ANNEX 5

ANNEX 78

EBC
Energy in Building and
Communities Programme

Performance of Portable Gas-Phase Air Cleaners and Impact on Indoor Air Quality. A Literature Review

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international cooperation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.).

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely ‘Objectives’ and ‘Means’. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of ‘low tech’, robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible; the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from ‘living labs’ to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the ‘objectives’ themes are final goals or solutions (or part of) for an energy efficient built environment, while the ‘means’ themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)

Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling (*)
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
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Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings
Annex 97: Sustainable Cooling in Cities

Working Group – Energy Efficiency in Educational Buildings (*)
Working Group – Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group – Annex 36 Extension: The Energy Concept Adviser (*)
Working Group – HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group – Cities and Communities (*)
Working Group – Building Energy Codes

IEA EBC Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications

The IEA EBC Annex 78 explored the integration of gas-phase air cleaning technologies to supplement traditional ventilation systems, focusing on balancing IAQ and energy efficiency

Ventilation accounts for approximately 20% of the global energy use for providing an acceptable indoor environment. The requirements for ventilation in most standards and guidelines assume acceptable quality of (clean) outdoor air. Worldwide, there is an increasing number of publications related to air cleaning and there is also an increasing sale of gas phase air cleaning products. This puts a demand for verifying the influence of using air cleaning on indoor air quality, comfort, well-being and health. It is thus important to learn whether air cleaning can supplement ventilation with respect to improving air quality i.e. whether it can partly substitute the ventilation rates required by standards. The energy impact of ventilation by using air cleaning as supplement of ventilation needs to be estimated.

IEA-EBC Annex 78 was divided in 4 Subtasks:

- Subtask A: Energy benefits using gas phase air cleaning
- Subtask B: How to partly substitute ventilation by air cleaning
- Subtask C: Selection and testing standards for air cleaners
- Subtask D: Performance modelling and long-term field validation of gas phase air cleaning technologies

IEA EBC Annex 5: Air Infiltration and Ventilation Centre

EBC Annex 5 was first established in 1979 under the name “Air Infiltration Centre” undertaking technical activities and providing information services with the task of minimizing air infiltration energy losses. In 1986, the name was changed to “Air Infiltration and Ventilation Centre” to reflect the importance of the coupling of a good airtightness with appropriate ventilation. Over time, the AIVC has been continuously evolving to respond to emerging concerns, challenges and opportunities. We have now entered the 46th year of the AIVC’s existence and the Centre’s main goal is to provide reference information on ventilation & air infiltration in the built environment with respect to efficient energy use and good Indoor Environmental Quality (IEQ).

In November 2020, the Executive Committee approved the continuation of the AIVC for the period 2022-2026. Peter Wouters and Arnold Janssens are on behalf of INIVE the operating agents for this period.

The AIVC holds a conference each year in September/October in one of the AIVC participating countries. More information can be found here: www.aivc.org/events/conferences

The AIVC organizes 1 to 2 workshops per year. More information can be found here: www.aivc.org/events/workshops

The AIVC organizes a number of webinars per year. More information can be found here: www.aivc.org/events/webinars

The AIVC has formal collaborations with the TightVent platform (https://tightvent.eu/), the venticool platform (https://venticool.eu/) and the IEQ-GA (https://ieq-ga.net/).

Moreover, there is a close interaction with several ventilation related annexes of IEA-EBC. This publication is the result of the collaboration between AIVC and Annex 78.

If you want to be kept informed on the activities of AIVC and related platforms, you can subscribe here.

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Summary

This report is a deliverable from IEA-EBC Annex 78 “Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications”. Annex 78 also looked at a new test method for gas-phase air cleaning technologies, how gas-phase air cleaning technologies may partly substitute for outside air, the energy impact of using air cleaners to improve indoor air quality and the long-term performance of gas-phase air cleaners.

This report presents a comprehensive review of the performance of portable gas-phase air cleaning technologies used in non-industrial indoor environments. The study evaluates the effectiveness, limitations, and applicability of various technologies, including adsorbent-based filtration (e.g., activated carbon and chemisorbents), photocatalytic oxidation (PCO), air ion generators, ozone generators, and plant-based biofiltration systems. Performance indicators such as clean air delivery rate (CADR), single-pass removal efficiency, and VOC decay rates are critically assessed. The review integrates findings from both experimental and modelling studies to identify key factors influencing device performance, such as airflow characteristics, pollutant types, environmental conditions, and maintenance requirements. Emerging innovations, including thermally regenerable filters and hybrid systems, are also discussed. The analysis highlights that while several technologies demonstrate promising pollutant removal capabilities under controlled conditions, long-term performance, energy use, by-product formation (e.g., ozone), and practical deployment challenges remain significant. The report underscores the need for standardised testing protocols and comprehensive field studies to validate the real-world effectiveness of portable gas-phase air cleaners. This work contributes essential knowledge to Annex 78, supporting informed decision-making for improved indoor air quality management.

1. Introduction

Portable gas-phase air cleaners use different technologies to remove gaseous pollutants, which include inorganic gases (e.g. carbon monoxide and nitrogen dioxide), ozone (O_3), and organic gases (e.g. volatile organic compounds (VOCs) and aldehydes). Hundreds of different gaseous pollutants have been detected in indoor air. Sources of inorganic gases include gas stoves, tobacco smoke, and vehicles. Sources of O_3 include infiltration from outdoors and O_3 generation from indoor sources, such as laser printers. Sources of organic gases include tobacco smoke, building materials, furnishings, animal metabolic processes, outdoor sources, cooking and plant products and such products as paints, adhesives, dyes, solvents, caulks, cleaners, deodorisers, cleaning chemicals, waxes, hobby and craft materials and pesticides. In addition, radon can also be found in indoor air and is typically emitted from the bedrock. Portable air-cleaning devices are not effective at reducing radon levels in a building and are not recommended as a radon mitigation measure (Environmental Protection Agency (EPA), 2009).

Several portable air-cleaning technologies are designed to either remove gaseous air pollutants or convert them into harmless byproducts using a combination of physical and chemical processes. There are six principal types of gas-phase air cleaners. The most commonly applied methods are adsorbent media air filters, such as activated carbon (AC), chemisorbent media air filters, photocatalytic oxidation (PCO), ion generators, plasma, O_3 generators and plant-based biofiltration.

This report aims to provide a comprehensive overview of the performance and limitations of portable gas-phase air cleaners in indoor environments. The analysis focuses on their efficacy, influencing factors, and practical considerations for implementation. It builds on and complements the findings of VIP 42—the 42nd Ventilation Information Paper (VIP) published under the umbrella of the IEA EBC Annex 78, typically by the Air Infiltration and Ventilation Centre (AIVC), which provides concise, practice-oriented guidance on key topics in indoor air quality (IAQ), ventilation, and air cleaning technologies. While VIP 42 offers a broader evaluation of air-cleaning technologies, this report focuses specifically on the gas-phase removal performance of portable systems and integrates recent findings from both laboratory and field studies. Readers are referred to VIP 42 for additional background on air pollutant sources, health impacts, and general filtration principles.

In this report, the performance of portable gas-phase air cleaners is assessed primarily in the context of improving indoor air quality in non-industrial buildings, including cases where the devices may supplement or partially replace ventilation. The requirements discussed below reflect this context and may not apply universally to all use cases, especially when targeting specific pollutants or operating in highly controlled environments.

