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Method for Testing Portable Air Cleaners

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Sultan, Z.M.; Nilsson, G.; Magee, R.J.;
Bradley, J.S.

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Method for Testing Portable Air Cleaners

Zuraimi Sultan, Gregory Nilsson, Robert Magee, John Bradley

Prepared for: Government of Canada, Clean Air Agenda, Indoor Air Initiative - Evaluation of IAQ Solutions in Support of Industry Innovation

Date Issued: 23rd March 2011

Canada

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1 Introduction

1.1 Purpose

This protocol establishes a test procedure for evaluating the performance of portable air cleaning (PAC) devices intended primarily for residential environments. The PAC device may utilize various media/technologies (singly or in combination) intended for capture of particles and/or specific gaseous contaminants. By testing the PAC units under standardized conditions which reflect actual usage, the results of these tests are expected to 1) assist manufacturers in the design, improvement and innovation in PAC production, and 2) provide a foundation for scientifically-sound PAC labeling systems by which consumers can evaluate a device's claimed indoor air quality (IAQ) impact.

1.2 Scope

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. A portable air cleaner (PAC) is defined as an energy-consuming device (including battery operated versions) used to reduce the concentration of airborne pollutants, including but not limited to dusts, particles, environmental tobacco smoke, allergens, micro-organisms (e.g., mold, bacteria, pollen, viruses, and other bioaerosols), fumes, gases or vapors 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.

1.3 Overview of Test Method

This protocol addresses portable air cleaner performance characteristics of importance to users: the ability of the device to remove particles and selected gaseous contaminants from an unoccupied room, evaluation of their emissions and by-product formations, acoustic properties and energy consumption. The four principles behind the test method are; 1) uniformity: results can be used to directly compare devices on a standardized basis irrespective of their application; 2) realistic: test conditions represent realistic indoor contaminant loads under typical environmental conditions; 3) flexibility: apply to diverse classes of room air cleaning devices and 4) comprehensive: cover critical test aspects in terms of by-products generation of some classes of devices, energy consumption and noise reduction.

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 will be used to determine the PACs emissions of selected pollutants and their by-product formation. For PAC particle and VOC removal, a “pull-down” method will be used to conduct the test (AHAM, 2006; Chen et al., 2005). Figure 1 shows the general schematic of the test method. Each test phase (gaseous or particulate contaminant removal tests) consists of two portions: 1) challenge injection phase and 2) decay condition phase. Known amount of particles of different sizes or selected VOCs are introduced (in different tests) during the challenge injection phase to achieve the desired target concentrations. Once target contaminant levels in the test chamber have been achieved, the challenge injection is stopped, and the concentration decay rate from the decay condition is measured. By repeating the test, with and without the PAC operating, the removal effectiveness of the unit can be determined from the difference in the 2 curves shown in Figure 1. The performance indices of the device for each VOC and different size particles using this test method are single pass efficiency (SPE) and the clean air delivery rate (CADR).

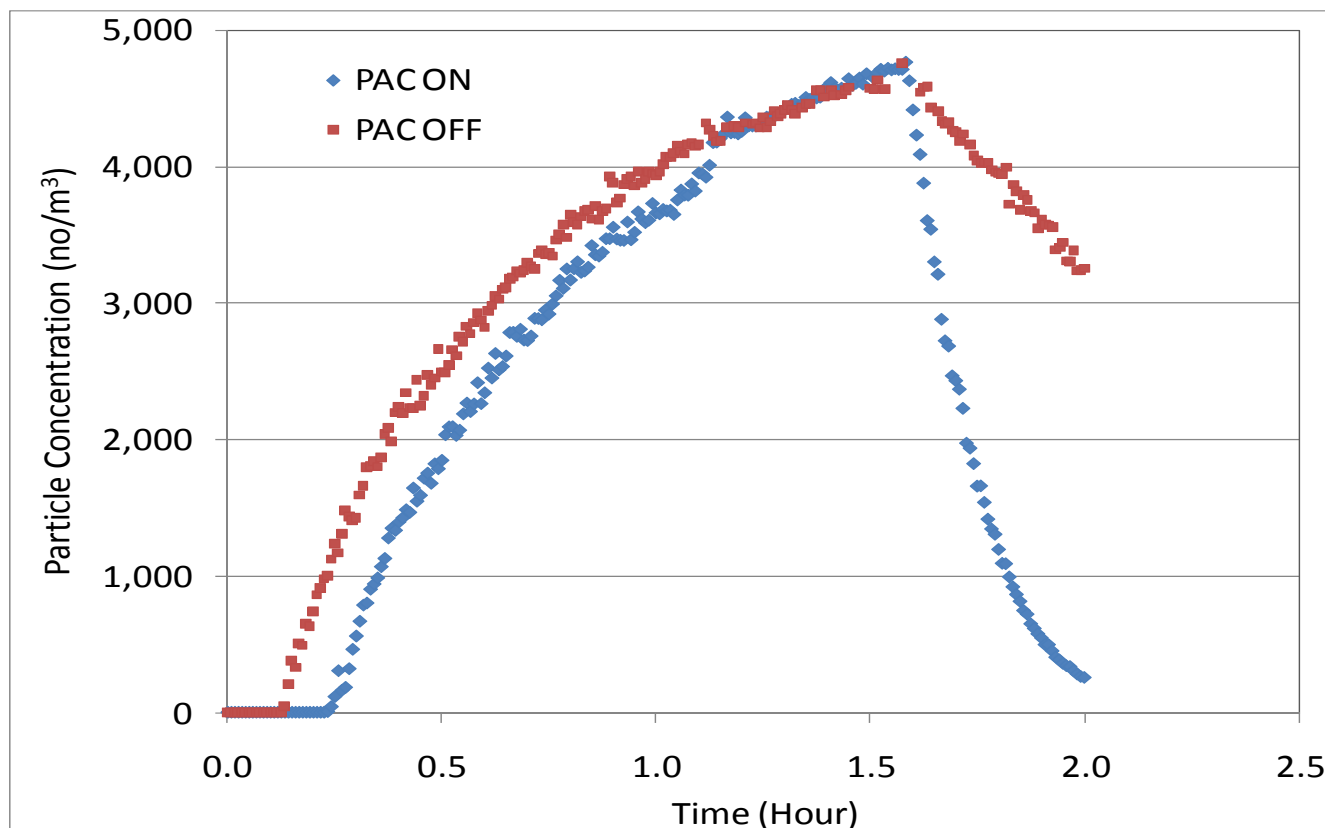


Figure 1 Time-concentration profile for a ‘pull-down’ test method.

The test is to be performed under full recirculation mode (chamber operated as closed system) to facilitate comparison with other test methods (AHAM, 2006). Particles and VOC removal performances and by-product emissions are to be performed at environmental conditions of air temperature 21.0 ± 2 °C, relative humidity (RH) 40 ± 5 % and chamber air exchange rate less than 0.05 air change per hour.

For acoustic measurements, the experiments are to be 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 to be 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 must have been 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 to be conducted under PAC running and standby modes.

2 Definitions and Acronyms

2.1 Definitions

Key terms are defined below for the purposes of this protocol.

adsorbent: a material that collects sorbates by adsorption.

adsorption: the attraction of a sorbate to the surface, both outer surface and inner pore surface, of a media by physical forces (Van der Waals forces). This is a reversible process.

aerodynamic particle sizer: an instrument capable of measuring aerodynamic particle size distribution from 0.5 μm to 5 μm diameter relevant for this protocol. The instrument also provides the total particle number concentration between this size ranges and is hereby defined as “total APS”.

air flow rate (chamber): the volumetric flow rate at test chamber supply and return diffusers.

air flow rate (device): the volumetric flow rate out of the supply inlet.

bypass: the proportion of the challenge particle, gas or vapor that passes around the filtration media bed or the device without contacting the media or the device itself.

byproduct: compounds formed as a result of the heterogeneous and homogeneous reactions of ozone and photocatalytic oxidation (PCO).

challenge particle: the airborne particle generated via nebulised NaCl solution having particle sizes detected from 0.05 μm to 10 μm diameter.

challenge VOCs: the 3 volatile organic compounds that are generated as the chemical contaminants of interest.

chamber: a room-size chamber that can house the portable air cleaners to be tested for their IAQ and acoustic performance and provide the required environmental conditions that are similar to portable air cleaners use in full-scale room conditions.

clean air delivery rate: the main index for assessing performance of portable air cleaners. It is the product of the device single pass efficiency (SPE) with the device air flow rate and defined as the delivery of contaminant free air by a device measured in cubic meters per hour (m^3/hr).

coarse particles: relatively large airborne particles with aerodynamic diameter ranging from 2.5 μm to 10 μm .

comparison method: the method in which the sound power level of a device under test is determined by comparing the averaged value (on a mean square basis) of the sound pressure levels produced by the device in a test chamber to the averaged value of the sound pressure levels produced in the same chamber by a reference sound source of known sound power output. The difference in sound pressure levels is equal to the difference in sound power levels when conditions are the same for both sets of measurements.

device: throughout this protocol the word “device” means portable air cleaner (PAC) used in general for the removal of particles and gas-phase contaminants, specifically, the portable air cleaner being tested.

effectiveness: describes the impact of device operation on room air concentrations under steady state conditions. It is bounded by zero and one, with zero indicating a completely ineffective air cleaner (0% of the pollutants are removed) and one indicating a perfectly effective air cleaner (100% of the pollutants are removed).

emissions: the mass of contaminants emitted from the portable air cleaners in the space per unit time (mg/h). For VOCs and particles, the emissions are determined two conditions: 1) with the portable air cleaners turned off and 2) with the portable air cleaners turned on. For ozone, the emissions are determined with the portable air cleaners turned on.

fine particles: airborne particles which are smaller than coarse particles. They have an aerodynamic diameter between 0.1 and 2.5 μm

generator: the instruments which produce challenge VOCs and particles at concentrations sufficiently meeting the requirements of the protocol.

