Importance of ventilation filters for particle concentrations in indoor air

Ordered by

Camfil Svenska AB

Study performed by

Lars Ekberg, CIT Energy Management AB

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Contents

Introduction

Background

Many factors are rather well known for their ability to create a good indoor climate, but when it comes to airborne particles, there is not a great deal of documentation from an environmental medicine standpoint for government agencies to consult and set requirements. Nor are there any other specific guidelines. In 2006, the National Board of Health and Welfare (*Socialstyrelsen*) in Sweden concluded in a report that it was important to minimize particle concentrations in both indoor and outdoor air from a health perspective. This may be interpreted as advice to apply "the principle of prudence". Today this means, in most cases, that Class F7 filters are installed as the de facto standard in Sweden, even if it is not actually known if filters of this efficiency are sufficient.

This report contains calculations of airborne particle concentrations in indoor air that have their source in outdoor air. The investigation was focused on studying how different choices of supply air filters are expected to impact the presence of particles indoors. The investigation covers residential buildings, offices and classrooms. Gaseous airborne pollutants are not taken up in the report.

The accuracy of the calculations was verified by comparing them with measurements in a full-scale test chamber.

Purpose

The purpose of the study described in this report was to use calculations to illustrate the extent to which it is possible to reduce the concentration of airborne particles in indoor air by cleaning the supply air with air filters. A theoretical model was used for making the calculations that takes into account the ventilation airflow rate, air leakage through the building envelope, the deposition of particles in the indoor environment, and the particle removal efficiency of filters. The investigation was focused on studying particles that originated outdoors, such as particles generated by vehicle traffic. The investigation covers residential buildings, offices and classrooms.

Since people spend a large part of their life indoors – often more than 85% of their time – a sharp reduction in the indoor particle concentration could considerably reduce the population's exposure to particles related to vehicle exhaust, among other pollutants. Supply air is often filtered through "fine filters", of which Class F7 filters are commonly used today. However, it happens that filters of a lower class, such as M5, are also used. The choice of filter class is also being made on a de facto basis. The reported study illustrates how different filter choices affect the concentration of particles in indoor air.

A brief description of the health effects of airborne particles

In recent years, a number of medical and environmental medicine studies have indicated that "ultrafine" particles can be more harmful to human health than larger particles [1a, 1b]. Small particles are formed during combustion, such as from combustion engines. Exhaust gases from vehicle traffic are consequently a substantial source of particles in areas situated by streets and roads with heavy vehicle traffic. Particles in outdoor air have a negative effect on the health of people – this has been established in many epidemiological investigations [2, 3, 4, 5, 6]. Many reports indicate that exhaust from vehicle traffic are especially dangerous to health. A significantly smaller number of studies have been dedicated to the health effects of particles generated indoors. Some of the studies indicate that particles from indoor sources are less important [7], while others claim that there is not enough scientific evidence to draw such a conclusion [8].

Airways are not the only part of the human body that is affected by airborne particles; research in the field of environmental medicine has also shown a connection between exposure to ultrafine particles and cardiovascular disease. The danger to health can be associated, of course, to the substance that the particle consists of, or the substances carried by the particle. Another important reason for the negative health impacts of particles seems to be related to the fact that they are so small. It is usually stated that ultrafine particles are all particles less than 0.1 micrometers (µm) in size, which is the same as 100 nanometers (nm), or one ten-thousandth of a millimeter.

Guidelines for good air quality

In a report titled *"Partiklar i inomhusmiljön – en litteraturgenomgång" ("Particles in indoor environments – a review of the literature"),* published in 2006 by Socialstyrelsen [9], the National Board of Health and Welfare in Sweden, it was generally concluded:

- that particles have a major negative impact on health;
- that documented knowledge was insufficient for being able to set a national limit for indoor environments;
- that it was important to minimize indoor and outdoor particle concentrations from a health perspective.

This can be interpreted to mean that there are strong reasons to apply the "principle of prudence" with regard to the health effects of airborne particles.

Specific national limits for good air quality actually do exist in Sweden but they are totally focused on the quality of ambient air for the most part. This is the case, for example, with Sweden's environmental quality standards [10], which contain guideline limits for airborne particles measured as PM2.5 and PM10. These measurements state the mass concentration of particles per unit volume of air: the mass concentration of PM2.5 particles smaller than 2.5 µm, and the mass concentration of PM10 particles smaller than 10 µm. These measurements are therefore the summarized mass concentration of particles over a wide particle size range. Different particle size distributions can therefore produce the same concentration value. Because large particles mainly have a significant mass, PM2.5 and PM10 are poor measurements if you want to study small particles.

Unfortunately, neither the Swedish standard for testing and classifying general ventilation filters, SS EN 779 [11], or SP's P-labeling system for filters [12], take the smallest particles into account. Nor does the new filter standard that is being developed – ISO/FDIS 16890 [13]. The latter standard covers PM1, PM2.5 and PM10, but not measurements of their mass concentrations. Instead, it concerns measurements of their concentration in numbers in several size intervals, from 0.3 µm and larger, and a theoretical calculation of the different mass concentration measurements.

According to regulation AFS 2009:2 [14] of the Swedish Work Environment Authority, "outdoor air, for example, in environments that are more polluted, … such as city centers, normally needs to be filtered". But the regulation does not state the filter class that might be required. On this subject, the guidelines of the Society of Energy and Environmental Technology in Sweden (Energi & Miljötekniska

Föreningen) [15] advises that air should be filtered in F7 filters as the lowest class (according to SS EN 779).

The building regulations [16] of Boverket, the National Board of Housing, Building and Planning in Sweden, require that the concentration of contaminants in the supply air may not exceed the current limit value for outdoor air. This requirement includes the general advice that clean outdoor air is defined by the environmental quality standards of Sweden's Air Quality Ordinance (2010:477). Boverket's building regulations also state that ”the quality of the air supplied in a building should be secured through a suitable placement and design of the outdoor air intake, intake chamber, air cleaning or similar arrangement”. The standard SS-EN-13779 [17] provides additional guidance for the design of the ventilation system and the selection of air filters.

Filter classes and filtration efficiencies

Figure 1 shows the measured and estimated filtration efficiency of five classes of glass-fiber filters, from class M5 to class F9. The diagram was included in a doctoral dissertation written by Bingbing Shi at the Chalmers University of Technology in Gothenburg, Sweden [18]. The data in the diagram comes from several different sources that appear to be rather much in agreement. The simulated curves agree rather well with the measurements. Table 1a lists the filtration efficiency on four particle sizes for the five filter classes. The efficiencies in the table have been compiled from Figure 1.

The efficiencies in Figure 1 and Table 1a are examples for glass-fiber filters in classes M5 to F9. However, the efficiency for a filter of a certain class can vary rather much between filter models. In other words, there are filters that fulfill the criteria by a wide margin in a certain class, while there are filters that barely meet the criteria. The data in Figure 1 and Table 1a may be considered as typical initial efficiencies for glass-fiber filters.

Table 1a. Filtration efficiencies of glass-fiber filters in five different filter classes on four different particle sizes. The data originate from Figure 1.

Filter class according to SS EN 779	Particle size			
	0.4 µm	*MPPS**	*50 nm*	*20 nm*
M5	4%	2%	17%	30%
M6	20%	14%	35%	63%
F7	58%	46%	62%	83%
F8	70%	55%	69%	90%
F9	81%	60%	77%	94%

* MPPS = "Most Penetrating Particle Size" [27], the particle size that is most difficult to filter, or the particle size with the greatest penetration ability. This size varies, depending on the structure and performance properties of the filter, the air velocity through the filter material, and the type of particle.

Table 1b. Approximate agreement between filter classes according to SS EN 779 and *ISO/FDIS 16890*.

Filter class	
According to SS EN 779 [11]	*According to ISO/FDIS 16890 [13]*
M5	ISO ePM_{10} 55%
M6	ISO $ePM_{2.5}$ 50%
F7	ISO ePM_{1} 60%
F8	ISO ePM_{1} 80%
F9	ISO ePM_{1} 85%

