Kunskapssammanställning 2019:5

Airborne Dust Removal using Mobile Air Cleaners in the Construction Sector

ARBETSMILJÖ VERKET

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Innehåll

List of Abbreviations

ACGIH	Association Advancing Occupational and Environmental Health
AHAM	Association of Home Appliance Manufacturers
ANSI	American National Standards Institute
CADR	CleanAir Delivery Rate
EC	Elemental Carbon
EEA	European Environmental Agency
EPA	Environmental Protection Agency
ESP	Electrostatic Precipitator
HEPA Filter	High Efficiency Particulate Air Filter
IARC	International Agency for Research on Cancer
ISO	International Organisation for Standardisation
LEV	Local Exhaust Ventilation
MMAD	Mass Median Aerodynamic Diameters
MPPS	Most Penetrating Particle Size
NIH	National Institute of Health (USA)
NIOHS	National Institute of Occupational Health (USA)
OEL	Occupational Exposure Limit
OSHA	Occupational Safety and Health Administration
PCB	Poly-Chlorinated Biphenyl
PM1	Particulate Matter with Aerodynamic Diameter less than 1 Micrometer
PM2.5	Fine Particulate Matter with Aerodynamic Diameter less than 2.5 Micrometer
PM10	Particulate Matter with Aerodynamic Diameter less than 10 Micrometer
PSL	Poly-Styrene Latex
SCOEL	Scientific Committee on Occupational Exposure Limits
SPF	Standard Particulate Filter
WHO	World Health Organisation

Förord

Arbetsmiljöverket har publicerat en rad kunskapssammanställningar där välrenommerade forskare sammanfattar kunskapsläget inom olika områden. Alla kunskapssammanställningar kan laddas ner utan kostnad från Arbetsmiljöverkets webbplats. Där finns även filmer och presentationer från seminarier som Arbetsmiljöverket ofta arrangerar i samband med publicering av kunskapssammanställningarna.

En vetenskaplig granskning av denna rapport har utförts av Dr. Joonas Koivisto, forskare vid Det Nationale Forskningscenter for Arbejdsmiljø i Köpenhamn. Den slutliga utformningen ansvarar dock författarna själva för.

Projektledare för denna kunskapssammanställning vid Arbetsmiljöverket har varit Carin Håkansta. Vi vill även tacka övriga kollegor vid Arbetsmiljöverket som varit behjälpliga i arbetet med kunskapssammanställningen.

De åsikter som uttrycks i denna kunskapssammanställning är författarnas egna och speglar inte nödvändigtvis Arbetsmiljöverkets uppfattning.

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Svensk sammanfattning

Syftet med arbetet är att redovisa kunskaper om mobila luftrenares möjligheter att minska dammhalter i luften vid byggnadsarbete. Målgrupper är arbetsmiljöansvariga, arbetsmiljöingenjörer, arbetsmiljöinspektörer samt företag som tillverkar och marknadsför mobila luftrenare.

På många byggarbetsplatser finns luftföroreningsproblem. Exponering för kvartsdamm och asbestfibrer är särskilt allvarliga. Hälsoriskerna vid inandning av dessa dammtyper är betydande. Särskilda försiktighetsåtgärder måste tillämpas. Olika metoder används för att begränsa riskerna vid sådana arbeten. Mest effektivt är att minimera emissionerna så nära källan som möjligt. Ofta används verktyg med inbyggt punktutsug eller vattenspray för att begränsa emissioner. Mobila luftrenare används som komplement. För att grovt vägleda projektet gjorde vi en enkätundersökning riktad till arbetsmiljöexperter inom byggbranschen. Den visade att mobila luftrenare är vanliga på svenska byggarbetsplatser. Luftrenare fungerar, eller uppges fungera, enligt ett antal olika principer.

Vi har gjort litteraturgenomgångar avseende mobila luftrenare. Vi har också gått igenom fysikaliska principer som olika typer av tekniker bygger på. Vi har då i första hand utgått från dels välbelagda kunskaper inom aerosolfysiken om grundläggande principer för partiklars rörelser i luft och hur de kan avskiljas, dels vetenskapligt granskade artiklar (peer-review). Det finns inte så många peer-review artiklar som direkt behandlar mobila luftrenare för byggarbetsplatser. Därför har vi i enstaka fall använt oss av oberoende vetenskaplig litteratur som inte är lika omsorgsfullt granskad samt litteratur med fokus på luftrenare för den allmänna inomhusmiljön.

Det finns olika tekniska lösningar för mobila luftrenare. Den vanligaste gruppen 1) bygger helt och hållet på mekanisk filtrering. Luftrenarna innehåller då filter av porösa material uppbyggda av små fibrer. När luften sugs eller trycks igenom filtret kommer dammpartiklarna med en viss sannolikhet att fastna i filtret när luften tvingas att böja av kring de små fibrerna. En annan typ 2) innehåller så kallade ”elektretfilter”. Dessa filter är uppbyggda av fibrer som polariseras elektriskt vid tillverkningen. De laddade fibrerna medför att insamlingseffektiviteten kan vara hög på grund av elektrostatisk kraftverkan. Det finns också ett antal olika anordningar 3) som bygger på att luften joniseras. Genom till exempel elektriska urladdningar skapas luftjoner. Luftjonerna hamnar på dammpartiklarna som kommer att påverkas av elektrostatiska fält. Det innebär att deras förmåga att dras till elektriskt laddade eller jordade ytor ökar och att de på detta sätt avskiljs från luften. Elektriska urladdningar kan ge upphov till den giftiga gasen ozon.

Det är viktigt att byta mekaniska filter i tid. När filtren börjar sätta igen kan detta leda till minskat luftflöde. Avancerade mobila luftrenare har en larmfunktion som indikerar att det är dags för filterbyte. I elektretfilter är fibrerna elektriskt laddade. Detta kan ge hög effektivitet och lågt tryckfall när filtrena är nya. Effektiviteten kan sjunka drastiskt när filtren åldras och tappar sin elektriska laddning. Det saknas bra sätt att bedöma när detta sker.

En vanlig utformning för elektrostatiska luftrenare är att partiklarna först laddas upp för att sedan samlas in på parallella plattor inne i utrustningen över vilka en spänning har anbringats så att det bildas ett elektriskt fält mellan plattorna (Elektrostatiska insamlare; ESP). För luftrenare med joniserande tekniker utan särskilda insamlingsplattor inne i anordningen är kunskaperna begränsade. Ett vanligt påstående är att jonisering leder till att "luftens partiklar klumpar ihop sig till större partiklar som snabbt faller till marken". I litteraturen fann vi inget som tyder på att denna mekanism (om den förekommer) skulle ha praktisk betydelse för att minska luftburet damm i arbetsmiljön.

Vid luftrening som utnyttjar jonisering, skapas antingen enbart positiva eller enbart negativa luftjoner (unipolär laddning) eller både positiva och negativa joner (bipolär laddning). Unipolära jonisatorer som sprider joner i ett rum gör att partiklarna får samma typ av laddning. Partiklarna tenderar då att i större utsträckning deponeras på ytor i rummet. Detta beror på att elektriska fält i rummet får partiklarna att röra sig mot ytor. Om det inte finns några elektriska fält från början kommer sådana att uppstå på grund av jonerna. Detta kan leda till nedsmutsning och exponering vid senare tillfälle genom att partiklar återförs till luften. Unipolär jonisering kan även leda till problem med ökad statisk elektricitet. Bipolär jonisering leder i normala fall till att partiklarnas laddning minskar (neutralisation). Detta har omvänd effekt jämfört med de unipolära jonisationerna och minskar istället deponeringen på ytor. Vi finner inte vetenskapliga belägg för att bipolär jonisering i sig bidrar till partikelreducering. Dammbekämpning med system som inkluderar bipolär jonisering bör därför bedömas enbart utifrån luftflöde och egenskaperna hos mekaniska filter som finns i utrustningen.

För luftrenare i vanliga inomhusmiljöer finns en hel del litteratur och även standardiserade tester för reningsförmåga och ozonemission. I testerna för partikelreduktion beräknas hur mycket tillförsel av partikelfri luft som luftreningen motsvarar (Ekvivalent luftflöde; CADR = Clean Air Delivery Rate). Detta gör det möjligt att jämföra olika typer av luftrenare. Filtrering och elektrostatiska insamlare har oftast de klart högsta CADR-värdena. Luftrenare som bygger på jonisering utan att de har inbyggda uppsamlingsplattor för avskiljning har generellt betydlig lägre CADR-värden. Det finns idag inget motsvarande standardtest för luftrenare i byggarbetsmiljö. Vid mekanisk filtrering går det att utifrån filtrets insamlingseffektivitet och luftflödet uppskatta CADR. Detta är dock inte möjligt för joniseringsmetoder.

Avgörande för en luftrenares förmåga att skydda människor mot exponering är att luftrenaren placeras nära källan eller att luftrenarens kapacitet är mycket hög jämfört med rummets storlek. En vanlig teknik på byggarbetsplatser är inkapsling där ofta en mobil luftrenare används för att skapa undertryck. Tryckskillnaden måste då vara tillräcklig för att minska läckage till omgivande lokaler. För arbete med asbest finns utförliga regler om vilken skyddsutrustning som ska användas. Detta ställer krav även på mobila luftrenare och hur de används. Eftersom mobila luftrenare flyttas runt på arbetsplatser finns risk att till exempel läckor runt filterkasetter kan uppstå i samband med transport eller på grund av vårdslös hantering. Det behövs därför regelbundna kontroller av enheterna, särskilt i samband med asbesthantering. National Institute of Health i USA har tagit fram en testprocedur som kan utföras i fält. I Tyskland finns ett antal kriterier som mobila luftrenare för byggsektorn ska uppfylla för att rekommenderas av arbetsskadeförsäkringsbolagen. Endast mobila luftrenare med mekanisk filtrering kan idag uppfylla dessa villkor.

Följande övergripande slutsatser dras: 1) Det är viktigast att sätta in åtgärder vid eller nära källan för att ge minskad exponering. 2) Det är möjligt att under vissa förutsättningar minska exponeringen av partikelformiga luftföroreningar med mobila luftrenare. Det är viktigt att vara medveten om att luftrenarna sällan skyddar mot gasformiga komponenter. 3) Bipolär jonisering har inte kunnat visas ha någon påverkan på partikelkoncentrationer utöver effekten av apparaternas mekaniska filter. 4) Unipolär jonisering kan sänka partikelhalter genom att deposition på lokalytor ökar. Det krävs då att en bedömning görs om luftreningen är värd ökad deponering på ytor. 5) Vid jonisering är det nödvändigt att tillse att inte hälsoskadlig ozongenerering förekommer. 6) Det finns uppgifter från arbetsplatser att luften upplevs som ren då olika typer av utrustning används. Det finns starka skäl att komplettera dessa upplevelser med studier där objektiva mätmetoder används i samråd med professionella riskbedömare inom området. Luftföroreningar kan vara skadliga utan att individen har förmåga att bedöma detta med sina sinnen.

Abstract

Workers at construction sites are often exposed to high levels of airborne particles in the form of silica dust and other pollutants. Conventional engineering controls are often not enough to reduce exposures to safe levels. The aim of this report was to summarize existing knowledge about how to reduce exposures using mobile air cleaners. Our primary source of information was peer-reviewed scientific studies and established knowledge in aerosol science. In a few cases where information was missing, non peer-reviewed studies from independent research institutes was used.

Most mobile air cleaners use conventional mechanical filtration. The main challenge of this kind of filters is a reduction of the flow rate as the filter becomes loaded with dust. In some cases electret filters are used. The disadvantage with electret filters is a loss of filtration efficiency with time as the filters lose their electrical charge. In work with asbestos, a filtration efficiency of 99.95% (minimum class H13) is required.

Electrostatic air cleaners that rely on altering the charge levels of airborne particles can be divided into electrostatic precipitators, collecting particles inside the device, and (open air) ionisers. Unipolar ionisation can lead to increased particle deposition on room surfaces. It has to be evaluated if this is desirable. Bipolar ionisation has not been shown to reduce dust concentrations in the air beyond effects of conventional mechanical filters in the equipment. When using electronic air cleaners, it is important to ensure that the toxic gas ozone is not emitted.

It is important to reduce dust emissions at the source. Mobile air cleaners are used as a complement to conventional techniques. Mobile air cleaners based on mechanical filtration may further reduce exposures at construction sites when a) positioned close to the source; b) when the capacity of the air cleaner is high compared to the room size; and c) when used to reduce the pressure during partitioning. The devices rarely protect against gas phase exposures. In Germany, there are requirements that mobile air cleaners need to fulfil to be recommended by the insurance liability associations. Only mobile air cleaners based on mechanical filtration fulfil these requirements.

There is a lack of peer-reviewed studies on how mobile air cleaners are best combined with conventional engineering controls at construction sites. The efficiency of novel air cleaner technology needs to be evaluated both in the laboratory and in workplaces.

1. Introduction

1.1 Particle air pollution

Exposure to air pollution is an important health risk. Air pollution consists of gaseous and particulate pollutants. In general, fine particle pollutants (particles smaller than 2.5 micrometres; PM2.5) are considered the most harmful pollutants for human health (e.g. EEA, 2018). The WHO ambient air quality guidelines for PM2.5 are 0.025 mg/m^3 for a 24-hour mean and 0.01 mg/m^3 for the annual mean (WHO, 2006). Particle exposure levels are often higher at workplaces than in ambient air (Viitanen et al. 2017). Minimising particle concentrations is one important measure for preventing a range of acute and chronic health risks.

1.2 Processes at construction workplaces

In the construction sector, there are many strong particle sources and exposure levels are often high (Flynn & Susi, 2003). Different processes are commonly performed indoors and outdoors at the same time. Because of limited dilution and ventilation, indoor emissions in particular can cause high exposure. Concentrations in the air can be reduced by controlling the emissions at the source, cleaning the polluted air by circulating the air trough filters, or increasing ventilation with clean air. Common particle air pollutants in the construction sector are silica dust, asbestos, combustion particles, polychlorinated biphenyl (PCB) and general construction dust.

1.3 Particle exposure and engineering control systems in construction environments

Exposure to respirable particles in the form of **crystalline silica dust** (quartz) is one of the most common airborne health risks in working life (Merget et al., 2002; Swedish Work Environment Authority, 2011), especially at construction sites. Despite the use of conventional engineering controls, reducing particle exposures to safe levels remains a challenge (Flynn & Susi, 2003). A number of work tasks in the construction sector, such as cutting, chiselling, and grinding expose workers to airborne silica dust particles in the respirable size fraction. The respirable size-range contains airborne particles with an aerodynamic equivalent diameter less than about 4 micrometers (µm), and represents the fraction of particles that can penetrate down to the deepest region of the human lungs (Vincent 1995). This is also the target region for many diseases related to silica dust exposure, such as fibrosis and silicosis. Health-based threshold limit values of 0.025 mg/m^3 have been established for respirable silica dust by ACGIH (Association Advancing Occupational and Environmental Health, USA). The Swedish Occupational Exposure Limit (OEL) for respirable silica dust is 0.1 mg/m^3. (The Swedish Work Environment Authority, 2018). Reference measurements from Swedish concrete industry workplaces were recently reported (Antonsson et al., 2016). Exposures above the OELs are common (Rappaport et al., 2003; Lumens et al., 2003). The highest exposures have been found during abrasive blasting, masonry chipping, scabbling concrete, tuck pointing, and tunnel boring (Sauve et al., 2012).

Asbestos fibres constitute another important particle exposure class at construction sites. Asbestos is still quite common, for example in demolition and renovation work. Due to their shape and biopersistence in the lungs, asbestos fibres (especially these longer than ~10 micrometres) can cause a range of serious health effects including mesothelioma, lung cancer and fibrosis (Donaldson et al., 2010; IARC, 2012a). Fibre-shaped particles such as asbestos can reach deep regions of the lungs due to their small diameter, even though they are comparatively long. Asbestos has an extremely low OEL, given as a number (count) concentration of 0.1 fibres per ml air. (The Swedish Work Environment Authority, 2018). This has important implications, and there are strict requirements for engineering controls and personal protection at workplaces where asbestos is handled.

Diesel exhaust is a third important exposure type that is common at construction sites. It consists of a mixture of particles and gases. The particles are nanometre-sized solid carbon agglomerates with a very high surface area per mass (Wierzbicka et al., 2014). Diesel exhaust is classified as a type 1 human carcinogen by IARC (2012b) and has also been linked to a range of other adverse health effects, including respiratory and cardiovascular disease. Hedmer et al. (2017) provided personal exposure measurements to diesel exhaust during tunnel construction. Today, Swedish OELs of diesel exhaust are given in terms of gas-phase exposures (nitrogen oxides and carbon monoxide). EU recently adopted a particle-based limit value under the carcinogen directive (SCOEL) given as 0.05 mg/m^3 elemental carbon (EC). This will come into effect in 2023 (2026 in underground mining). Health-based limit values for diesel exhaust to control risks in terms of lung cancer are as low as 0.001 mg/m^3 elemental carbon (Vermeulen et al., 2014).

Also, different forms of **larger dust particles** that are of lower toxicity are very common in construction workplaces. These have much higher OELs, (The Swedish Work Environment Authority, 2018) e.g., inorganic inhalable dust of 5 mg/m^3 (2.5 mg/m^3 for respirable fraction).

If it is not possible to eliminate the source, primary engineering controls should be used directly at the source to prevent the occurrence of dust exposure. Examples in the construction industry are local exhaust ventilation (LEV) and wet-based methods (Flynn & Susi, 2003). In local exhaust ventilation, which also includes ventilated tools, the air is extracted close to the generation point. In wet-based methods, water is used for particle removal at the generation point and to bind the dust to the floor.

Using large data sets and statistical methods it was found that, on average, both these techniques led to a reduction of exposures by around 70 percent (Sauve et al., 2012).

A technique used to prevent the generated pollutants from dispersing within the workplace is to encapsulate the working area with plastic walls and apply a negative air pressure. This can be effective, provided that it is ensured that the negative pressure in the enclosure is strong enough to prevent leaks and spread of particles to surrounding areas (Kokkonen et al., 2017). Such procedures are **required** and strongly regulated in the case of asbestos (The Swedish Work Environment Authority, 2014). Similar procedures are **recommended** when handling silica dust.

Different work practices are used in industrial environments. The way a task is performed can affect the exposure levels. For instance, video recording of tasks can be useful for designing and training good work practices when combined with measurement of airborne particle concentrations. In case primary engineering controls cannot reduce exposures to safe levels, respiratory protective equipment (RPE) can be highly efficient with protection factors up to and over a million (Koivisto et al., 2015). When RPEs are used, the focus should be on preventing pollutant dispersion within the workplace. Personal protective equipment must be conscientiously cleaned and maintained to remain effective (Airborne dust, WHO, 1999).

1.4 Basic principles of mobile air cleaners

One way to further reduce exposures that has become more common over the last 10–15 years is to introduce mobile air cleaner systems that can be easily moved within and between workplaces (Miller, 2013; Newcomer et al., 2018). The principles of mobile air cleaner devices based on mechanical filtration are well understood. However, it is less clear how mobile air cleaners should be used and combined with other engineering controls at construction work places. Recently, there has been an increased use of electrostatic air cleaner devices based on ionisation technologies in the construction sector. These devices are marketed as effective for reducing dust exposure. However, both the principles for particle removal and the efficiency of the ionising systems in removing airborne particles in the industrial workplace domain need to be clarified. Of further concern is that some mobile air cleaners may emit toxic gases such as ozone.