natural decay: the reduction of particles or VOCs due to natural processes (i.e. surface deposition, sink effects, air exchange) in the chamber.

net emission rate: the mass of contaminants emitted from the portable air cleaners in the space per unit time (mg/h) taking into account other removal processes.

operating electrical power: the average electrical power in device operation mode, measured in Watts.

particle diameter: the diameter of a sphere of unit density (1g/cc) that has the same gravitational settling velocity as the particle in question. A particle's aerodynamic diameter affects penetration depth in the human respiratory tract, capture efficiency by a filter, as well as transport behavior and suspension times in indoor environments.

polydisperse: a characteristic of an aerosol for which the width of its number distribution shows a geometric standard deviation of $\delta_g > 1.5$

portable air cleaner: A transportable electric appliance with the function of removing particles and gas-phase contaminants from the indoor air.

reference sound source: a stable sound source emitting steady, broad-band noise with adequate sound power over a wide frequency range, calibrated in accordance to with ISO 6926.

room size: the maximum room size for effective portable air cleaner use.

scanning mobility particle sizer: an instrument capable of measuring particle size distribution from 0.05 µm to 0.5 µm diameter relevant for this protocol. The instrument also provides the total particle number concentration between this size ranges and is hereby defined as “total SMPS”.

single pass efficiency (SPE): that fraction of challenge particles / gas molecules which is removed by the device.

sorption: a process in which fluid molecules (gas or liquid) are removed by a media by absorption or adsorption.

sound power level: the rate of acoustic energy emitted from the device at maximum setting measured in decibels (dB).

standby mode: The lowest electrical power consumption mode which cannot be switched off by the user and that may persist for an indefinite time when a device is connected to the main electricity supply.

standby electrical power: the average electrical power in device standby mode, measured in Watts.

steady state: a condition where measurement concentrations do not fluctuate greater than ± 10% during a 30 minute period.

ultrafine particles: airborne particles which are smaller than fine particles. They have a diameter that is less than 0.1 µm

2.2 Acronyms and Abbreviations

ACH	Air change per hour
ALTER	Acceptable long-term exposure range
ASHRAE	American Society for Heating, Refrigerating and Air-conditioning Engineers
AHAM	Association of Home Appliance Manufacturers
ANSI	American National Standards Institute
APS	Aerodynamic particle sizer
ASTM	American Society for Testing and Materials
CADR	Clean air delivery rate
CCHT	Canadian Centre for Housing Technology
CPC	Condensation particle counter
CSA	Canadian Standards Organization
DAS	Data acquisition system
DNPH	2-4 dinitrophenyl hydrazine
DMA	Differential mobility analyser
EI	Energy efficiency index
EPA	United States Environmental Protection Agency
ESP	Electrostatic precipitator

ETS	Environmental tobacco smoke
GC	Gas chromatograph
GCMS	Gas chromatograph mass spectrometer
HC	Health Canada
HCHO	Formaldehyde
HEPA	High efficiency particulate air
HPLC	High performance liquid chromatography
HVAC	Heating, ventilating and air-conditioning
IAQ	Indoor Air Quality
ILG RSS	ILG reference sound source
ISO	International Organization for Standardization
KCl	Potassium chloride
LIM	d-limonene
NRC	National Research Council Canada
NaCl	Sodium chloride
O ₃	Ozone
OP	Operating electrical power
OPC	Optical particle counters
PAC	Portable air cleaner
PCI	Plasmacluster ion
PCO	Photocatalytic oxidation
PRR	Particle removal rates
ppb	Parts per billion by volume
ppm	Parts per million by volume
PTFE	Teflon or Polytetrafluoroethylene
RH	Relative humidity (%)
RR	Removal rates
SPE	Single pass efficiency
TOL	Toluene
TFE	Teflon or PTFE (see PTFE)
UFP	Ultrafine particles
UV	Ultraviolet light
UVGI	Ultraviolet germicidal irradiation
UV-VIS	Ultraviolet –visible light
VOC	Volatile organic compounds
ε	Effectiveness

2.3 Referenced Documents

- ANSI/AHAM AC-1-2006 Method for Measuring Performance of Portable Household Electric Room Air Cleaners.
- ANSI/ASHRAE Standard 129 1997. Test method for air change effectiveness.” American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc., Atlanta, Georgia.

- ASTM D 5197-09 Test Method for “Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler Methodology)”
- ASTM D 6196 – 03 (Reapproved 2009) Standard Practice for Selection of Sorbents, Sampling, and Thermal Desorption Analysis Procedures for Volatile Organic Compounds in Air
- ASTM D 6670 – 01 (Reapproved 2007) Standard Practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products
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3 Test Apparatus

3.1 Test Chamber for IAQ Performance

The considerations for room size chamber in determining performance of removing VOCs and particles and by-product emissions are given below. The chamber should be made from inert materials and fully characterized and its performance tested according to guidance provided in ASTM D6670. The following are key elements of suitable chamber design:

- Control:** The chamber system should be able to provide accurate control of airflow rate, temperature, relative humidity, pressure and background levels of particles, VOCs and ozone. The range of control conditions considered is typical for residential rooms found in Canadian buildings.
- Inert:** The chamber system and its apparatus should not generate particles and VOCs in the interior. Further, adsorption VOCs within the interiors should be minimal.
- Airtightness:** The chamber system should be airtight to reduce ambient air infiltration into the chamber and exfiltration out of chamber air.
- Airflow:** The chamber system should be able to simulate air velocities, flow patterns, and air distribution that are found typically in real ventilated residential room with mixing-type ventilation systems. Chamber mixing should be evaluated with and without the presence of the operating PAC device.
- Monitoring:** The chamber system should be able to provide on-line and remote monitoring/operation of the test conditions including airflow rates, air temperature, relative humidity, particles and VOCs generation and measurements, pressure inside the chamber and within the ventilation ducts. The remote monitoring/operation of the chamber should ensure that during the conduct of the test, it would not require a person to enter the chamber
- Ports:** The chamber system should have adequate ports for sampling and power and communication cables within the chamber. Also, there should be adequate ports in the ventilation ducts for air flow measurements.
- Maintenance:** The chamber system should be easily accessible for cleaning and maintenance.
- Modular Design:** The chamber system should be able to simulate typical residential room design layout.

Table 1 Chamber specifications for environmental conditions

Specification	Control Range	Control Precision	Reference
Air flow rates	2.5 to 142 L/s	±3.0 %	1
Air exchange rates	0.05 ^a to 1.0 ACH	±3.0 %	1
Temperature	17 to 27 °C	±0.5 °C	2, 3
Relative Humidity	20 to 60 %	±5.0 %RH	2, 3

^a Total air leakage in 100% recirculation.

[1] Reardon (2007)

[2] Gilbert et al. (2006)

[3] NRC, CCHT internal data.

NRC's "full scale chamber", used in the development of this method, has inside dimensions of 5.0 x 4.0 x 2.75m (Volume: 55m³). The envelope (from the interior) is comprised of 11 gage stainless steel sheets for the floor and 14 gage for the ceiling and walls Type 304, No. 4 surface finish stainless steel sheets, 100 mm fibreglass insulation, and 12,7 mm plywood. The stainless steel, floor, ceiling and walls of the test chamber are welded together. A stainless steel pass through panel at the side of the chamber has adequate connectors for power, communications and sampling cables for remote control. The door of the test chamber is 1.45 x 1.93 m and has an observation window of dimension 0.46 by 0.46m. Double TFE-fluorocarbon gaskets are used for the door (one mounted on sealing surface of the door, the other mounted on the sealing surface of the wall) to form a good seal when the door is closed. Recessed illuminating lights are used in the chamber.

The air supplied into the test chamber should be preconditioned. This can be achieved by passing the air through dehumidifying coils and/or chilled water cooling coils. The air should be treated with HEPA particle filters to remove particles and activated carbon filters to remove VOCs. Airflow rates can be measured by using orifice plates in the supply, return and exhaust air ducts. To reduce contamination generated by the HVAC system, all the components downstream of the carbon adsorbent and upstream of the return duct are to be made of stainless steel. To replicate the air distribution in a typical residential bedroom with floor mounted air supply diffuser and wall mounted return grill, the supply air diffuser to the chamber should be upward facing while the return air grill should be sideward facing.

3.2 Test Chamber for Acoustic Performance

The experiments to evaluate the acoustic performance should be performed in a reverberant test chamber conforming to the requirements of the ISO 3743-1 method (ISO, 1999). Here, the tests evaluating the acoustic performance of the PAC were conducted in a reverberant test chamber in NRC which conforms to the requirements of the ISO 3743-1 method. The chamber room has dimensions 7.96 x 7.09 x 4.87 m high and a volume of 251.7 m³. The surfaces of the room are hard painted concrete. Five low frequency sound absorption panels were installed in the room to reduce the low frequency spatial variation of sound levels in the room.

3.3 Test Apparatus for Particles

Particulates found in indoor environments cover a wide range to types and size ranges (Figure 2 provides a simple overview). According to Health Canada’s Guidelines for Residential IAQ, size of particles may range from 0.005 µm to 100 µm in diameter. The size range of concern when human health effects and indoor air quality are considered is from 0.01 µm to 10 µm in aerodynamic diameter. PM₁₀ are particles that are 10 µm or less in aerodynamic diameter; coarse particles are those with aerodynamic diameters between 2.5 and 10 µm. Above 15 µm, most particles are too large to be inhaled. PM_{2.5} are particles of 2.5 µm or less in diameter. For fine particulate matter (≤2.5 µm mass median aerodynamic diameter), HC sets an Acceptable Long-Term Exposure Range (ALTER) for residential indoor air of ≤40 µg/m³. Allergenic materials such as spores, pollen, and cat dander are typically larger than 2.5µm, thus the PAC impact on both fine and “coarse” particle fractions should be considered. The finer particles pose a threat to human health because they can travel deepest into the lungs.