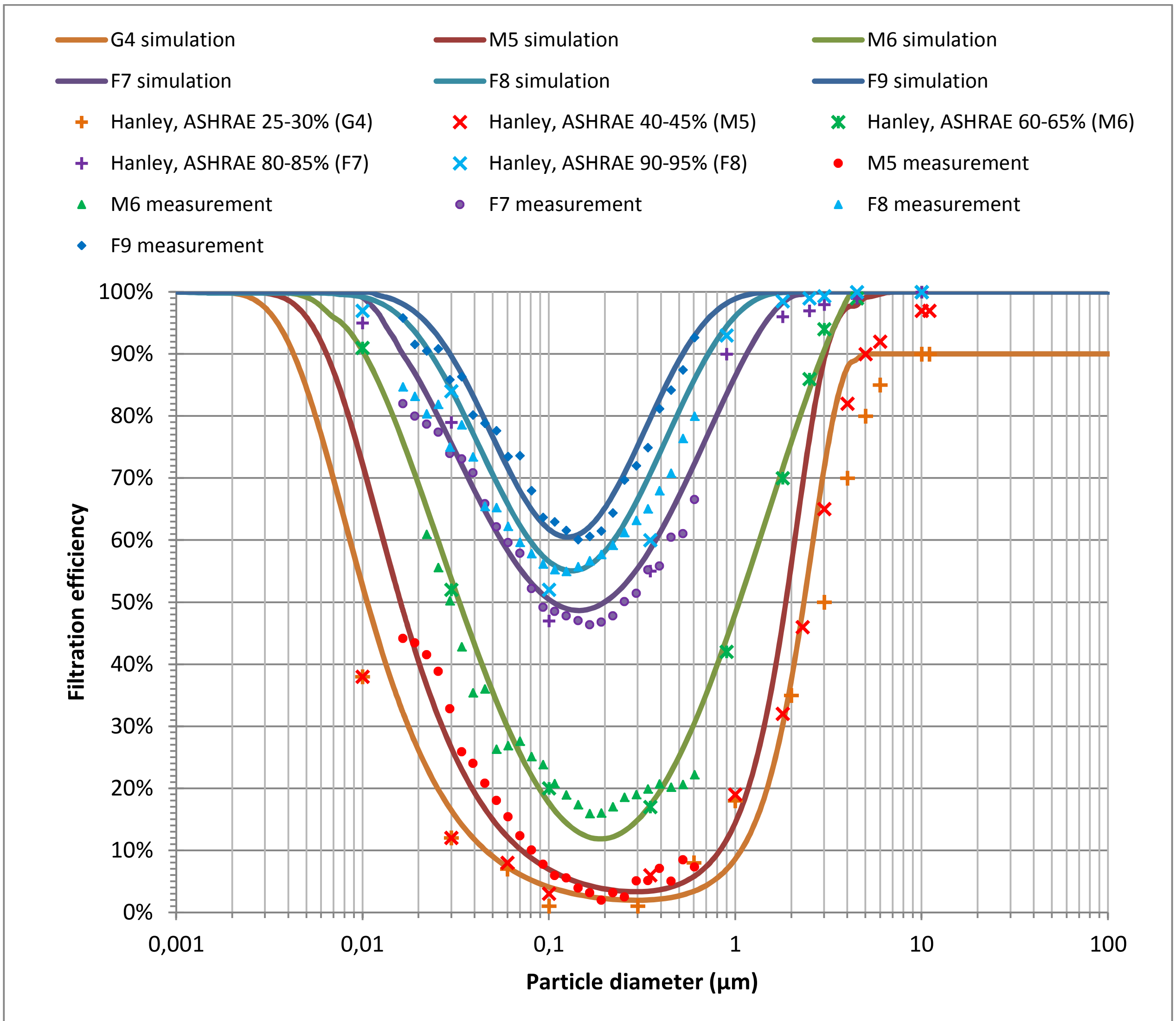
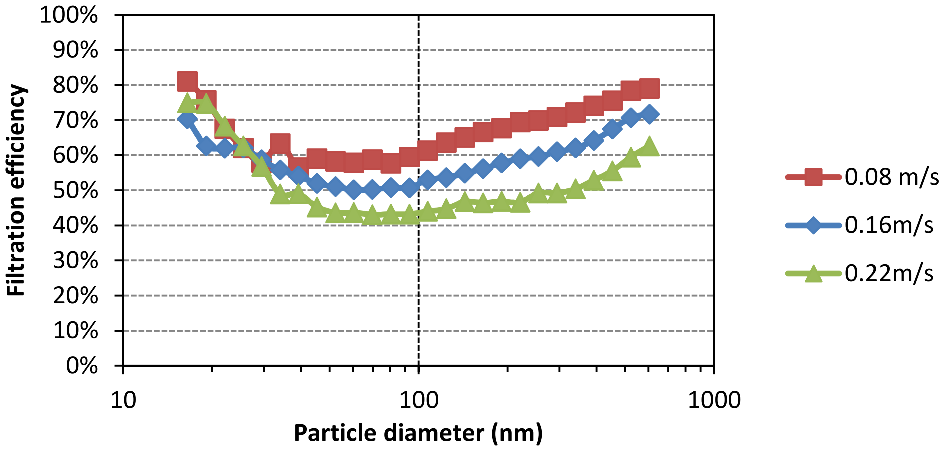
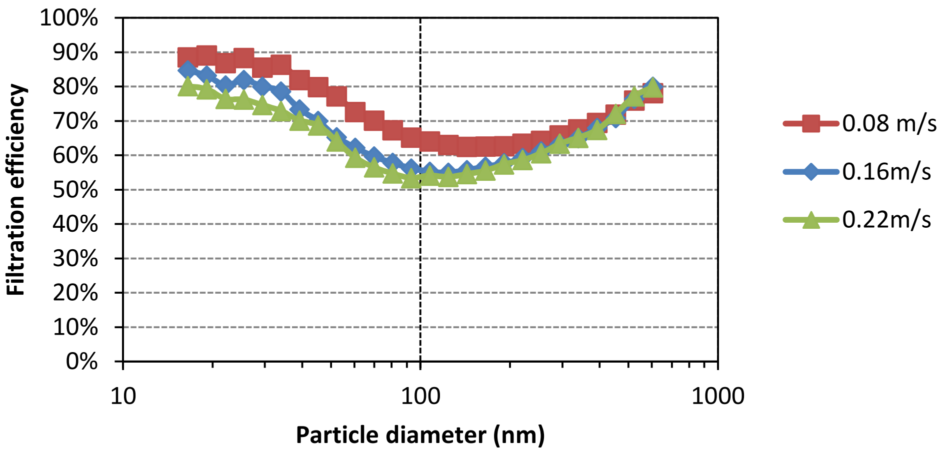


Figure 1. Filtration efficiency of glass-fiber filters class G4 to F9. The diagram has been sourced from Shi [18]. The efficiency for an M5 filter on 0.02 µm (20 nm) particles is approximately 40%, according to the measurement designated as "M5 measurement", but only about 20% according to the measurement made by Hanley [26]. The efficiency shown in Table 1a is the average filtration efficiency for the two reported measurement results.

Figures 2a and 2b show examples of efficiencies for a new electrostatically charged filter (a) and a new glass-fiber filter, both class F8/9. The diagrams have been sourced from Shi [18]. As shown in the diagrams, we find the MPPS for the electrostatically charged filter at much smaller particle diameters, compared to the glass-fiber filter. Additional measurements reported in Shi's dissertation [18] confirm that this is normally the case. The electrostatically charged filter in Figure 2 has a lower filtration efficiency than the glass-fiber filter on "ultrafine" particles, or particles with a diameter smaller than 0.1 µm. The electrostatically charged filter also seems to be more sensitive when the air velocity is increased through the filter media.



(a)



(b)

Figure 2. Examples of filtration efficiency measured at different air velocities through the filter material for a new electrostatically charged synthetic filter (a) and a new glass-fiber filter (b). Filter class F8/9. Data from [18].

Other factors having a significant impact on the concentration of particles in indoor air

This section briefly describes the following factors:

- The ventilation airflow rate
- Effective ventilation
- Air leakage through the building envelope
- Deposition of particles indoors

Ventilation airflow rate

Residential buildings

In Sweden, Boverket, the National Board of Housing, Building and Planning, requires 0.35 l/s per m^2 of flooring [16], corresponding to approximately 0.5 air changes per hour when the ceiling height is 2.4 m. Far from all dwellings in Sweden have ventilation meeting Boverket's minimum requirement. Other dwellings are much better ventilated, such as apartments specially designed for persons with allergies. A reasonable interval for residential ventilation is 0.3 to 0.7 changes/hour.

Offices

The regulations of the Swedish Work Environment Authority, Arbetsmiljöverket, state that the supply airflow (outdoor air) should be at least 0.35 l/s per m^2 of flooring plus 7 l/s per person [14]. Applied to an office cell with 10 m^2 of floor area and a ceiling height of 2.7 m, this corresponds to 1.4 air changes per hour. This air change rate can be assumed to be the lowest required airflow in office buildings with a waterborne comfort cooling system. In buildings with airborne cooling, the ventilation airflow rate will be dimensioned to meet the cooling requirement. In buildings like these, it is not unusual that the ventilation airflow is around 3.0 changes per hour. A reasonable interval for office ventilation is 2.0 to 3.0 changes per hour.

Schools

To exemplify a calculation, we can use a classroom for 30 students and one teacher. If the floor area is 80 m^2, the regulations of the Swedish Work Environment Authority [14] state that the ventilation airflow has to be a minimum of 245 l/s. If the ceiling height is 2.7 m, this corresponds to 4.1 air changes per hour. To satisfy the authority's recommended maximum acceptable concentration of carbon dioxide in indoor air [14] approximately 10 l/s per person is usually set as the requirement. In classrooms with a small floor area per person, this can correspond up to 6.0 air changes per hour. A reasonable interval for classroom ventilation is 4.0 to 6.0 changes per hour.

Effective ventilation

The ventilation air should be distributed within the entire occupancy zone. For ventilation to function well, it is essential to select the right type of supply air device and to locate the devices correctly. In general, the temperature of the supply air in relation to the room air temperature is also of great importance.. If this arrangement is inadequate, part of the clean supply air will be directly transported and removed along with the exhaust air. The extent to which the ventilation is “short-circuited” can be studied and calculated with an index called the ”local ventilation index”, see Nordtest’s method NT VVS 114 [19]. According to Boverket’s building regulations in Sweden, the local ventilation index should not be less than 90%, signifying that at least 90% of the supply air is to fill the occupancy zone, where it should be used to remove air contaminants.