While preparing this report we consulted the Norwegian work environment authority regarding their stance on the use of mobile air cleaners (Norwegian Work Environment Authorities, 2018, personal communication). They reported a need for more information regarding the efficiency of mobile air cleaners at workplaces. They specifically state that they have insufficient knowledge about the efficiency of novel air cleaner technology systems, for example based on ionisation.

The scientific literature on smaller air cleaners used in indoor environments is rather extensive. For mobile air cleaners in indoor air, there are certified test methods both regarding ozone emissions and particle removal efficiency. The efficiency of air cleaners is expressed as the Clean air delivery rate (CADR). That is the equivalent air flow rate that the particle removal corresponds to. However, less published work has focused on mobile air cleaner technologies for dusty work environments such as construction sites. Air cleaners designed for the construction sector have higher air flow circulation and thus larger dimensions and potentially higher noise levels than those designed for indoor and office environments.

There are two main ways to use mobile air cleaners, which place different demands on their performance. Both use air circulation through the device, where the air is returned to either a) room air (non-ventilating) or b) the outdoors or surrounding areas (ventilating). It is important to note that in case a) this does not increase ventilation which means that non-filtered pollutants accumulate (e.g. gas pollutants such as ozone if no gas cleaning stage is used), and thus, there is always a need for extra ventilation. This is especially important when working in small spaces. In case b), the room can be set to negative pressure (Kokkonen et al., 2017), which reduces dispersion of pollutants outside of the working area, and in addition, extra dilution reduces concentrations. In case b), air pollutants in the replacement air may need to be taken into account in some cases.

In some workplaces, windows and doors may not be assembled, and thus, natural ventilation is high. For such cases an air cleaner returning the air to the room may be lower in clean air delivery rates than the ventilation air volume flow. For example, a 600 m^3 per hour volume flow rate of filtered air from an air cleaner in a 300 m^3 room would correspond to an air exchange rate of 2 per hour, which may be low compared to pre-existing ventilation.

1.5 Aims of this knowledge review

The overall aim is to clarify the principles and efficiency for particle removal of mobile air cleaners of various types used in the construction working environment. A special focus has been put on technologies based on ionisation. The report should contribute to increased knowledge in the target group, which consists of those responsible for the working environment, everyone that is exposed to dust in the working environment, occupational health services, occupational and environmental medicine clinics, and work inspectors. It is also aimed towards those who sell and rent out mobile air cleaners for industrial work environments.

This review is limited to mobile/portable air cleaners that can easily be moved between and within workplaces, and that are designed to be used as free-standing secondary engineering controls in addition to primary approaches. It has to be noted that the mobile air cleaners evaluated here are sometimes combined with extraction systems that can be put near the source similar to LEVs. Furthermore, the focus is on physical removal of aerosol particles from air in the workplace. Removal of gas phase components and specific removal/inactivation of biologically active particles is only very briefly discussed. The project started out by compiling a questionnaire on the use of mobile air cleaners in the construction industry. The questionnaire was sent to companies in the construction sector within our existing network. Literature searches were made in scientific databases such as Web of Knowledge and Medline. The primary source of information was peer-reviewed literature. To evaluate the physical principles of different types of mobile air cleaners, well-established knowledge from aerosol science about particle transport and how particles can be collected was used. We found only a small number of peer-reviewed studies that directly addressed mobile air cleaners in the construction environment. Therefore a few exceptions were made were independent reports from well-established research institutes were included. When comparing mobile air cleaners of different technologies, peer-reviewed literature for the general indoor environment was used.

1.6 Overview and structure of the report

The results of the brief survey are given in Chapter 2. In Chapter 3, particle size distributions as well as physical mechanisms for particle removal are described. Chapter 4 gives an overview of the different technologies used in mobile air cleaners and brief descriptions on filter efficiency and filter-based techniques. In chapter 5, a detailed description of the mechanisms of electrostatic air cleaners is given. In chapter 6, results from standard methods that allow comparison of particle removal efficiencies of different smaller air cleaners in indoor air are summarised. Chapter 7 focuses on different strategies for using mobile air cleaners based on mechanical filtration at construction workplaces. The chapter includes specific regulations regarding asbestos, field-testing and recommendations for air cleaners used in the construction sector. Chapter 8 discusses the use of ioniser systems in construction workplaces and chapters 9 and 10 contain the summary, conclusions, and recommendations for future work.

2. Brief survey on the use of mobile air cleaners at Swedish construction workplaces

The authors and the advisory group prepared a questionnaire (given in appendix A). The aim was to get a rough overview of the usage of mobile air cleaners within the construction sector in Sweden.

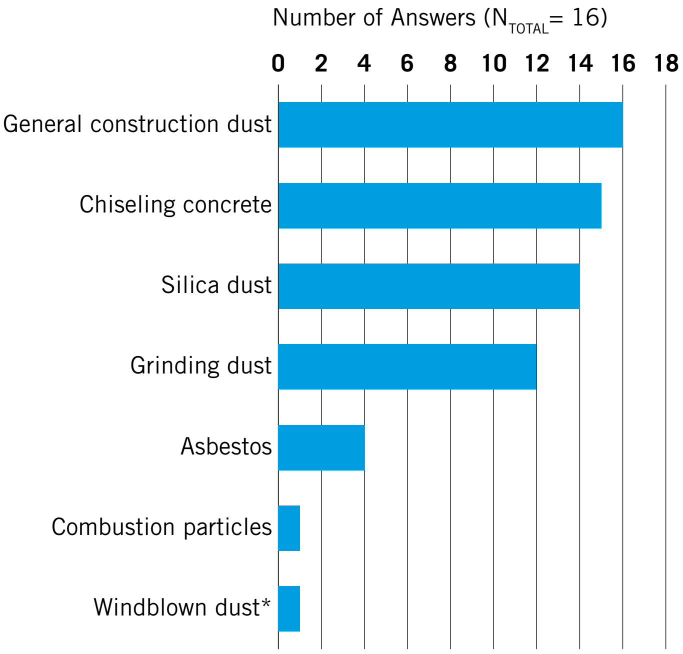
The questions included the following:

- During what exposures are mobile air cleaners used?
- What types of air cleaners are used?
- How was the air cleaner model selected when purchased?
- Have you estimated or measured the efficiency of the air cleaner for reducing exposures?
- What need is there for more information about the air cleaner's performance?
- Was the introduction of air cleaners accompanied by any reduction or alteration of other engineering controls.

The survey was sent to our existing network in the Swedish construction industry. Within the companies, the questionnaire was then distributed to individuals with expertise on dust exposures and control technologies. In total, 13 small and large construction companies operating in Sweden were contacted. 11 companies answered the questionnaire. Two of the large companies provided responses from more than one part of the organisation. In total, we obtained 16 responses to the survey. The occupations of those that submitted the survey included safety officers, work environment engineers, safety coordinators and owners (for small companies).

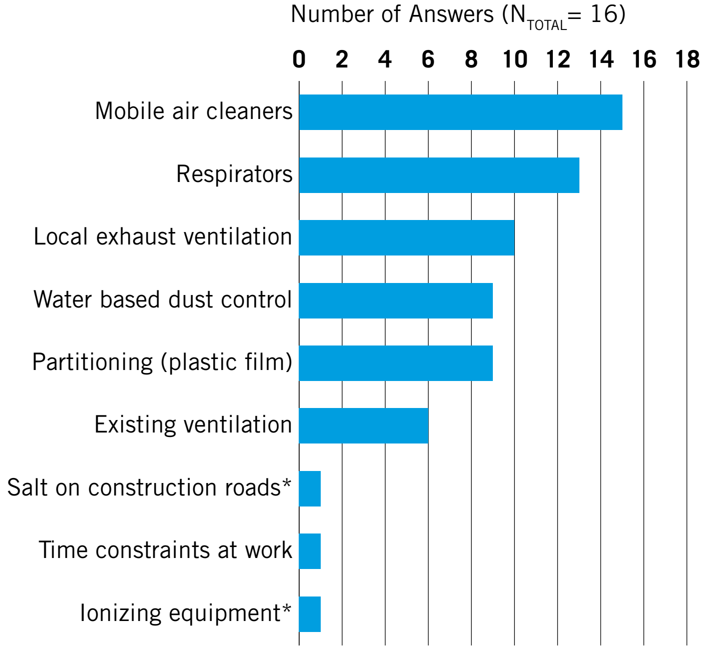
In all 16 responses, either occasional or frequent exposures to high levels of particle and dust concentrations were reported (Question 1). The workplace particulate exposures (Question 2) were mainly reported to be silica dust and dust generated through general construction, chiselling, and grinding (Figure 2.1). Exposure to asbestos, glass fibre, and combustion-generated particles were also reported.

Figure 2.1. Question 2: What type of particle/dust exposure? (* from free text).



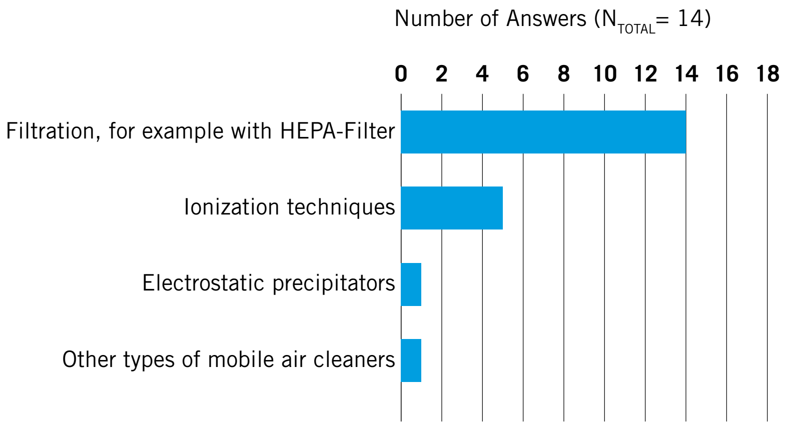
The reported protective measures (Question 3) taken to prevent particle exposure are shown in Figure 2.2. The results indicate that mobile air cleaners are common tools for exposure control when it comes to dust and particulate matter. It is commonly used as a complement to LEVs and/or water-based methods. Mobile air cleaners are also commonly used alongside personal respirators and negative pressure enclosures using plastic construction film.

Figure 2.2. Question 3: What protective measures are used to reduce exposures? (* from free text).



The types of mobile air cleaners used were specified in 14 survey answers (Question 4). All 14 reported usage of HEPA filtration mobile air cleaner technologies, 5 reported use of air ioniser technologies, and 1 reported the use of electrostatic precipitators (Figure 2.3).

Figure 2.3. Question 4. Which air cleaner technology is used?



The choice of mobile air cleaner type was either based on recommendations from others in the same occupation or recommendations from a rental company (Question 5). Almost half of the respondents (7 out of 16) reported that it was "relatively easy" to find meaningful information when choosing air cleaners (Question 6).

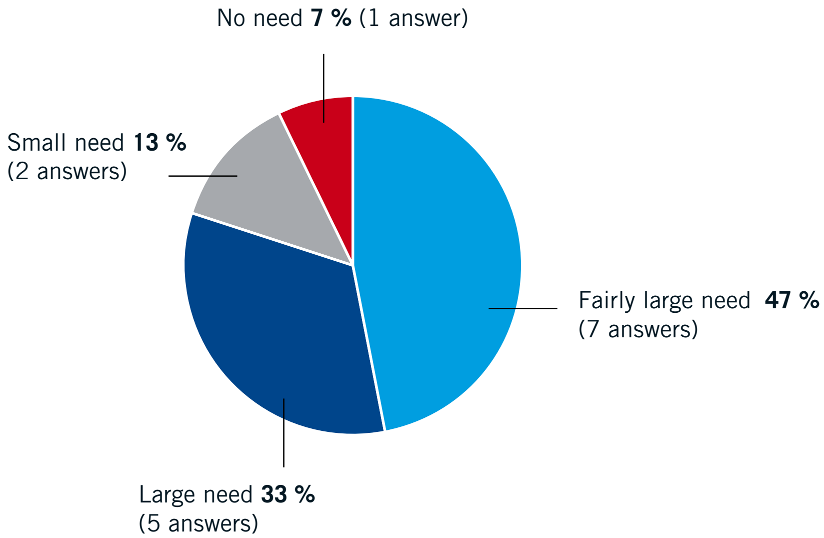
All responded that the previous usage of mobile air cleaners in the company (Question 7) was estimated to several years (and in a few cases decades). The number of mobile air cleaners within each company varied between 1 and 50. The floor area per air cleaner varied between 30 and 500 m^2 (Question 8). Mobile air cleaners were found to be frequently used in concrete chiselling/demolition work, in asbestos and PCB decontamination work, in closed spaces with poor ventilation, and in indoor work such as bathroom renovations (Question 9).

To question 10, "Do you see an improvement when the mobile air cleaner is used?" 15 out of the 16 respondents answered that they estimated that use of mobile air cleaners made a difference to improve the air quality. However, only 1 of the 15 reported that this was supported by measurements.

In response to question 11, "Have you omitted any safety measures that were in use prior to your use of mobile air cleaners?", the majority reported that while introducing mobile air cleaners they have maintained earlier used protective measures (13 answers). However, two answers indicated that personal respiratory protection and local exhaust ventilation had been less frequently used after the introduction of mobile air cleaners.

In response to question 12, "Is there need for more information on the use of mobile air cleaners and their efficiency?", a majority of the answers indicated a large (7 answers) or fairly large (5 answers) need for improved information (Figure 2.4).

Figure 2.4. Question 12: "Is there need for more information on the use of mobile air cleaners and their efficiency?"



The survey showed that mobile air cleaners based on both mechanical filtration and ionisation are available from major rental companies for construction machinery, and that thus, they are easily available.

The frequency of using mobile air cleaners found in our study (15 out of 16 answers) may be the result of a biased sample. It is possible that after we sent the questionnaire to our contacts in the various organisations, the survey may have been directed to departments/divisions where exposures are high, and which preferentially use mobile air cleaners. Be this as it may, the study still shows that mobile air cleaners are commonly used in the construction sector in Sweden today.

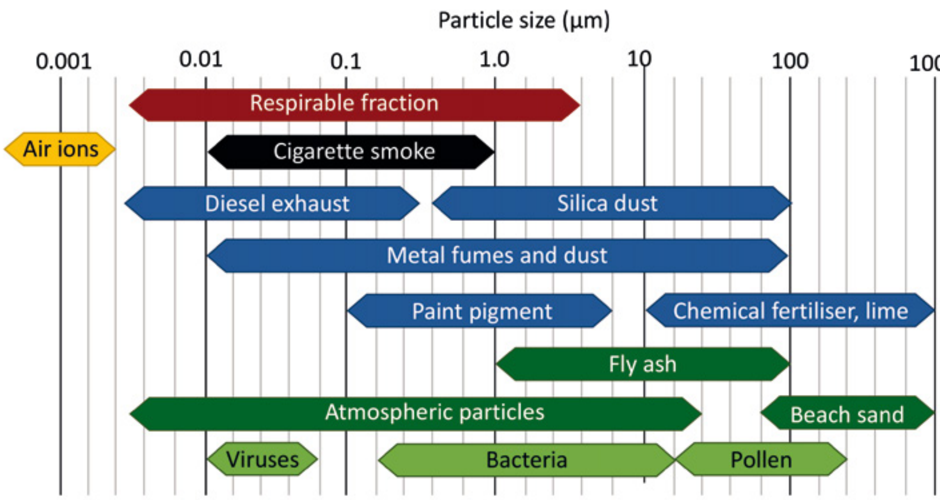
3. Particle size distributions in construction environments and particle deposition mechanisms

3.1 Size distributions of common aerosols in the construction environment

The removal efficiency of air cleaners is commonly particle size dependent. Therefore, information on the particle size distributions is important when assessing the performance of each combination of air cleaner and particle source. This is also important when extrapolating from lab tests to real-world exposures. Furthermore, the particle size distribution is a very important parameter in determining the doses of an inhaled pollutant received in the different parts of the respiratory tract. Inertial impaction and sedimentation are important deposition mechanisms for coarse particles, as are diffusion and interception for small particles.

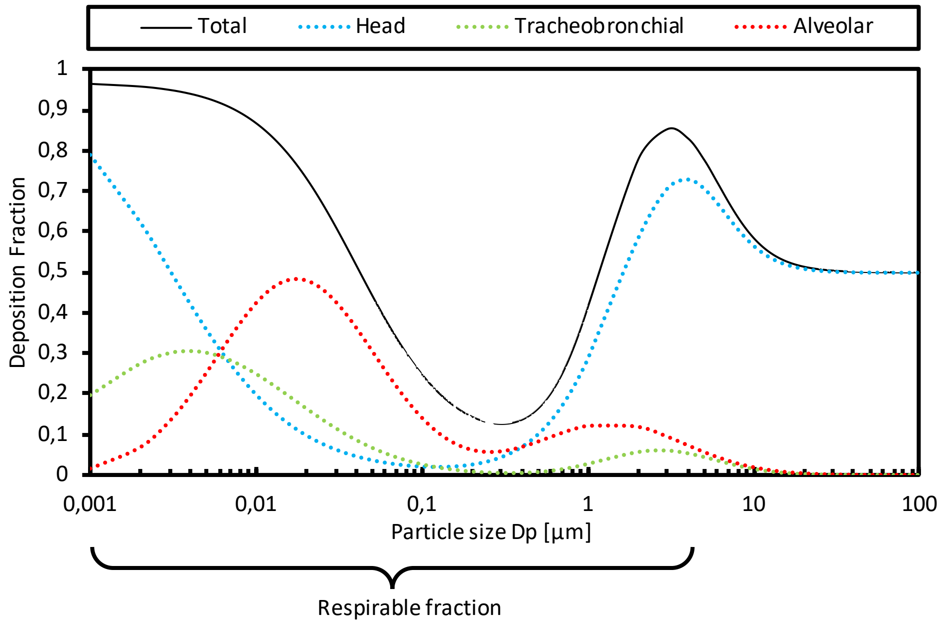
Size ranges of particles from a few common sources including emission sources at construction sites are listed in Figure 3.1. As an example, the mass median aerodynamic diameters (MMAD) during crystalline silica dust exposure ranges from 3 to 10 µm, with lower particle diameters for processes with a higher energy input.

Figure 3.1. Approximate size range of some major particle sources in the working environment (blue boxes) and in the outdoor ambient air (green). The particle sizes within the respirable fraction are marked with a red box, and the size of air ions with a yellow box. Scale from 0.001 to 1,000 µm.



Particle emission from diesel exhaust has an MMAD of around 0.1–0.3 µm (Park et al., 2003; Rissler et al., 2012). The large difference in particle size between silica dust and diesel exhaust also makes a difference to how they are deposited in the respiratory tract and has implication for the efficiency of mobile air cleaner devices. The influence of particle size on the deposition in different parts of the respiratory system is presented in Figure 3.2.

Figure 3.2. Deposition probability in the respiratory tract as function of particle size, computed for a healthy man at light exercise using the ICRP model (ICRP, 1994). The approximate size range of the sampling standard for the respirable fraction is indicated below the plot. As can be seen, the respirable fraction approximately describes the particle size range that can reach and deposit in the alveolar region of the deep lung.