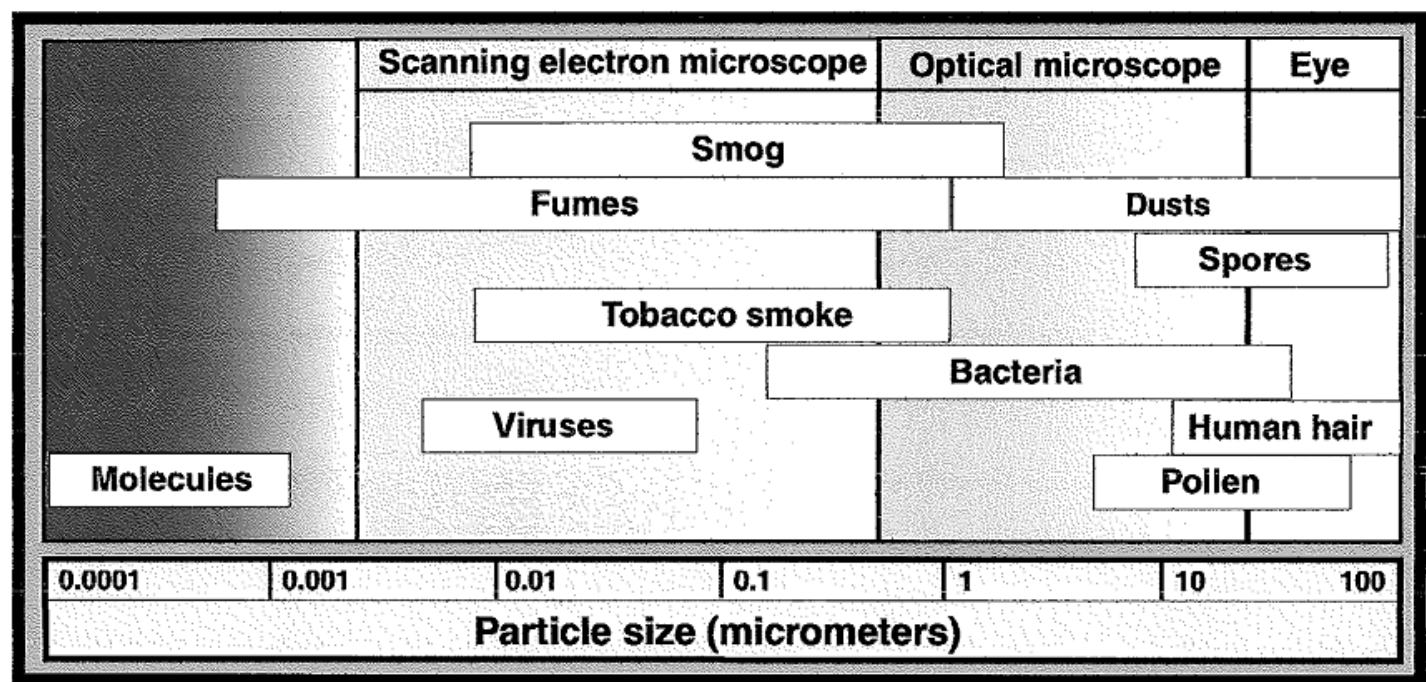


Figure 2 Common particulate air contaminants and their relative sizes (source: Hinds, 1982)

Ultrafine particles (UFPs) which have an aerodynamic diameter of <0.1 µm, are potentially the most dangerous owing to their small size, large surface area/volume ratio, high content of redox cycling organic chemicals, deep penetration, and high rates of retention in the lung (Nel, 2005). There are no standards/guidelines on ultra-fine particles at the moment in Canada for residential settings. However, scientific discussions are ongoing on the formation of a standard. Nevertheless, Table 2 provides some reference concentrations.

Table 2 Reference ultrafine particle (UFP) concentrations

Environment	UFP Concentration (no/cm ³)
Unoccupied homes	2000-12000
Occupied homes	2000-80000
Office air	2000 – 4000
Ambient air in urban area	10000 – 30000
Polluted outside air	> 50000

Wallace, 2009; Bhangar et al., 2011

No single analytical method can span the full range of particulates found indoors, thus characterization of PAC performance with regards to particulate removal (or unintended generation) will require the use of several classes of analytical instruments. Similarly, more than one class of particle generation device may be needed to provide the particle challenge atmospheres necessary to fully test PAC performance.

3.3.1 Particle Generation

The particle generator shall provide stable test particles of sufficient concentration over the 0.05 to 5 µm diameter size range to meet the requirements of Section 5 without overloading the aerosol particle counter.¹ The test particles shall be polydisperse potassium chloride (KCl) or sodium chloride (NaCl) particles generated from an aqueous solution. Polydisperse liquid particles are usually produced by nebulizing the particle substance through a binary nozzle using compressed air. A drying process is then required prior to introduction of the particulates into the test chamber. Since electrically charged particles are removed more effectively by filters than are uncharged particles, the particles should be electrically neutral to fairly assess PAC performance. Thus the dried particles shall be brought to a Boltzman electrostatic charge distribution by a beta or gamma radiation generator with an activity of at least 185 MBq (5 mCi) or a corona discharge ionizer. The corona discharge ionizer shall have a minimum corona current of 3 µA and shall be balanced to provide equal amounts of positive and negative ions.

3.3.2 Particle Measurement

The particle measuring systems shall be capable of counting and sizing individual KCl / NaCl particles in the 0.05 to 5 µm diameter size range. Since the test particles straddle the range from ultrafine (<0.1µm) to fine particles (0.1 to 2.5 µm) to coarse particles (above 2.5 µm), no single instrument will be capable of measuring the complete particle spectrum. Both size-specific and total particle concentrations in two size groups are to

¹ Ideally, the performance of the PAC in particle removal should be evaluated over the entire range of health-relevant particle sizes expected to be present during its intended use. This range would encompass particles from approximately 0.01 to 10 microns. Preliminary measurements showed however, there are technical problems in generating and/or measuring particles below 0.05 microns and above 5 microns.

be acquired. The two particle size groups are the: 1) ultrafine particle group and 2) fine and coarse particle group.

Typically, total ultrafine particle concentration can be measured using a condensation particle counter (CPC). CPC could come in the form of bench-top as well as portable units. Classifying ultrafine particles is normally conducted using a differential mobility analyser (DMA) which is based on electrical mobility of particles. The electrical mobility of a particle is a function of the particle size and the number of charges the particle has. A CPC which enlarges small particles by condensation of a vapour before being subjected to light scattering measurements is used in conjunction with the DMA. Alternatively, ultrafine particles can be measured using equipment based on charging the particles system and multiple electrometers to get signals from all particle sizes simultaneously.

For fine and coarse particles, optical particle counters (OPC) which determines particle size based on the intensity of the particle's scattered light can be used. A better alternative is the use of aerodynamic particle sizer (APS) which determines particle size by measuring the time of flight of the particle. Typically, OPCs would demonstrate good correlation in measuring particle size concentrations with an APS. It is highly recommended that an APS shall first be tested with KCl/NaCl to establish the relationship between the aerodynamic particle size and the light-scattering particle size determined by an OPC.

3.4 Test Apparatus for VOCs

3.4.1 VOC Generation

The target VOCs used for the protocol include formaldehyde, toluene and d-limonene (Table 3). These target VOCs are typically encountered in Canadian indoor environments (Otson et al, 1994; Gilbert et al., 2005; 2006). They represent organic compounds from various VOC classes. In residences, they represent the various sources of VOCs—formaldehyde is known to be from wood-based products; toluene is reported to be from solvents and gasoline; and d-limonene is from cleaning products and air fresheners.

Methods for generation of VOCs mixtures can be in the form of syringe injection systems, compressed gas cylinders containing mixtures at levels suitable for delivery via precision flow control systems, permeation tubes, bubbler/impinger or liquid vaporization systems. The generation of gaseous VOCs from liquid standards has to consider the various volatility characteristics. Unvaporized aerosol particles might underestimate the VOC filtration performance. The test method recommends that the challenge liquid VOCs be vaporized into a carrier gas. Safety and health aspects must be considered taking into account irritancy and toxicity of individual challenge VOCs as well as their explosive and flammable limits during vaporization.

For VOCs generation, clean air is to be supplied where the content of individual target VOCs in the influent air shall not exceed 1.0 ppm and shall not exceed 0.2% of the

challenge concentration for each VOC tested. The VOC generator shall be designed to ensure that the VOC challenge can attain the target concentrations within a nominal $\pm 5\%$.

Table 3 Target VOCs for test challenge

VOC	Abbrev.	CAS no	VOC class	Molecular Weight (g/mol)	Density (g/m ³)	Boiling Point (° C)
Formaldehyde	HCHO	50-00-0	aldehyde	30.03	0.815	-21
Toluene	TOL	108-88-3	aromatic	92.14	0.86	110.6
d-limonene	LIM	5989-27-5	terpene	136.24	0.84	176

3.4.2 VOC Measurement

As with particulate contaminants, a wide range of gaseous or volatile pollutants exist in indoor environments. These include compounds with extremely high volatility (such as formaldehyde) to much heavier compounds that are classified as being semi-volatile. Add to this the variable chemical nature of these compounds (for example in terms of polarity), and it can be seen that accurate measurement and generation of gas-phase PAC challenges will also require more than one device.

3.4.2.1 VOC Sampling

For VOCs sampling, chamber transport through PTFE and 316 stainless steel sample lines is advocated. Sampling line lengths should be kept to a minimum to limit adsorptive losses. The airflow rate of sampling systems shall be as low as possible consistent with the transport requirements of the chamber supply airflow rate. A compromise must therefore be reached between minimizing sample lag times while also controlling impact on chamber ventilation conditions.