Regardless of the type of technology, three requirements must be fulfilled when the goal is to partially replace ventilation. First, high clean air delivery rate (CADR) and filtration efficiency must be provided for a broad range of chemical substances. Second, low airflow resistance (small pressure drop) is required. Finally, the release or generation of harmful substances must be prevented. In addition, the noise from the portable air cleaner must be low due to its proximity to the occupants. If the device is intended only to target specific pollutants, high removal efficiency for one compound may be sufficient. To fulfil these requirements, the design and operation of a portable gas-phase air cleaner should consider the following factors:

- device flow rate, and velocity through the media,
- filter type and efficiency,
- construction quality, particularly as it affects the air-bypass around the filter,
- type and concentration of target pollutants in the air,
- room conditions, such as air temperature and humidity, which affect the capacity of adsorbents to remove odours and chemicals, and
- unit placement in the room
- mode and schedule of operation.

At least three primary descriptors of the efficiency of cleaning systems exist:

- the VOC decay rate in a prespecified or test space volume/chamber, in ACH or 1/h,
- the single-pass removal efficiency – concentration reduction relative to the air entering the air cleaner, in %, and
- the clean air delivery rates - the clean air volume delivered by the treatment system for specific target pollutants, in m^3/h.

2. Filtration – Gaseous Materials

2.1. Adsorbent Media

A variety of gas-phase air cleaners remove gases using adsorbent media, such as active carbon (AC), to adsorb the pollutants in the air passed through them. Other forms of adsorbents are activated aluminium, silica gel, zeolites and organic synthetics (Spry, 2007). Adsorption is a mass transfer process in which gases collide with a solid surface, are attracted to a surface, and remain on the surface. A variety of VOCs can be adsorbed, but the process is typically inefficient for low molecular weight constituents and permanent gases (Daniels, 2007) for instance Nitrogen, Oxygen, Carbon dioxide. The adsorption process can be divided into two main groups: physical adsorption (e.g. the adsorption of gas on AC) and chemical adsorption (e.g. activated alumina or AC impregnated with potassium or sodium permanganate, which reacts with formaldehyde and several other compounds) (Fisk, 2007, 2006). Typical physical adsorption based adsorbents have a very high surface area per unit mass due to extensive microscopic pores, and the process is reversible (i.e. adsorbed VOCs can be released and emitted back into the air). However, the chemical adsorption process is irreversible; consequently, the reacted compound is not subsequently released back into the air.

Schieweck (2020) conducted a systematic experimental study dedicated to the removal of museum pollutants. The authors assessed the filtration efficiency of 37 different adsorbent media under both active and passive conditions (with and without forced air exchange). Adsorbents comprised ACs with and without impregnation, including AC cloths, carbon-coated foams, natural and synthetic zeolites, molecular sieves, silica gels, archival cardboard, polymer-impregnated matrixes, and others. The results revealed that the filtration of formaldehyde was challenging for nearly all adsorbents tested. Just 5 out of 37 products exhibited very good (one -pass removal efficiency > 80%) or good performance (removal efficiency > 60%).

The study results by Bayer and Hendry (2005) illustrate the difficulties of evaluating adsorbent system performance in uncontrolled field studies. The VOC concentrations can be low, leading to significant measurement errors.

In general, the adsorption of organic compounds onto carbonaceous adsorbents is primarily controlled by five potential interactions: the hydrophobic effect, - bonds, hydrogen bonds, Van der Waals interactions, and covalent and electrostatic interactions (Wang et al., 2013). Biochar is a kind of carbon material prepared by slow pyrolysis of biomass under an inert atmosphere similar to AC. The production of biochar might result in the release of VOCs, such as methanol, acetic acid, acetone, methyl acetone and acetaldehyde (Tiilikkala et al., 2010). However, biochar has high adsorption efficiency and low cost, so it still has excellent potential for VOC adsorption.

Réguer et al. (2011) studied the effect of varying toluene concentrations on the breakthrough from ACs. The breakthrough curves were modeled and experiments made at an inlet concentration 10 times higher than the indoor air level. The results lead the authors to the conclusion that the henry coefficient (the ratio between the concentration of toluene in ACs at equilibrium and the concentration of toluene in the gas phase at equilibrium) stayed the same at the varying concentrations. Weschler et al. (1992) installed panels filled with AC in a test duct with a 0.61 m by 0.30 m cross-section and measured VOC concentrations upstream and downstream of the AC with passive samplers. The air entering the test duct was drawn from indoors; thus, the test duct simulated real deployment. The test duct contained six 2.54-cm-thick carbon-filled panels installed in a zig-zag pattern. The total panel face area was 2.0 m^2, and the total mass of AC was 20.4 kg (45 lb). The airflow rate through the duct was 0.28 m^3/s; thus, the nominal retention time in the carbon bed was 0.18 s, well above the recommended minimum of 0.1 s. The system contained 73 kg of carbon per 1 m^3/s of airflow (75 lb per 1000 cfm). The long-term study results of adsorbent performance in a single building demonstrated the initial efficiency and efficiency after 18 months for toluene at 90% and 90%, for p-xylene at 80% and 90%, and for o-xylene at 60% and 70%.

Xiao et al. (2018) developed an *in situ* thermally regenerated air purifier (TRAP) comprising two chambers and three valves. The switching of the valves enabled pollutant adsorption, adsorptive material recycling, and outdoor air intake. Chen et al. (2019) developed a novel flexible adsorption board module with an adjustable surface temperature fabricated with AC, polyimide, and copper foil, as illustrated in Figure 1. Its laminated structure reduced airflow resistance by two orders of magnitude compared with the packed adsorption bed. The built-in copper foil generated Joule heat rapidly and efficiently delivered this heat to the adsorbent, effectively reducing energy consumption. The overall removal efficiency of the fabricated laminated plate was about 30% at the face velocity of 0.8 to 1.2 m/s. The pressure drop was about 5 Pa. Its removal ability can be regenerated *in situ* in 8 min by increasing the surface temperature to 80°C. The fabricated laminated plate exhibited good durability after 52 cycles of adsorption-regeneration tests. Chen et al. (2021) proposed a vertical macro-channel modified method to achieve rapid diffusion into the adsorbent during the initial adsorption period. Regular, vertical macro-channels through the adsorption board based on the study by Chen et al. (2019) were fabricated using laser drilling to enhance the mass transfer inside the board. The experimental results demonstrated that, after modification, the penetration times for formaldehyde and xylene extended from 3.8 to 6.2 h and from 62 to 99 h, respectively. The simple macro-channel modification of the adsorption board may be used as an alternative design for adsorption applications in indoor air purification.

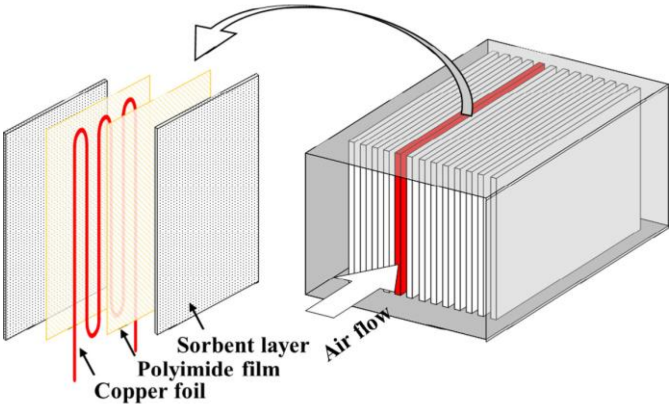


Figure 1: Illustration of the surface temperature adjustable laminated plate structure (left) and the air purifier module comprising multiple parallel plates (right). (Chen et al., 2019)

Modeling and performance prediction: Adsorption based air filters/cleaners are often used to remove gaseous contaminants to improve indoor air quality (IAQ) for residential and office buildings. The performance of a sorbent filter is affected by the sorbent filter design parameters (i.e., granular particle size, packing density), the environmental conditions (i.e., flow velocity, challenge gas concentration, temperature, and relative humidity) and the sorbent properties such as sorption isotherm and in-pellet diffusion coefficient. It is the combined effects of all these parameters that determine the performance of the filter. Pei and Zhang (2010) developed a model and simulation software to predict the removal efficiency of sorbent-based gas filters. In this study, "Convective Mass Transfer" (C-MT) model and "Convective and Diffusive Mass Transfer" (C&D-MT) model (Figure 2a) were developed and numerically implemented to simulate the fundamental transport and sorption processes in sorbent-based filters. The models' behaviors were investigated by simulating the effect of different parameters, and were validated by comparison with experimental data (Figure 2b). Detailed mechanism analysis was conducted based on both modeled and experimental results, which indicates that the surface diffusion is a much more important mechanism than pore diffusion, and the external convective mass transfer process is a controlling factor compared to pellet diffusion. This model also provides a useful tool for designing, selecting or maintaining sorption-based filter/air cleaner for non-industrial building applications based on the predicted filter performance over its service life.