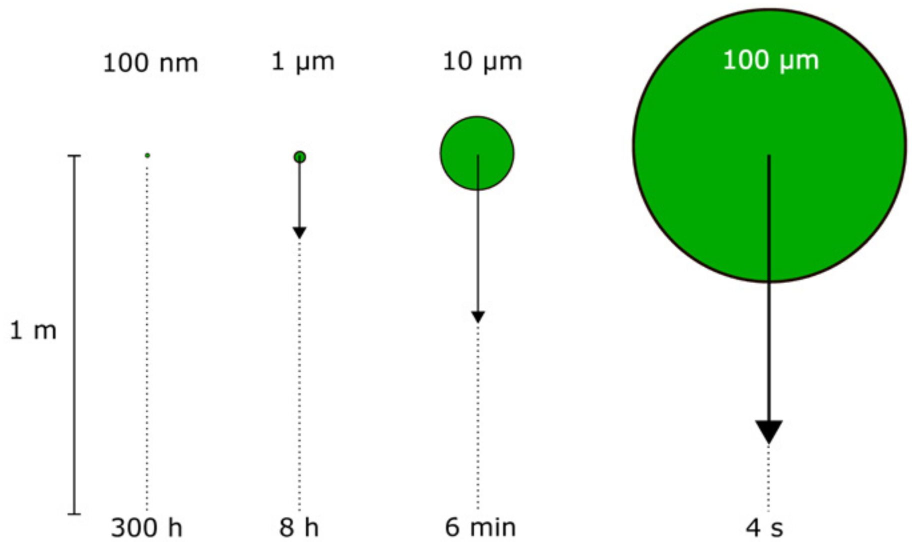


3.2 Mechanisms for removal of particles from air

The specific physical deposition mechanisms used to collect particles in different types of mobile air cleaners are vital information for assessing the applicability of these cleaners to different exposure situations. These deposition mechanisms (Hinds, 2012) are of importance when describing and predicting particle collection in both filter-based and electrostatic air cleaners. (Figure 3.4) Knowledge of these mechanisms is also required for understanding the deposition of particles in the respiratory tract and deposition of particles at workplace surfaces. Once a particle deposits on a surface, it stays there. However, as a thick layer of dust builds up on a surface, for example during construction work, deposited particles may be re-emitted (often as larger agglomerates of many original particles) to air. Resuspension of deposited material can be caused by various processes in the construction environment, such as shovelling of dust.

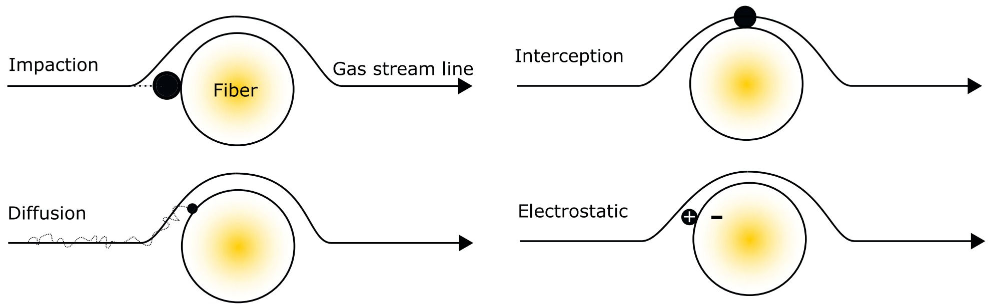
Sedimentation (gravitational settling) is a well-known deposition mechanism. As illustrated in Figure 3.3 below, the sedimentation velocity increases rapidly with increasing particle size. For particles with diameters of 1 µm the sedimentation velocity is ~0.004 cm/s, while for 10 µm particles it is 0.3 cm/s. This estimation assumes the particles to have the density of water. Thus, large dust particles of 10 µm are removed from air within ~10 minutes, while particles of a diameter of 1 µm can stay airborne for a long time, and may thus infiltrate other areas of the workplace. Sedimentation is also an important deposition mechanism in the deep lung (alveolar region), and is responsible for the increased local deposition of particles larger than about 0.5 µm.

Figure 3.3. Sedimentation time from 1 m height to the ground for particles of different sizes (aerodynamic equivalent diameters).



Inertial impaction is a deposition mechanism that becomes increasingly important as particle size increases. Aerosol impaction is the process by which particles are removed from an air stream by forcing the air flow to make a sharp bend. This is important for increasing the collection efficiency of fibrous filters with increasing particle size. It is also the main mechanism for collecting large particles in the upper parts of the respiratory tract, including the nose, and protects our deep lung from exposure to particles larger than about 4 µm (hence the definition of the respirable fraction).

Figure 3.4. Schematics of particle collection/deposition mechanisms onto a single fibre in a filter. Impaction is when a particle is too large/heavy to follow the bend of the airflow around the fibre, and thus hits the fibre. Diffusion is the random motion small particles receive from collisions with gas molecules that in this case makes it hit the fibre. Interception is when a particle succeeds in following the air stream but due to its large size hits the fibre. Electrostatic deposition is when a charged particle (or polarised neutral particle) is deposited due to attraction to an oppositely charged fibre.



Diffusion is the main deposition mechanism for particles smaller than ~0.2 µm in fibrous filters and the respiratory tract. It can be understood by thinking of the aerosol particle as a large gas molecule that is caused to move randomly by collisions with surrounding gas molecules. Deposition by diffusion increases with decreasing particle diameter and is very strong for particles below 0.01 µm.

Interception is a deposition mechanism caused by transportation of particles very close to surfaces. It is of importance when the particle dimensions are comparable to the geometries where they are transported. This includes in fibrous filters in the region where other mechanisms are weak (0.1–1 µm). It is also of importance for deposition of long fibres (for example asbestos fibres) in the respiratory tract.

Electrostatic deposition is a central concept in this knowledge review. It is of importance when particles are highly charged and/or affected by strong electrical fields. It can also be of importance for particles with relatively low charge levels in situations when other mechanisms are weak (for example between 0.1 and 1 µm). Electrostatic deposition can even affect uncharged particles by the mechanism of dielectrophoresis. For example, in an electret filter, when globally neutral particles can become polarised due to inhomogeneous electric field caused by electrically charged filter media. Electrostatic deposition is discussed in more detail in chapter 4 in the context of electret filters and in chapter 5 in the context of electrostatic air cleaners. For air cleaners based on air ionisation, electrostatic precipitation, and electret filters, electrostatic deposition is a dominating deposition mechanism. Unipolar air ionisers operate by increasing the deposition rate of particles onto indoor surfaces by increasing electrostatic deposition. It is very important to consider that this may also increase particle deposition in the respiratory tract or onto human skin and clothing surfaces.

Thermophoresis (particle movement from hot to colder regions) describes deposition of particles due to temperature gradients. This is the reason why an increased particle deposition can sometimes be seen on cold surfaces. However, the thermophoretic forces are weak, and therefore, this mechanism is not commonly used in mobile air cleaners.

4. What physical principles do air cleaners rely on?

A summary of common air cleaner technologies for particle removal is presented in Table 4.1. Chapter 4 briefly outlines the physical principles of air cleaners based on mechanical filtration and combined mechanical and electrostatic filtration (electret filters), while a detailed description of electrostatic devices is given in chapter 5. Technical details of the cleaning techniques used in general indoor air can be found in several review articles (Luengas et al., 2015; Shaughnessy & Sextro, 2006; Zhang et al., 2011) and reports (U.S. Environmental Protection Agency, 2018). Mobile air cleaners designed for workplaces commonly employ the same technologies to remove particulate air pollutants as many portable air cleaners for indoor air and office work.

Table 4.1: Summary of the main air cleaner technologies for particle removal

Category	Air cleaner technology	Principles of particle removal	Chapter
Mechanical filtration	Fibrous filters	Particle removal in porous filter media.	4.1, 4.2, 6, 7
Combined mechanical and electrostatic filtration	Electret filters	Particle removal in electrically charged porous filter media.	4.1, 4.3, 6, 7
Electrostatic devices	Electrostatic precipitators	Charged aerosol particles deposit by electrical mobility on collector plates.	5, 6, 8
	Air ionisers (unipolar and bipolar)	Charged aerosol particles deposit by electrical mobility on existing surfaces	5, 6, 8

Hybrid air cleaners typically employ fibrous filters or electrostatic precipitators for particle removal and an additional technique for the **removal of gas phase pollutants** (Daisey & Hodgson, 1989; Niu et al., 1998; Shaughnessy et al., 1994; Shaughnessy & Sextro, 2006). Briefly, sorption filtration, ultraviolet-photocatalytic oxidation (UV-PCO), ozone oxidation, and air ionisation using plasma are techniques employed in portable units aimed towards removing gas-phase pollutants in indoor air (Chen et al., 2005; U.S. Environmental Protection Agency, 2018). In their comparison of different technologies, Chen et al. (2005) found that sorption filtration techniques were the most effective. In sorption techniques, the gases are removed by physical attraction or chemical reactions (chemisorption) to sorbent surfaces. The type of sorbent is determined by the target species and cost. The capacity and thereby the interval of replacement of the sorbent may vary depending on the price category. Typical sorbents used in air cleaners are: activated carbon, zeolite, and activated alumina (Chen et al., 2005; Luengas et al., 2015). Gas-phase filtration is less common in mobile air cleaners designed for industrial workplaces.

4.1 Particle filter efficiency and classification

In this section, we aim to briefly introduce different filter classification standards and their implications for air cleaners. Classifications of particulate filters are based on their particle collection efficiency and their pressure drop. The classification, standardised test procedure, and the definitions of efficiencies are different for **standard particulate filters (SPF)** and **high efficiency air filters**.

SPFs with comparatively high filtration efficiencies are widely used in general ventilation systems and air conditioning systems to clean incoming ventilation air, exhaust air, or room air by circulating the air through the filter. SPFs with the lowest filtration efficiency are commonly used to remove very large particles and pollen, and as pre-filters for standard filters with higher filtration efficiencies. SPFs with comparatively high filtration efficiencies are also used as pre-filters for high efficiency air filters and in conjunction with gas-phase filtration methods (for example active carbon filters).

SPFs are classified according to ISO 16890, which replaced the previous standard EN 779:2012 in 2018. The older standard had several filter classes, while in the newer standard (ISO 16890) filters are classified in narrow steps (5 percent) based on their efficiency for a given particle size range. In ISO 16890, the covered particle size range spans between 0.3 and 10 µm. This is divided into: PM1 (0.3–1 µm), PM2.5 (0.3–2.5 µm), and PM10 (0.3–10 µm). Two test aerosols are used: liquid droplets of Di-Ethyl-Hexyl-Sebacat (DEHS) in the size range of 0.3–1 µm, and solid potassium chloride (KCl) particles in the size range 1–10 µm. The size-dependent fractional collection efficiency is measured and the PMx efficiency is determined by mathematically applying a standardised particle size distribution to the collection efficiency curve.

A filter which fails to retain at least 50 percent of the PM10 mass is classified as a **coarse** filter. The test procedure prescribes that the filter be tested up to a 300 Pa pressure drop, and after being discharged using isopropanol (IPA) fumes. This ensures that filter performance will remain high after filter loading, and takes degradation of electrostatic properties (electret filters) into account. To meet the classification for a specific particle size range, the filter must have an average efficiency (mean of the untreated and discharged efficiency tests) greater than 50 percent, and retain at least 50 percent of PM10. Filters that meet the criteria are classified as ISO ePM10, ISO ePM2.5, and ISO ePM1, where the “e” stands for efficiency. The filter efficiency in a specific particle size range is indicated as in the following example: ISO ePM1 65% (65 percent efficiency as PM1). Because particle mass concentrations do not necessarily correlate well with particle number concentrations, filters classified according to their retention of particle mass can, depending on the aerosol, have significantly lower collection efficiency by number concentrations.

High efficiency air filters are classified according to EN 1822:2009 and ISO 29463. These filters are tested individually and certified according to their removal efficiency at the **most penetrating particle size** (MPPS). MPPS is usually in the particle size range 0.12–0.25 µm. The standards do not prescribe a specific test aerosol, but the reference method should be a liquid aerosol based on or with similar qualities as DEHS, Polyalphaolefin, or Paraffin oil. Examples of high-efficiency filter classifications are shown in Table 4.2. According to the European standard, HEPA filters of the class H13 have a minimum efficiency at MPPS of 99.95 percent.

Table 4.2: Particle removal efficiencies for common high-efficiency air filters according to ISO 29463 and EN 1822:2009.

Filter Class			Overall Value	
EN 1822:2009		ISO 29463	Efficiency at MPPS	Penetration at MPPS
EPA	E10	-	≥85%	≤15%
	E11	ISO 15 E	≥95%	≤5%
	-	ISO 20 E	≥99%	≤1%
	E12	ISO 25 E	≥99.5%	≤0.5%
	-	ISO 30 E	≥99.90%	≤0.1%
HEPA	H13	ISO 35 H	≥99.95%	≤0.05%
	-	ISO 40 H	≥99.99%	≤0.01%
	H14	ISO 45 H	≥99.995%	≤0.005%

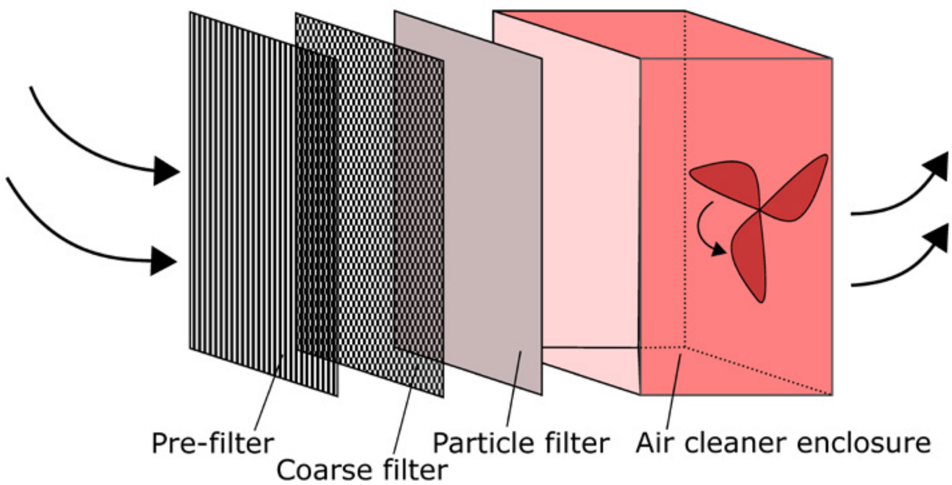
During work with asbestos, minimum dust removal efficiencies of 99.95 percent are required for devices providing negative pressure inside enclosures and when recirculating air inside the enclosures (EU-OSHA; The Swedish Work Environment Authority, 2014). Negative air units, and mobile air cleaner units used for these purposes require filter standards equal to or higher than H13 (ISO 35H). It is important to note that only filters of class H13 and H14 guarantee that the minimum efficiency (over the lifetime) will be 99.95 percent and 99.995 percent, respectively, and that the name HEPA is not protected for all cases in air cleaners and does not in itself guarantee that particle removal standards are met.

4.2 Mobile air cleaners based on mechanical filtration

Mobile air cleaners based on mechanical filtration techniques commonly use a series of one to two SPFs followed by a HEPA filter to capture particulate pollutants (Figure 4.1). The SPFs increase the lifetime of the more expensive and delicate HEPA filter. A fan is used to draw air through the set of filters. The filter efficiencies depend on the type and class of filter, as described in the previous section.

As will be described in more detail in chapter 6, **Clean air delivery rate (CADR)** is commonly used to determine the efficiency of air cleaners. CADR corresponds to the equivalent clean air flow rate that the particle removal corresponds to. For mechanical filtration, CADR depends on filter efficiency and air flow rate through the filters, modified by losses in the enclosure and potential leaks in or around the filter.

Figure 4.1. Major components of a mobile air cleaner based on mechanical filtration.



In mechanical filtration, particles in the air will deposit on the filters by impaction, diffusion, and interception (Figure 3.4). Particle removal efficiencies are size-dependent and depend on filter material, pore size, and air flow rate through the filter (Luengas et al., 2015).

Conventional mechanical filtration-based air cleaners have relatively high pressure drops. There is a trade-off between collection efficiency and pressure drop highly efficient filters require more energy input to generate the required flow rate, which in most cases also entails a louder noise level. Additionally, most indoor air cleaners use uncontrolled fans to draw the air through the filter. In such cases, a higher pressure drop results in a lower flow rate, and thus lower CADR. Higher efficiency filters may therefore be counterproductive in some cases. Thus, in general, fibre filter CADR can be maximised by minimising the filter pressure drop at the cost of filtration efficiency or by increasing power consumption by using fans that are more powerful and controllable and thus suitable for higher efficiency filters, with the latter being preferable for reducing the concentration of the particles in the air.

Mechanical filters become saturated with particles over time, which results in an increased pressure drop and a reduced flow rate (Luengas et al., 2015) as long as the filter is intact. The initial particle removal efficiency and the lifetime of the filter material are therefore important factors for air cleaners based on mechanical filtration. In mobile air cleaners for construction workplaces it is important that pre-filters and coarse filters are exchanged or cleaned regularly to increase the life-time of the high efficiency filter and to minimise the pressure drop of the system. The high efficiency filter should not be cleaned as it may cause leaks. Modern air cleaners for construction applications are often equipped with an alarm when the flow rate is decreased below a given limit to show when filters need to be changed or cleaned.

The fact that the filter collection efficiency does not decrease with age for these filters is an advantage when mobile air cleaners are used to provide negative pressure during partitioning, especially when substances with relatively high toxicity, such as silica dust, are handled.

4.3 Mobile air cleaners based on combined mechanical and electrostatic filtration (electret filters)

In electret filters the fibres are electrically charged. Particles will deposit by mechanical filtration, and in addition, by coulomb attraction (charged particles) or induced dipoles (uncharged particles) which significantly enhance collection efficiencies. While conventional mechanical filtration-based air cleaners have relatively high pressure drops, electret filters can offer equivalent initial collection efficiencies at lower pressure drops due to their electrical properties. With lower pressure drops, the energy consumption and the noise level are both reduced, and thus, they are often found in air cleaners aimed at indoor air.

However, it is very important to be aware that the filtration efficiencies of electret filters drop dramatically when the electret properties degrade and the fibres loose their charge (Lehtimäki & Heinonen, 1994; Thakur et al., 2013). Such a drop in efficiency is not necessarily accompanied by an increased pressure drop, and as a result it may be **impossible to identify lost air cleaner efficiency** without empirical measurements (Schumacher et al., 2018a). The particle size with the lowest collection efficiency for electret filters depends on the filter and the charge level of the particles, and typically occurs for particle sizes below 100 nm. As discussed previously the testing standards take into account electrically discharged filters, thus limiting the possibility to classify electret filters for example as H13 filters. These challenges makes this type of filter unsuitable when material with high toxicity such as silica dust is used.