Air leakage through the building envelope

Requirements for the tightness of buildings are normally stated in terms of the maximum permitted leakage flow per m^2 of the building’s total enclosure area, at a pressure difference of 50 Pa over the building envelope. An SP report by Sikander and Wahlgren [20] explains how air leakage can be calculated at various pressure differences. In Sweden, the computer software BV2 is used to calculate the heat balance in duration diagrams (*BV2 – Byggnadens värmebalans i varaktighetsdiagram, version 2012*) [21]. The software can calculate air leakage at normal conditions, taking into account the wind pressure and the thermal force that develops at different indoor and outdoor temperatures.

Table 2. Recalculation of leakage measured during a pressure test for leakage during normal operation. The calculation is based on the assumption that the temperature difference indoors/outdoors is 10 degrees C and the wind pressure is 5 Pa. The calculation was made with software used in Sweden to calculate the heat balance in duration diagrams (*BV2 – Byggnadens värmebalans i varaktighetsdiagram, version 2012*) [21].

Leakage at 50 Pa (l/s per m^2)	**Air changes per hour during normal operation** (h^{-1})	
	Depending on wind pressure	Depending on wind and thermal effect
0.3	0.08	0.09
0.6	0.16	0.19
0.8	0.21	0.25
1.6	0.41	0.51

In Sweden, Boverket’s building regulations from 1994 state 0.8 l/s per m^2 for residential buildings and 1.6 l/s per m^2 for office premises. Today, building regulations contain only one alternative requirement for residential buildings – a maximum airflow of 0.6 l/s per m^2. Nowadays, the requirement for low-energy buildings is usually 0.3 l/s per m^2 at 50 Pa.

In view of the above, it can be concluded and assumed that air leakage in tight buildings corresponds to approximately 0.1 air changes per hour (h^{-1}). However, even lower figures are sometimes reported [22]. Untight buildings can leak more than 0.3 air changes per hour.

Air leaking through the building envelope is basically unfiltered when it reaches the interior space. However, Figure 3 contains an example showing that some of the air is filtered, especially with regard to very small and very large particles. According to the figure, the penetration is 0.98 for all particles between 10 nm and 3-4 µm in diameter.

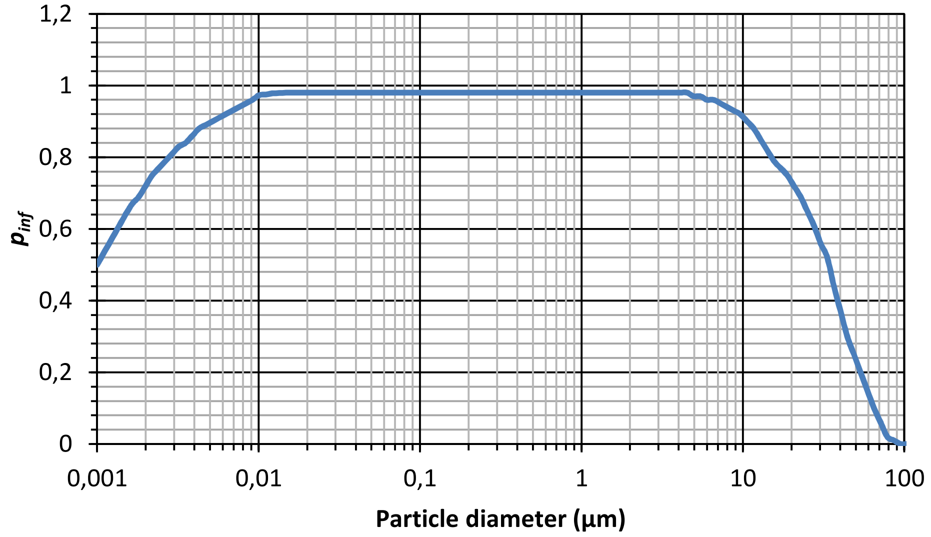


Figure 3. Penetration through an untight building envelope (p_{inf}) as a function of the particle diameter. The diagram has been sourced from Liu and Nazaroff, 2001 [23]. The data are for a building envelope with evenly distributed cracks that have a height of 0.05-2.0 mm and a length of 3 cm. The pressure difference over the construction has been set at 4 Pa.

Deposition of particles indoors

Figure 4 gives an example of how the deposition of particles to indoor surfaces can vary with different sizes of particles. The deposition rate is stated "per hour", which is a unit equivalent to the number of air changes per hour. The table below shows the deposition rates for a few given particle diameters. The figures originate from Figure 4. Note that the stated figures are examples from literature. Other references state higher figures. According to [28], the deposition rate can vary by more than one order of magnitude for the same particle size. For example, there is information that k_{dep} for 0.4 µm particles could reach values exceeding 1 h^{-1}.

Particle diameter	k_{dep}
0.4 µm	0.08 h^{-1}
0.1-0.2 (MPPS)	0.04 h^{-1}
50 nm	0.08 h^{-1}
20 nm	0.25 h^{-1}

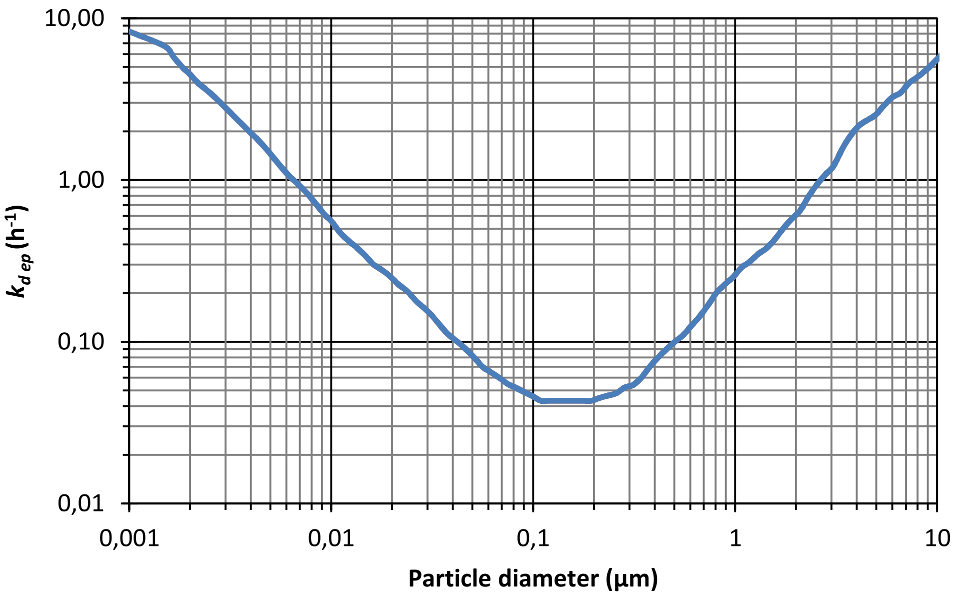
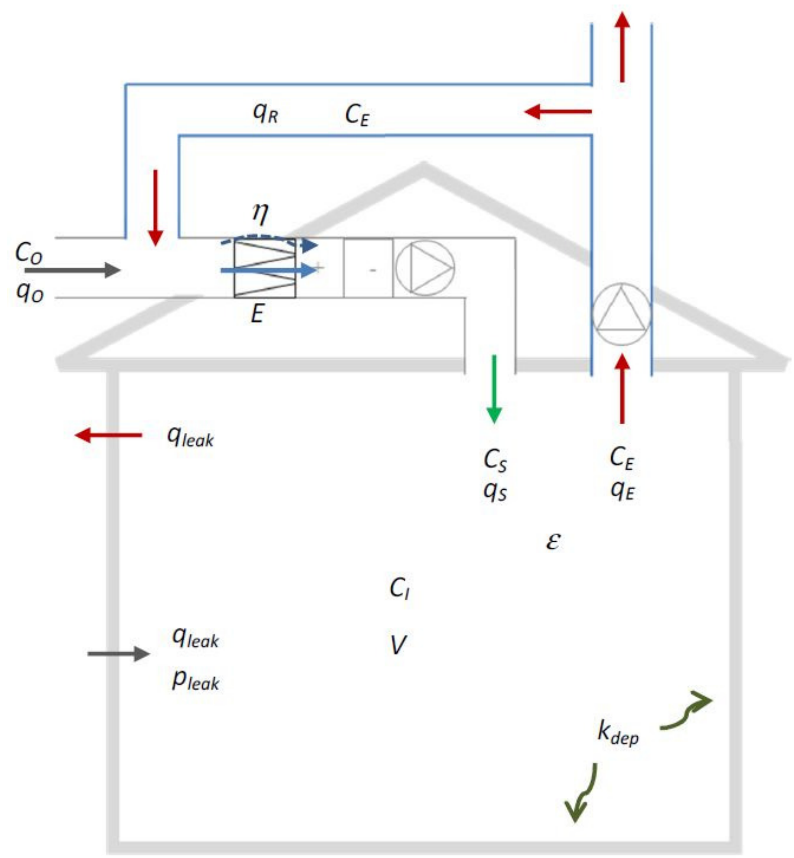


Figure 4. Deposition rate (k_d) as a function of particle diameter. The diagram has been sourced from Riley et al., 2002 [24].