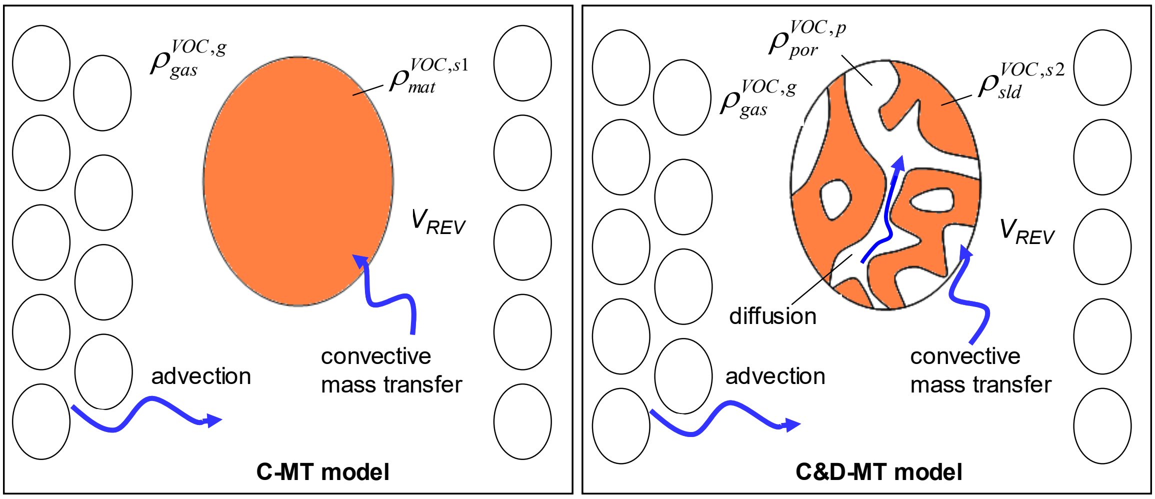


Figure 2a: Schematic presentation of adsorption mechanism in sorbent bed (Pei and Zhang, 2010)

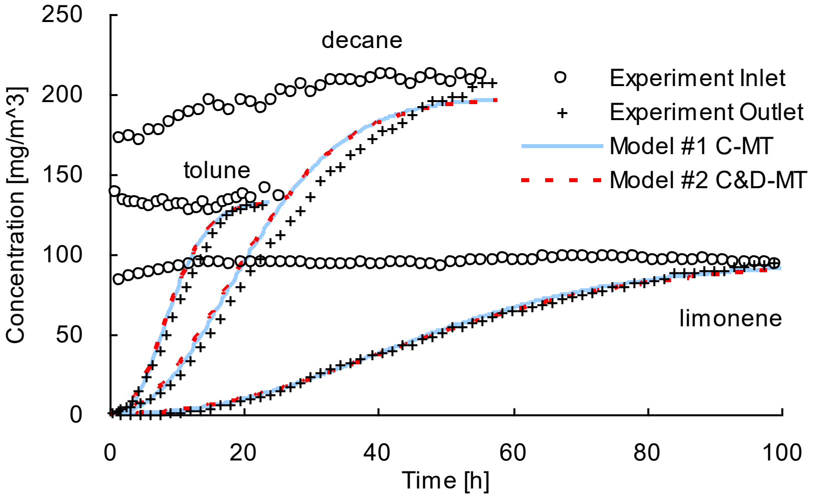


Figure 2b: Comparison of model simulations with experimental data (Pei and Zhang, 2010)

2.1. Photocatalytic Oxidation

The PCO process is one where, upon adsorption of a photon, a semiconductor acts as a catalyst in producing reactive radicals, primarily hydroxyl radicals, which can oxidise organic compounds and mineralise them (Goswami, 2003). Common photocatalysts in PCO are titanium dioxide (TiO_2), zinc oxide (ZnO), tungsten trioxide, zinc sulphide, and cadmium sulphide (Gaya and Abdullah, 2008; Tseng et al., 2010). By light irradiation with a corresponding wavelength, electrons from the valence band are transferred to the conduction band, forming electron-hole pairs (Figure 3).

The excited electrons can proceed in a single-electron reduction and, in the presence of O_2, form a superoxide radical anion O_2 •−. Simultaneously, the electron holes (h+) can react with H_2O to yield hydroxyl radicals OH• (single-electron oxidation). These resulting radicals are highly reactive and can degrade a wide range of VOCs and potentially mineralise VOCs into less harmful oxidation products, such as water and carbon dioxide (Héquet, 2018; Mo et al., 2009; Pelaez et al., 2012).

Photocatalytic active coatings made of the semiconductor TiO_2 (Mo et al., 2009) have been developed for indoor air application. The application of TiO_2 for photodegradation of organic contaminates has generated significant attention due to its unique characteristics and environmental friendliness (Ji et al., 2017; Tejasvi et al., 2015). In its anatase modification, TiO_2 has a bandgap of 3.2 eV and can be activated under ultraviolet (UV) light (λ = 387 nm).

Compared with conventional PCO under UV light (254 or 365 nm), vacuum UV (VUV) light can significantly enhance photocatalytic degradation efficiency. Moreover, by providing a strong oxidation environment and preventing the generation and accumulation of intermediates, VUV light reduces catalyst deactivation (Huang et al., 2017; Shayegan et al., 2017). Despite these benefits, performing PCO with VUV lamps produces O_3 molecules as a byproduct. O_3 is a powerful oxidising species that can react with VOC pollutants and promote photocatalytic efficiency. However, residual O_3 can damage the environment and human health.

Destaillats et al. (2012) studied the degradation of seven VOCs using a prototype air cleaner provided with flat or pleated PCO filtering media in a 20-m^3 stainless-steel chamber at ACH = 1 h^{-1} under realistic indoor conditions. The media was made of quartz fibres (9 µm in diameter) coated using a sol-gel process with a mixture of 10% to 25% of nanosized TiO_2 and 50% to 90% of silicon dioxide and with a BET specific surface area of 120 m^2 g^{-1}. The authors measured the VOC removal efficiency of PCO air purifiers with airflow from 178 to 878 m^3 h^{-1}. The results indicate that the VOC concentration decreased only marginally across the PCO air purifiers at high airflow rates, whereas a decrease in the airflow rate increased the VOC removal efficiency from 5% to 44%. Consequently, they concluded that the PCO cleaning efficiency was not improved when the air recirculation rate was set at higher values.

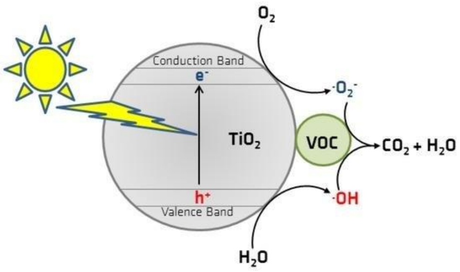
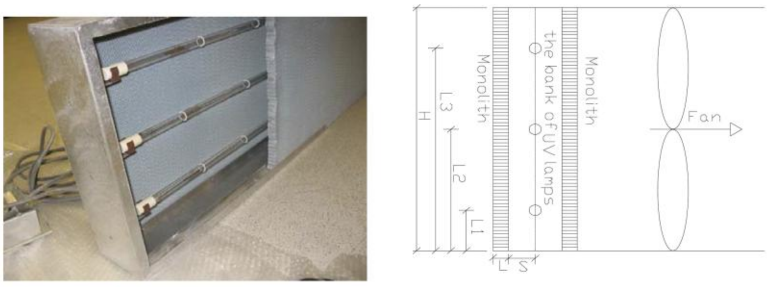


Figure 3: Schematic representation of photocatalytic oxidation of a volatile organic compound (VOC) (Mull et al., 2017).