5. Detailed description of electrostatic air cleaners

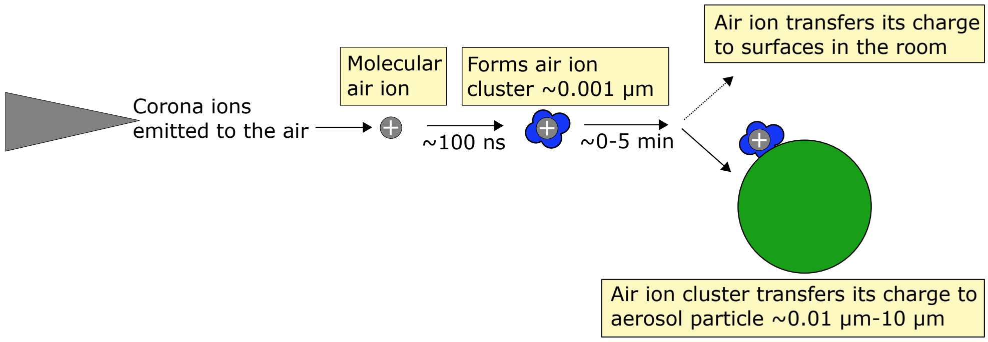
Electrostatic air cleaners utilise the mobility of charged particles in electrical fields to remove particles from the air (Luengas et al., 2015). Electrostatic air cleaners are divided into electrostatic precipitators and ionisers (ion generators), (Luengas et al., 2015; Shaughnessy & Sextro, 2006). Both electrostatic precipitators and ionisers employ techniques to charge (ionise) air molecules, for example, using corona discharges to form air ions. Attachments of charged air ions onto aerosol particles lead to an increased charge level of the aerosol particles, which increases their mobility in electric fields, thus facilitating collection. With an **electrostatic precipitato***r*, the charged aerosol particles are collected on collector plates, often inside the device. With an **open-air ioniser**, the produced ions are emitted to room air to charge particles in the room. This can create an electrical field that may cause charged particles to migrate towards surfaces onto which they adhere. Most open air ionisers generate negative ions, but systems with generation of positive ions and bipolar ions also occur. Some systems used in construction environments use bipolar ionisation, i.e., generation of both positive and negative ions.

First, we need to introduce a few key concepts regarding aerosol physics and air ions before moving on to the functions of the various types of electrostatic air cleaners and their potential effects on particle concentrations and exposures.

5.1 Air ions and aerosol particles

Air ions are formed in the ambient atmosphere primarily due to natural radioactive decays. The decay leads to charging of individual air molecules. These charged molecules rapidly grow by taking up a small number (5–20) of trace molecules, e.g., water vapor (Figure 5.1). Air ions commonly remain very small in size (diameter < 0.003 µm). In the atmosphere, the air ion concentration varies between 200–2,500 cm^{-3} for both positive and negative ions (Hirsikko et al., 2011). The air ion concentration in normal indoor environments is lower (~100–500 cm^{-3}). This is because the air ions are easily lost to indoor surfaces and to surfaces in the ventilation system due to their very high mobility in electric fields and high probability of sticking to surfaces (Fletcher et al., 2008; Martinac, 1993). Air ions may also be lost by collision with the much larger aerosol particles in air, altering the charge level of the aerosol particle. Air ions have a lifetime of just a few minutes in indoor air (Fletcher et al., 2008).

Figure 5.1. Illustration of formation of molecular ions, growth to air ion cluster, and transfer of charge to larger aerosol particles or surfaces in the room.



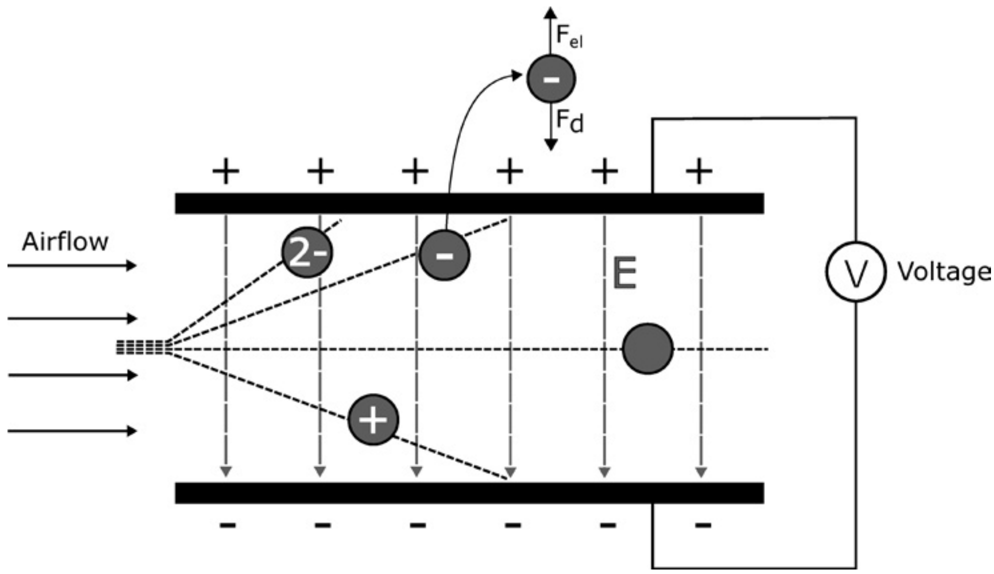
In older literature (Martinac, 1993), the distinction is sometimes made between small air ions (smaller than 0.003 µm) and large air ions. Here, we denote all charged particles larger than 0.003 µm as "charged aerosol particles". Normally, the size of air ions is stable within a limited size range (0.0005–0.002 µm). However, under certain circumstances, small clusters (both neutral molecular clusters and air ions) can grow to become aerosol particles larger than 0.003 µm by uptake of sulphurous and organic components (Tröstl et al., 2016). In some cases, air ion clusters grow more efficiently than neutral clusters (Kirkby et al., 2016).

Aerosol particles are substantially larger than air ions, and commonly consist of thousands (smallest combustion generated particles) to billions (mechanically generated dust) of molecules. The net charge level of an aerosol particle ranges from no charge or a few elemental charges for particles far away from the source to hundreds of charges per particle for larger sizes near some sources or after exposure to very high concentrations of air ions of only one polarity (unipolar charging). The charge level of workplace aerosols is discussed further in chapter 5.3.

5.2 Effects of electrical fields on the transport of charged particles

The effect of electrical fields on the motion of charged aerosol particles is well understood. Theories describing the effects of electrical fields on particle transport and removal are available in many textbooks on aerosol science (Akselsson et al, 1994; Hinds, 2012). Here, we start with a simplified example to illustrate how particles with different charge levels and polarities are affected by a static electrical field, **E** (Figure 5.2). Two electrodes held at different voltages generate the field. The static electrical field flows is in the direction from the positive electrode to the negative electrode. The strength of the electric field is given in Volts per m, and in this simplified case it is the voltage difference divided by the distance between the electrodes. Positively charged particles will be attracted to the negative electrode and negatively charged particles to the positive electrode, while particles with no net charge are unaffected by the electrical field.

Figure 5.2. Illustration of particle motion caused by an electrical field, E, between two charged plates (grey vertical arrows), for particles with different polarities and charge levels. Charged aerosol particles are attracted to the oppositely charged plates, and the higher the particle charge, the stronger the attraction force. The uncharged particle is unaffected by the static electrical field and follows the airflow. The force balance between the electrical force, F_{el}, and the air resistance, F_d, is also illustrated.



The particles rapidly acquire a constant velocity in the field. At this stage (equation 1), the electrical force, $\mathbf{F}_{el}$, is balanced by the air resistance (drag force: $\mathbf{F}_d$). From this force balance, the terminal electrical velocity, $\mathbf{V}_e$, can be calculated using equation 2. For a given particle size, $\mathbf{V}_e$ increases linearly with the electrical field strength, **E** and with the particle charge level (number of elemental charges, **n**, times the charge of the electron, **e**). Typical field strengths in workplace/indoor air are within the range 1–100 V/cm.

Another key parameter is the electrical mobility of the aerosol particles, Z (equation 2). It is the ratio of the terminal electrical velocity to the electrical field strength, and thus it describes the relative ease with which a particle is affected by the electrical field. The electrical mobility is a strong function of particles size, $\mathbf{d_p}$, in addition to the number of net charges the particle carries. It also depends of the air viscosity, $\boldsymbol{\eta}$. **Cc** is the Cunningham factor.

Thus, to assess the functionality and efficiency of electrostatic air cleaners we need information regarding the electrical fields that are generated by or exist within the electrostatic air cleaner and the particle electrical mobility (which depends on net charge level, polarity, and particle size).

$$F_{el} = \mathrm{neE} = \frac{d_p * 3 * \pi * \eta * V_e}{C_c} = F_d \quad \text{Equation 1}$$

$$V_e = \frac{E * C_c * n * e}{d_p * 3 * \pi * \eta} = E * Z \quad \text{Equation 2}$$

It should be noted that the example and equation 2 only applies to homogeneous electrical fields. Inside electret filters, the field is highly inhomogeneous, and dielectrophoresis caused by the polarisation of the particles induces removal for uncharged particles, too.

5.3 Charge level of workplace aerosol particles

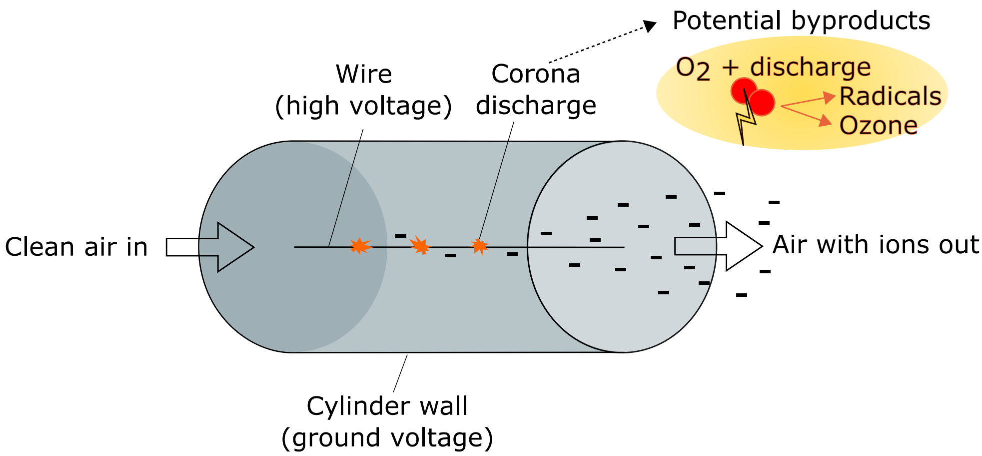
The charge level of airborne particles near the particle source depends primarily on the electrical charge level the particles obtained during their emission/formation. When formed, particles from mechanical disintegration processes, such as activities at construction sites, are commonly highly charged due to the strong shear forces involved in their emission (Johnston et al., 1987; Johnston et al., 1985; Vincent, 1986; Vincent et al., 1985). Such tribological charging also depends on the material pairs, e.g., between the work-tool and the material that is treated. Johnston et al. (1985) concluded that: "a) the particle charge levels varied markedly between factories and between different workplaces within the same factory, b) charge levels in many instances were comparable with those measured for laboratory-generated dusts, and c) charging in all the cases examined was approximately uniformly distributed between particles with positive and negative net charge". The number of charges per particle increases rapidly with increasing particle diameter. An example of this is given in Figure 5.4 below.

Emissions from high temperature processes such as diesel exhaust particles and welding fumes have comparatively low charge levels when freshly emitted compared to particles from mechanical disintegration processes. This is most likely due to high concentrations of air ions of both polarities at the high temperature conditions. This shifts the bipolar equilibrium charge distribution so that it includes slightly higher charge levels compared to ambient conditions (Johnston et al., 1985).

5.4 Ion generation and particle charging

A common way to create high concentrations of air ions which can be used to electrically charge aerosol particles is the Corona charger (Hinds, 2012). Very strong electrical fields are produced (for example between a fine wire and a surrounding cylinder) so that a corona discharge is formed and the air is ionised (Figure 5.3). The electrical field will attract ions of one polarity while ions of the opposite polarity will be repelled and ejected to the surrounding gas.

Figure 5.3. Schematic of corona charger, including formed ions. Ozone and radicals may be co-emitted.



Other techniques commonly used in commercial ionisation systems include dielectric barrier discharge (DBD) and plasma techniques. In the ionisation process, a range of reactive compounds may be co-emitted, including ozone and a number of radicals (Kempe, 2012). Formation of ozone and emission of such species from ionisers will be discussed further in section 5.8. By combining two unipolar chargers operated at opposite polarity, high ion concentrations of both polarities can be generated.

Consider a charged aerosol particle surrounded by air ions of both polarities. Ions of opposite polarity to the particle will then be attracted to the particle. Ions of the same polarity as the particle will be repelled. The air ions will collide with air molecules, causing additional motion of the ions and thus leading to their diffusion through the aerosol. When the air ions collide with aerosol particles, this leads to changes in particle charge levels. When ions of both polarities are present, ion diffusion (diffusion charging) leads to a decrease in the net average particle charge level, a process called **neutralisation**.

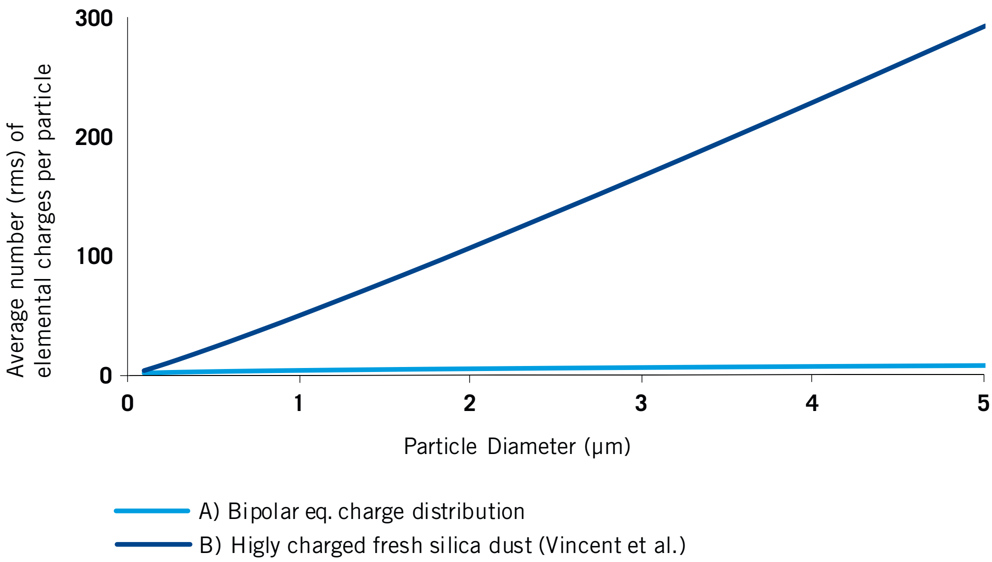
If the ion concentration (**N**) is high enough, and the residence time (**t**) in the "ion-cloud" long enough, the particles will obtain a bipolar equilibrium charge distributions (Hoppel & Frick, 1986; Wiedensohler, 1988). Commonly an **N*t** product larger than $5*10^6$ s/cm^3 is needed (Liu & Pui, 1974). This means that at typical ambient (outdoor) ion concentrations, about one hour is needed for charge neutralisation. If a bipolar ioniser is used to increase air ion concentration, this time will be shortened.

At the bipolar charge equilibrium, the net charge of the aerosol is zero and the average number of charges per particle is low (although not zero). There is for each particle size a given probability for the particle to have X number of charges (Wiedensohler et al., 1988). For aerosols at bipolar charge equilibrium, electrostatic deposition on indoor/workplace surfaces is relatively weak compared to other loss mechanisms such as removal by ventilation, gravitational settling for larger particles and diffusion for smaller particles.

So far, we have mainly discussed bipolar charging. If, instead, one polarity strongly dominates the ion concentration, unipolar particle charging will occur as the ions diffuse and collide with aerosol particles. A major difference to the bipolar diffusion charging process described above is that there will be an increased degree of rejection between the ions and the particles (they will move away from each other) as the particles reach increased charge levels. Additionally, unipolar charging is commonly carried out in the presence of an external electric field (field charging), which causes additional motion of ions towards the particles.

As shown in equation 2, both particle size and the number of charges per particle are central in predicting how much an electrical field can influence the movement of particles in air. In Figure 5.4, a comparison is given between the average number of charges per particle for a highly charged case and a neutralised aerosol at bipolar charge equilibrium. The highly charged case is taken from freshly produced particles from stone crushing at a quarry (Vincent et al., 1986). It is found that the number of charges per particle increases approximately linearly ($\mathbf{n*e \sim d_p}^{1.1}$) with increasing particle size. The highly charged case in Figure 5.4 may also describes the particle charge level produced using a unipolar charger in indoor air well (Uk-Lee et al., 2004). There is one important difference, however: the freshly produced workplace aerosols have a highly charged bipolar charge distribution. That is, particle is highly charged, either with a positive net charge or a negative net charge. For the unipolar charger case, all particles have the same charge polarity (either positive or negative).

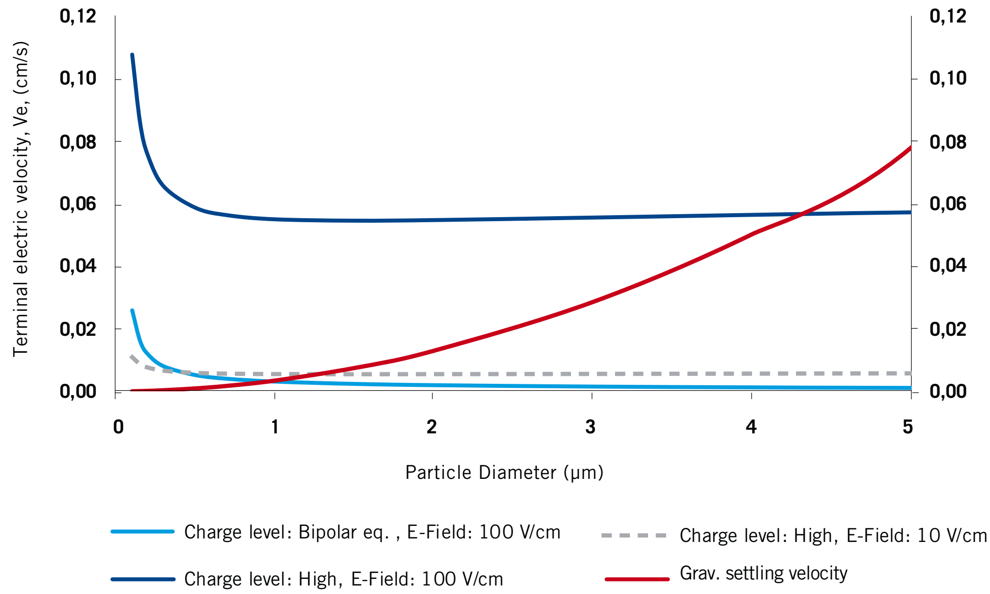
Figure 5.4. Dependence of mean absolute charge level (root mean square) on particle size for two cases. A) "Neutralised" particles at bipolar charge equilibrium and B) Highly charged case, freshly generated silica dust near the source. Both parameterisations are taken from Vincent et al., (1986).



Combining the charge levels in Figure 5.4 with Eq. 2 allows us to calculate the terminal electrical velocity as a function of particle size. Terminal electrical velocity determines how easily particles will travel in an electric field. In the case of interest here, the higher this value, the faster the particles will deposit on nearby surfaces. The results are given in Figure 5.5 for two electrical field strengths. 10 V/cm is a common value for indoor air while 100 V/cm is a very high value that may be achieved with a strong unipolar ioniser in indoor air.