For VOC sampling, two collection cartridge types are used: 1) 2-4 dinitrophenyl hydrazine (DNPH) to collect formaldehyde; and 2) Tenax tubes are used to collect toluene and d-limonene. The volume through the sample cartridges should range from 10 mL to 10 L depending on the concentration of the VOCs in test chamber. Samples should be taken after injection at stated levels at 0 min, 5 min, 10 min, 15 min, 20 min, 25 min, 30min, 45 min, 1 hr, 1.5 hr, 2 hr, 3 hr and 4 hr during VOC removal performance testing. Duplicate samples should be taken. Sampling rate should not be higher than 200 mL/min.

3.4.2.2 VOC Analysis

For VOC analysis, the quantitative analysis of the target compounds cannot be achieved by applying a single technique. Two analytical methods were selected in this study: 1) Gas Chromatograph – Mass Spectrometer (GCMS) technique; and 2) High Performance Liquid Chromatograph (HPLC) technique.

In the GCMS, principal methodology is to use a thermal desorption system for elution of collected toluene and d-limonene into a GC where they are separated using a non-polar capillary column and quantified using a mass spectrometer. Extracted ion rather than total ion technique using individual response factors for mass calculations is preferred due to the method's enhanced precision and accuracy.

For formaldehyde analysis, ASTM D 5197-03 Test Method for "Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler Methodology)" (ASTM, 2003) should be followed. This involves the elution of collected cartridges with acetonitrile under gravity feed and analysis by the HPLC system equipped with Zorbax ODS (or equivalent) column and UV-VIS detector using acetonitrile in water as a mobile phase for separation of compounds. Alternatively EPA Method TO-11A (EPA, 1999c) may be employed.

3.5 Test Apparatus for Acoustic Measurements

The instrumentation used for the acoustical measurements of the ILG reference sound source and each test source should include: a microphone, microphone preamp, microphone power supply and a calibrator. The calibrator should be calibrated annually.

3.6 Test Environment Monitoring and Data Acquisition System for IAQ Performance

3.6.1 Temperature

The air temperature measuring instruments should be able to measure between the ranges of 15 to 35°C with an accuracy of $\pm 0.1^\circ\text{C}$. This accuracy shall be guaranteed for a difference between air temperature and mean radiant temperature equal to or less than 10°C. During measurements, precautionary steps to protect the sensor from any influence of thermal radiation from neighbouring heat sources, e.g analyzers, PAC devices, contaminant generators, should be taken. Response time for the instrument should be the shortest response time possible (1 sec maximum). The resolution of the instrument should be at least 0.1 °C.

3.6.2 Relative Humidity

There are many instruments available for measuring the relative humidity of air. This includes psychrometers, chilled mirror and hygrometers. The air relative humidity measuring instruments should be able to measure between the ranges of 0 to 100 % with an accuracy of $\pm 1\%$. The resolution of the instrument should be 0.1 %. Response time for the instrument should be the shortest response time possible (1 minute minimum).

3.6.3 Air Velocity

The test chamber air motion shall be determined by air velocity measurements. An omni-directional anemometer shall be used to measure the air velocity. Directionally-sensitive anemometers may be used as an alternative if carefully oriented to indicate the true air speed at any test position. This may require a smoke test to determine the primary flow direction. Examples of instruments measuring air velocity include hot-wire anemometer, hot-sphere and thermistor anemometer, ultrasonic anemometer, and laser-doppler anemometer. The instrument should be able to measure air velocity within the range of 0.1 to 5 m/s at an accuracy of ± 0.05 m/s or $\pm 5\%$ of reading, whichever is greater. The resolution of the instrument should be at least 0.01 m/s. The response time of the instrument should be 0.2 seconds minimum.

3.6.4 Ozone

Health Canada's proposed residential indoor air quality guideline for ozone has been set at 20 ppb ($40 \mu\text{g}/\text{m}^3$) for 8 h exposure. Ozone levels in the chamber air shall be determined using an analyzer based on either chemiluminescence or UV absorption at 254 nm. The range of measurements for the instrument shall be from 1.5 ppb to 100 ppm with accuracy of 1.5 ppb or 2% of reading and resolution of 0.1 ppb. The response time of the equipment should be at most 1 minute.

3.6.5 Chamber Mixing

The test chamber shall have proper mixing verified via the mixing procedure of the standard practice for full scale chamber determination of volatile organic compounds emissions from indoor materials/products, ASTM D6670, Sections titled Air Distribution in the Chamber and Air-Mixing in a Chamber or ASHRAE Standard 129 test method (ASHRAE, 1997). A mixing level of higher than 80% may be considered satisfactory. The test chamber shall not create local airflow across the surface of the product under test exceeding 0.1 m/s.

3.6.6 Air Exchange Rate

Chamber air exchange rate measurements shall be determined using concentration decay of tracer gas techniques. Sulphur hexafluoride is recommended as a tracer gas although other gases (e.g. perfluorohydrocarbons) can be considered if they do not reduce collection efficiencies and increase sample breakthrough of the VOC adsorption tubes. The procedure, similar to ASTM E 471-00 Test Method for "Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution" (ASTM, 2006) is recommended for chamber air exchange rate analysis.

3.6.7 Data Acquisition System

Remote monitoring of indoor parameters using a data acquisition system (DAS) is highly recommended. The DAS should comprise of a microcomputer/DAS software, interface boards/multiplexor plus sensors/power supplies/cables for measuring airflow rates,

temperatures, relative humidities, air velocities, pressures, concentrations at selected locations in the test chamber and in the HVAC ducts. The DAS should be able to remotely turn on or off the portable air cleaner without person entry into the chamber.

4 Background Conditions for IAQ Performance

4.1 System Qualification and Calibration

The purpose of the system qualification and calibration tests is to verify the accurate measurements of the PAC performance can be made in the test facility. The qualification tests include checks on the following measurements:

- Volumetric airflow rates, chamber pressure differential, temperature and humidity
- Background particle count number concentrations and upper concentration limit for particle analyzers
- Background VOC and ozone concentrations
- Chamber mixing – uniformity of particle, VOC and ozone challenge
- Minimum VOC sink effects on chamber walls
- System response time
- Calibration of instruments should be performed as per manufacturer's recommendation

4.2 Conditions for Measurement

For performance assessment related to IAQ, all the measurements shall be conducted in the test chamber illustrated in Figure 3 under the following conditions:

- Portable air cleaner sitting on floor in the middle of the test chamber
- Test chamber temperature is to be 21.0 ± 2 °C with relative humidity (RH) of 40 ± 5 %
- Test chamber air exchange rate is to be less than 0.05 ACH with chamber mixing more than 80%.
- Supply air grill to the chamber should be upward facing while the return air grill should be sideward facing towards the middle of the chamber.
- Sampling locations for temperature, relative humidity and air velocity at the supply and return grills, and the middle and corner of the chamber as given in Figure 3.
- Particle measurements and individual VOC sampling will be conducted in the middle of the chamber.
- Particle and VOC dosing locations will be from the wall at the side of the chamber at a height of at least 1 meter above the floor.
- Test chamber particle concentrations
 - Maximum background concentration:
 - 50 particles/cm³ (total SMPS)
 - 5 particles/cm³ (total APS)

- Minimum concentration range after injection:
 - 1000 no/cm³ (for all size bins measured using SMPS)
 - 10000 no/cm³ (for total SMPS)
 - 20 no/cm³ (for all size bins measured using APS)
 - 200 no/cm³ (for total APS)
- Test chamber VOC concentrations
 - Maximum background concentration:
 - 10 µg/m³ (for all test VOCs)
 - Minimum concentration range after injection:
 - 800 µg/m³ (for toluene and d-limonene)
 - 200 µg/m³ (for formaldehyde)
- Test chamber ozone concentrations
 - Maximum background concentration:
 - 5 ppb
- Conditioned VOC sorbent tube shall not exceed 50% of target VOCs mass collected during the background concentration

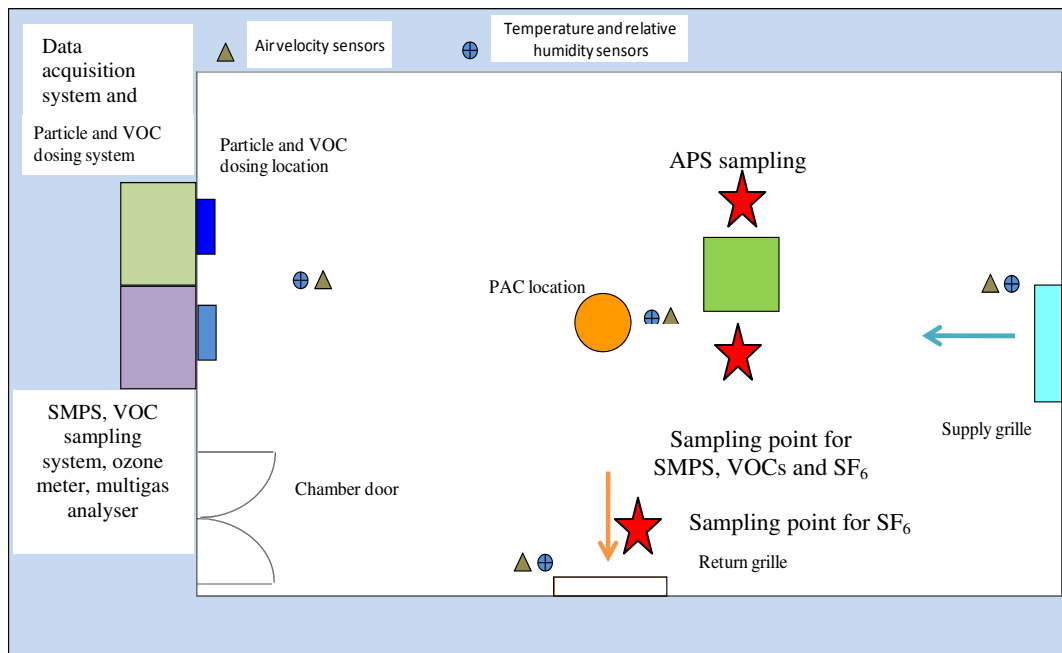


Figure 3. Schematic layout of the test chamber assessing IAQ performance of the portable air cleaner

5 Test Procedure for Determining Performance

5.1 IAQ Performance Test

The IAQ performance test is summarised in Table 4. After the device and test chamber have been prepared (see Section 4), the sequence of performance tests on each device shall be as follows:

Table 4 Summary of IAQ performance test procedure

Parameter	PAC impact		PAC performance		
	Emissions and By-product Formation		Particle Challenge		VOC Challenge
Test:	1	2	3	4	5
PAC status	off	on	off	on	on
Ozone	off	off	off	off	off
Particles	off	off	on	on	off
VOC	off	off	off	off	on
Temperature (°C)	21	21	21	21	21
Relative Humidity (%)	40	40	40	40	40
Air exchange rates (h ⁻¹)	0.05	0.05	0.05	0.05	0.05

5.1.1 Portable Air Cleaner Emissions and By-product Formation

The VOC, ozone and ultra-fine particle emissions of the portable air cleaner under working and non-working conditions within the chamber is evaluated (Test 1 and 2).