Zhang and Hsieh (2020) demonstrated a dual-functional polyester fibrous air filter consisting of self-assembled TiO_2 nanoparticles and percolated silver nanowires with high air permeability, electrostatic particulate matter removal, and photocatalytic formaldehyde decomposition abilities. With the aid of the photocatalytic TiO_2 nanoparticles, the network can effectively degrade gaseous formaldehyde under UV irradiation.

In the design of UV-PCO-based air cleaners for improving IAQ, multiple compounds interference effects need to be quantified because indoor environment has multiple VOCs under low concentrations (typically at ppb and sub-ppb levels). Chen and Zhang (2008) presented a systematic experimental investigation using a lab-scale UV-PCO reactor under individual vs. multiple VOC challenges. Tests were conducted for two aromatics (toluene and ethylbenzene) and two aldehydes (formaldehyde and acetaldehyde) as individual compound and binary mixture, and three alkanes (octane, decane and dodecane) as individual compound, binary and ternary mixtures. An annular tube reactor coated with Degussa TiO2/3% WO3 (by weight) was placed in a small-scale (50 L) stainless steel chamber. The test chamber had a continuous feed flow and the system operated as a continuous stirred tank reactor. The concentration of test VOCs at chamber inlet ranged from 0.5 to 35 mg/m^3. The overall reaction rates were measured. The mass transfer effects were quantified. The average reaction rate constants were then determined. Reversible deactivations were observed for toluene and ethylbenzene as individual VOCs and as mixture. For the individual compound tests, the bimolecular L-H rate form fit experimental data best. For the binary mixture tests, the bimolecular L-H rate model with the binary component competitive adsorption considered described the trend of experimental data well, and the rate coefficients from the PCO reaction of individual compound could apply. As for alkanes and aldehydes, the reaction rate was linearly dependent on the reactant concentration within the tested concentration range. The competition/interference effects between different compounds (except octane in one ternary mixture test) were insignificant under test conditions. Results also indicate that mass transfer resistance needs to be considered under low VOC concentration levels and high UV intensities (typical for an annular tube reactor as UV lamp is in the middle of the tube) because it is likely in the same order of magnitude as the reaction resistance.

Modeling and performance prediction: A computer simulation model and a “model-based” design procedure were developed for UV-PCO devices by Chen (2007). The model focused on a typical configuration in which a bank of UV lamps is sandwiched between two honeycomb monoliths coated with TiO2 (Figure 4). The model consists of a one-dimensional fluid and concentration field model, a VOC reaction kinetics sub-model and a UV-irradiation sub-model (Figure 5). The intrinsic rate models and coefficients obtained from literature or from independent kinetic experiments are needed as model inputs. The parametric and trend analysis was conducted to investigate the interference effects of other VOCs on toluene removal observed in full-scale experiments. The model developed is useful for investigating the multi-VOC interference effects (surface competition, byproduct generation, etc.) on the effectiveness of UV-PCO devices under various design and operating conditions as well as for predicting the removal efficiency of UV-PCO devices (Figure 5a) and their impact on the concentrations in a ventilated space (Figure 5c).



(a) real device

(b) schematic

Figure 4: Full-scale honeycomb UV-PCO reactor

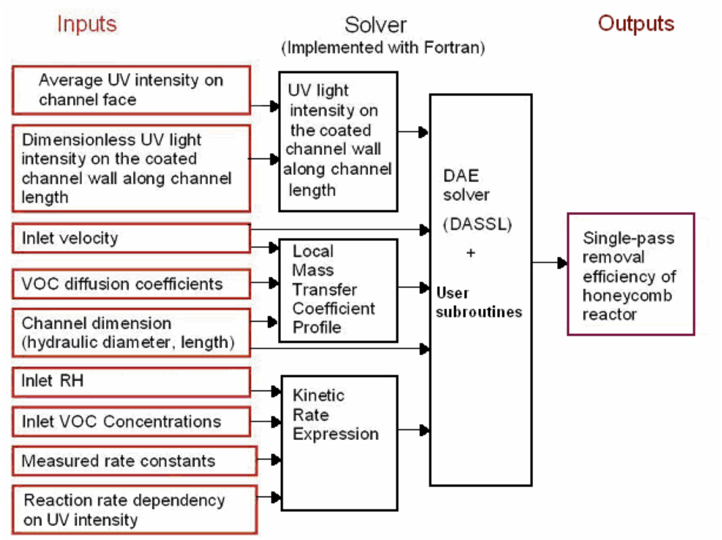


Figure 5a: PV-PCO device design model structure and implementation (Chen 2007) - Flow and concentration field sub-model

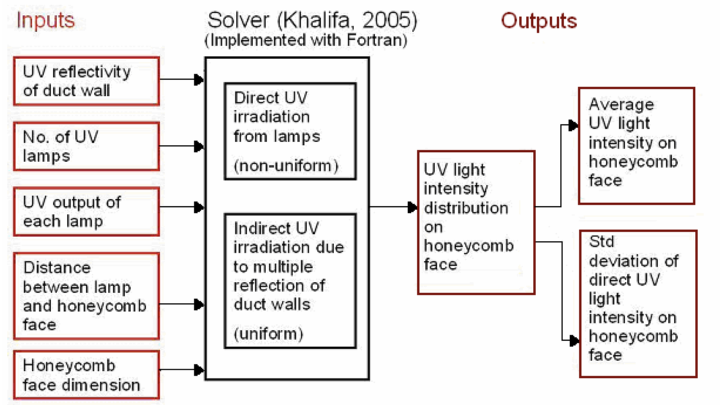


Figure 5b: PV-PCO device design model structure and implementation (Chen 2007) - Sub-model for computing UV intensity on monolith face for honeycomb reactor

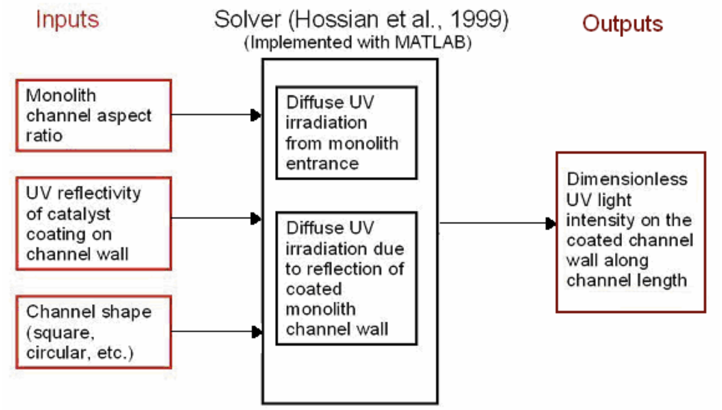


Figure 5c: PV-PCO device design model structure and implementation (Chen 2007) - Sub-model for computing UV intensity inside monolith channel for honeycomb reactor