First of all, it is clearly shown that the highly charged particles are much more affected by the field compared to the charge-neutralised particles. Thus, when exposed to a strong electrical field, highly charged particles will be deposited on surfaces to a higher degree than charge neutralised particles. It is also interesting to note that for particles larger than about 0.5 µm, $\mathbf{V_e}$ is close to independent of particle size. This is because the increase in particle charge with increasing particle size offsets the decreased electrical mobility with increasing size. For particles at bipolar charge equilibrium and highly charged particles with the low E-Field, gravitational settling is a more effective removal mechanism than electrostatic removal when particles are larger than 1 µm. The highly charged particles at high E-Field are removed at constant velocity, and for **dp**>4.2 µm particle gravitational settling becomes more efficient than electrostatic removal. Charged particles below ~0.1 µm are removed more efficiently due to their high electrical mobility.

Figure 5.5. Illustration of the terminal electrical velocity, V_e, (left y-axis) and its dependence on particle size, particle charge level (cases in Figure 5.4), and strength of the electric field. The gravitational settling velocity (assuming spherical particles with density of water) is given for comparison.



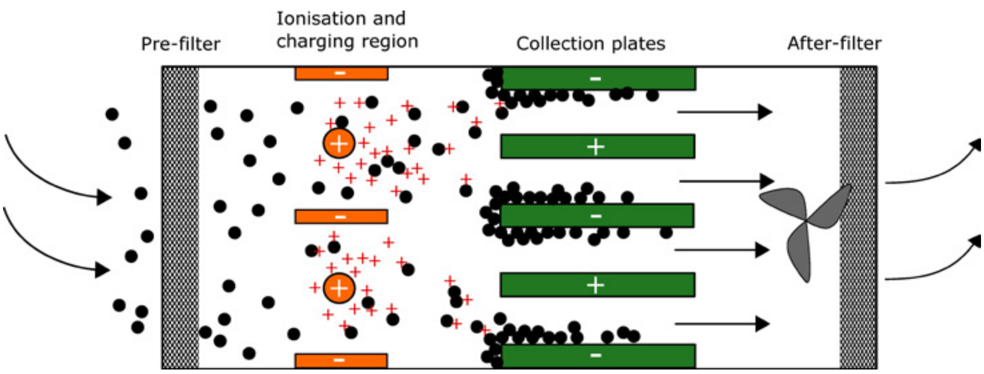
In the following section we will discuss how particles can be charged and collected inside electrostatic precipitators (ESPs; section 5.5). Potential influences on the ion concentration and increased particle deposition on surfaces by air ionisers is discussed for unipolar ionisers in section 5.6 and for bipolar air ionisers in section 5.7.

5.5 Electrostatic precipitators

Electrostatic precipitators (ESPs) can be effective collectors of airborne particles. An ESP commonly consists of a unipolar particle charger, a particle charging region, and a particle collection region (Figure 5.6). Workplace air containing particles enters the ESP aided by a fan, passing the charger, which commonly consists of multiple wire-type corona chargers. In the unipolar charging region, high concentrations of formed ions from the charger attach to incoming aerosol particles. In the particle collection region of the ESP, the particle laden air flow passes close to a number of collection plates that are held at different potentials, enabling a strong electrical field. Given that the particles obtained a sufficient number of electrical charges, they have received an electrical mobility high enough to be effectively collected onto the plates having opposite potential. If this is the case, air with significantly reduced particle concentrations can be returned to workplace air (Luengas et al., 2015; U.S. Environmental

Protection Agency, 2018, Kim et al., 2018). Since the charger may generate ozone and other reactive components, a gas adsorbent after-filter can be used as the final stage of the air cleaner. However, this also increases the pressure drop of the system, thus increasing the energy demand (and noise level). ESPs require routine cleaning for collection efficiencies to remain high.

Figure 5.6. Principle for electrostatic precipitator (ESP).



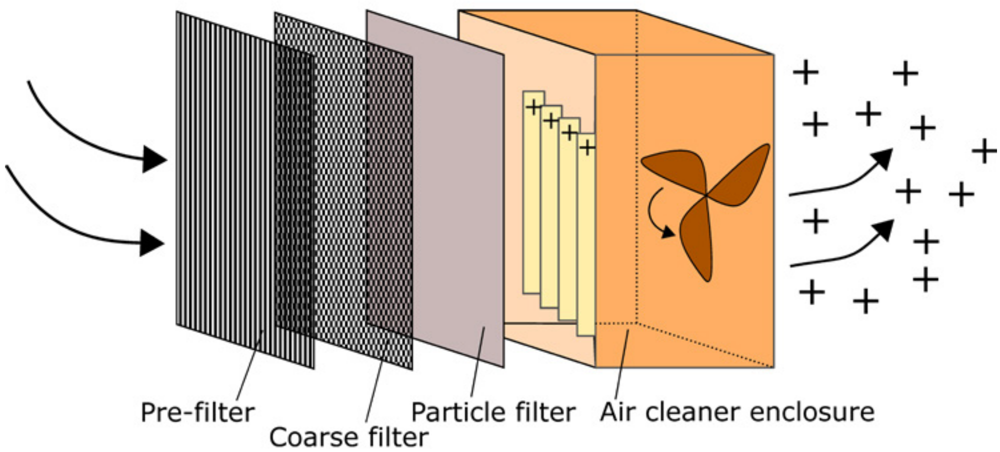
Well-designed ESPs commonly achieve collection efficiencies close to 100% of the particles entering the device. Well-designed ESPs for indoor air are further known to have relatively high Clean Air Delivery Rates (CADR; section 6), often above 200 m^3/h, in the same range as filter-based techniques. The design can be scaled up to achieve high flow rates combined with high collection efficiency. ESPs are used for a range of applications, from the need to remove particles in small experimental setups to large-scale particle removal technologies in large combustion systems and power plants. ESPs intended for cleaning of indoor air were first presented by Friedlaender and Friedlaender (1954).

ESPs are used for a variety of workplace applications. These include mobile air cleaners for welding with adjustable extraction hoods that can be positioned over the welding point.

5.6 Unipolar air ionisers

Unipolar ionisers are common in the general indoor environment. In a unipolar air ioniser, ions of one polarity are released directly into room air. This can strongly increase the ion concentration, and create a strong imbalance between the concentration of positive and negative air ions. Aerosol particles are then charged with one polarity in the open air when air ions are attached to them. The aim is to increase the deposition on walls, floor, and ceiling from electrostatic repulsion or attraction (Bohgard & Eklund, 1998; Luengas et al., 2015; U.S. Environmental Protection Agency, 2018). Unipolar ionisers may be installed in ventilation systems or openly in the indoor/work environments (Kempe, 2012). Unipolar air ionisers exist in a great variety of designs. An illustration of a more advanced ioniser that consists of a set of particle filters, a fan, and corona chargers is given in Figure 5.7. There are also unipolar air ionisers without fans, including some systems that are intentionally mounted near an indoor surface that serves as a collection plate similar to an ESP. However, as described in detail in chapter 6, unipolar ionisers are known to have **low** Clean Air Delivery Rates (CADR), typically 0–80 m^3/h, compared to ESPs and filter-based technologies. Roof-installed upscaled versions of unipolar ionisers have been used to control organic dust in poultry houses (Cambra-López et al., 2009).

Figure 5.7. Illustration of a unipolar air ioniser of a more advanced type that includes a set of particle filters and a fan. Much simpler types, without particle filter and fan, which have only a corona charger operating openly in the room, are also commonly used for indoor air.



The accepted physical mechanism for particle removal by unipolar ionisers is that combined field and diffusion charging leads to highly charged aerosol particles in the air. The charged particles and ions represent a space charge, which in turn introduces an electrical field towards indoor surfaces, thus leading to particle transport towards the indoor surfaces (Grabarczyk, 2001). This increases the deposition of particles from the air to the surfaces, thereby potentially reducing the airborne particle concentration. This is illustrated in Figure 5.8.

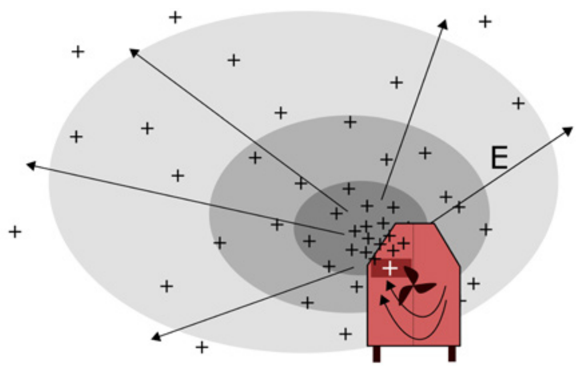
A higher ion emission rate increases the particle removal efficiency (Grinshpun et al., 2005). The efficiency of the particle charging and thereby the efficiency of particle removal from the air also depends on the ability to disperse the ions throughout the room. This can to a degree be aided by a fan in the system, air movements from the ventilation system or other convective air flows.

However, since the lifetime of the ions is only a few minutes in typical indoor/workplace air (Fletcher et al., 2008), relatively high air movement is required to enable sufficient dispersion of ions throughout the room before they are lost to walls. This means that an ioniser with a built-in fan will commonly have a higher efficiency than one that relies on existing room air movements.

The speed of particle removal by deposition onto surfaces also depends on the distance to the surfaces. In a room with a low volume-to-surface ratio, deposition will be faster as compared to a room with high volume-to-surface ratio. Thus, unipolar ionisation air cleaners are more efficient in small spaces (Uk Lee et al., 2004; Waring et al., 2008; Yu et al. 2017).

The ion concentration drops rapidly with increasing distance from the ioniser (Wu et al., 2006). A drawback of producing very high ion concentrations is that charge build-up can occur at the room surfaces. This increases the risk of **problems with static electricity** but can also counteract the electrical field that is responsible for the transport of charged particles from the room towards the surfaces. This taken together creates a practical limitation in the achievable CADR to numbers **substantially lower** than those commonly achieved with ESPs and filter-based systems. A major difference is also that the CADR of an ioniser is dependent on the room size and geometry, which is not the case for filter or ESP based air cleaners. If increased ion emissions are obtained by using a higher voltage in a corona charger, the emission levels of ozone and other reactive compounds may also increase. Ozone formation and emissions from ionisers is discussed in detail in section 5.8.

Figure 5.8. Illustration of the space charge mechanism causing increased particle transport to indoor surfaces when applying unipolar air ionisers.



Some manufacturers claim that the use of ionisers enhances particle coagulation, meaning that small particles aggregate with larger ones, which in turn sediment faster to the ground. This is highly unlikely to happen for ionisers that produce ions of single polarity, since attractive forces only appear between particles with opposite charge polarity. The choice of the ion polarity (negative or positive) has little effect on the particle removal efficiency, however a slightly higher ion mobility for negative ions make them diffuse somewhat faster. (Harrison, 1997).

Unipolar ioniser air cleaners can increase the removal of particles in the air by increased deposition on surfaces. This leads to surfaces being covered with particles, which in turn puts a higher demand on cleaning procedures. The high charge levels also increases particle deposition on human skin (Schneider et al., 1994) and possibly also in the human airways, thus counteracting the potential health benefit from removing particles from the air.

The typical charge level per particle (as a function of particle size) for unipolar charging is quite well represented by the highly charged case in Figure 5.4 (Uk-Lee et al., 2004). Thus, it follows that upon unipolar charging, the particle velocity that the electrical field imposes increases with decreasing particle size but is roughly independent of particle size from about 0.5 µm and up. However, in practice effects of unipolar chargers are most prominent on particles in the size range 0.05–1 µm, since the other main particle transport mechanisms (diffusion and sedimentation) are weak in this size range. Therefore, the relative importance of ionisation on the particle loss rate decreases for particles larger than 1 µm, because losses by sedimentation increases.

Several studies have shown that the use of unipolar ionisers may inactivate biological particles (virus, bacteria etc). However, it is not clear how much of the action is due to the presence of ions and how much is due to the presence of ozone (Fletcher et al., 2007) and other emitted reactive compounds. Further discussion on potential deactivation of biological particles by ionisers or by deliberate ozone production is beyond the scope of this study.

Ionisation as a means of removal of a few VOC's of relevance for the working environment was investigated by Wu & Lee (2004). The negative air ion concentration was around 1 million ions per cm^3, while no positive ions and no Ozone was detected. Removal efficiencies after 12 h of reaction were 13 percent for toluene, 8 percent for chloroform, and 98 percent for 1,5-hexadiene. A review of the use of different ionisation techniques on VOC degradation is given by Kim et al., (2017).

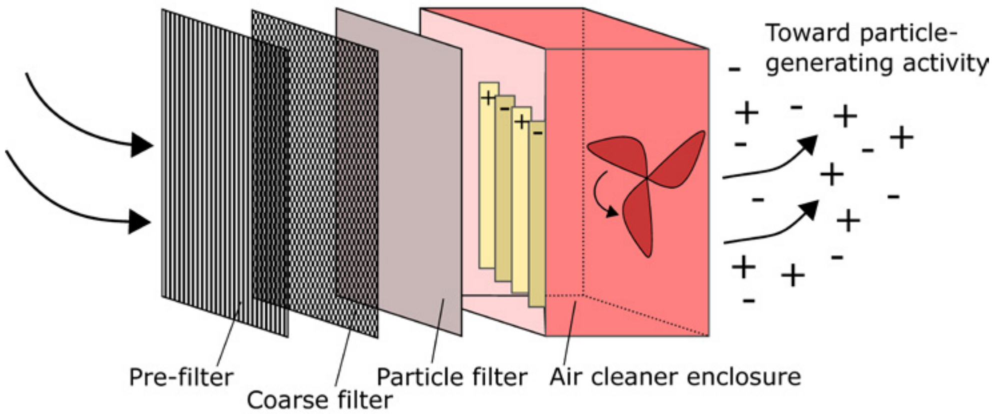
5.7 Bipolar air ionisers

Bipolar ioniser systems are common in general indoor environments, and have recently also seen increased use at construction workplaces. Using a bipolar ioniser, the indoor air concentration of air ions of both polarities can be increased. As shown in section 5.4 and Figure 5.5, this would lead to a reduction of particle deposition by reducing the charge level of both the particles and the surfaces thus decreasing electrostatic deposition. If particles were initially highly charged, the space charge effect and associated increased transport to indoor surfaces described for unipolar ionisation will also be decreased upon neutralisation of particles and surfaces. It is also important to note that the lifetime of the generated air ions is short (seconds to minutes) and that they are easily deposited on nearby indoor surfaces. Ions of the two polarities attract each other, and due to their small size (and high electrical mobility) they easily recombine, leading to neutralisation, which is a strong removal mechanism of bipolar air ions. Thus, the concentration of air ions rapidly decreases with increasing distance from the ioniser.

Bipolar ionisation is used in the electronics industry as a method to discharge electronic structures and nearby surfaces with the aim of decreasing the risk of deposition of charged particles (Steinman, 2004; Vinson & Liou, 2000).

A typical bipolar ioniser for indoor air and workplace air consists of the following elements: 1) One to two particle pre-filters, 2) A main particle filter, 3) a fan, 4) ionisation tubes of both polarities facilitating the formation of ions of both polarities (Figure 5.9).

Figure 5.9. Main components of a typical bipolar ioniser system that includes particle filters and a fan. Similar systems are used both for indoor air and at construction workplaces.



A common claim is that the release of bipolar ions makes airborne particles collide and grow in size (coagulation) to such a degree that they will rapidly fall to the ground through sedimentation. Note that similar claims can sometimes be seen for both unipolar and bipolar ionisers. We find no evidence in the scientific literature for enhanced coagulation due to the increased concentration of both negative and positive ions caused by a bipolar ioniser.

First of all, the coagulation rate can increase if the particles in an aerosol are **highly** charged with a bipolar charge distribution (Vemury et al., 1997). It is therefore possible that coagulation is enhanced for freshly produced silica dust particles that are highly charged with a bipolar distribution. However, a bipolar ioniser and exposing such a sample to increased concentrations of bipolar ions will reduce the charge level of the aerosol particles, thus reducing any increased coagulation rate, due to electrical charges.

Bipolar charging is commonly used in aerosol science and measurement to provide a well-defined charge state of aerosol particles through the processes of charge neutralisation. Bipolar chargers are thereby well-studied, common integrated parts of several types of particle measurement systems. Maisels et al. (2004) modelled particle coagulation for uncharged particles and neutralised particles at bipolar equilibrium and found that differences in coagulation rate were less than a few percent. Maisels looked at coagulation in bipolar chargers, i.e. where the ion concentration is highest, but the residence time is short. Vemury et al. (1997) found that a symmetric bipolar charge distribution of the particles increases coagulation, but that the effect was small. Eliasson and Egli (1991) numerically found a noticeable effect if the small particles are charged to one polarity and the larger ones to the opposite polarity. However, this would not occur in air cleaners.

In conclusion, we find support in the scientific literature for mechanisms that strongly increasing the level of bipolar air ions may lead to a decreased charge level of workplace airborne particles and a discharge of static electricity on indoor surfaces. However, the effects may be local and limited to the area near the ioniser's outlet.

We do **not** find evidence for mechanisms that this causes an increased deposition of particles to the indoor surfaces, either directly by altering the charge state of the workplace particles and surfaces, or indirectly by increased coagulation followed by increased deposition to surfaces. Thus we do not find any evidence for enhanced dust removal using bipolar ionisation.

5.8 Ozone emissions from electrostatic air cleaners

The ionisation process used in electrostatic air cleaners may produce ozone, O_3. This occurs by the simplified steps shown in Equation 3 (Yagi & Tanaka, 1979).

$$O_2 + e \Rightarrow 2O + e$$
$$O + O_2 + M \Rightarrow O_3 + M \qquad \text{Equation 3}$$

In Equation 3, **e** is an electron (generated by the discharge) that facilitates the formation of **O** atoms by electron impact, and **M** could be either an $\mathbf{O_2}$ molecule or an $\mathbf{N_2}$ molecule.

Ozone is known to cause inflammation and irritation in the human respiratory tract, and is potentially deleterious to human health even in trace amounts (U.S. EPA, 1996). The Occupational Safety and Health Administration (OSHA-USA) has established an OEL of 100 ppb for an 8-hr exposure and short-term exposure limit (STEL) of 300 ppb for a 15-min exposure. The same values are used in the Swedish OELs (AFS 2018:1). Ensuring safety of air cleaners involves asserting no harmful chemical substances are emitted. Since 2010, the California Air Resources Board requires certification (California Code of Regulations, Title 17, §94800–§94810) of all mobile air cleaners aimed for general indoor environments to meet a maximum ozone emission of 0.05 ppm. Sweden has no ozone emission standard specifically for mobile air cleaners at workplaces. Thus, it is important that ozone emission tests are made for mobile air cleaners that utilise ionisation.

Ozone is also a strong oxidising agent, reacting rapidly with unsaturated volatile organic compounds (VOCs). It has been found that reactions between ozone and VOCs yield a variety of harmful and irritating secondary VOCs (including formaldehyde) and secondary organic aerosols (Weschler, 2000). Ozone reacts comparatively slowly with traditional solvents in the work environment, such as Toluene.