Calculation model

Figure 5 shows a sketch of a building with a mechanical supply air and exhaust air ventilation system. The factors affecting the indoor particle concentration, as described in the preceding section, have been highlighted in the figure. The model also takes into account that part of the exhaust air can be recirculated in the room by being mixed with the outdoor airflow before passing through the supply air filter. Indoor sources of particles have not been included in the model.



C_I = indoor concentration [particles/m^3]

C_O = outdoor concentration [particles/m^3]

C_S = concentration in supply air [particles/m^3]

C_E = concentration in exhaust air [particles/m^3]

ε = local ventilation index [-]

q_S = supply airflow [m^3/h]

q_E = exhaust airflow [m^3/h]

q_O = outdoor airflow [m^3/h]

q_R = return airflow [m^3/h]

q_{leak} = leakage through the building envelope [m^3/h]

p_{leak} = particle penetration through the building envelope [-]

E = filtration efficiency [-]

η = portion of airflow passing through the filter media [-]

k_{dep} = particle deposition indoors [h^{-1}]

V = room volume [m^3]

Figure 5. Sketch of a ventilated building with a mechanical supply air and exhaust air ventilation system in which part of the exhaust air can be recirculated and mixed with the outdoor airflow before passing through the supply air filter.

If the conditions do not vary over time, and the particle concentration in the indoor air is constant, the concentration is said to be at steady state. In this case, the number of particles introduced through the ventilation system is as large as the number removed. A balance equation can be prepared. After “simplification”, the following equation (1) is derived:

$$C_I = C_U \; \frac{(1-\eta \cdot E)\,\varepsilon \cdot q_O + p_{leak} \cdot q_{leak}}{\varepsilon\,(q_O + q_R) + q_{leak} + k_{dep} \cdot V - (1-\eta \cdot E)\,\varepsilon \cdot q_R} \qquad (1)$$

The equation (1) can be used to calculate the concentration of particles in indoor air that has been supplied from outdoors. The equation is valid when the concentration is at steady state. As shown in Figure 5, the model is only applicable when the supply air is filtered in a single bank of filters. Therefore, the mixture of outdoor and return air passes through the same filter bank. In a system in which outdoor air is filtered in a filter bank and the exhaust air in another, the calculation result will be the same, as long as both filter banks are equipped with filters of the same efficiency. In systems without return air, the calculation is made by setting the return airflow rate to zero in the equation (1).

Results

Figure 6 shows the calculated results for particles 0.4 µm in diameter. Particles 0.4 µm in diameter are being used here because the diameter can be considered as a reference size; filters are classified for removing 0.4 µm particles in accordance with SS EN 779 [11] and SP's P-marking [12] are based on criteria for this particle size, which is why the most data and experience are available for this specific particle. Similar data for other particle diameters are shown in Appendix 1-3. All results reported in this section refer to cases without return air, meaning that the supply airflow is made up of 100% filtered or unfiltered outdoor air. The results for a few cases with return air are reported in Appendix 5.

The diagram shows how the particle concentration in indoor air varies with the ventilation airflow rate, which is expressed as the number of air changes per hour. The concentration is stated as the number of particles for the volume of air, and the figures are valid when the outdoor concentration has an arbitrary value of 100. This means that the figures in the diagram reflect how high the indoor concentration will be as a percentage of the concentration in outdoor air.

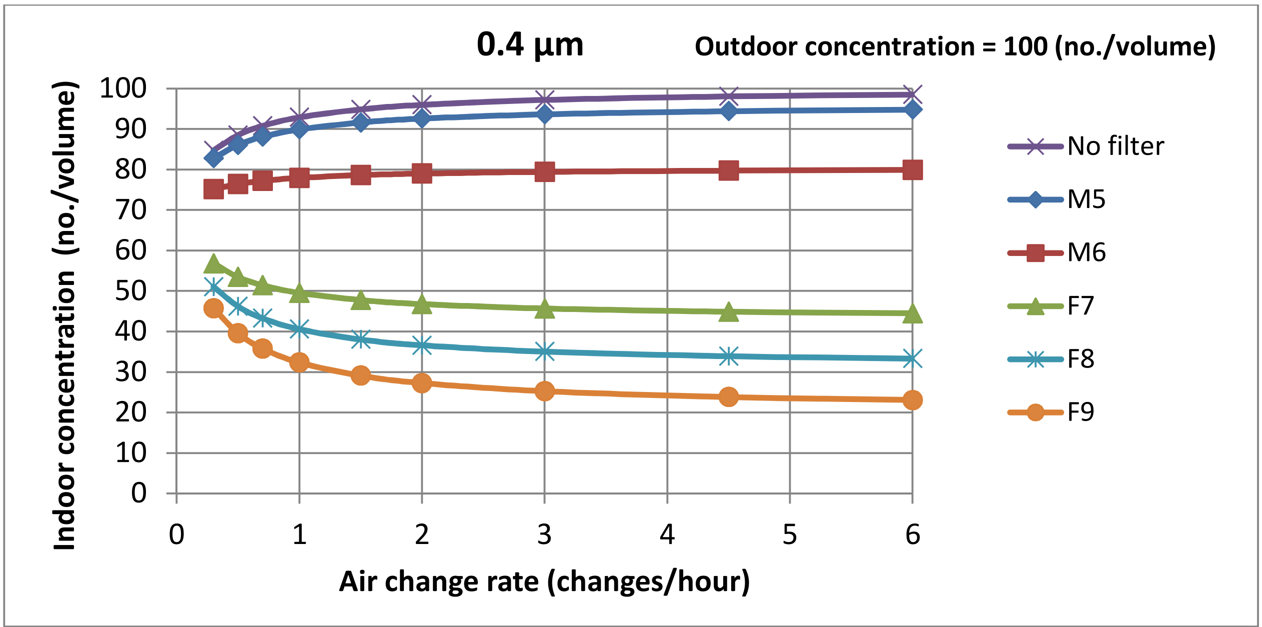


Figure 6. The concentration of particles with a diameter of 0.4 µm has been calculated on the assumption that the outdoor concentration has a value of 100. Air leakage through the building envelope has been set at 0.2 air changes per hour and 2% of the outdoor airflow is assumed to leak and by-pass the filter without being cleaned. The efficiency is for glass-fiber filters whose performance properties have been described in the preceding section.

For 0.4 µm particles, Figure 6 shows a marginal difference between filtration with class M5 filters and no filters at all. When the air is filtered in class M6 filters, the indoor particle concentration will be 75% to 80% of the outdoor concentration, depending on the number of air changes. When class F7 filters are used, the indoor concentration will be approximately 45% of the outdoor concentration in cases when the air is changed at an approximate rate of more than two changes per hour. When class F9 filters are used, the corresponding figure will be about 25%. When class F7-F9 filters are used, the indoor concentration will increase sharply when the air change rate is reduced to less than a few changes per hour.

As shown in Figure 6, there is a fundamental difference between filter class M6 and lower on the one hand, and filter class F7 and higher on the other. With filters of a low class, the concentration of indoor particles rises when the number of air changes is increased. With filters of a high class, the situation is the reverse: the indoor concentration decreases as the number of air changes is increased. In both cases, the efficiency of the filter will become increasingly important as the filtered airflow is increased more and more. If the filtered airflow is instead near zero, only the infiltration of unfiltered air and the deposition of particles will affect the concentration of particles and their number in the indoor air. If the filtered flow is zero, the indoor concentration will be a result of the balance between the quantity of particles supplied through leakage through the building envelope and the quantity removed through deposition. With the data in Figure 1 (k_d = 0.08 h^{-1} and q_{leak}/V = 0.2 h^{-1}), the indoor concentration is 70% of the outdoor concentration, if the filtered airflow is reduced to zero. If the filtered airflow increases, the indoor concentration will change towards a value determined by the number of particles that pass through the filter, or 1 minus the efficiency ($1\text{-}E_F$). If a filter of M6 class is used, for example, the value will be 80% because the filter's efficiency is set at 20%. This means that the indoor concentration, with filter class M5, increases as the ventilation flow increases, which is precisely what Figure 6 shows. If a class F7 filter is used instead, the concentration will change to 42% because the efficiency has been set at 58%. In this case, the concentration decreases, as shown in Figure 6.

An equivalent calculation for a very tight building, with infiltration corresponding to 0.03 h^{-1}, indicates that the indoor concentration will be approximately 25% of the outdoor concentration when the ventilation flow is reduced to zero. In this case, the indoor concentration will increase when the airflow is increased, even for filter class F7 and F8, see Figure 7.