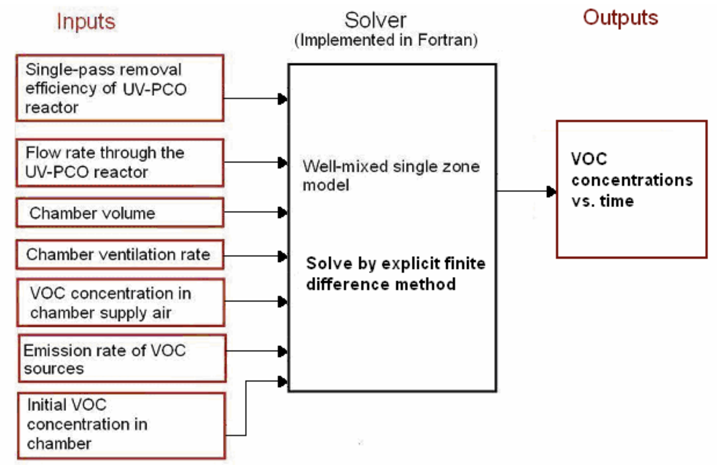


Figure 5d: PV-PCO device design model structure and implementation (Chen 2007) - Sub-model for computing effect of UV-PCO device on indoor VOC concentration

2.2. Air Ion Generators

Air ions are electrically charged molecules or atoms in the atmosphere (Goldstein and Arshavskaya, 1997). An air ion is formed when a gaseous molecule or atom receives sufficiently high energy to eject an electron (Laza, 2000). Negative air ion (NAI) generators gain electrons, whereas positive air ion generators lose electrons. Several types of negative air ion generators are based on corona discharges, thermionic electron emission, photoexcitation, and the Lenard effect for creating NAIs (Lin and Lin, 2017). Among these mechanisms, the corona discharge is an efficient method to generate NAIs. When a high negative voltage is applied to a conductor/electrode and the generated electric field is sufficiently high, corona discharge occurs (Altamimi et al., 2014; Ogar et al., 2017). This type of NAI generator has been commercialized and is the most commonly employed variant. The schematic picture of this technology is presented in Figure 6. Under certain use conditions, ion generator air cleaners can produce levels of O_3 significantly above those thought to be harmful to human health (EPA, 2021).

Wu and Lee (2004) reported that no byproducts were generated at a discharge voltage below 16.0 kV. The concentrations of O_3 and nitrogen oxides (NOx) increased with the discharge voltage above 17.0 kV. Therefore, the discharge voltage should be set at 15.0 kV to avoid the generation of O_3 or NOx.

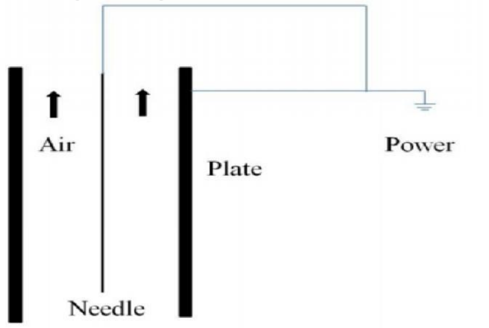


Figure 6: Schematic view of the corona discharge ioniser technology (Rahimi, 2013)

Air ionisation systems have been installed in domestic and office locations to improve indoor air quality. They have also been installed to control volatile compounds and particulates in institutional, commercial and industrial locations.

Daniels (2001) investigated a case study where an air ionisation system was installed in a large engineering centre (Siemens AG, Berlin) with several hundred office workers in a multifloor facility. Indoor VOCs and O_3 levels were measured continuously in this facility during operational periods with and without air ionisation. The author reported reductions in the levels of 59 specific VOCs representing nine broad classes. For instance, the total VOC (TVOC) level was reduced by 50%, and the aromatic substances were reduced by 47%. The arithmetic mean ozone concentration over one month of operation without air ionisation was 0.7 ppbv, with a maximum of 5.8 ppbv, while over one month of operation with air ionisation it was 6.6 ppbv, with a maximum of 14.4 ppbv. The ozone concentration in the outside air were not measured directly but were calculated in the range of 10 to 20 ppbv.

Daniels (2001) investigated another case study involving a billing centre near a major international airport (Visa, Zurich) where office workers were subjected to exhaust gases from ground transportation and airplane jet engines. Three representative VOCs were quantitated with and without ionisation. The results indicated that the concentrations of isooctane, benzene and toluene were reduced by approximately 35%, 58% and 46%, respectively.

Air ionisation systems are also combined with air filtration to enhance the removal of VOCs and particulates. Tian et al. (2020) proposed and fabricated new electrostatically assisted heterocaking (EAHC) filters using polyurethane (PU) foam with an extremely low pressure drop as base filters and heterogeneously loading high-ε_r heterocaking (HC) (including manganese dioxide, AC, ZnO, copper oxide, and barium titanate). Some hazardous gases found indoors, such as O3 and formaldehyde, are expected to be removed when the loaded HC fibres are made of an adsorbent or catalyst.

A schematic illustration of the EAHC air filter module is presented in Figure 7a. Figure 7b presents a schematic illustration of HC fibres in a polarising field compared with standard filter fibres. The HC filter preparation process is displayed in Figure 7c. The experiments revealed that the EAHC filter has high single-pass filtration efficiency—over 90% for airborne PM, approximately 80% for ozone, and around 70% for formaldehyde—as well as low pressure drop and low power dissipation. Tian et al. (2021) and Gao et al. (2021) developed new surface coatings on the filtration fibers that achieved over 90% reduction in airborne particles and approximately 80% reduction in ozone concentration.

Chen et al. (2020) developed an ioniser-assisted filtration method with an external electrostatic field to efficiently remove gaseous diisobutyl phthalate and dibutyl phthalate. They used low pressure drop PU foam as substrate filters and loaded fine AC powder into PU foam as PU-C foam. With this proposed method they developed a new filter based on an existing inexpensive coarse particle filter, which is easy to implement for the active control of gaseous PAEs.

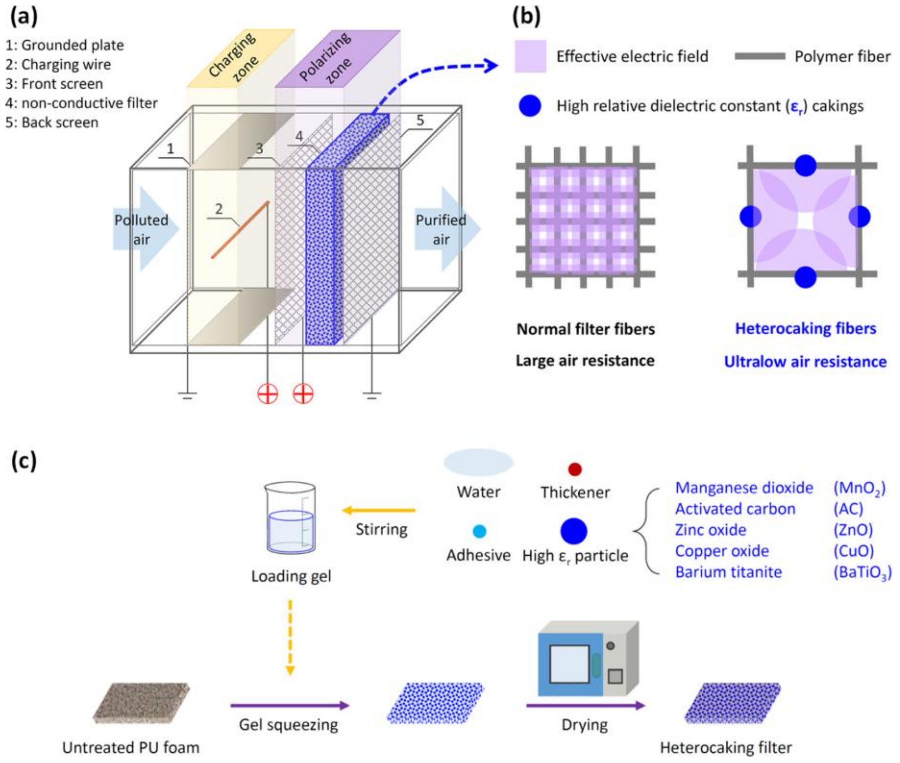


Figure 7: (a) Schematic of the electrostatically assisted heterocaking (EAHC) air filter module, (b) schematic of heterocaking (HC) fibres in a polarising field compared with standard filter fibres, and (c) preparation process of HC filters by a fast and large-scale roll-to-roll gel squeezing method. (Tian et al., 2020)

Modeling and performance prediction: Volatile organic compounds (VOCs) can be oxidized by ozone (O3) and hydroxyl radicals (OH•) under a series of reactions to produce secondary emissions indoors in addition to primary emissions.