Several types of wearable and stationary ionisation air cleaners aimed for indoor environments have been tested for their ozone production in experimental chambers and realistic indoor environments. Measured ozone concentration values varied between the devices and were 12–165 ppb, corresponding to calculated ozone emission rates of 0.034–2.2 milligrams of O_3 per hour (Alshawa et al., 2007; Britigan et al., 2006; Grinshpun et al., 2005; Shi et al., 2016). However, some of the ionisers had negligible ozone emissions. Ozone emission rate in ionisation air cleaners (Shi et al. 2016) is a function of the polarity, the intensity of electron current, material and dimensions of the cathode, and the corona wire surface temperature.

In ESPs of the type where the particle collection is enclosed inside the device, a sorbent filter is commonly installed at the exhaust side (Figure 5.6). This can effectively reduce the ozone emissions from the devices, but care needs to be taken that the adsorbent is replaced regularly.

6. Comparing the efficiency of different types of air cleaners

6.1 Clean air delivery rate (CADR)

Efficiencies of portable air cleaners should be measured in relation to their ability to reduce the concentrations of airborne pollutants. It may be challenging to compare the efficiency of the vastly different air cleaner technologies discussed in this report. However, a measure of air cleaner efficiency that is very common for indoor air applications allows comparison between portable air cleaners using various techniques. It is the **Clean Air Delivery Rate (CADR)** (Mølgaard et al., 2014; Shaughnessy & Sextro, 2006; Zhang et al., 2011) method that forms the basis for standardised testing of air cleaners intended for indoor air.

CADR is the equivalent volume of clean air provided in unit time to the space by an air cleaner. Whitby et al. (1983) evaluated indoor air cleaners for control of smoke and gas-phase hydrocarbons. Offermann et al. (1985) described the effectiveness of the air cleaner as an Effective Cleaning Rate in units of a volumetric flow rate. The methodology first described in these papers formed the basis for the first published American National Standards Institute (ANSI)/Association of Home Appliance Manufacturers (AHAM) standard AC-1 (Shaughnessy & Sextro, 2006).

The common principle for determining CADRs is measurements of the decay rate of a pollutant with the air cleaner unit turned on in a closed room (with ventilation turned off). The room is filled with particles, but the particle source is turned off before the experiment starts. The decay rate with air cleaner on is then compared with the decay rate with the unit turned off. In this way, particle removal by sedimentation and other loss mechanisms are accounted for by the decay rate with the air purifier turned off (Shaughnessy & Sextro, 2006). **CADR** can be calculated from Equation 4, where $\mathbf{V}_{\mathbf{chamber}}$ is the volume of the chamber, and $\mathbf{k}_{\mathbf{AC}}$ and $\mathbf{k}_{\mathbf{nat}}$ are the particle decay rates with the air cleaner turned on and off, respectively. More information of the method and examples of data can be found in the literature (for example Schumacher et al., 2018a).

$$CADR = (k_{\mathrm{AC}} - k_{\mathrm{nat}}) \times V_{\mathrm{Chamber}} \qquad \text{Equation 4}$$

For the special case with air cleaners based on mechanical filtration as well as for electrostatic precipitators, the **CADR** ideally equals the particle removal efficiency of the device multiplied with the volumetric flow rate. It should be pointed out that the removal efficiency of the device includes the filtration efficiency supplemented by particle loss in the housing and the fan. The filtration efficiency of the device may be lower than the nominal efficiency of the filter component if leaks occur or if the filter is damaged.

For the portable air cleaner to be effective, the removal rate with the air cleaner on must be significantly larger than the natural removal rate. Natural particle removal rates in indoor air are relatively low in the size range 0.05–1 µm. However, for large particles the natural removal rate increases as the sedimentation velocity increases. This means that only air cleaners with high CADR values are efficient at reducing indoor/workplace concentrations of larger particle sizes.

6.2 Certifications of indoor air cleaners based on CADR

Standard protocols enable comparison between different air cleaners and ensures that the volume of the room in which the test was conducted in is accounted for. A standard protocol for CADR measurements has been developed for household air cleaners by (ANSI/AHAM). Another commonly used standard based on CADR is the Chinese standard GB/T 18801 (2015). Tested particles and particle sizes according to the AHAM standard are (1) cigarette smoke (particle diameter 0.09–1.0 µm), (2) dust (0.5–3.0 µm), and (3) mulberry pollen (5–11 µm) (Sublett et al., 2010). While the cigarette smoke test particles in the ANSI/AHAM standard are between 0.09–1.0 µm, the Chinese standard GB/T 18801 does not include particles below 0.3 µm (Schumacher et al., 2018a).

According to the ANSI/AHAM AC-1 protocol, the test procedure is only valid up to CADRs of 760 m^3 per hour. This standard aims at home appliances and therefore the test chamber has "living room-like" sizes, e.g., 30 m^3 in the case of GB/T 18801-2015. This clean air delivery rate is in the range of the smallest, lightweight (~10 kg) filtration based mobile air cleaner units used at industrial workplaces. However, it does not cover the range for larger air cleaner units where flow rates can be up to 4,000 m^3 per hour (16.7 m^3 per minute). Therefore, this testing methodology is not directly applicable to many mobile air cleaners aimed at reducing occupational exposure to air pollutants at construction sites or similar worksites.

6.3 Comparisons of air cleaner efficiencies of different technologies: small systems for indoor/office air

A number of studies where the CADR of different types of air cleaners for household office spaces have been compared are available in the peer-reviewed literature. It should be pointed out that these are research studies and that not all of them were carried out in accordance with the standards mentioned above. For example, several studies have extended the range to include particles smaller than those given in the standards.

Measured CADRs for particles associated with environmental tobacco smoke (ETS) ranged from 277–407 m^3 per hour for HEPA air cleaners, 197–499 m^3 per hour for ESPs, and 2–51 m^3 per hour for ionisers (Offermann et al., 1985; Shaughnessy & Sextro, 2006). Waring et al. (2008) used a stainless-steel chamber (14.75 m^3) and particles in the size range 0.013–0.514 µm to study the CADR of five portable air cleaners: two filter-based (HEPA), one electrostatic precipitator, and two ionisation air cleaners. As the two ionisers did not include a fan, this study may not well represent ionisers used in working environments. Measured CADRs were similar between the HEPA filters (188 and 324 m^3 per hour) and the electrostatic precipitator (284 m^3 per hour) while the ionisers were significantly less efficient (with CADRs of 41 and 35 m^3 per hour, respectively).

Mølgaard et al. (2014) measured CADRs of five other portable air cleaners (at "normal" or auto setting): three filter-based technologies, one electrostatic precipitator, and one unipolar ioniser. Like Waring et al. (2008), the tested ioniser did not have a fan. Similar to Waring et al. (2008), Mølgaard et al. (2014) found that at particle sizes larger than 0.056 µm, the measured CADR of the ioniser was 1.5–9.5 times less than the filter-based air cleaners.

Sultan et al. (2011) assessed CADRs of twelve portable air cleaners, including two negative air ionisers with fans and one bipolar air ioniser with a fan. The authors conclude that among the tested air cleaners, those based on filtration and electrostatic precipitation had the best removal performances of ultrafine particles. In their study, CADRs of filter-based technologies and an electrostatic precipitator ranged from 60 m^3 per hour to 498 m^3 per hour (based on the total ultrafine particle concentration). The ionisers had CADRs between 8 and 18 m^3 per hour. When the bipolar ioniser was installed with an external HEPA filter, the **CADR** increased dramatically to 348 m^3 per hour from previously 11 m^3 per hour. The study used a common type of bipolar ioniser aimed towards indoor environments, the plasmacluster ion (PCI) technique (Bolashikov & Melikov, 2009; Sultan et al., 2011).

CADRs were calculated for a device with built in HEPA filter, activated carbon filter, and an ioniser (Chan & Cheng, 2006). The HEPA filter and activated carbon filter could be removed and the efficiency of the ioniser was compared to the filter and the combined efficiency of filter and ioniser. With only the HEPA filter installed, the CADR was 85 m^3 per hour. With only the activated carbon filter, the CADR was 56 m^3 per hour. With only the ioniser on (HEPA and activated carbon filter removed), the CADR was 52 m^3 per hour. The combined CADR (all filters and ionisers included) was 90 m^3 per hour. CADRs were determined with respect to PM10 of an incense burning or cigarette smoke aerosol. The CADR of the ioniser was thus approximately 3/5 of the HEPA filter and had a negligible effect in the combined setup. On the other hand, ozone concentrations were monitored, and only low levels were detected, which suggests that the ioniser did not have a negative effect on air quality.

A study on five air cleaners available on the Danish market (Ardkapan et al., 2013) found that two unipolar air ionisers with fan had 5–10 times lower CADRs (21-50 m^3 per hour). compared to a filter-based technology (with respect to ultrafine particles in a test chamber). Additionally, the small amounts of ozone produced by non-thermal plasma and corona discharge-based technologies was found to produce ultrafine particles in the room.

In an early Swedish study, Olander et al. (1988) investigated the "equivalent air flow rates" (defined similarly to CADR) for a total of 31 room air cleaners. In general, unipolar ioniser air cleaners had relatively low equivalent air flow rates (<100 m^3 per hour). For air cleaners based on mechanical filtration and electrostatic precipitators, the corresponding numbers were up to 360 m^3 per hour.

Ardkapan et al. (2015) tested five air cleaners available on the Danish market in an office room. One of the tested units was a unipolar corona discharge ioniser with fan that had lower but comparable CADR to the two tested filter-based technologies. One other ionising technologie had poor performance and significantly lower CADR with respect to the filter-based unit.

For air cleaners employing electret filters, degradation of electret properties is detrimental to air cleaner efficiency, and results in significant reduction of CADR over time (Schumacher et al., 2018a).

In conclusion, the available literature in which CADRs of portable air cleaners intended for indoor air and office use, have been compared, is notably consistent. Filter-based air cleaner technologies and fan-driven electrostatic precipitators can reach the highest CADRs with respect to particulate pollution, namely 85–407 and 197–499 m^3 per h, respectively. Portable air ionisers utilising non-thermal plasma or corona discharges for unipolar emission (almost exclusively negative) were reducing airborne concentrations, but commonly with CADRs an order of magnitude lower (2–100 m^3 per h) than the most efficient filter-based technologies.

6.4 Air cleaner efficiency for particle sources relevant to construction environments investigated in the laboratory

Peck et al. (2016) investigated CADRs of five different “true” HEPA filter air cleaners designed for indoor air, using diesel exhaust particles from a space heater and model particles consisting of potassium chloride. They found that for a given particle size, CADRs were consistently slightly higher for diesel particles compared to the reference particles (KCl), although the difference was small. This may be related to the complex aggregate structure of diesel exhaust particles. Schumacher et al., (2018b) observed similar effects and concluded that the difference is due to the dielectric properties of particles.

6.5 Measurements of air cleaner efficiency in real indoor environments

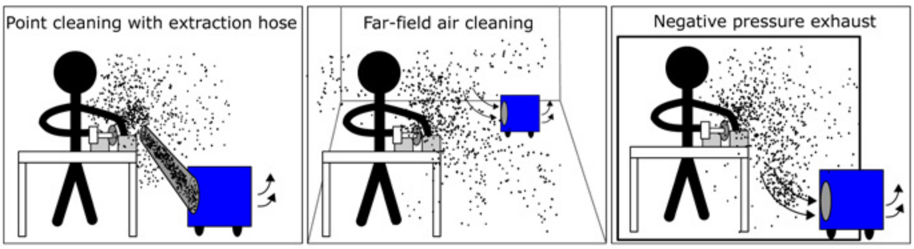
Portable HEPA air cleaners were shown to significantly reduce indoor concentrations of traffic-related (fraction of black carbon) and other indoor aerosols in a recent intervention study including 43 homes. HEPA filtration reduction of PM2.5 concentrations was 50–65 percent, while for black carbon (a marker of traffic exhaust particles) the reduction was 80–85 percent (Cox et al., 2018).

7. Air cleaners based on mechanical filtration in construction work environments

7.1 How are mobile air cleaners used in the construction work environment?

Mobile air cleaners can potentially reduce exposure for workers near the source, and further decrease the spread of dust within the workplace. Because of the ease with which mobile air cleaners can be moved within and between construction workplaces, they are used in many different configurations. The following are common applications found in the literature (Christensen et al., 2012). Mobile air cleaners may be positioned near the source (a) with the aim of reducing emissions directly at the source (the air cleaner is then often connected to an extraction hose). Other strategies include (b) positioning the air cleaner further away from the source to reduce far field exposures and (c) using the mobile air cleaner to create negative pressure in an enclosure during partitioning. There are also combined strategies involving the use of multiple air cleaners to direct the air flows in the workspace. One such application uses a second mobile air cleaner device to blow fresh air towards the working zone.

Figure 7.1. Different ways of applying mobile air cleaners in the construction sector: a) close to the emission point with an extraction hose (similar to LEV), b) far away from the emission point, to reduce the general concentration in the room (far field), and c) to provide a negative pressure in an enclosed area (partitioning).



7.2 Simple mass balance model for predicting mobile air cleaner performance

A simple box model (Hewett & Ganser 2017) can be used to calculate how concentrations will be affected by an air cleaner with a specific clean air delivery rate; $\mathbf{CADR}_{\mathbf{air\ cl.}}$ (m^3/s) in a room assuming **perfect mixing** of air. We assume that we have a room of volume **V** (m^3), and ventilate that room with a ventilation rate of $\mathbf{Q}_{\mathbf{vent}}$ (m^3/s) of clean air, and that we have a particle source with the source strength **S** (mg/s). We then get a concentration in the air, **C** (mg/m^3). $\mathbf{v}_{\mathbf{d}}$ is the mean particle deposition rate (m/s) to surfaces in the room. $\mathbf{v}_{\mathbf{d}}$ is dependent on particle size and turbulence circumstances in the room. **A** is the total surface area of the room (m^2) and **t** (s) is the time that has elapsed since the cleaner was started.

This allows us to **formulate** a mass balance of airborne dust (equation 5):

$$V\frac{dC}{dt} = \mathrm{S} - \mathrm{C(t)} \cdot (Q_{vent} + CADR_{air\ cl.} + v_d \cdot A) \qquad \text{Equation 5}$$

This equation expresses that the change of the dust mass in the air over time equals the formation of new dust (**S**) minus removal by three different mechanisms: general ventilation ($\mathbf{Q}_{\mathbf{vent}}$), the air cleaner ($\mathbf{CADR}_{\mathbf{air\ cl.}}$) and wall loss ($\mathbf{v}_{\mathbf{d}} \cdot \mathbf{A}$). The air cleaner only has a significant impact on the concentration in the air when the CADR is larger than or in the same order of magnitude as the sum of the ventilation rate and wall loss. For particles below a few micrometres, removal by ventilation is commonly the dominating factor, but for larger particles sedimentation is fast and particle deposition may dominate. The equation has the following solution ($\mathbf{C}_{\mathbf{0}}$ is the initial concentration in the room):

$$\mathrm{C(t)} = C_0 \cdot e^{-\frac{(Q_{vent}+CADR_{air\ cl.}+v_d \cdot A)t}{V}} + \frac{S}{Q_{vent}+CADR_{air\ cl.}+v_d \cdot A} \cdot \left(1 - e^{-\frac{(Q_{vent}+CADR_{air\ cl.}+v_d \cdot A)t}{V}}\right) \qquad \textbf{Equation 6}$$

When the particle generating activity has finished, the source term can be set to zero (**S=0**). Then the decay in concentration vs. time can be calculated by:

$$\mathrm{C(t)} = C_0 \cdot e^{-\frac{(Q_{vent}+CADR_{air\ cl.}+v_d \cdot A)t}{V}} \qquad \text{Equation 7}$$

We find that if the CADR of the air cleaner is greater than the removal by ventilation plus wall loss, operating a mobile air cleaner can lead to a faster reduction of particle concentrations.

Finally, if a source is active for a long period of time, a steady state concentration $\mathbf{C}_{ss}$ will be reached, which can be calculated as:

$$C_{ss} = \frac{S}{Q_{vent} + CADR_{air\ cl.} + v_d \cdot A} \qquad \text{Equation 8}$$

If the mobile air cleaner provides an air exchange rate of 15 times per hour to the room and the emission factor from the particle generating source is constant, then steady state is reached within ~10 minutes.

The simple model described in Equations 5–8 can give estimations of how much reduction we will get if we use air cleaners with a given CADR. One assumption is that you have perfect or near perfect mixing of the air in the room. However, you would normally get different concentrations in the near field (close to the emission source) and the far field. Model predictions can underestimate exposures for persons who are positioned close to the source. Often you have different mixing conditions in the near field compared to the far field. The predictions can be made more precise using two-box models. Such models, and some more detailed descriptions and theoretical treatments, are given by Ganser and Hewett (2017) and Hewett and Ganser (2017).

Mobile air cleaners for the construction sector are offered in different sizes, ranging from flow rates of ~ 300 m^3/h up to ~ 4,000 m^3/h. Often an air exchange rate of 10 or 15 (BG BAU 2018) is assumed when selecting an appropriate air cleaner device. For example, during a bathroom renovation, the room volume is say 24 m^3 (floor area of 10 m^2 and height of 2.4 m). The required CADR (which can be approximated as the air flow rate when using an H13 filter) then becomes 360 m^3/h if an air exchange rate of 15 per hour is required. If the room to be considered is large, say 240 m^3 (floor area of 80 m^2 and a height of 3 m) then the required CADR would be 3,600 m^3/h, which is close to the higher end of mobile air cleaners for the construction sector.

7.3 Field experiences using mobile air cleaners in the construction industry and other dusty work environments

Karlsson and Christensson (2008) and Christensson et al. (2012) carried out extensive investigations into the effects of various engineering controls to reduce personal exposure to dust for a number of activities at Swedish construction sites (excluding work with asbestos). One of the technologies was mobile air cleaners based on mechanical filtration. The effect of different engineering controls was investigated by gravimetric measurements of the dust concentration (respirable and total dust) in the breathing zone.

Mobile air cleaners placed in the same room as the main dust generating activity had very low effects on the exposure levels except when: a) the worker was positioned directly within the fresh air flow from the air cleaner or b) the mobile air cleaner was positioned directly at the dust-generating source, or c) the room volume was very small compared to the rated capacity of the mobile air cleaner. When the dust emissions are very strong, for example during shovelling of chiselled dry bathroom floor dust, the capacity of ordinarily used mobile air cleaners is insufficient. The reason for this is that the worker is close to the dust source, and the exposure is only marginally affected as the air cleaner is not extracting emissions close to the source. The air cleaner lowers the background concentration in the room and the concentration is also reduced faster after the activity has ended. To reduce spread of dust from the source and thereby reduce exposures effectively, the air cleaner should be fitted with a moveable extraction system positioned near the source or be complemented with a separate local exhaust ventilation system. (Christensson et al., 2012)

It is not enough to position the air cleaner in a doorway for example during demolition work in connection with pipe replacement. A lot of dust may pass the air cleaner and enter surrounding areas, especially if work with high dust production rates is carried out. To reduce the spread of dust to surrounding areas, plastic foil is often placed in the doorway, with a cut to allow workers passage in and out. The air cleaner intake is inserted into a hole in the plastic. Air is then extracted from near the dust source to the air cleaner, and after passing the particle filter in the air cleaner, it is ventilated out to neighbouring areas. This use of the air cleaner will reduce the air pressure in the room containing the dust source. This will in turn force air from the neighbouring room to pass into the dusty work space. (Christensson et al., 2012)

Recent research from the Finnish Institute of Occupational Health recommends direct measurements of the pressure difference between the enclosure and surrounding areas in these situations (Kokkonen et al., 2017). The recommended minimum pressure difference is 5 Pa, which means that the enclosed area needs to be well sealed. The Swedish Work Environment Authority (2015) gives the current requirements and recommendations regarding work involving silica dust in Sweden.