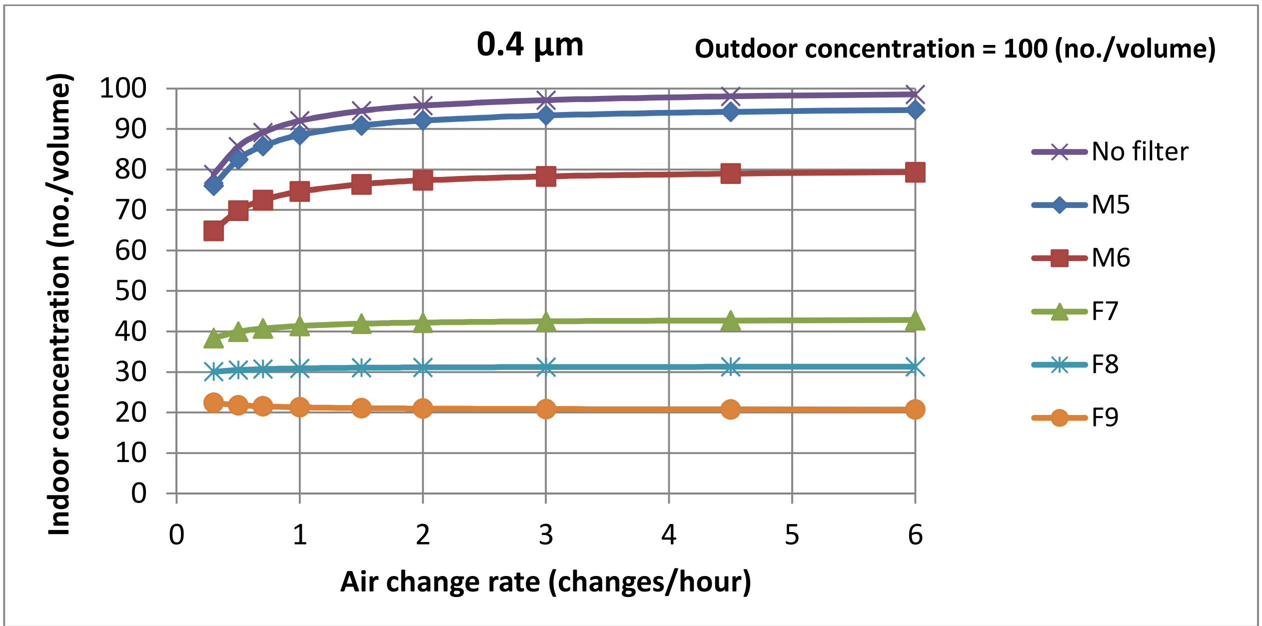


Figure 7. The concentration of 0.4 µm particles has been calculated on the assumption that the outdoor concentration is 100. The calculation is for a very tight building. Air leakage through the building envelope has been set at 0.03 air changes per hour and 2% of the outdoor flow is assumed to leak and by-pass the filter, without being cleaned. The filtration efficiency is for glass-fiber filters whose performance properties have been described in the preceding section.

The above analysis indicates that a filter's efficiency will become increasingly important as the filtered ventilation flow rate becomes larger and larger, and as leakage of unfiltered air into the building becomes lower and lower. The conclusion here is obvious: an efficient filter has better possibilities to maintain a low particle concentration in the indoor air in tight buildings with a high ventilation flow, compared to untight buildings with a low ventilation flow.

Different types of buildings

Figure 8 shows the result of calculations made for glass-fiber filters in residential buildings, offices and schools for particles 0.4 µm in diameter. The figure shows that the indoor concentration will be between 88% and 98% of the outdoor concentration if the air is not filtered at all. The indoor concentration is lower because particles deposit to surfaces indoors. The figure also shows that class M5 filters reduce the concentration negligibly for 0.4 µm particles. Filter class M6 will provide some improvement while the concentration will not decrease appreciably until the filter class is changed to F7 or higher. With class F7 filters, the concentration in residential buildings will be slightly higher than 50% of the concentration in outdoor air. In offices and schools, the concentration will decrease to approximately 45%. With filter class F9, the concentration will be just below 40% in residential buildings and around 25% in offices and schools.

Corresponding diagrams for other particle sizes are shown in Appendix 1. These show, for example, that the concentration of ultrafine particles with a diameter of 20 nm can be reduced to about 40% of the outdoor concentration if class M6 glass-fiber filters are used (regardless of the three types of buildings included in the study). With class F7 glass-fiber filters, the concentration of 20 nm particles in residential buildings will be approximately 30% of the outdoor concentration. In offices and schools, the corresponding result will be as low as 20%. Class F9 filters are estimated to bring down the concentration (20 nm) to about 25% in residential buildings and 10-15% in offices and schools.

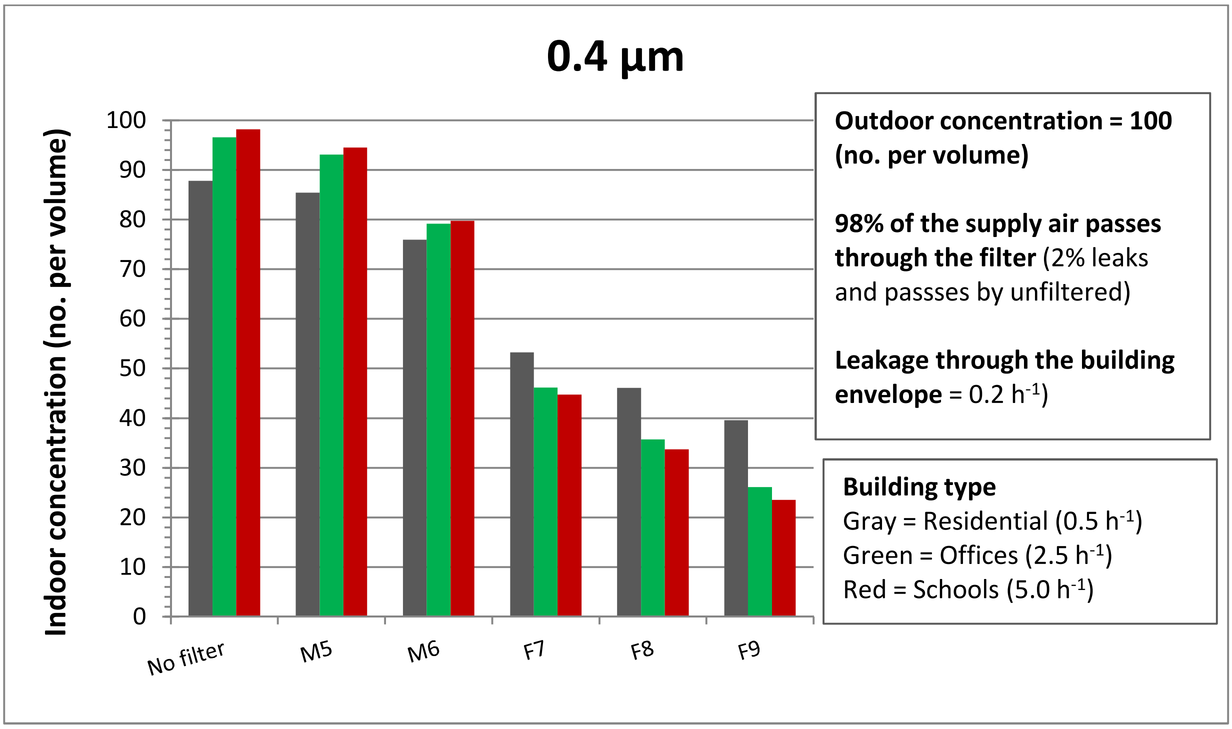


Figure 8. The concentration of 0.4 µm particles has been calculated on the assumption that the outdoor concentration has a value of 100. Data are reported for residential buildings (0.5 air changes/hour), offices (2.5 air changes/hour) and schools (5 air changes/hour). Air leakage through the building envelope has been set at 0.2 air changes per hour for all three building types and 2% of the outdoor airflow is assumed to leak and by-pass the filter, without being cleaned. The filtration efficiency is for glass-fiber filters whose performance properties have been described in the preceding section.

Calculations for buildings with different ventilation flows and tightness

Particle measurements in various buildings can yield rather varying results and it can be difficult to make generalizations. There are two important reasons why the results will vary: various buildings are ventilated to a different extent and their tightness can vary. To illustrate this, calculations have been made for three building categories using various assumptions about the air change rate and leakage through the building envelope. Figure 9a shows the results from calculations for 0.4 µm particles in residential buildings. Figure 9b and 9c show the corresponding results for offices and schools. The filtration efficiencies of the filters are for glass-fiber filters whose performance properties have been described in the preceding section.

The figures show that a significantly larger spread of the particle concentration can be expected in residential buildings than in offices and schools. This is because the filtered airflow is rather low in residential buildings and leakage through the building envelope will therefore be of greater significance. Figure 9a shows that in residential buildings filtered with class F7-F9 glass-fiber filters, the indoor particle concentration can change 10 to 20 percentage points when air leakage varies between 0.1 and 0.3 changes per hour. In offices, the corresponding change in concentration will be less than 10 percentage points, see Figure 9b, and in schools, 5 percentage points, see Figure 9c.

The corresponding results for other particle sizes are shown in Appendix 2.