5.1.1.1 Emission Measurements with PAC turned off

The following test is intended to check for the possibility that the PAC may itself be a source of IAQ contaminants (VOCs, ozone, and ultrafine particles).

5.1.1.1.1

Establish the environmental and chamber conditions in accordance with Section 4.

5.1.1.1.2

The air cleaner is placed in the chamber, tested for proper operation and then switched off.

5.1.1.1.3

Perform VOC sampling and analysis to determine concentrations for the 3 VOCs under steady state conditions. Steady state concentrations for each of the target VOCs shall not exceed 10 µg/m³.

5.1.1.1.4

Perform particle measurements to determine steady state concentrations. Concentrations should not exceed 50 no/cm³ for total ultrafine particles and 5 no/cm³ for total fine and coarse particles under steady state conditions.

5.1.1.1.5

Perform ozone measurements to determine background steady state concentration. Background ozone concentrations shall not exceed 5ppb under steady state conditions.

5.1.1.1.6

Net emission rates of ozone, VOCs and total ultrafine particles are calculated as per Section 7.1.

5.1.1.2 Emission Measurements with PAC turned on

5.1.1.2.1

Establish the environmental and chamber conditions in accordance with Section 4.

5.1.1.2.2

The air cleaner is switched on at maximum setting (if PAC incorporates multiple technologies, then all available systems should be operated at maximum mode according to manufacturer's instructions).

5.1.1.2.3

Perform VOC measurements to determine steady state concentrations for the target VOCs under steady state conditions.

5.1.1.2.4

Perform particulate measurements determine steady state concentrations for total ultrafine particles.

5.1.1.2.5

Net emission rates of VOCs and total ultrafine particles are calculated as per Section 7.1.

5.1.1.2.5.1

Compare the calculated formaldehyde net emission rate of the device with the expected 'standard' emission rate which will give a steady state formaldehyde concentration of 40 ppb as per Section 7.1. Rate the formaldehyde emission as per Section 7.1

5.1.1.2.5.2

Compare the calculated net particles (total ultrafine particles) emission rate of the device with the background levels as per Section 7.1. Rate the particle emission as per Section 7.1

5.1.1.2.6

Perform ozone emissions measurements.

5.1.1.2.6.1

Measure the background (outside of the chamber) ozone concentrations as per Section 3.4.4 for 5 minutes

5.1.1.2.6.2

Measure the ozone concentrations for 24 hours. The equilibrium ozone concentration which is defined by the average of all 30 minute background corrected steady state concentration is computed.

For devices where ozone concentration did not increase under steady state conditions, the test is to be terminated.

5.1.1.2.6.3

After 24 hours, turn off the PAC and continue to monitor the ozone concentration. Ozone concentration acquisition should be at least 30 minutes where a minimum of 9 valid ozone data points is required for the analysis

5.1.1.2.6.4

The first order decay constant and net emission rate are calculated for ozone as per Sections 6.6 and 7.1.

5.1.1.2.6.5

Compare the calculated net emission rate of the device with the expected 'standard' emission rate which will give a steady state ozone concentration of 20 ppb as per Section 7.1. Rate the ozone emission as per Section 7.1

5.1.2 Portable Air Cleaner Particle and VOC Removal

This section relates to the evaluation of portable air cleaner performance under particle (Tests 3-4) and VOC (Test 5).

5.1.2.1 Particle Challenge

The particle challenge test includes two sets of measurements: 1) natural decay measurements and 2) particle removal with natural decay measurements (Tests 3-4).

5.1.2.1.1 Particle Removal with Natural Decay Measurements

5.1.2.1.1.1

The air cleaner is placed in the chamber, tested for proper operation and then switched off.

5.1.2.1.1.2

Establish the environmental and chamber conditions in accordance with Section 4.

5.1.2.1.1.3

Prepare $2.9\text{E-}03 \text{ mol/m}^3$ NaCl solution to be added to the container of 6-jet atomizer. The pressures and airflows to the nozzle of the atomizer should be adjusted accordingly to achieve minimum concentration specified in Section 4.2.

The initial concentration of the total ultrafine particle should reach a minimum $10000 \text{ particles/cm}^3$ while initial concentration of the total fine and coarse particles should reach $200 \text{ particles/cm}^3$. The corresponding initial concentration for all size bins for ultrafine particles and fine and coarse particles should reach a minimum 1000 and 20 particles/cm^3 respectively. After the minimum concentrations have been attained, the particle challenge is stopped and the generator is shut down.

5.1.2.1.1.4

After 3 minutes, acquisition of particle concentrations begins and the initial concentration at time ($t=0$) is recorded.

5.1.2.1.1.5

Particle concentration acquisition should be at least 30 minutes at a maximum of 3 minute sampling intervals. A minimum of 9 particle data points is required for the analysis.

5.1.2.1.1.6

The first order decay constant is calculated for particle size bins as per Section 6.1.

5.1.2.1.1.7

The acceptability of the challenge test is calculated using the correlation coefficient and standard deviation of the first order decay constant as per Sections 6.2 and 6.3. A minimum correlation coefficient of 0.95 and 0.90 for total and size resolved particles respectively determines if the test is acceptable.

5.1.2.1.2 Particle Removal with Natural Decay Measurements

5.1.2.1.2.1

Establish the environmental and chamber conditions in accordance with Section 4.

5.1.2.1.2.2

Prepare $2.9\text{E-}03 \text{ mol/m}^3$ NaCl solution to be added to the container of 6-jet atomizer. The pressures and airflows to the nozzle of the atomizer should be adjusted accordingly to achieve minimum concentration specified in Section 4.2.

The initial concentration of the total ultrafine particle should reach a minimum $10000 \text{ particles/cm}^3$ while initial concentration of the total fine and coarse particles should reach $200 \text{ particles/cm}^3$. The corresponding initial concentration for all size bins for ultrafine particles and fine and coarse particles should reach a minimum 1000 and $20 \text{ particles/cm}^3$ respectively. After the minimum concentrations have been attained, the particle challenge is stopped and the generator is shut down.

5.1.2.1.2.3

The air cleaner is turned on in the chamber. The time at which the air cleaner is turned on is recorded as $t=0$.

5.1.2.1.2.4

After 2 minutes of turning on the air cleaner, acquisition of particle concentrations begins and the initial concentration is recorded.

5.1.2.1.2.5

Particle concentration acquisition should be at least 30 minutes at a maximum of 3 minute sampling intervals. A minimum of 9 particle data points is required for the analysis.

5.1.2.1.2.6

The first order decay constant is calculated for particle size bins as per Section 6.1

5.1.2.1.2.7

The acceptability of the challenge test is calculated using the correlation coefficient and standard deviation of the first order decay constant as per Sections 6.2 and 6.3. A minimum correlation coefficient of 0.95 and 0.90 for total and size resolved particles respectively determines if the test is acceptable.

5.1.2.1.3 Portable Air Cleaner Performance

5.1.2.1.3.1

Determine the CADR of the portable air cleaner as per Section 6.4

5.1.2.1.3.2

Determine the acceptability of the test CADR of the portable air cleaner as per Section 6.5. A standard deviation less than $\text{CADR} = 39 \text{ m}^3/\text{hr}$ or 20%, whichever is greater, determines if the test is acceptable.

5.1.2.2 VOC Challenge

The VOC challenge test involves the VOC removal with natural decay measurements (Test 5). As the sink effects of VOCs on the stainless steel chamber is insignificant, it is to be ignored from the calculation of the natural decay constant. The VOC natural decay constant, $k_{n,V}$ (h^{-1}), due to air exchange is to be obtained from the air exchange rates measurements.

Some portable air cleaner technologies may possess non-linear decay characteristics (Chen et al., 2005). This may make the direct fitting of all experimental data to in step 5.1.2.2.1.7 inappropriate. An alternative data regression fit is to be used (see section 5.1.2.2.1.7).

5.1.2.2.1 VOC Removal with Natural Decay Measurements

5.1.2.2.1.1

Establish the environmental and chamber conditions in accordance with Section 4.

5.1.2.2.1.2

Prepare the VOC solutions and load them in the syringe pump. The syringe pumps are used to introduce VOCs into the chamber. The initial concentration of the target VOCs should reach the minimum concentration levels stipulated in Section 4.2. After the concentration levels have been attained, the VOC challenge is stopped and the syringe pumps are shut down.

5.1.2.2.1.3

The air cleaner is turned on in the chamber after one minute the dosing has stopped. The time at which the air cleaner is turned on is recorded as $t=0$.

5.1.2.2.1.4

After 5 minutes of turning on the air cleaner, acquisition of VOC concentrations begins and the initial concentration is recorded.