Christensson et al. (2012) noted that the exposures for the primary exposed worker were reduced when standing in the air flow from the outlet of a mobile air cleaner based on mechanical filtration. Another study investigated efforts to reduce the exposure in the near field by blowing clean air towards the breathing zone (Tsuji & Fukuhara, 2000). They found that reductions were evident over time periods of less than 20 minutes, but that issues related to maintaining a clean air supply and polluting adjacent areas were raised. They concluded that this technique may reduce exposures for low toxicity nuisance dust, but that it cannot be recommended for dust of higher toxicity, such as silica dust, as there is a risk that it will **increase the spread** of the emissions further away in the workplace.

Mobile air cleaners positioned near the ceiling are relatively common at bakeries, where they are intended to reduce exposures to respirable flour dust. However, the effect on dust exposures was found to be low due to the long distance from the primary emission zone to the air cleaner inlet (Karlsson et al., 2006).

7.4 Specific regulations and recommendations for work involving asbestos

Exposure to asbestos occurs frequently in renovation and demolition work. Improper handling of asbestos-containing material results in the release of asbestos fibres to the air. Asbestos fibres are particularly dangerous and carcinogenic to humans (IARC, 2012), and the occupational exposure limit is extremely low, 0.1 fibres per cm^3 of air. The Swedish Work Environment Authority have strict rules regarding personal protective equipment, industrial vacuum cleaners, and air filtration systems to reduce exposure levels when working with asbestos-containing materials. When working indoors, partitioning with an enclosure, including air-lock should be used. Air filtration systems should be used in conjunction with negative pressure to prevent the release of contaminated air to the surroundings (The Swedish Work Environment Authority, 2014). The air filtration unit (that may be a mobile air cleaner) should have a minimum dust removal efficiency of 99.95 percent (minimum H13 filter) to prevent the release of particles to the surrounding air. It is further recommended that the air inside the enclosure is exchanged 10 times per hour. This means that if the enclosure is 30 m^3, then a mobile air cleaner providing the negative pressure needs to have an airflow of at least 300 m^3/h. However, as stated above, recent research recommends that the pressure difference between containment and surrounding air should be monitored at all times (Kokkonen et al., 2017). For asbestos work, a pressure difference of 20 Pa has been recommended (EU-OSHA, 2012).

Exhaust the mobile air cleaner outside of the building (Newcomer, 2018). However, if the ongoing work is only of limited extent or involving work procedures with low exposure levels and if a discharge into the open air is impossible or requires disproportionate effort. Then mobile dust extractors that return the air to the work area may be used. (EU-OSHA, 2012). The same filtration efficiency (99.95 percent) applies to any air filtration units returning the air to the room (The Swedish Work Environment Authority, 2014). Vacuum cleaners, negative air units, and mobile air cleaner units that recycle the air thus require filter standards equal to or higher than H13.

7.5 Field- and performance tests for complete mobile air cleaner systems based on mechanical filtration

To meet expected performance standards, manufacturers mandate careful handling of the filter and proper installation by trained technicians. Aging mechanisms of HEPA filters after installation have been discussed by First (1996). Testing of HEPA filters at the time of manufacture establishes the quality of particle capture and airflow parameters.

However, mobile air cleaners are frequently moved between different workplaces due to the short-term nature of environmental remediation and indoor renovation projects. Incidentally, these portable units are mishandled and subject to dropping, which could damage the HEPA filter, device cabinet, or other key components. Sometimes, damage may not be visibly evident to the user, such as when a HEPA filter is dislodged from its filter mount. The HEPA filter's efficacy is sensitive to handling and use. This requires that mobile air cleaners based on HEPA filtration are regularly tested for the performance of the whole device (Riala & Riipinen, 1998). This also applies to personal respirators, where studies have shown that the asbestos fibre filtration performance of respirators with electret-filters rapidly deteriorate when the electrical properties degrade (Cheng et al., 2006).

Also, standards requiring performance testing of complete mobile air cleaner devices are lacking. This is in contrast to HEPA filters used in stationary systems such as Biological safety cabinets, which undergo standardised leak testing to verify the efficiency of the filtration device during operation (Newcomer et al., 2018).

Newcomer et al. (2018) investigated the filtration efficiency of 86 HEPA-based mobile air cleaners (referred to as PHEAF devices in their study) of eight different models. The air cleaners were of different ages, and had all been used at construction work sites. They used a field-deployable Laskin Nozzle aerosol generator to produce a polydisperse test aerosol consisting of Poly-Alpha-Olefin oil (PAO). The particle size distribution of the test aerosol was not discussed. The aerosol was generated and injected to the intake side of the HEPA filter. Particle penetration was then measured using a photometer connected to an isokinetic sampling probe at the filter outlet. The air-flow rate through the filter was measured with a hot-wire anemometer technique. The particle collection efficiency, which was deduced from measurements upstream and downstream from the air cleaners, varied widely. The average overall filter collection efficiency ranged from 42 percent to ≥99.97 percent, with more than 88 percent of the tests failing to achieve the 99.97 percent capture efficiency that is required for HEPA filters according to the US standard. However, there were clear differences between manufacturers, with some models scoring a 99.97 percent removal efficiency throughout the tests.

The case for leak testing HEPA-based mobile air cleaners is conceivable. However, one argument against it is that the test equipment is cumbersome and not ideally suited for use in a field environment. Another drawback is that the test equipment can be expensive to purchase. One deciding factor for selecting the right measuring instrument is a validated protocol for conducting the leak test in a field environment.

The National Institute of Health (NIH) in the USA has recently implemented field testing of the particle penetration of their HEPA devices. The field test is required before starting any asbestos remediation project. For other works, the device must have successfully passed a performance test within the last 3 months. This technique is taken from the recent paper by Newcomer et al. (2018). The requirement for the field performance test is a capture efficiency of the **combined system** (including the effects of leaks around the HEPA filter etc) of >99.0 percent. They also demand that devices have passed a visual inspection prior to each project (National Institute of Health, 2018).

7.6 Ensuring the function of mobile air cleaners in the absence of field leak tests

In the absence of actually leak testing the device, the industrial hygienist can take other precautions to address obvious concerns. The following are recommendations for ensuring the function of mobile air cleaners in the absence of a leak test (Newcomer & Lapuma 2017 and Newcomer 2018).

- Replace HEPA filters according to the device manufacturer's recommended practice. A trained technician should be responsible for filter replacement. The owner or operator of the mobile air cleaner should know when the filter was last replaced. Ask for criteria for determining when the filter should next be replaced.
- Repair all damaged devices before they are deployed for use. Dents and other damage to the cabinet can cause the particle filter to become misaligned in the filter mount frame. Also, inspect and verify that the HEPA media and corrugated separators are not damaged.
- Exhaust the mobile air cleaner **outside** of the building. Exceptions to this rule should be considered only when the industrial hygienist's professional judgement indicates a low risk of exposure to occupants.
- Verify that the owner or operator conducts routine inspections of the mobile air cleaner while it is in service. The inspections should include replacement of the pre-filter and ring filter.
- Tighten the HEPA filter's retaining brackets. Loose brackets can permit gaps to form between the filter gasket and mounting frame.

7.7 German recommendations for mobile air cleaners at construction workplaces

The German employer's liability insurance association (BG BAU 2019) recommends the use of mobile air cleaners during construction work. They recommend a number of air cleaner models, which all fulfil a set of requirements including the following:

- A minimum of a two-stage filter system, where the main filter must either consist of filters that are either equivalent to dust class M or have been tested as dust class H (EN 60335-2-69). The air cleaner is labelled as either air cleaner with M-filter or as air cleaner with H-filter.
- For each air cleaner on the recommended list a maximum room size is given (given as m^2 floor area). In the calculation of the maximum room size, the device air flow rate was used and an air exchange rate of 15 and a room height of 3 m was assumed.
- The filter must be free of leaks when installed, and should be able to withstand the flow rate used in the device.
- The device should be designed so that during a filter exchange, dust from the used filter cannot be released to workplace air.
- The mobile air cleaner should be equipped with a display that gives off an *alarm* if the air flow rate drops below the minimum requirement.
- The mobile air cleaner should be equipped with either an extraction hose or an exhaust hose.

Only mechanical filtration-based techniques can fulfil these recommendations. There is also a subsidiary, 25 percent of the acquisition costs (max. 500 EUR), when buying an air cleaner that fulfils the requirements. The filter classes mentioned in this German recommendation are based on the EN 60335-2-69 standard. This standard covers industrial vacuum cleaners but not mobile air cleaners in general.

8. Use of ionisers at construction workplaces

Our questionnaire showed that devices that utilise ionisation are relatively common at Swedish construction workplaces. Air cleaning devices intended for the construction industry that include bipolar ionisation are available from major Swedish retailers and renting companies. These devices are available in different sizes for applications ranging from renovations of bathrooms and chiselling to large-scale demolitions or renovations. The devices are claimed to reduce dust exposures, to remove strong odours and reduce mould growth.

Ionisers are often recommended to be positioned so that the airflow is directed towards the main activity/particle source, which differs from conventional use of mobile air cleaners at work places. This is most likely done to maximise interactions between ions and emitted particles at the workplace, since ion concentrations decrease with increasing distance from the ioniser. As pointed out in section 7.3, blowing fresh air towards the primary emission zone may reduce exposure for the main operator, but also risks spreading airborne dust within the workplace.

Ionisation systems for construction environments commonly include conventional particle filters with significantly lower collection efficiencies compared to HEPA (H13) filters. The presence of particle filters in the bipolar ioniser system can reduce the dust concentration in workplace air. It should be noted that a lower efficiency particle filter may have a lower pressure drop than a HEPA filter, and that the reduction of particles may thus still be substantial (section 4.2). The disadvantage is that particle concentrations may be substantial in the air recirculated to the workplace.

Ionisers are not intended to be connected to extraction systems from the near field. Ioniser systems are also not designed to create negative pressure inside enclosures when handling toxic exposures such as asbestos fibres and silica dust, as the particle removal in the system's filters is commonly well under 100%.

We found no scientific studies that evaluated bipolar ionisation for dust particle removal in construction environments. Sultan et al. (2011) investigated an indoor air cleaner that included bipolar ionisation and a fibrous particle filter. The device was also tested using only bipolar ionisation. The device had very low efficiency when only bipolar ionisation was active (CADR 1–18 m^3/h). When the fibrous particle filter was added, the CADR increased dramatically to 348 m^3/h, a value typical for air cleaners based on mechanical filtration in indoor air. This is consistent with the lack of a strong physical driving force to increase the deposition velocities of airborne particles towards indoor surfaces when using bipolar ionisation. According to basic aerosol physics (ch. 5.7) and these limited observations from indoor air studies, bipolar ionisation itself can not be recommended for removal of dust particles from air in workplaces. We conclude that the particle removal efficiency of systems that include bipolar ionisation should be assessed based on the efficiency of included conventional particle filters and the flow rate.

Ozone may be emitted from electrostatic air cleaning devices such as ionisation systems (section 5.8). It is especially important to consider ozone exposure levels when operating mobile air cleaners in small spaces. The lifetime of the ions is short (~minutes) and losses to walls increase in small spaces. Therefore, there is a limit to the maximum ion concentration that can be reached. However, ozone is lost to walls much slower, and may also pass through particle filters in the air cleaner device. Therefore, even for moderate ozone emissions, toxic levels may accumulate inside enclosures unless gas-phase filtration such as activated carbon filters (which may remove ozone efficiently) are installed in the system. The Swedish 8 h OEL for ozone is 0.1 ppm and the 15 min OEL is 0.3 ppm (The Swedish Work Environment Authority, 2018). In electrostatic air cleaning techniques, it is also important to provide safety reminders in potentially explosive atmospheres (ATEX).

9. Summary and conclusions

Mobile air cleaners are commonly used with the aim to reduce exposures to crystalline silica (quartz) dust, asbestos, and general construction dust at Swedish workplaces. There is a need for more information about the efficiency of mobile air cleaners and recommendations on how to use them. The most commonly used type of mobile air cleaner is based on traditional mechanical filtration. However, devices based on ionisation have recently also become more common at Swedish workplaces.

Exposure reduction during construction work should primarily be carried out at the source. Examples of primary measures include local exhaust ventilation (including ventilated work tools) and water-based techniques. These alone are often insufficient for achieving safe exposure levels. In such cases, mobile air cleaners are often used to further reduce exposures.

The principles for particle collection using mechanical filtration are well known. It is important to use pre-filters to increase the life-time of the main filter. As the filters collect high amounts of particles, the pressure drop increases which can result in a decreased flow rate through the device. This reduces the efficiency of the air cleaner device correspondingly. It is therefore important that the filters are replaced in time.

Electrically charged fibre filters (electret filters) can have very low pressure drops and high collection efficiencies when new. However, the filters commonly lose their charge over their lifetime. This will cause a significant reduction of their collection efficiency. It is difficult to assess when this happens, which limits use of electret filters in mobile air cleaners for toxic dusts such as silica.

Electrostatic air cleaners are based on generation of air ions that alter the charge of airborne particles, thereby altering the efficiency of particle collection using electrical fields. Electrostatic air cleaners can be divided into electrostatic precipitators (ESPs) and ionisers. With an ESP, the particles are first charged and then collected using an applied electrical field, commonly inside the device. With an ioniser, the aim is to increase the deposition velocity of airborne particles onto surfaces in the room by altering the particle charge level.

The operating principle of ESPs is well known. The operating principles of ionisers are less clear, and sometimes conflicting mechanisms are presented. A common misconception is that ionisers increase the collision rates of airborne particles, causing the particles to grow large enough to rapidly settle to the floor by sedimentation. There is no scientific evidence that this has any practical effect on exposure levels in workplaces.

It is important to distinguish between ionisers of unipolar (generating ions of either positive or negative charge) and bipolar (generating air ions of both polarities) types. Unipolar ionisers can increase the deposition velocity of particles to indoor surfaces. The increased concentration of air ions and charged particles results in an electric field towards indoor surfaces. However, the effects are limited, and problems caused by static electricity may increase. It's important to note that the particles are not collected inside the device and that particles deposited on indoor surfaces may later be resuspended to the air. The deposition velocity may also increase on other surfaces, including human skin.

The use of bipolar ionisers can result in a reduced charge level of particles in the air (neutralisation). This has the opposite effect of the unipolar case, leading to reduced deposition on indoor surfaces. There is no evidence that bipolar ionisation itself leads to particle removal from air of any practical significance at workplaces. Based on current knowledge, dust removal with systems using including bipolar ionisation should be assessed solely on the filter collection efficiency and flow rate through particle filters installed in the devices.

The toxic gas ozone can be formed as a by-product of the ion generation process. There is therefore a risk that utilising ionisers could lead to increased ozone exposures. There are ionising air cleaners for indoor air with very low ozone emissions. It is unclear if this also applies to systems used in the construction sector. Most mobile air cleaners used at construction workplaces have no filtration stage to remove gases and thus offer no protection towards gas emissions.

For air cleaners in the general indoor environment there is an extensive literature and there are also standardized test methodologies for ozone emissions and comparisons of the particle removal efficiencies of various air cleaner technologies. The tests measure the equivalent Clean Air Deliver Rate (CADR) that each device can provide. Filtration-based and ESP-type air cleaners commonly have the highest CADR values, while air cleaners based on ionisation have about an order of magnitude lower values. There are no corresponding testing standards for mobile air cleaner devices used in the construction sector. When it comes to mechanical filtration-based devices, air cleaner performance can be estimated from the filter efficiency and the air flow rate. It is important that the given air flow rate is reported with the correct filter installed.

It is of vital importance that the mobile air cleaners are positioned in an optimised way at the workplace. Mobile air cleaners based on mechanical filtration can reduce exposures when they are placed very close to the source, or when their capacity is high compared to the volume of the room. Mobile air cleaners are also commonly used to provide negative pressure in work areas that have been enclosed with plastic films to reduce the spread of airborne dust to neighbouring areas. This is a required practice when handling asbestos indoors, and a recommended practice when handling silica dust. It is important that the enclosure be airtight enough to establish a sufficient pressure difference. When working with asbestos fibres, there are precise rules concerning the use of engineering controls and personal protection. This also places specific demands on mobile air cleaners.

Mobile air cleaners are easy to move between workplaces, and their performance risks being degraded due to mistakes in handling of the devices. This includes risks of damage to the particle filters and leaks around the filter casing. The National Institute of Health, USA have recently implemented a method for periodic testing of mobile air cleaners based on mechanical filtration. In Germany, criteria for mobile air cleaners in the construction sector have been formulated by the German liability insurance association (BG BAU). These include requirements regarding filtration efficiency, the capacity of the device (room size), an alarm for reduced air flow, and guidelines for avoiding exposures during filter exchanges. Today, only mobile air cleaners based on mechanical ventilation can fulfil these requirements.

In conclusion, mobile air cleaners based on mechanical filtration can reduce dust exposures during construction work when combined with primary engineering controls. However, mobile air cleaner performance needs to be regularly tested, and the devices also need to be used in an optimised fashion to have an effect on the exposure.

10. What information is lacking for future recommendations of mobile air cleaners? Future research needs

- In the peer-reviewed literature, there is a general lack of studies on the use of mobile air cleaners at construction workplaces. Air cleaner field performance studies are needed.
- The function of mobile air cleaners based on mechanical filtration is well understood. However, more work is needed to develop a set of recommended practices for **combining** the mobile air cleaners with other engineering controls. This way, exposures to both those working close to the source and those working further away could be reduced.
- Novel air cleaner technologies have been claimed to be efficient for reducing dust exposures. This needs to be supported by objective measurements carried out both in the laboratory and at real-world construction workplaces. The latter measurements should be performed in collaboration with professionals who are trained in carrying out risk assessments at workplaces.
- Generation of gaseous pollutants from electrostatic air cleaners, particularly ozone, should be carefully evaluated. Certification may be necessary in order for the end user to evaluate what ventilation flow rate is required to keep room air ozone levels at safe levels. There are two aspects that need to be distinguished here: a) emission of gaseous pollutant from the air cleaner, and b) removal of gaseous pollutants by the air cleaner, e.g. O_3, VOC, NO_2 etc. This requires the use of an adsorbent, e.g., activated carbon.

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Appendix A. Enkät om luftrening i dammiga arbetsmiljöer

På uppdrag av Arbetsmiljöverket gör vi på Lunds Universitet en undersökning om åtgärder som används på olika företag i Sverige för att minska mängden partiklar i luften i arbetsmiljön. Frågorna 4-9 handlar om mobila luftrenare. Har ni ingen sådan på er arbetsplats så fyll endast i fråga 1–3.