Liu et al. (2009) developed a mathematical model that accounts for ventilation, surface adsorption, oxidant generation, ozone and hydroxyl radicals-initiated chemical reactions was developed for evaluating the pollution loads and concentrations in a ventilated space. The model focused on major chemical reactions that were responsible for stable products from secondary emissions as detected in full-scale chamber experiments (Figure 8). The experiments were simulating a realistic ventilated room and how a source of O3 and OH• _would affect the concentrations of VOCs. The modeled results were in line with the experimental results. Alpha-pinene and heptanal were selected to illustrate the model prediction results as an example given their relatively high reaction rates with O3 and OH•. Limitations of the model and the needs for further development were also identified.

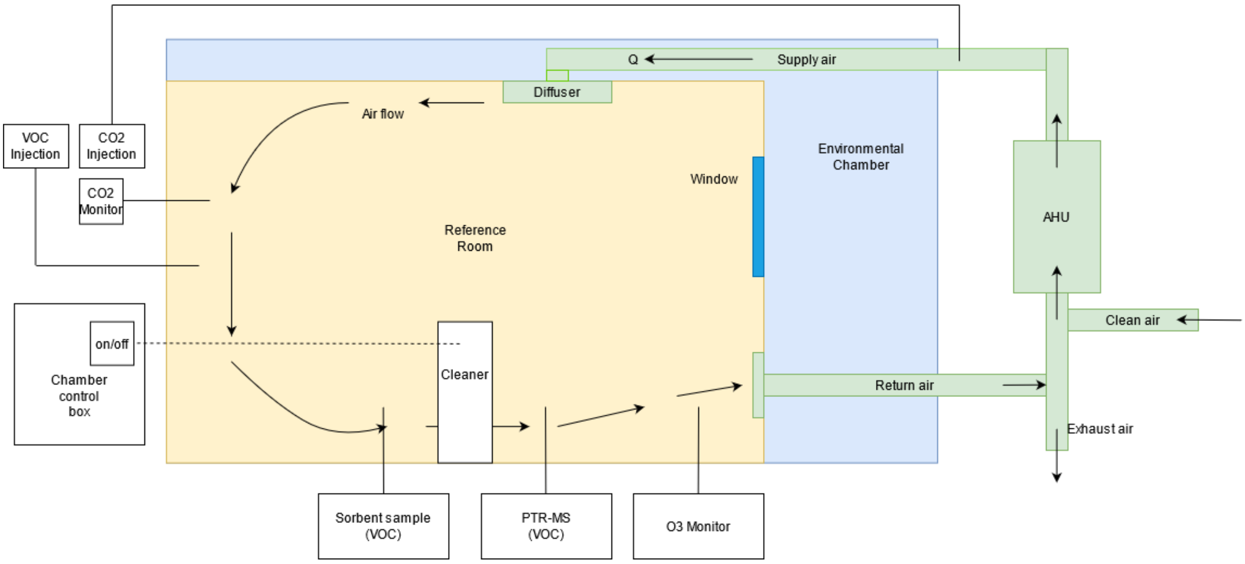


Figure 8: Realistic test room setup and conditions for modelling the effects of an ionization-based air cleaner on indoor VOC concentrations.

2.3. Ozone Generators

An O_3 generator is a device that produces O_3 by adding energy to oxygen molecules (O_2), which causes the oxygen atoms to separate and temporarily recombine with other oxygen molecules. The process can be accomplished in the following methods: corona discharge and UV radiation. The corona discharge is described above and produces O_3 through a method equivalent to lightning, and the UV radiation method is comparable to how the sun's UV radiation splits O_2 molecules to form individual oxygen atoms. Figure 9 illustrates how a corona discharge O_3 generator operates.

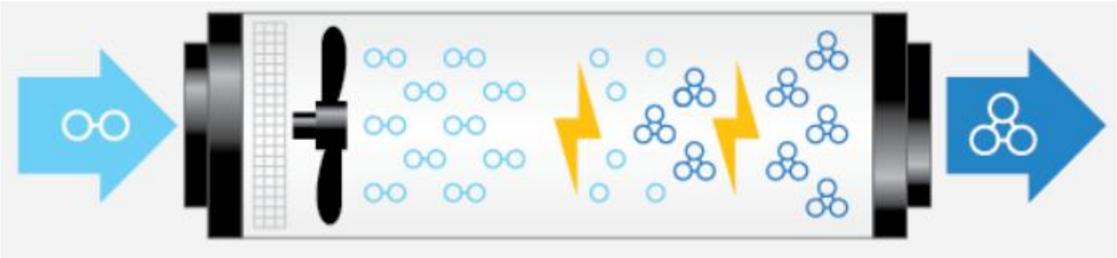


Figure 9: Visualization of how a corona discharge ozone generator operates (Ozone solutions. 2021). https://ozonesolutions.com/blog/what-is-ozone/.

Ozone generators have been used to control indoor air pollution. However, O_3 is associated with adverse health effects, and it is vital to ensure that people and pets are not exposed to high levels of O_3. In addition to the harmful effects of O_3 itself, indoor O_3 can react with building materials, furnishings, and other indoor chemical compounds. Long et al. (2000) studied the indoor chemical reactions involving O_3 and found that the chemical reactions can be a significant source of indoor ultra-fine particles (Zannoni, et al., 2021).

Shaughnessy et al. (1994) reported that O_3 generators are not effective in removing carbon monoxide. In addition, Esswein and Boeniger (1994) reported that O_3 generators are not effective in removing carbon formaldehyde. Weschler et al. (1992) conducted a laboratory experiment that mixed O_3 with chemicals from new carpets. The authors reported that O_3 reduced many of these chemicals, including those that can produce new carpet odour. However, in the process, the reaction produced a variety of aldehydes, and the total concentration of organic chemicals in the air increased rather than decreased after the introduction of O_3. The reaction rates of O_3 with most VOCs were slow in indoor environments because the characteristic residence times of air and pollutant mixtures in typical indoor settings were too short for the reactions to proceed effectively (Weschler, 2000). Chen et al. (2005) evaluated several air cleaners in the indoor environment and found low VOC removal efficiencies by O_3-based air purifiers and that the indoor O_3 could be at unsafe levels.

2.4. Plants

Several articles have described air-cleaning plants used by NASA (Wolverton, 1996). Wolverton et al. (1989) found that indoor plants can scrub the air of cancer-causing VOCs, such as formaldehyde and benzene. Orwell et al. (2004) found that soil microorganisms in potted plants also play a part in cleaning indoor air. In another study, Kim et al. (2010) examined 86 species of houseplants from five general classes for their ability to remove formaldehyde. In their experiments, ferns had the highest formaldehyde-removal efficiency of all the plants tested, especially *Osmunda japonica*, commonly known as the Japanese royal fern or *zenmai*. These studies have positively shown that potted plants could reduce VOC concentrations in a space by between 10% and 90% in 24h (Llewellyn and Dixon, 2011). More importantly, however, Larsson (2004) examined formaldehyde and TVOCs. The author concluded that the indoor plants reduced formaldehyde by 0.1 to 1.0 mg FAD m^{-2} h^{-1} during the daytime, and the reduction for TVOCs was 0.1 to 2 mg TVOCpas m^{-2} h^{-1} during the daytime. The author stated that none of the above-reported effects were considered so critical that they would become an applicable tool in altering indoor air quality. This conclusion has been confirmed by later studies. For instance, Hanoune et al. (2015) and Salthammer (2019) found that the effectiveness of potted plants in reducing VOC concentrations is minimal under real indoor conditions. Their findings suggest that, similar to ozone generators, plants are unlikely to serve as a reliable or scalable solution for air purification unless deployed in very high densities or with forced air systems.