5.1.2.2.1.5

For target VOC measurements, sampling may be performed at time = 5 min, 10 min, 15 min, 20 min, 25 min, 30min, 45 min, 1 hr, 1.5 hr, 2 hr, 3 hr and 4 hr. Sampling flow rate shall be at 200 ml/min. A minimum of 9 data points (including those at time = 5 min and 4 hr) is required for the analysis.

5.1.2.2.1.6

The first order decay constant is calculated for VOCs as per Section 6.1.

5.1.2.2.1.7

The correlation coefficient and standard deviation of the first order decay constant as per Sections 6.2 and 6.3 shall be computed and reported. A minimum correlation coefficient of 0.9 determines if the test is acceptable.

If the data cannot fit the measured concentration decay curve well (i.e. regression coefficient $R^2 < 0.85$), regress the concentration versus time with a double exponential decay format. A minimum correlation coefficient of 0.9 determines if the test is acceptable.

5.1.2.2.2 Portable Air Cleaner Performance

5.1.2.2.2.1

Determine the CADR of the portable air cleaner for the target VOCs as per Section 6.4

5.1.2.2.2.2

Determine the acceptability of the test CADR of the portable air cleaner as per Section 6.5.

5.1.2.2.2.3

Determine the SPE of the portable air cleaner for the target VOCs as per Section 7.2.2.

5.2 Sound Power Level Measurements

The maximum output sound power level of each portable air cleaner is measured following the procedure of ISO 3743-1 to provide 'engineering' grade measurements of the sound power levels. ISO 3743-1 is a comparison procedure which compares the measured sound pressure levels of a test source such as a PAC with the levels measured for a calibrated reference sound source at the same positions in a reverberant test room. The sound power output of the reference sound source, such as the ILG source, must first be measured to a 'precision' grade using the ISO 3741 procedure. The reference sound source must also comply with the requirements in ISO 6926 for reference sound sources.

5.2.1

As specified in ISO 3743-1 the portable air cleaner should be placed on the floor of the reverberation chamber at least 1 m from all walls.

5.2.2

While the sound levels of the portable air cleaner are measured, it should be operating at its maximum setting with all additional features switched on.

5.2.3

Measure the sound pressure levels of the portable air cleaner in accordance with the ISO 3741-3 standard. Following this standard calculate sound power levels by comparison with the measured sound pressure levels of the reference sound source at the same measurement locations and using the previously determined sound power levels of the reference sound source.

5.3 Electrical Power Measurements

5.3.1 Electrical Operating Power Measurements

5.3.1.1

Connect the electrical power measuring equipment between the power supply and the air cleaner.

5.3.1.2

Turn on the air cleaner at maximum setting, reset power measuring equipment and adjust the power supply indicator to 120 Volts – 60 Hertz

5.3.1.3

Leave the air cleaner to stabilize for 5 minutes. Record the watt readings for 10 minutes at one-minute intervals. The operating power result is obtained by averaging the 10 readings.

5.3.2 Electrical Standby Power Measurements

5.3.2.1

Connect the electrical power measuring equipment between the power supply and the air cleaner in the standby mode.

5.3.2.2

Leave the air cleaner to stabilize for 5 minutes. Record the watt readings for 10 minutes at one-minute intervals. The standby power result is obtained by averaging the 10 readings.

5.4 Air Flow Rate Measurements

The velocities and cross section area at the supply air outlet of the PAC shall be measured. A hotwire anemometer velocity meter shall be used to measure air velocities at multiple points on the supply outlet of the PAC. Measurements are to be computed according to the following procedure:

5.4.1

Measure the dimensions (e.g. length and width) of supply air outlet of the PAC and determine the cross-section area.

5.4.2

Determine the measuring points on the cross-sectional area of the supply air outlet. The measuring points along the plane of the outlet shall be made at the intersection of imaginary lines that will cross the outlet vertically and horizontally. At least twenty-five points shall be considered.

5.4.3

Turn on the air cleaner at maximum setting, with all additional features switched on.

5.4.4

Take measurement at each measuring points, record reading and then move the velocity probe to the next measuring point.

5.4.5

Determine the average value of the velocity measurements from the twenty-five measuring points

5.4.6

Determine the product of cross-section area and the average velocity to obtain the PAC air flow rate.

6 Calculation Procedures

6.1 Calculating the First Order Decay Constant

Equation X1 described the first order decay constant, k , for contaminant:

$$C_t = C_o e^{-kt} \quad (X1)$$

Where C_t is the contaminant concentration at time t (no/m³ or mg/m³)
 C_o is the initial contaminant concentration at time 0 (no/m³ or mg/m³)
 k is the first order decay constant (1/h)
 t is the time (h)

Taking the natural log of both sides and rearranging equation X1 gives

$$k = \frac{\left(\sum_{i=1}^n t_i \ln C_{t_i} \right) - \frac{1}{n} \left(\sum_{i=1}^n t_i \right) \left(\sum_{i=1}^n \ln C_{t_i} \right)}{\sum_{i=1}^n t_i^2 - \frac{1}{n} \left(\sum_{i=1}^n t_i \right)^2} \quad (\text{X2})$$

Where t_i is the time at i (h)
 $\ln C_{t_i}$ is the natural logarithm of the contaminant concentration at time t_i
 n is the number of pair of measurements

Concentration of particles and VOCs measured sequentially during the decay period are statistically fit to the log form of model equation using linear regression. The first order decay constant is obtained from the slope of the fit.

6.2 Calculating the Correlation Coefficient

The measure of linear association between the time and natural logarithm of the contaminant concentration is estimated by the correlation coefficient r given in equation X3

$$r^2 = \frac{\left(\sum_{i=1}^n x_i y_i \right)^2}{\left(\sum_{i=1}^n x_i^2 \right) \left(\sum_{i=1}^n y_i^2 \right)} \quad (\text{X3})$$

Where

$$\sum_{i=1}^n x_i y_i = \sum_{i=1}^n t_i \ln C_{t_i} - \frac{1}{n} \left(\sum_{i=1}^n t_i \right) \left(\sum_{i=1}^n \ln C_{t_i} \right)$$

$$\sum_{i=1}^n x_i^2 = \sum_{i=1}^n t_i^2 - \frac{1}{n} \left(\sum_{i=1}^n t_i \right)^2$$

$$\sum_{i=1}^n y_i^2 = \sum_{i=1}^n \ln C_{t_i}^2 - \frac{1}{n} \left(\sum_{i=1}^n \ln C_{t_i} \right)^2$$

6.3 Calculating the Standard Deviation

The unbiased estimate of the standard deviation for the regressed line is given as the following equations (X4-5)

$$S_{line} = \sqrt{\frac{1}{(n-2)} \cdot \left(\sum_{i=1}^n t_i \ln C_{t_i}^2 - \frac{1}{n} \left(\sum_{i=1}^n \ln C_{t_i} \right)^2 - b \cdot \left(\sum_{i=1}^n t_i \ln C_{t_i} - \frac{1}{n} \left(\sum_{i=1}^n t_i \right) \left(\sum_{i=1}^n \ln C_{t_i} \right) \right) \right)}^2 \quad (X4)$$

This equation can be rearranged into

$$S_{line} = \sqrt{\frac{1}{(n-2)} \cdot \sum_{i=1}^n \left(\ln C_{t_i} - b - m \cdot t_i \right)^2} \quad (X5)$$

Where S_{line} is the unbiased estimated of the standard deviation
 $\ln C_{t_i}$ is the natural logarithm of the contaminant concentration at time t_i
 n is the number of pair of measurements
 b is the regression line intercept (no/m³ or mg/m³)
 m is the slope of the regression line (1/h)
 t_i is the time at i (h)

The estimate of the standard deviation for the regression line slope for particle and VOCS is given as the following equation (X6)

$$S_{slope} = \sqrt{\frac{S_{line}^2}{\left(\sum_{i=1}^n t_i - \frac{1}{n} \left(\sum_{i=1}^n t_i \right) \right)}} \quad (X6)$$

6.4 Calculating the CADR

The particle size resolved CADR shall be computed using equation (X7).

$$CADR = V(k_{PAC} - k_n) \quad (X7)$$

Where $CADR$ is the clean air delivery rate (m³/h)
 V is the volume of the chamber (m³)
 k_{PAC} is the first order decay constant with PAC turned on

k_n is the first order decay constant with PAC turned off

The VOC specific CADR shall be computed using equation (X8).

$$CADR = V(k_{PAC,V} - k_{n,V}) \quad (X8)$$

Where $CADR$ is the clean air delivery rate (m³/h)
 V is the volume of the chamber (m³)
 $k_{PAC,V}$ is the first order decay constant with PAC turned on
 $k_{n,V}$ is the air exchange rate of the chamber

6.5 Calculating the Standard Deviation of CADR

The standard deviation of the CADR for particles can be computed using equation (X9).

$$S_{CADR} = V \sqrt{S_{slope,k_{PAC}}^2 + S_{slope,k_n}^2} \quad (X9)$$

Where S_{CADR} is the standard deviation for the clean air delivery rate.
 $S_{slope,k_{PAC}}$ is the standard deviation for the regression line slope with PAC turned on.
 S_{slope,k_n} is the standard deviation for the regression line slope with PAC turned off
 V is the volume of the chamber (m³)

The standard deviation of the CADR for VOCs can be computed using equation (X10).

$$S_{CADR} = V \sqrt{S_{slope,k_{PAC}}^2 + S^2} \quad (X10)$$

Where $S_{CADR,V}$ is the standard deviation for the clean air delivery rate.
 $S_{slope,k_{PAC}}$ is the standard deviation for the regression line slope with PAC turned on.

S	is the standard deviation for air exchange rates (constant i.e. = 0)
V	is the volume of the chamber (m^3)

6.6 Ozone First Order Decay Constant Calculation

The first order decay constant, k , for ozone is calculated by interpreting the experimental data after the PAC is turned off using equation X1 as per Section 7.1.