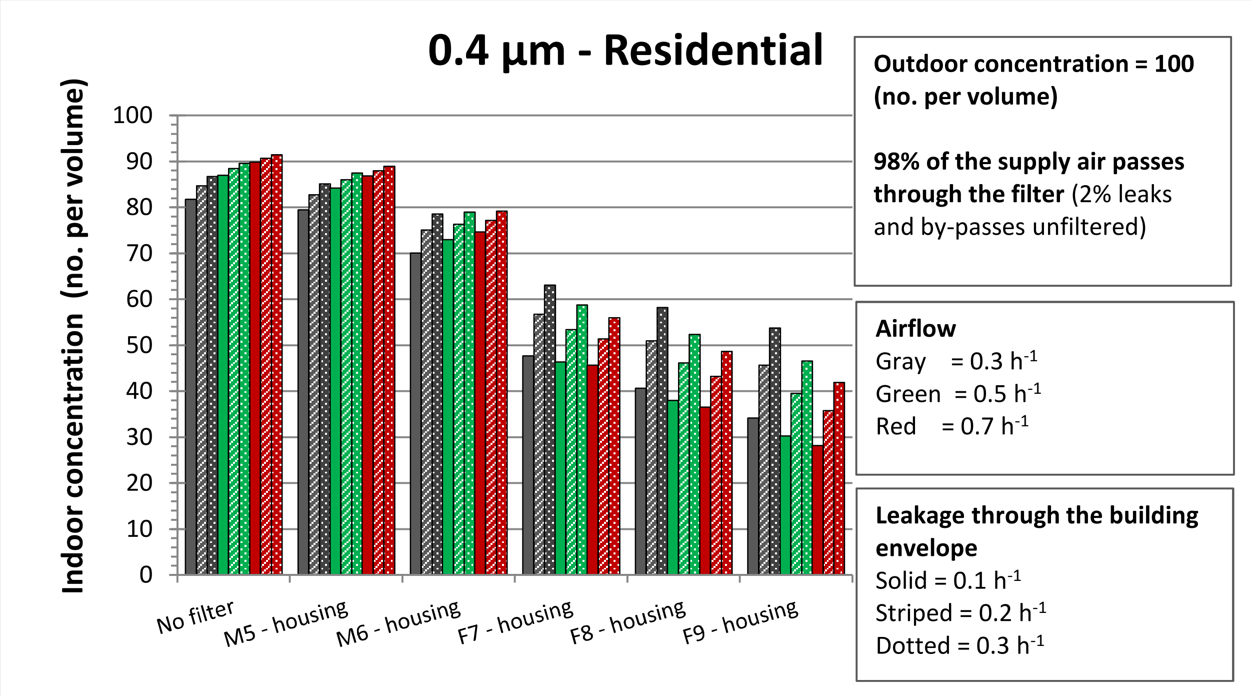


Figure 9a. Particle concentrations in residential buildings calculated for ventilation flows corresponding to 0.3 to 0.7 air changes per hour and for different amounts of air leakage through the building envelope (between 0.1 and 0.3 air changes per hour). The filtration efficiencies of the filters are for glass-fiber filters whose performance properties have been described in the preceding section.

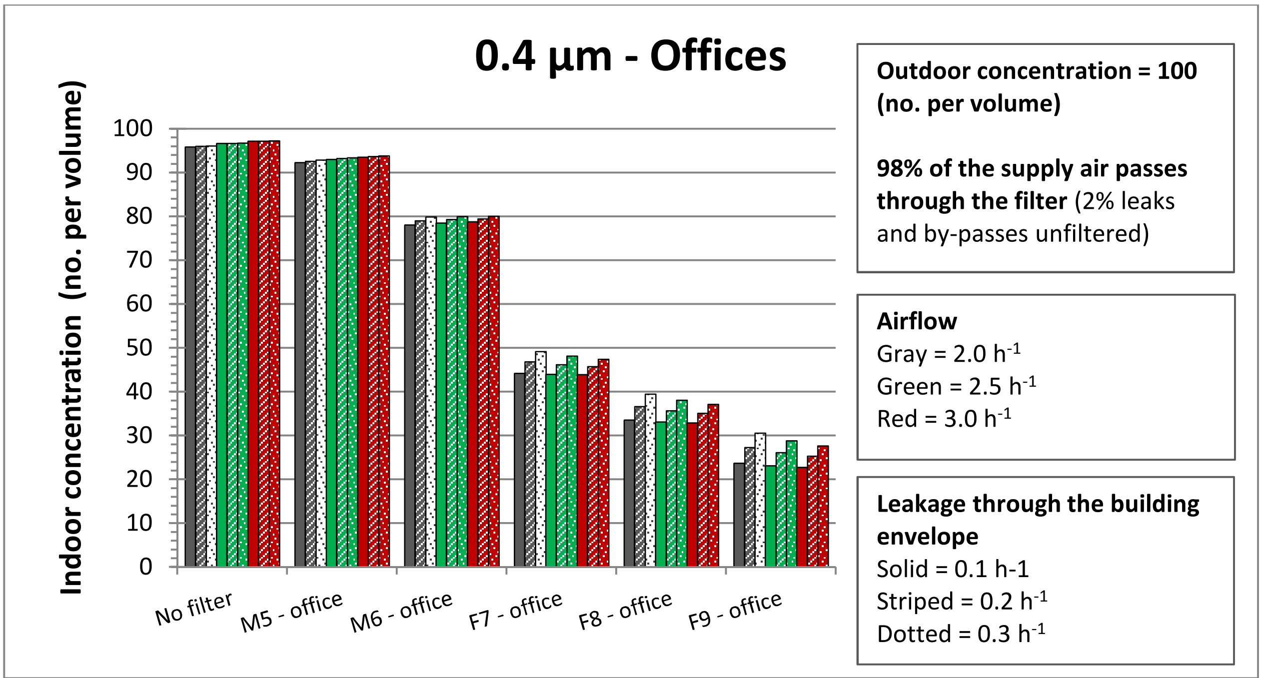


Figure 9b. Particle concentrations in offices calculated for ventilation flows corresponding to 2.0 to 3.0 air changes per hour and for different amounts of air leakage through the building envelope (between 0.1 and 0.3 air changes per hour). The filtration efficiencies of the filters are for glass-fiber filters whose performance properties have been described in the preceding section.

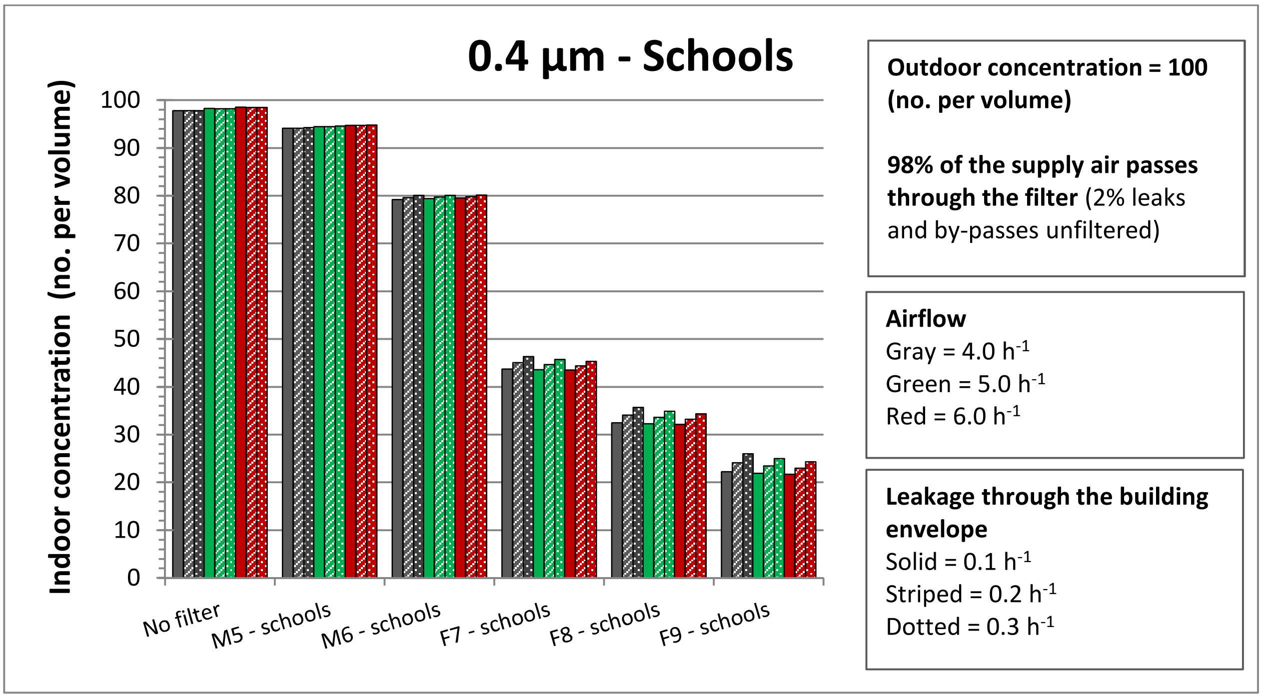


Figure 9c. Particle concentrations in schools calculated for ventilation flows corresponding to 4.0 to 6.0 air changes per hour and for different amounts of air leakage through the building envelope (between 0.1 and 0.3 air changes per hour). The filtration efficiencies of the filters are for glass-fiber filters whose performance properties have been described in the preceding section.

Leakage by-passing the filter

Air can leak and by-pass the filter and part of the supply airflow will not be filtered as a consequence. This is a small or negligible problem as long as the filter has been correctly installed with its gaskets mounted in the right way. Standard SS-EN 1886:2007 [25] states that the maximum permissible air leakage (by-pass leakage) as a percentage of the nominal (rated) airflow through the air handling unit, see Table 3.

Table 3. Maximum permissible air leakage (by-pass leakage) at a test pressure of 400 Pa.