1. Uppstår arbetsmiljöer på ert företag där det genereras höga partikel- eller damm-koncentrationer i luften?

a. Ja, ofta
b. Ja, ibland
c. Sällan
d. Inte alls

2. Vilken sorts partiklar är det?

a. Kvartsdamm
b. Asbest
c. Partiklar från glasfiber
d. Bilning av betong
e. Slipdamm
f. Övrigt byggdamm
g. Förbränningspartiklar från motorer, el-aggregat
h. Annat, vad? : ______________________________

3. Vilken teknisk skyddsutrustning och andra åtgärder använder ni för att minska arbetstagarnas exponering av luftburna partiklar (svara gärna med flera alternativ)?

a. Befintlig ventilation
b. Punktutsug
c. Sätter upp skyddsplast för att minska spridningen ut till andra rum
d. Andningsskydd
e. Tidsbegränsningar i arbetet
f. Mobil luftrenare/dammfälla
g. Vattenburna metoder
h. Annat, vad? : ______________________________

4. Om ni använder er av en mobil luftrenare, vilken luftreningsprincip använder den och vad är det för modell/märke?

a. Filtrering med t.ex. HEPA-filter
b. Jonisering
c. Elektrostatisk insamlare
d. Ozongenerator
e. Övriga typer

Ange gärna luftrenarens märke och modell: ____________________

5. Hur valdes typen och modellen av luftrenaren som köpts in?

a. Rekommendation från andra i samma bransch
b. Säljare av luftrenare som tog kontakt

Annat, vad? : ______________________________

6. Var det lätt att få användbar information som underlättade valet av luftrenare?

a. Det var lätt
b. Det var ganska lätt
c. Det var ganska svårt
d. Det var svårt

7. Hur länge har ni använt mobila luftrenare?

Ange tid: ______________________________

8. Hur många mobila luftrenare har ni, ungefär vilken yta renar varje luftrenare ?

Ange antal: ______________________________

Ange ytarea per luftrenare: ______________________________

9. På vilka platser och vid vilka arbetsmoment använder ni mobila luftrenare?

Svar: ______________________________

10. Märker ni någon förbättring med er luftrenare jämfört med utan luftrenare (möjlighet finns att välja två svarsalternativ)?

a. Ja, det känns som att den gör skillnad
b. Nej, det känns inte som att den gör skillnad
c. Ja, vi har gjort mätningar som visar att luften blir renared.
d Nej, vi har gjort mätningar som visar att luften blivit sämre
e. Vet ej

11. Har ni tagit bort några av de tekniska skyddsåtgärderna som ni använde innan ni skaffade mobila luftrenare?

a. Ja
b. Nej

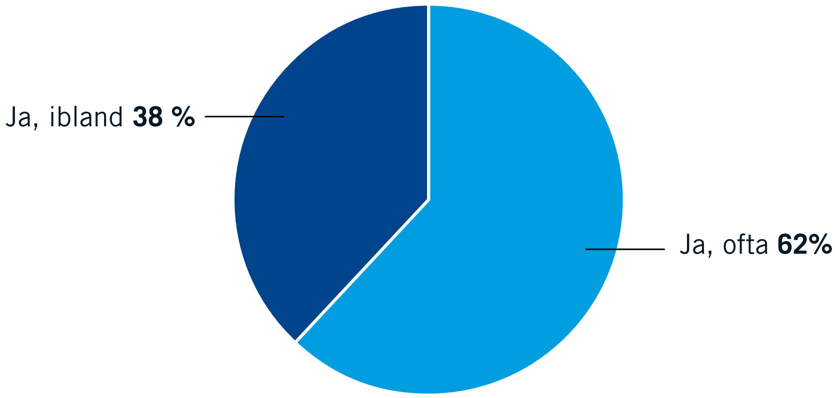
Om Ja, vilka åtgärder har tagits bort: ______________________________

12. Allmänt sett, ser ni ett behov av att få mer kunskap om luftrenares effektivitet och användning?

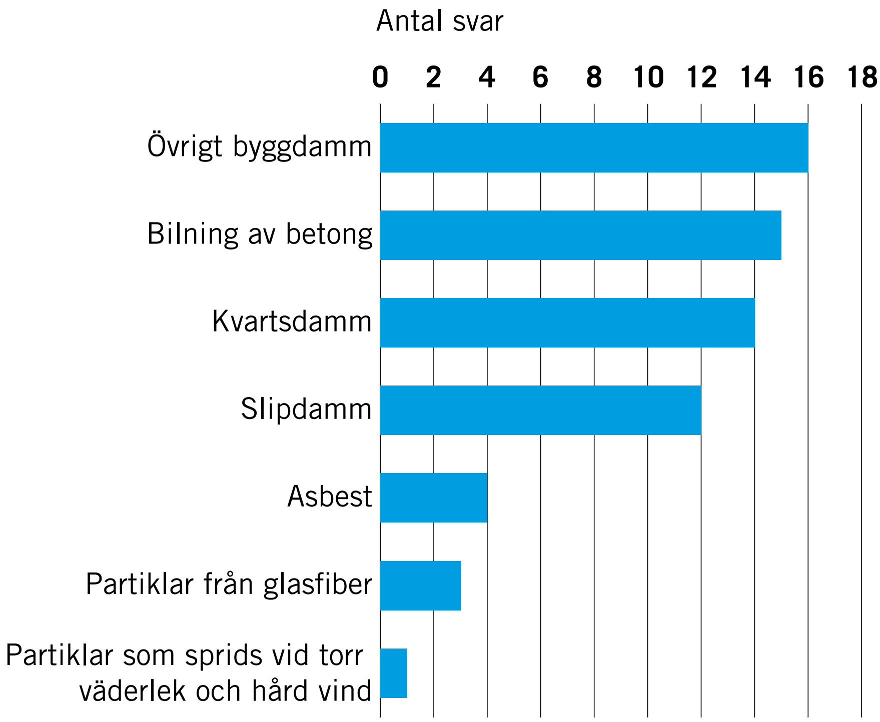
a. Stort behov
b. Ganska stort behov
c. Ganska litet behov
d. Inget behov

Appendix B. Sammanställning av enkätsvar

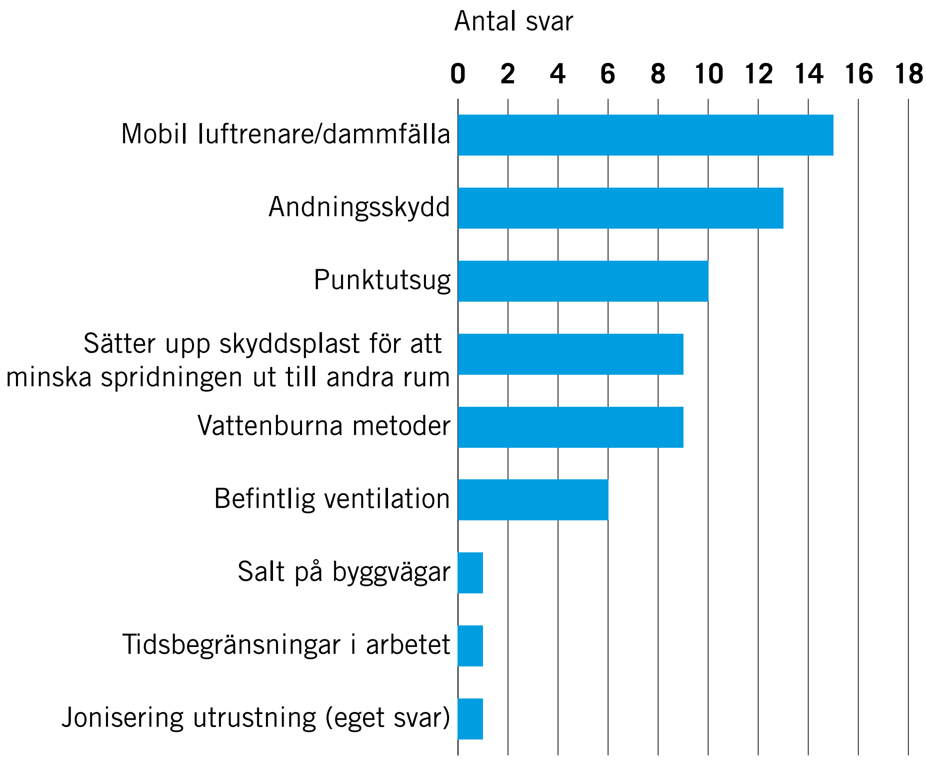
Figur B1. Svar till fråga 1, Uppstår arbetsmiljöer på ert företag där det genereras höga partikel- eller damm-koncentrationer i luften?



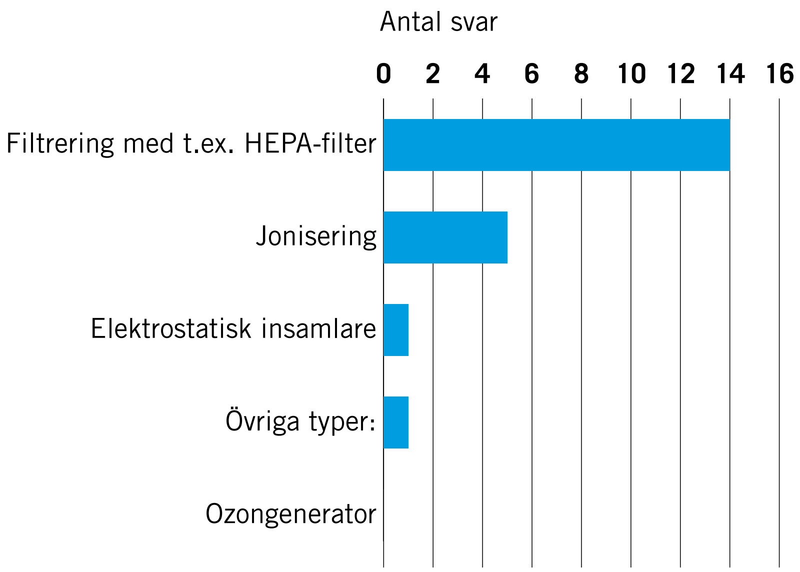
Figur B2. Svar till fråga 2, Vilken sorts partiklar är det?



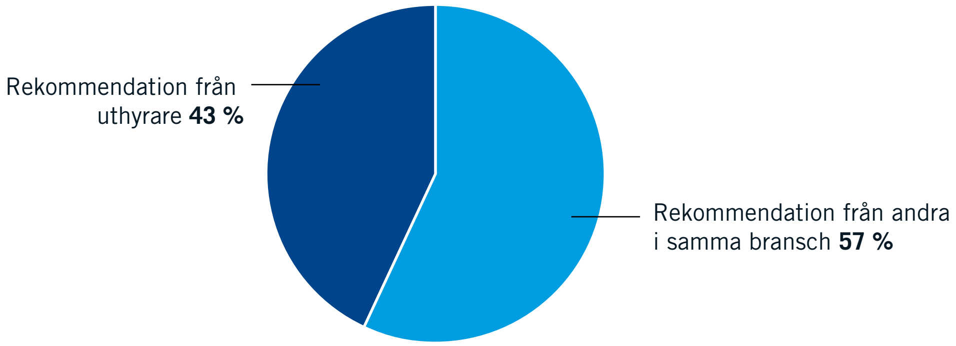
Figur B3. Svar till fråga 3, Vilken teknisk skyddsutrustning och andra åtgärder använder ni för att minska arbetstagarnas exponering av luftburna partiklar? (svara gärna med era alternativ)



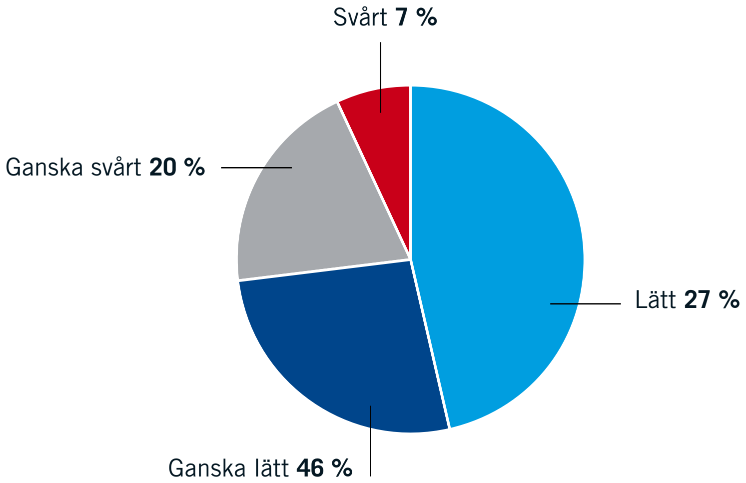
Figur B4. Svar till fråga 4, Om ni använder er av en mobil luftrenare,vilken luftreningsprincip använder den och vad är det för modell/märke?



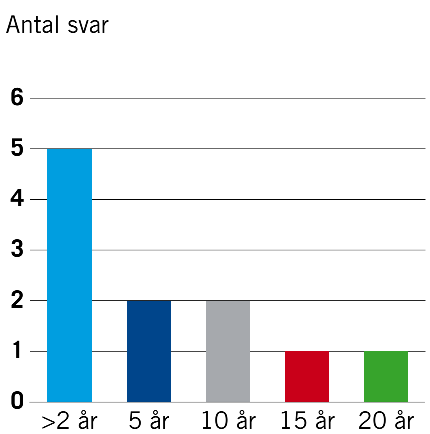
Figur B5. Svar till fråga 5, Hur valdes typen och modellen av luftrenaren som köptes in?



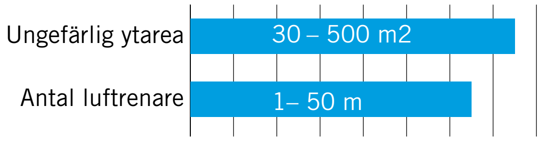
Figur B6. Svar till fråga 6, Var det lätt att få användbar information som underlättade valet av luftrenare?



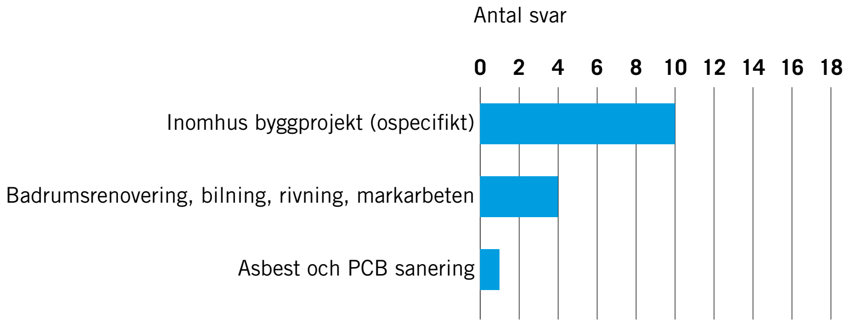
Figur B7. Svar till fråga 7, Hur länge har ni använt mobila luftrenare? Ange tid:



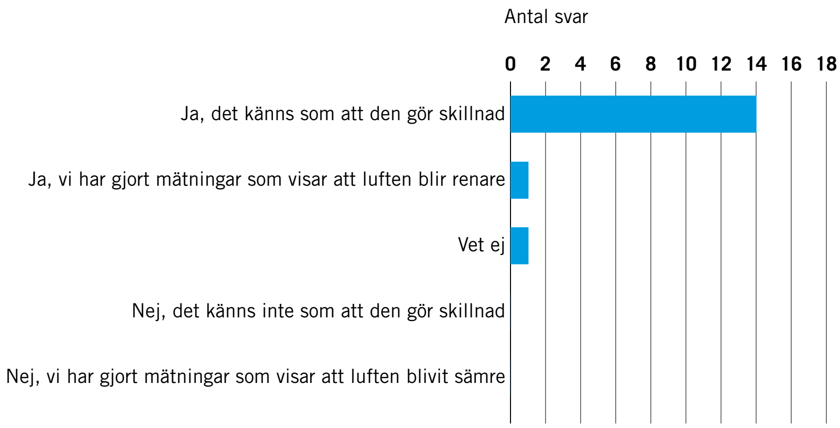
Figur B8. Svar till fråga 8, Hur många mobila luftrenare har ni, ungefär, vilken yta renar varje luftrenare? Ange antal enheter och vilken ytarea per luftrenare:



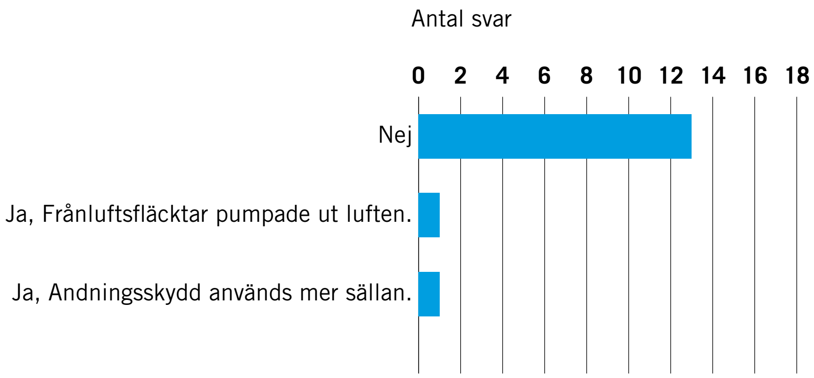
Figur B9. Svar till fråga 9, På vilka platser och vid vilka arbetsmoment använder ni mobila luftrenare?



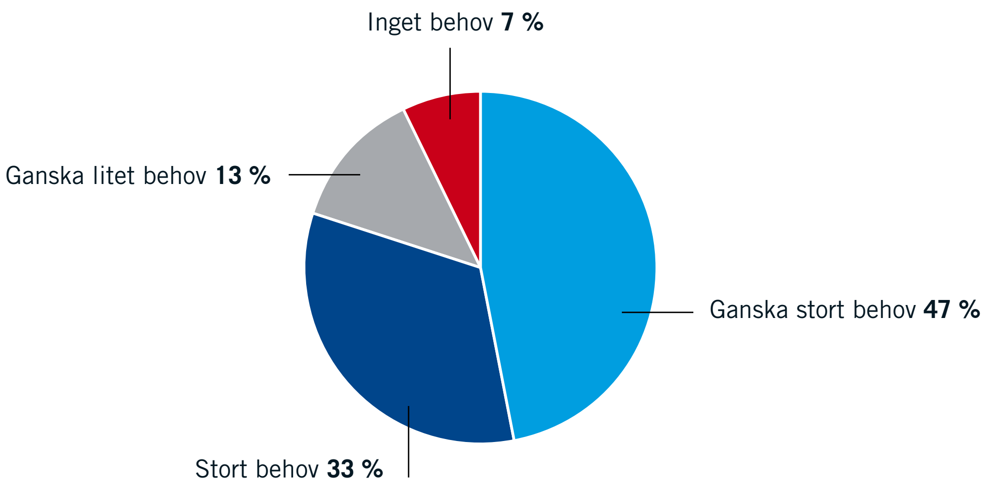
Figur B10. Svar till fråga 10, Märker ni någon förbättring med er luftrenare jämfört med utan luftrenare? (Möjlighet att välja två svarsalternativ)



Figur B11. Svar till fråga 11, Har ni tagit bort några av de tekniska skyddsåtgärderna som ni använde innan ni skaffade mobila luftrenare? Om ja, ange vilka åtgärder har tagits bort under ”övrigt.



Figur B12. Svar till fråga 12, Allmänt sett, ser ni ett behov av att få mer kunskap om luftrenares effektivitet och användning?



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Vår vision: Alla vill och kan skapa en bra arbetsmiljö

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