7 PAC Performance and Rating

7.1 PAC Emissions and By-product Formation Rating

7.1.1 Ozone

7.1.1.1 Ozone Net Emission Rate Calculation

The net emission rate for ozone is calculated using the equilibrium concentration using equation X11.

$$E = C_e \cdot k_e \cdot V \quad (\text{X11})$$

Where E is the net emission rate for ozone (mg/h)
 C_e is the equilibrium concentration for ozone measured during the steady state condition (mg/m^3)
 k_e is the first order decay constant for ozone (1/h)
 V is the volume of the chamber (m^3)

Calculate the expected 'standard' emission rate which will give a steady state ozone concentration of 20 ppb ($40 \mu\text{g}/\text{m}^3$) using equation X12

$$E_{std,o} = C_{std,o} \left(k_d \cdot \frac{A_C}{V_C} + N_C \right) \cdot V_C - C_{out,o} \cdot N_C \cdot V_C \quad (\text{X12})$$

Where $E_{std,o}$ is the 'standard' emission rate for ozone indoors that will give a concentration of 20 ppb for ozone in a typical Canadian room (mg/h)
 $C_{std,o}$ is the 'standard' concentration for ozone served as the threshold guideline (mg/m^3)
 $C_{out,o}$ is the daytime outdoor concentration for ozone during summer (mg/m^3)
 k_d is the the ozone deposition velocity (m/h)
 A_C is the interior surface area of a typical Canadian room (m^2)
 V_C is the interior volume of a typical Canadian room (m^3)
 N_C is the ventilation rate of a typical Canadian room (1/h)

The calculation of $E_{std,o}$ is to be determined assuming the following conditions: 1) outdoor ozone concentration during daytime in summer, 2) building ventilation rates in a typical Canadian room during summer, 3) typical room volume of Canadian room, 4) ozone deposition velocity and interior area and volume is representative of that in a typical Canadian room.

Liu et al (1995) conducted an ozone exposure assessment study in Toronto, Ontario, during the winter and summer of 1992. Indoor, outdoor and personal exposure measurements were taken weekly during the winter and daily in the summer in 40 homes. They reported mean daytime home outdoor ozone concentration during summer of 19.1 ppb (38.2 ug/m³).

Typical values of Canadian residential room volume are obtained from the intervention field study conducted in Quebec City (Schleibinger et al., 2011). Data obtained from 62 houses recorded mean volume of 28 m³.

Reardon (2007) measured ventilation rates 3848, 12735 and 4162 buildings from Ottawa Vancouver, and Saskatoon respectively. Reported mean ventilation rates for the 3 respective cities were 0.4, 0.4 and 0.3 h⁻¹. Gilbert et al (2006) measured mean ventilation rates of 0.2 h⁻¹ in 96 Quebec City homes while the intervention field study conducted in Quebec City recorded 0.3 h⁻¹. The average of the ventilation rates data from these cities is used (0.3 h⁻¹).

Weschler (2000) summarized ozone deposition velocities and A_c/V_c values measured from 22 studies where 4 involves residences. The average product of deposition velocity with A_c/V_c for the 4 residential studies is 4.6 h⁻¹.

Using the above values, the calculated $E_{std,o}$ amounts to 5.2 mg/h.

7.1.1.2 Ozone Emission Rating

In terms of ozone emissions rating, the PAC is rated as follows:

- 1) negligible - no predicted ozone formation effect
- 2) low – if device $E < E_{std,o}$ in a typical Canadian house
- 3) high- if device $E > E_{std,o}$ in a typical Canadian house

7.1.2 VOC

7.1.2.1 Net VOC Emission Rates Calculation

The net emission rates for VOCs are calculated using the equilibrium concentration using equation X13.

$$E = C_i \bullet N \bullet V \quad (\text{X13})$$

Where E is the net emission rate for VOCs (mg/h)
 C_i is the steady state concentration for VOCs measured (mg/m³)
 N is the air exchange rate of the chamber (1/h)
 V is the volume of the chamber (m³)

Calculate the expected 'standard' emission rate which will give a steady state formaldehyde concentration of 40 ppb (50 µg/m³) using equation X14

$$E_{std,f} = \left(C_{std,f} - C_{out,f} \right) \bullet N_C \bullet V_C \quad (\text{X14})$$

Where $E_{std,f}$ is the 'standard' emission rate for formaldehyde indoors that will give a concentration of 40 ppb for formaldehyde in a typical Canadian room (mg/h)
 $C_{std,f}$ is the 'standard' concentration for formaldehyde served as the threshold guideline (mg/m³)
 $C_{out,f}$ is the outdoor concentration for formaldehyde during summer (mg/m³)
 V_C is the interior volume of a typical Canadian room (m³)
 N_C is the ventilation rate of a typical Canadian room (1/h)

Median ambient concentration of 0.575 ppb (0.77 µg/m³) was provided by Aiello and McLaren (2009). N_C and V_C values are similar to those used in Section 7.8.

Using the above values, the calculated $E_{std,f}$ amounts to 0.41 mg/h.

7.1.2.2 VOC Emission Rating

In terms of VOC emissions, the PAC is rated as follows:

- 1) low – if device $E < E_{std,f}$ in a typical Canadian house
- 2) high- if device $E > E_{std,f}$ in a typical Canadian house

7.1.3 Net Particle Emission Rates Calculation

The net emission rates for total ultrafine and total fine and coarse particles are calculated using the equilibrium concentration using equation X15.

$$E = C_n \bullet k_n \bullet V \quad (\text{X15})$$

Where E is the net emission rate for particles (no/min)
 C_n is the steady state concentration for particles (no/m³)
 k_n is the first order decay constant for particles determined in Section 7.1 (1/h)
 V is the volume of the chamber (m³)

7.1.3.1 Particle Emission Rating

In terms of particle emissions, the PAC is rated as follows:

- 1) low – if device records emission rate that is not significantly different than chamber background levels during operation.
- 2) high - if device records emission rate is significantly higher than chamber background levels.

Emission rates from total ultrafine or total fine and coarse particles are used to determine the rating.

7.2 Portable Air Cleaner Particle and VOC Removal

7.2.1 Particle Removal Rates (PRR)

The particle removal rates (PRR) values for a portable air cleaner shall be based on four composite average CADR values developed from test in accordance with 5.1.2.1 and 7.4.

The size resolved particle CADR values in the 21 particle sizes shall be averaged and the resultant 4 average CADRs (RR₁, RR₂, RR₃, RR₄) shall be reported as given in Table 5.

The removal rate value for particles in the specified size ranges for rating purposes shall be in accordance with Table 6.

Table 5 Particle size range groups

Average CADR Designator	Corresponding particle size range group, microns.
RR ₁	0.050 to 0.30
RR ₂	0.30 to 1.0
RR ₃	1.0 to 3.0
RR ₄	3.0 to 5.0

Table 6 PAC Particle Removal Rates (PRR) Parameters

PRR Values	Composite average particle CADR values in size range, microns			
	Range 1 0.050 to 0.30	Range 2 0.30 to 1.0	Range 3 1.0 to 3.0	Range 4 3.0 to 5.0
1	$RR_1 < 10$	$RR_2 < 10$	$RR_3 < 10$	$RR_4 < 10$
2	$RR_1 < 10$	$RR_2 < 10$	$10 \leq RR_3 \leq 20$	$10 \leq RR_4 \leq 20$
3	$RR_1 < 10$	$10 \leq RR_2 \leq 20$	$10 \leq RR_3 \leq 50$	$10 \leq RR_4 \leq 50$
4	$RR_1 < 50$	$20 \leq RR_2 \leq 50$	$10 \leq RR_3 \leq 50$	$50 \leq RR_4 \leq 10$
5	$RR_1 < 50$	$50 \leq RR_2 < 100$	$50 \leq RR_3 < 100$	$50 \leq RR_4$
6	$RR_1 < 100$	$100 \leq RR_2 < 200$	$100 \leq RR_3 < 200$	$100 \leq RR_4$
7	$RR_1 < 200$	$200 \leq RR_2$	$200 \leq RR_3$	$200 \leq RR_4$
8	$200 \leq RR_1 < 400$	$300 \leq RR_2$	$300 \leq RR_3$	$300 \leq RR_4$
9	$400 \leq RR_1 < 500$	$500 \leq RR_2$	$500 \leq RR_3$	$500 \leq RR_4$
10	$500 \leq RR_1$	$500 \leq RR_2$	$600 \leq RR_3$	$600 \leq RR_4$

7.2.2 VOC Single Pass Efficiency (SPE)

VOC removal for a portable air cleaner shall be based on the SPEs of the three target VOCs (formaldehyde, toluene and d-limonene). The SPEs shall be reported in terms of percentage (%) and obtained by dividing the VOC CADR with the device air flow rate.

7.3 Energy Efficiency Index

The energy efficient PAC performance index, *EEI* is computed by the following equation (X16)

$$EEI = \frac{CADR_{TotalAPS}}{OP} \quad (X16)$$

Where $CADR_{TotalAPS}$ is the clean air delivery rate for total APS (m³/hr)
 OP is the electrical operating power of the air cleaner (watt).

PAC must produce a minimum CADR of 85 m³/hr to be considered as energy efficient. An energy efficient PAC must have a minimum performance requirement of ≥ 3.4 CADR/watt.

7.4 PAC Acoustic Performance Rating

The acoustic performance rating of the PAC is determined by using the measured sound power levels of the unit to estimate the expected A-weighted sound pressure level of the unit in a typical Canadian residential room. A study that included measurements in 600 homes, found the average residential room volume to be 57.0 m³ and the average mid-frequency reverberation time to be 0.4 s (Bradley, 1986).