Filter class	G1 – M5	M6	F7	F8	F9
Maximum air leakage	6%	4%	2%	1%	0.5%

Figure 10 shows the indoor concentration of 0.4 µm particles calculated for various amounts of by-pass leakage. The figure refers to residential buildings. Regression lines are shown for cases with glass-fiber filters of class M6, F7 and F9. For each percentage point the leakage increases and by-passes an M6 filter, the indoor concentration will increase approximately 0.15%. For filter class F9, the indoor concentration will increase about 1% for every percentage point the leakage increases. The corresponding calculation for schools and class F9 filters shows that the indoor concentration increases approximately 3% for each percentage point that the leakage increases through the filter. The results for other building types and various particle sizes are shown in Appendix 3.

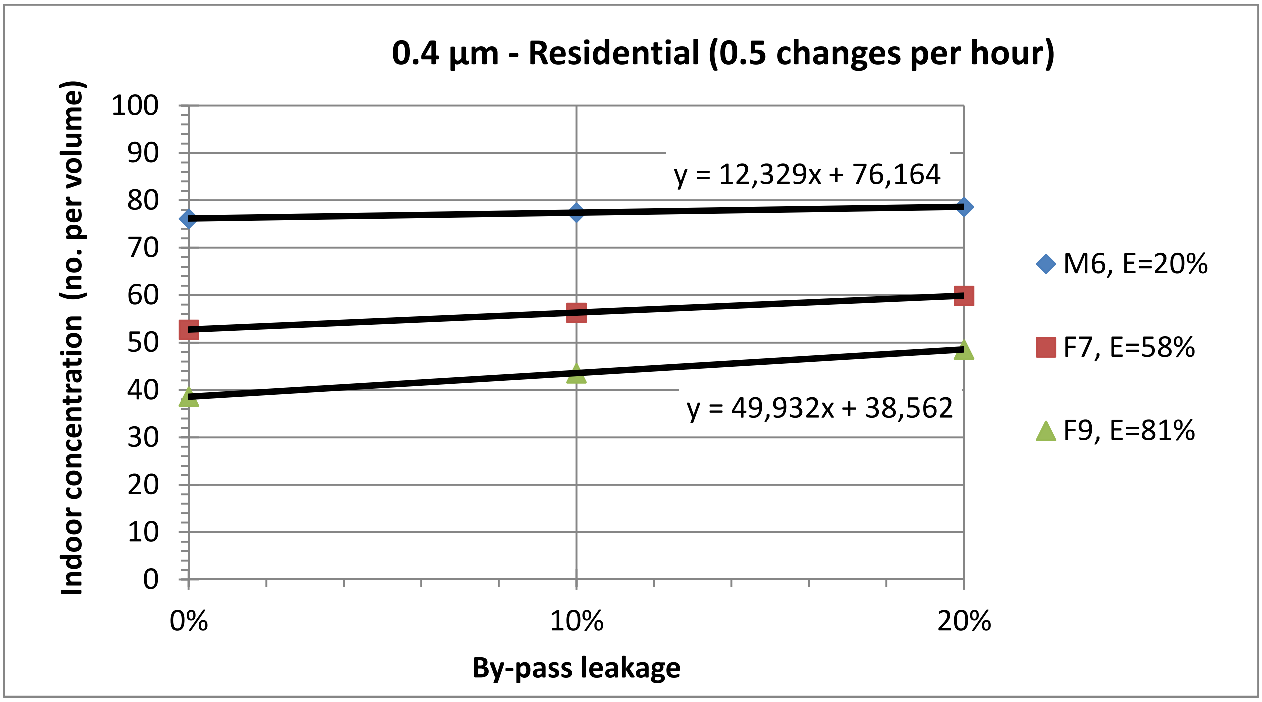


Figure 10. Concentration of 0.4 µm particles in residential buildings, calculated as a function of air leaking and by-passing the filter.

Summary and conclusions

The results of the calculations are compiled in Table 4-6. It is evident that the particle concentration will be higher in an untight building with a low ventilation flow, compared to a tight and well-ventilated building. This is why the data reported in the tables are divided into these two building categories. In summary, the reported calculations indicated the following about the ability of ventilation filters to reduce the indoor concentration of particles originating from outdoors:

- The difference between the air cleaning effect of the various filter classes is less in residential buildings than in offices and schools. This is because the infiltration of outdoor air and the deposition of particles to surfaces will have an increasingly large impact as the filtered ventilation flow decreases.
- The class M5 fiber-glass filters in the study reduced the indoor concentration of particles 0.4 µm in diameter and the MPPS negligibly, but can be expected to reduce the concentration of 20 nm particles 15 to 25% in residential buildings, and up to 30% in offices and schools, compared to cases in which no filters are used.
- Class M6 glass-fiber filters reduce the indoor concentration of particles 0.4 µm in diameter and the MPPS to a small extent, but can be expected to reduce the concentration of 20 nm particles approximately 30% in untight residential buildings with low ventilation airflows, and up to 60% in tight and well ventilated schools, compared to cases in which no filters are used.
- Class F7-F9 glass-fiber filters considerably reduce the indoor concentration of all studied particle sizes, compared to filters of lower class.
- In residential buildings, class F7 glass-fiber filters can reduce the concentration of ultrafine particles 20 nm in size 40-70 %, compared to cases in which no filters are used. Values at the lower end of this range pertain to untight buildings with low ventilation airflows. Changing from filter class F7 to F8 or F9 reduces the concentration further but on a smaller magnitude, compared to the case where M6 was changed to F7.
- In offices and schools, class F7 glass-fiber filters can reduce the concentration of 20 nm ultrafine particles 70-80%, compared to the case in which no filters were used. Changing from filter class F7 to F9 would further reduce the concentration approximately by a factor of two.
- In offices and schools, class F9 glass-fiber filters can reduce the concentration of 20 nm ultrafine particles 80-90%, compared to the case in which no filters were used.

Table 4. Summary of calculation results for 0.4 µm particles. The percentages refer to the filter's reduction of the indoor particle concentration, compared to the case in which no filters were used.

Case		M5	M6	F7	F8	F9
Residential	Untight with low ventilation airflow	2%	9%	27%	33%	38%
	Tight and well ventilated	3%	17%	49%	59%	69%
Offices	Untight with low ventilation airflow	3%	17%	49%	59%	68%
	Tight and well ventilated	4%	19%	55%	66%	77%
Schools	Untight with low ventilation airflow	4%	18%	53%	63%	73%
	Tight and well ventilated	4%	19%	56%	67%	78%

Table 5. Summary of calculation results for MPPS (Most Penetrating Particle Size). The percentages refer to the filter's reduction of the indoor particle concentration, compared to the case in which no filters were used.

Fall		M5	M6	F7	F8	F9
Residential	Untight with low ventilation airflow	1%	2%	22%	26%	28%
	Tight and well ventilated	2%	12%	39%	47%	51%
Offices	Untight with low ventilation airflow	2%	12%	39%	46%	51%
	Tight and well ventilated	2%	13%	44%	52%	57%
Schools	Untight with low ventilation airflow	2%	13%	42%	50%	54%
	Tight and well ventilated	2%	13%	44%	53%	58%

Table 6. Summary of the calculation results for particles 20 nm in diameter. The percentages refer to the filter's reduction of the indoor concentration, compared to the case in which no filters were used.

Case		M5	M6	F7	F8	F9
Residential	Untight with low ventilation airflow	14%	30%	39%	42%	44%
	Tight and well ventilated	25%	53%	70%	76%	80%
Offices	Untight with low ventilation airflow	25%	53%	70%	76%	79%
	Tight and well ventilated	28%	60%	78%	85%	89%
Schools	Untight with low ventilation airflow	27%	57%	75%	82%	85%
	Tight and well ventilated	29%	61%	80%	87%	90%

Note that the results refer to filters with the efficiencies given in this report. The data has been sourced from tests of glass-fiber filters. Similar results can be expected for other glass-fiber filters that have passed testing according to SS EN 779 and long-term tests in connection with SP's P-labeling of filters.

The calculations are therefore not valid for other types of filters, such as electrostatically charged synthetic filters. As illustrated in Figure 2, these filters have another type of "efficiency curve", such as the MPPS being found at smaller particle sizes within the ultrafine size range. If the filter loses its electrostatic charge, there is a considerable risk that it cannot meet the requirements for SP's P-labeling for particles 0.4 µm in diameter. It is highly unclear how such filters would function to remove ultrafine particles. Today, there are no current or upcoming standards to assure the quality and selection of filters for these particles.

Appendix 4 reports the results of full-scale laboratory tests performed in a test chamber. While the tests were carried out, the particle concentration was measured inside the test chamber and compared with the outside concentration in relation to the ventilation flow rate, air leakage and filter quality. The results are reported as the concentration in the test chamber as a percentage of the outside concentration. The difference between the measured and estimated results was 7 percentage points at the most, indicating that the measurements and estimates were in good agreement.

Experimental field tests are required to further study the problem in question in order to map how filters of varying quality and classes can protect against exposure to airborne particles in different types of buildings. The results in this report should provide a good basis for planning such tests.

