capacity test is conducted at elevated challenge concentrations to shorten the test, hence reducing the costs. As a consequence, the performance data cannot be transferred to real use conditions directly. The results can be extrapolated, but this will not always be correct. ASHRAE 185.1 (2020) also mentions that the performance over service life cannot be predicted with the results of the test and that the equipment provider should be expected to give an estimate of the service life characteristics for the expected operating conditions.

8 CONCLUSIONS

The review points out that there are many differences between the investigated test standards. One of the main differences concerns the test method that is used. Using a test chamber or a test duct imposes a different way of testing, which also influences the test duration and the definition of effectiveness. In contrast, the test conditions and the operating mode/flow rate through the air cleaner show little difference. The test pollutants used vary widely, but this is partly a consequence of the targeted type of air cleaners to be tested. If a device using UV-C technology is tested for example, only the decay of microorganisms is relevant to test.

The test standards provide a method to compare the air cleaning devices, but they do not provide results on the real use performance or the long-term performance. A non-targeted analysis to search for potentially harmful by-products is also a knowledge gap in most of the test methods.

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