Using this average room information, the expected residential A-weighted sound pressure level can be calculated from the measured sound power levels as follows,

$$L_p(A) = L_w(A) + 10\log\{(4 \bullet T_{60}) / (0.161 \bullet V)\} \tag{X17}$$

Where $L_p(A)$ is the estimated A-weighted sound pressure level (dBA) in a typical Canadian residential room,
 $L_w(A)$ is the A-weighted sound power level (dBA) of the PAC determined using ISO 3743-1,
 T_{60} is the average mid-frequency reverberation time (0.4 s) in a typical Canadian residential room,
 V is the volume (57.0 m³) of a typical Canadian residential room.

Using the average room volume and reverberation time of a typical Canadian residential room, the term $10\log \{(4 \bullet T_{60}) / (0.161 \bullet V)\}$ is -7.6 dB and equation (X17) becomes equation (X18).

$$L_p(A) = L_w(A) - 7.6 \tag{X18}$$

The PAC sound output is categorized in terms of the A-weighted overall sound pressure level expected in a typical residential room, $L_p(A)$, because these are the sound levels people will experience in their homes when using the devices. The three rating categories A, B and C are given in Table 7 and are described in terms of the expected reactions of residents to these noise levels. It is to be noted that this table does not indicate any health effect of the sounds produced by the PAC units because no such effects have been established for the sound levels of typical PAC devices. Of course, the sound from the PAC units may be more disturbing to some people than to others and this will often vary with their personal activity. For example, people may be more sensitive to the noise from units when trying to sleep. The rating categories are intended simply to rank order the general acceptability of the noise from the PAC units.

Table 7 Portable air cleaner sound rating

Sound Rating Category	Range of A-weighted residential sound pressure levels, $L_p(A)$, (dBA)	Comment
A	< 35	Clearly acceptable
B	35 to ≤ 50	Acceptable for some situations
C	> 50	Not acceptable

8 Reporting of the Test Results

The test report shall generally include the following information:

- 1) Description of the test method and any deviations from it.
- 2) Testing organization, date of test and name of test operator
- 3) Device identification, description, manufacturer, physical description of construction, dimensions, type of technologies, and its application
- 4) Test conditions of Tests 1-5 including air temperature, relative humidity, air velocity, air exchange rates and chamber mixing.
- 5) The type and identification of the particle measuring and VOC sampling and analytical equipments used.
- 6) Results:
 - a. Byproduct Formation and Emissions of Portable Air Cleaner; Steady state formaldehyde, ozone and total ultrafine particle (UFP) concentrations should be recorded.
 - b. Performance of Portable Air Cleaner; Size-resolved and Total APS CADRs for particles, single pass efficiencies (SPE) for target VOCs are to be reported. Size resolved CADRs should be plotted on a graph (Figure 4) and tabulated (Table 7)
 - c. Standard deviation of CADRs and single pass efficiencies for size resolved particles and individual VOCs should be tabulated (Table 8)
 - d. Device electrical operating and standby power are to be reported.
 - e. Device sound power level measurements are to be reported. For each portable air cleaner unit tested, the total sound power output of the unit should be reported for its maximum operating setting with all options turned on. This should be in terms of the octave band sound power levels (125 to 8k Hz), the A-weighted overall sound power level, and the calculated A-weighted sound pressure level expected in a typical Canadian home.
- 7) The PAC performance ratings in terms of emissions and byproduct capabilities (ozone, VOC and particle emissions rating), initial particle and VOC removal (PRR and SPE values), energy efficiency (EEI value) and acoustic rating shall be reported.

9 Effectiveness and Room Dimensions for PAC Use

While CADR is used to describe the performance of a PAC with respect to particle removal, the benefit of using an air cleaner needs to be assessed in the context of its actual use. For a particular PAC with a total fine and coarse particle CADR value, how can it be effectively utilized in a Canadian residence? For example, PAC particle removal rate must compete with other removal processes that occur within the indoor environment. Other removal mechanisms indoors include deposition and ventilation.

The concept of PAC effectiveness has been used to examine acceptable values for CADR. Effectiveness, ε , has been defined by Miller-Leiden et al. (1996) as the difference in indoor concentration due to PAC ($C - C_{PAC}$) compared with the “no cleaning” case, C :

$$\varepsilon = (C - C_{PAC}) / C \quad (X19)$$

The closer the effectiveness is to 1, the more ideal the performance of the PAC is in removal of the pollutant. The protocol recommends for an effectiveness of 80% reduction in steady-state particle concentrations in a typical Canadian residential room.

To achieve 80% effectiveness and combining equation X19 with X7, we have the following equation:

$$CADR = 4V(k_n) = 4V(k_{dep} + k_v) \quad (X20)$$

Where k_{dep} and k_v are removal rates by deposition and ventilation. Equation X20 requires that the CADR should be four times the removal rate by ventilation and deposition combined times the volume of the room where the PAC will be used.

To determine the size of room where the PAC is expected to achieve 80% effectiveness, we assume a floor to ceiling height of 2.4 m, and ventilation rate of 0.3 h⁻¹ and deposition rate of 0.1 h⁻¹. Using these values, equation X20 is arranged in terms of floor area A (m²), and is given as:

$$A(m^2) = 0.26 * CADR(m^3/h) \quad (X21)$$

Using equation X21, a PAC with a total fine and coarse particle CADR value of 400 m³/h is appropriate to clean a room of 104 m² floor area. Likewise, equation X21 can be used to determine the CADR value of a PAC required to clean a room of a given floor area. For example, for a room with floor area of 50m², the required CADR of a PAC is at least 192 m³/h.

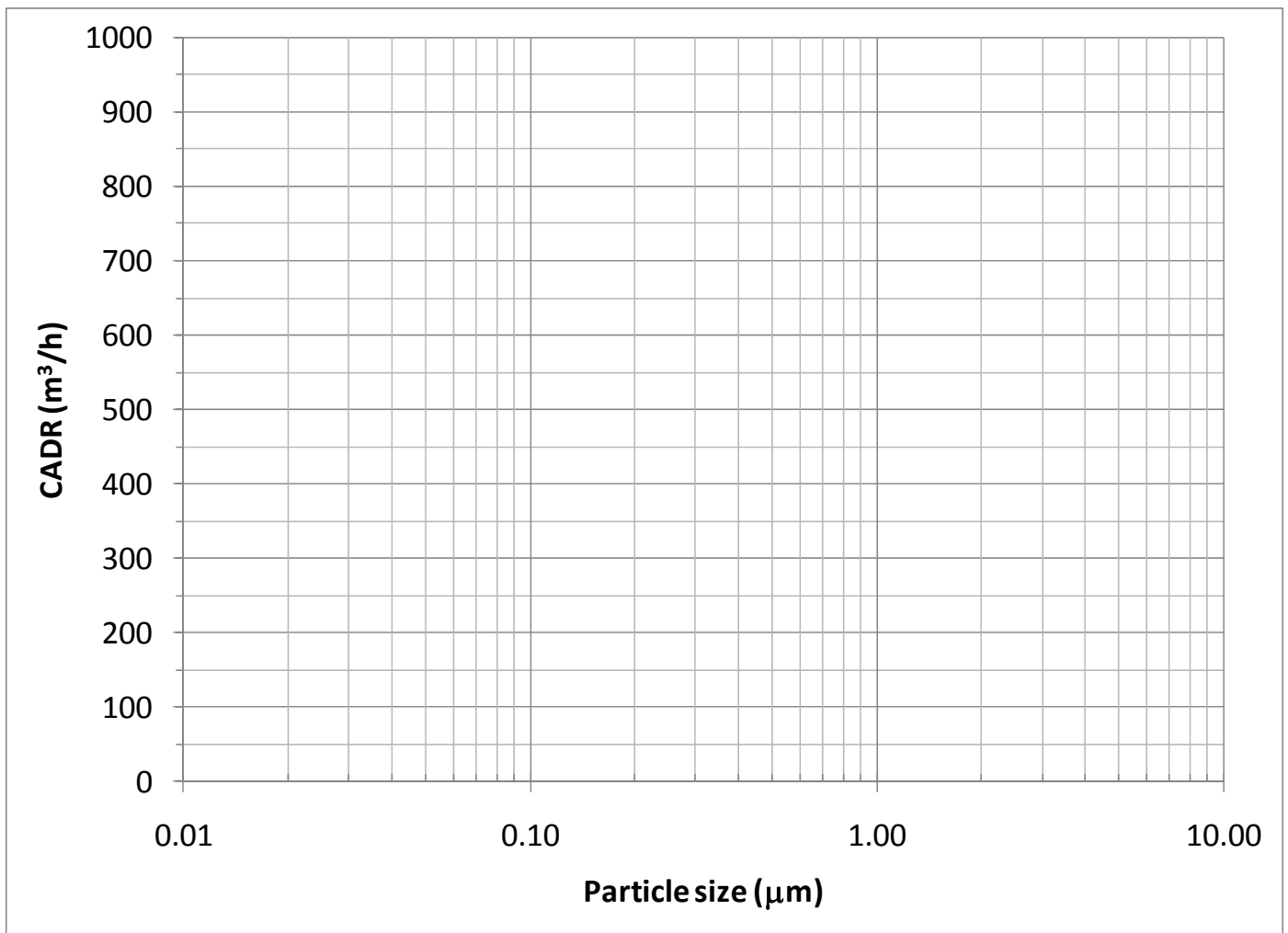


Figure 4 Plot of CADR versus particle size

Table 7 CADR and standard deviation for various particle parameters

Particle size (µm)	CADR (m ³ /h)		
Mean	Mean	Standard deviation	R ²
0.05			
0.06			
0.07			
0.08			
0.09			
0.10			
0.20			
0.30			
0.40			
0.50			
0.60			
0.70			
0.80			
0.90			
1.00			
1.50			
2.00			
2.50			
3.00			
4.00			
5.00			
Total APS			

Table 8 CADR and single pass efficiencies and standard deviation of target VOC

Target VOC	CADR (m ³ /h)		Single pass efficiency (%)
	Mean	R ²	
Formaldehyde			
Toluene			
d-limonene			