While the plants leaves are not effective for improving IAQ, their route system has been shown to be effective by both chamber and full-scale experiments by Wang and Zhang (2010). In this study, a dynamic botanical air filtration system (DBAF) was developed for evaluating the short and long-term performance of botanical air cleaning technology under realistic indoor conditions. It was a fan-assisted with controlled air-flow, activated-carbon/hydroculture-based potted-plant unit (Figure 10). The DBAF was first tested using a full-scale stainless chamber to evaluate its short-term performance. It was then integrated into the HVAC system of a new office space (96.8m^2) to study the effects of moisture content in the root bed on the removal efficiency, and the long-term performance. The results indicated that 5% outdoor air plus botanical filtration led to the similar indoor formaldehyde/toluene concentration level as 25% outdoor air without filtration, which means that the filtration system was equivalent to 20% outdoor air (476m^3/h). The DBAF was effective for removing both formaldehyde and toluene under 5–32% volumetric water content of the root bed. It also performed consistently well over the relatively long testing period of 300 days while running continuously (Figure 11). The reduction in outdoor ventilation rate while using the botanical filtration system to maintain acceptable air quality would lead to 10–15% energy saving for the cold climate (Syracuse, NY), based on simulation analysis using EnergyPlus. For winter conditions, the filter was also found to increase the supply air RH by 20%, which would decrease the dryness of air. For summer conditions, the increase of RH in summer would be within 15% of the RH condition when no botanical air filtration is present.

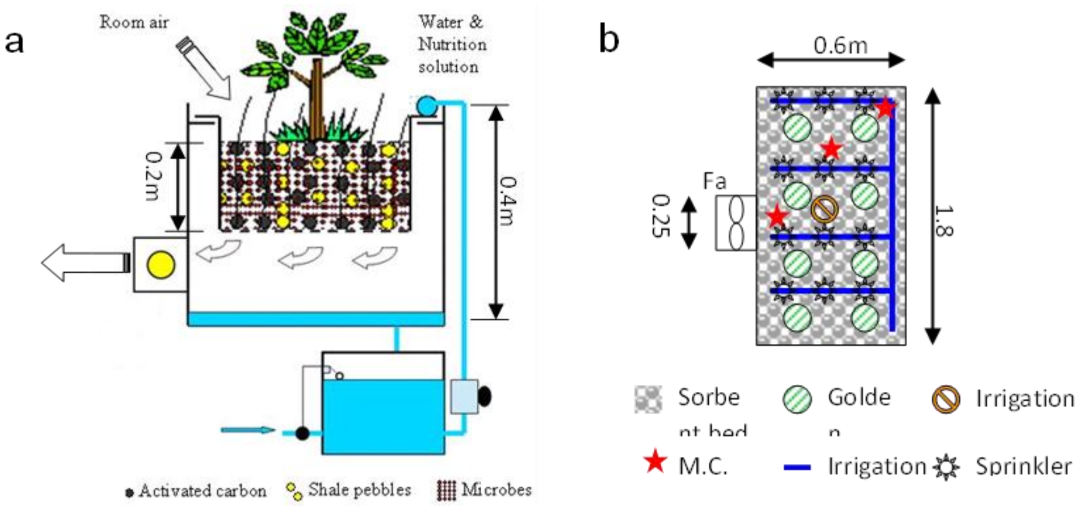


Figure 10: Schematic of dynamic botanical air filtration (DBAF) system: (a) side view, (b) top view. Moisture content sensor (M.C. sensor) (Wang and Zhang, 2010).

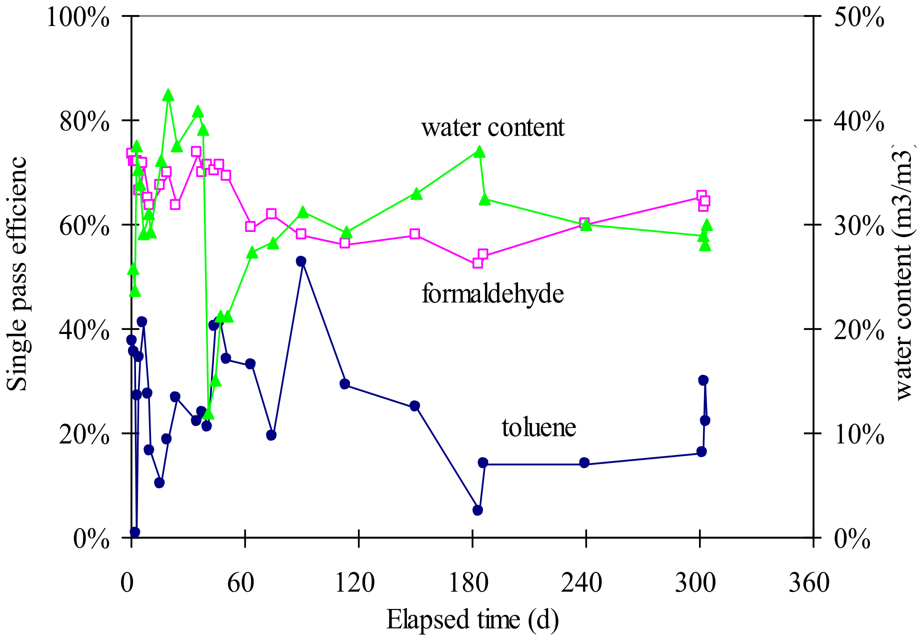


Figure 11: Measured single pass removal efficiency for toluene and formaldehyde (left axis), and water content (right axis) for 10 months (Wang and Zhang, 2010)

Modeling and performance prediction: A numerical model for simulating the performance of a dynamic botanical filtration system has been developed for the first time that accounts for the various transport and storage processes including air and contaminant convection, adsorption of non-water soluable compound by activated carbon, absorption of water soluable compound by water, bio-degradation of chemicals by microbes in the root bed as well as the automatically controlled irrigation system for the root bed (Figure 12). The model was built upon an existing Coupled heat, Air, Moisture and Pollutant Simulation for Building Envelope System (CHAMPS-BES) model with the addition of bio-degradation process and the irrigation system. Model parameters were estimated from the experiments. The simulation results showed that the model could describe the pressure drop and airflow relationship well by using the air permeability as a model parameter. The water source added in the model also led to the similar bed moisture content and outlet air RH as that in a real test case. The simulation results also showed that the developed model worked well in analyzing the effect of different parameters. It was also found that the critical bio-degradation rate constant was 1×10^{-5} s^{-1}, below which the DBAF would not be able to sustain the formaldehyde removal performance. The bio-degradation rate constant of the reduced scale filter system tested was estimated to be in the range of $0.8\text{–}1.5\times10^{-4}$ s^{-1}.

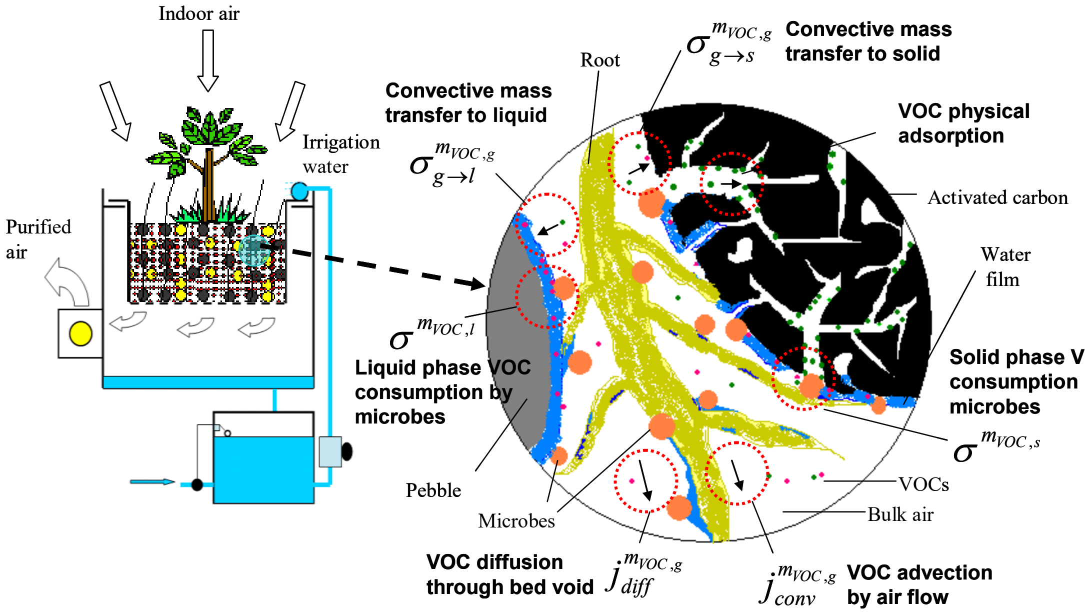


Figure 12: Schematic of the root bed system and associated transport and storage processes modeled (Wang et al. 2012)

2.5. Energy

Energy use is a critical performance parameter for portable gas-phase air cleaners, especially when they are operated continuously in occupied spaces. High energy demand not only increases operational costs but also undermines the environmental benefits of improving indoor air quality. The type of filtration technology, system design, and airflow resistance significantly influence the overall energy footprint. Therefore, understanding and comparing the energy implications of different technologies is essential for informed decision-making.

Middlebrooks (2000) compared pressure drops in three systems with the same mass of granular AC and a 1.0 m/s (200 fpm) face velocity. The reported pressure drops were 38 Pa in the system with 20 to 50 mesh carbon bonded to a pleated nonwoven media, 640 Pa with 20 to 50 mesh carbon in trays, and 75 Pa (0.3-inch H_2O) with seven-fold larger 4x8 mesh carbon in trays. These results indicate that both the mesh size and the configuration of the carbon significantly affect airflow resistance, with pleated media offering the lowest pressure drop and thus better energy performance.

The advantages of PCO are the relatively low pressure drop, ability to treat a wide variety of compounds, and the theoretically long lifecycle of the reactive process. The disadvantages include the electricity used in the lamps and ballasts if fluorescent lamps are used. The power consumed by the largest model is approximately 180 watts, which is equivalent to the combined power usage of about two standard 100-watt light bulbs (AiroCide, 2021).

The O_3 concentrations achieved by ozone generators generally increase with augmented power. Ozone produced from the air may require up to 15 W/g of O_3, as the power cost of air compression must be included in the cost of O_3 production (Baratharaj, 2013). This highlights the relatively high energy demand of ozone-generating devices, which can limit their practicality and efficiency as room air cleaners, especially when used continuously.

2.6. Summary of the technologies[1]

Table 1: Summary of the technologies.

	Advantage	Disadvantage	Application
Adsorbent	• Gaseous pollutants adsorb on porous granular media or condense in pores of media. • Many types of sorbents with activated carbon most commonly used. • Widely available technology • Can remove broad range of gaseous pollutants with moderate to high efficiency	• Pollutants can be released from sorbent into indoor air • Low effectiveness for low molecular weight pollutants including formaldehyde • Must periodically replace sorbent • Sorbent lifetime for indoor air applications not well understood • Large amount of sorbent needed for long lifetime • High sorbent cost • Often high airflow resistance increasing fan energy use	• Installed in heating, ventilating and air conditioning systems or in stand-alone portable air cleaners
Chemisorbent	• Gaseous pollutants adsorb on and chemically react with porous granular media • Widely available technology • Can remove broad range of gaseous pollutants with moderate to high efficiency	• High chemisorbent cost • Often high airflow resistance increasing fan energy use	• Installed in heating, ventilating and air conditioning systems or in stand-alone portable air cleaners
Photocatalytic Oxidation	• Gaseous pollutants adsorb on a surface coated with a photocatalyst that is irradiated with a light source, usually a source of ultraviolet light; some adsorbed pollutants decompose • Can remove a range of gaseous pollutants • Usually lower airflow resistance than sorbents and chemisorbents, thus, lower fan energy use • Can destroy some bioaerosols • Many systems have low pollutant removal efficiency	• Lamp energy use • Cost of periodically replacing lamps • Photocatalysts become inactive, with unknown photocatalyst life • Incomplete breakdown of some pollutants can result in formation of new pollutants potentially harmful to health	• Installed in heating, ventilating and air conditioning systems or in stand-alone portable air cleaners
Air Ion Generator	• Radicals (small reactive molecules) created by electric discharge can oxidize and decompose volatile organic compounds and nitrogen oxides • Quiet and energy efficient • May improve particle removal performance of some particle air cleaners	• Very limited data available on pollutant removal performance in buildings • Can produce ozone, see comments on ozone air cleaners	• Usual application is a standalone portable air cleaner
Ozone Generator	• Ozone generated and released into indoor air can react with and breakdown some airborne volatile organic compounds • Quiet and energy efficient	• Releases ozone into indoor air and ozone is a harmful pollutant • Generally ineffective in significantly reducing airborne volatile organic compounds unless ozone concentrations are very high • Reactions of ozone with airborne volatile organic compounds can lead to production of formaldehyde and ultrafine particles that pose health risks	• Usual application is a standalone portable air cleaner
Plant	• Plants in buildings can remove some volatile organic compounds • Quiet and energy efficient	• Not proven to significantly reduce indoor pollutant levels with practical number of plants • Plants and molds on plants and soil can be a source of pollutants	• Plants placed throughout building or in attached greenhouse • One system forces air through plant root zone

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[1] For more information, see the ASHRAE Position Document on Filtration and Air Cleaning.

3. Conclusions

Adsorbent-based gas-phase air cleaning is effective for removing a variety of gases, vapours and odours if appropriate types and amounts of adsorbents are used. This removal may impose quite a high pressure drop. Although the filter replacement interval is a critical operational factor—affecting both cost and performance, it was not extensively discussed in this review and warrants further investigation.

Available scientific evidence indicates that O_3 is generally ineffective at controlling indoor air pollution at concentrations that do not exceed public health standards. In the process of reacting with chemicals indoors, O_3 can produce other chemicals that can be irritating and corrosive. Many factors affect O_3 concentrations produced by machines that generate O_3, including the amount of O_3 produced by the machines, size of the indoor space, amount of material in the room with which O_3 reacts, outdoor O_3 concentrations and ventilation. These factors make it challenging to control O_3 concentrations, regardless of whether the technology used intentionally generates ozone or as a byproduct. PCO has high conversion efficiencies for VOCs at a low pressure drop. However, PCO air cleaners produce O_3 molecules as a byproduct. The NAI generator air cleaners can, under certain conditions, produce levels of O_3 and NOx significantly above the levels thought to be harmful to human health.

Throughout this review, we found that additional research is needed for more reliable conclusions on the long-term performance of portable gas-phase air cleaners, e.g. the noise level of the portable air cleaners when working at full capacity, O_3 emission rates, energy use and related costs are often not reported. In addition, studies should be conducted both in the laboratory and field to compare the performance of portable air cleaners in a well-controlled laboratory environment to that in a real situation. Finally, the performance criteria that must be met to use portable air cleaners must be defined, and the testing criteria for room air cleaners must be specified.

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