References

1a. Stölzel, M., Breitner, S., Cyrys, J., Pitz, M., Wolke, G., Kreyling, W., Heinrich, J., Wichmann, H.E., Peters, A., 2007. Daily mortality and particulate matter in different size classes in Erfurt, Germany. J Expo Sci Environ Epidemiol, vol. 17, no. 5, Aug, pp. 458-67.

1b. Wichmann, H.E., Spix, C., Tuch, T., Wolke, G., Peters, A., Heinrich, J., Kreyling, W.G., Heyder, J., 2000. Daily mortality and fine and ultrafine particles in Erfurt, Germany part I: role of particle number and particle mass. Research report (Health Effects Institute), no. 98, pp. 5-86; discussion 87-94.

2. Douglas W. Dockery, C A P, Xiping Xu, John D. Spengler, James H. Ware, Martha E. Fay, Benjamin G. Ferris, and Frank E. Speizer, 1993. An Association between Air Pollution and Mortality in Six U.S. Cities. The New England Journal of Medicine, vol. 329, pp. 1739-1759.

3. Janssen, N A H, Schwartz, J, Zanobetti, A, Suh, H H, 2002. Air conditioning and source-specific particles as modifiers of the effect of PM10 on hospital admissions for heart and lung disease. Environ Health Perspect, vol. 110, no. 1, pp. 43-49.

4. Long, C M, Suh, H H, Kobzik, L, Catalano, P J, Ning, Y Y, Koutrakis, P, 2001. A pilot investigation of the relative toxicity of indoor and outdoor fine particles: in vitro effects of endotoxin and other particulate properties. Environ Health Perspect, vol. 109, no. 10, pp. 1019-1026.

5. Pope, C A, Burnett, R T, Thun, M J, Calle, E E, Krewski, D, Ito, K, Thurston, G D, 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Jama-Journal of the American Medical Association, vol. 287, no. 9, pp. 1132-1141.

6. Wei, Y, Han, I K, Shao, M, Hu, M, Zhang, O J, Tang, X, 2009. PM2.5 constituents and oxidative DNA damage in humans. Environ Sci Technol, vol. 43, no. 13, Jul 1, pp. 4757-4762.

7. Wilson, W E, Mage, D T, Grant, L D, 2000. Estimating separately personal exposure to ambient and nonambient particulate matter for epidemiology and risk assessment: why and how. J Air waste Manag Assoc, vol. 50, no. 7, Jul, pp. 1167-1183.

8. Clausen, G, 2004. Ventilation filters and indoor air quality: a review of research from the International Centre for Indoor Environment and Energy. Indoor air, vol. 14 no. 7, pp. 202-207.

9. Socialstyrelsen, Swedish National Board of Health and Welfare (2006), Partiklar i inomhusmiljön en litteraturgenomgång. http://www.folkhalsomyndigheten.se/publicerat-material/publikationer/Partiklar-i-inomhusmiljon---en-litteraturgenomgang/

10. Luftkvalitetsförordning (Swedish Air Quality Ordinance) SFS 2010:477, Miljödepartementet (Ministry of the Environment and Energy, Sweden), 2010.

11. SS EN 779:2012, Particulate air filters for general ventilation – Determination of the filtration performance. Svensk Standard, CEN – European Committee for Standardization.

12. SP-metod 1937, P-märkning av luftfilter, Sveriges Tekniska Forskningsinstitut, Borås, Utgåva 5 2011 (P-labeling of air filters, SP Technical Research Institute of Sweden).

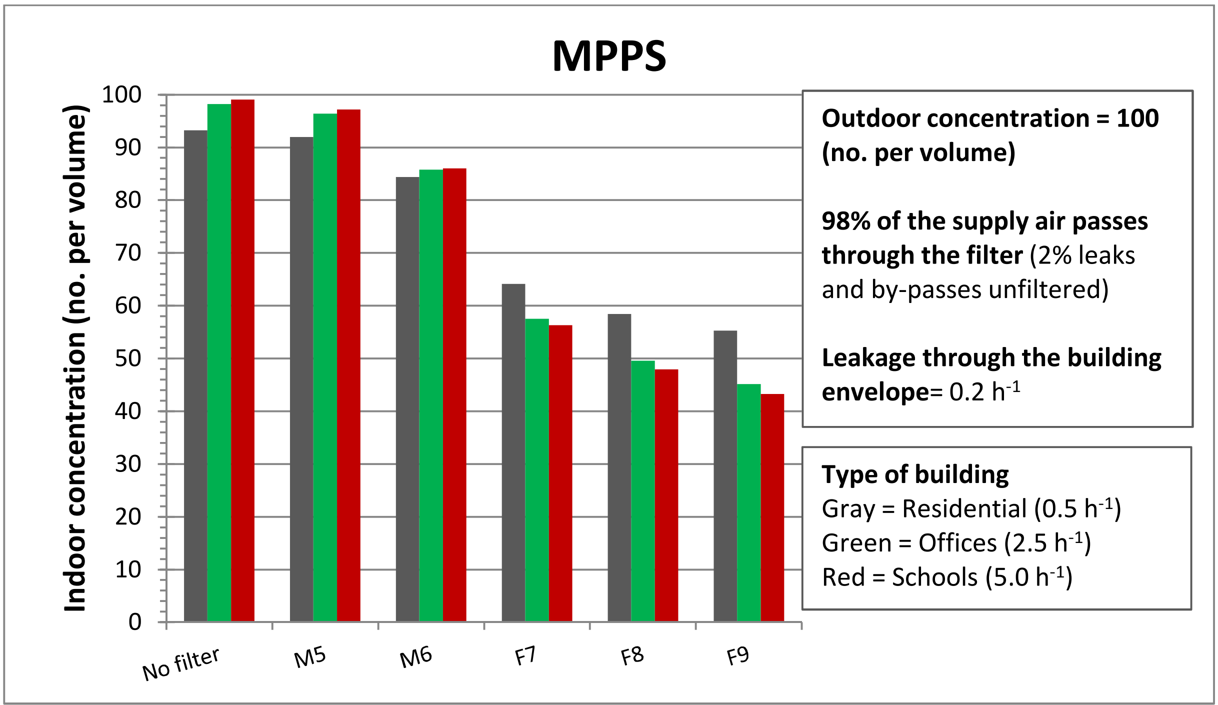
13. ISO/FDIS 16890-1:2016. Air filters for general ventilation — Part 1: Technical specifications, requirements and classification system based upon particulate matter efficiency (ePM), Final draft International Standard, ISO.
14. AFS 2009:2 med ändringar t o m AFS 2013:3. Arbetsplatsens utformning, Arbetsmiljöverkets föreskrifter om arbetsplatsens utformning samt allmänna råd om tillämpningen av föreskrifterna. (Swedish Work Environment Authority's regulations regarding the design of workplaces).
15. R1 Riktlinjer för Specifikation av Inneklimatkrav, Energi & Miljötekniska Föreningen, 2013 (guidelines for specifying indoor climate requirements, Society of Energy and Environmental Technology, Sweden).
16. Boverkets Byggregler – föreskrifter och allmänna råd, BFS 2011:6 med ändringar t o m BFS 2015:3, BBR22 (The Swedish building code – general regulations and advice regarding construction, National Board of Housing, Building and Planning, Sweden).
17. SS EN 13779, Luftbehandling – Funktionskrav på ventilations- och luftkonditioneringssystem, Utgåva 2, 2007 (functional requirements for ventilation and air conditioning systems).
18. Shi, Bingbing (2012). Removal of ultrafine particles by intermediate air filters in ventilation systems. Evaluation of performance and analysis of applications. Institutionen för Energi & Miljö, Avdelningen för Installationsteknik, Chalmers Tekniska Högskola, Göteborg. ISBN/ISSN: 978-91-7385-782-6 (Division of Building Services Engineering, Chalmers University of Technology, Gothenburg, Sweden).
19. NT VVS 114, Indoor Air Quality: Measurement of CO_2, Espoo, Finland, 1997.
20. Sikander, E. och Wahlgren, P. 2008. Alternativa metoder för utvärdering av byggnadsskalets lufttäthet Energiteknik, SP Rapport 2008:36, SP Sveriges Tekniska Forskningsinstitut (alternative methods for evaluating the air tightness of building envelopes, SP Technical Research Institute of Sweden).
21. BV2 – Byggnadens värmebalans i varaktighetsdiagram, version 2012, http://www.bv2.se/ (Building energy simulation software).
22. Blomsterberg, Å. And Burke, S. 2012, Airtightness of office and educational buildings in Sweden – Measurements and analyses, 33rd AIVC Conference Optimising Ventilative Cooling and Airtightness for [Nearly] Zero-Energy Buildings, IAQ and Comfort, Copenhagen, Denmark, 10-11 October 2012.
23. Liu, D. and Nazaroff, W.W. (2001) Modeling pollutant penetration across building envelopes, Atmos. Environ., Vol. 35, No. 26, pp. 4451-4462.
24. Riley, W.J., McKone, T.E., Lai, A.C., Nazaroff, W.W. (2002) Indoor particulate matter of outdoor origin: Importance of size-dependent removal mechanisms, Environ. Sci. Technol., Vol. 36, No.2, pp. 200-207.
25. SS-EN 1886:2007 Luftbehandling – Luftbehandlingsaggregat – Mekaniska Egenskaper, Svensk Standard, CEN – European Committee for Standardization (Swedish standard for air handling – air handing units).

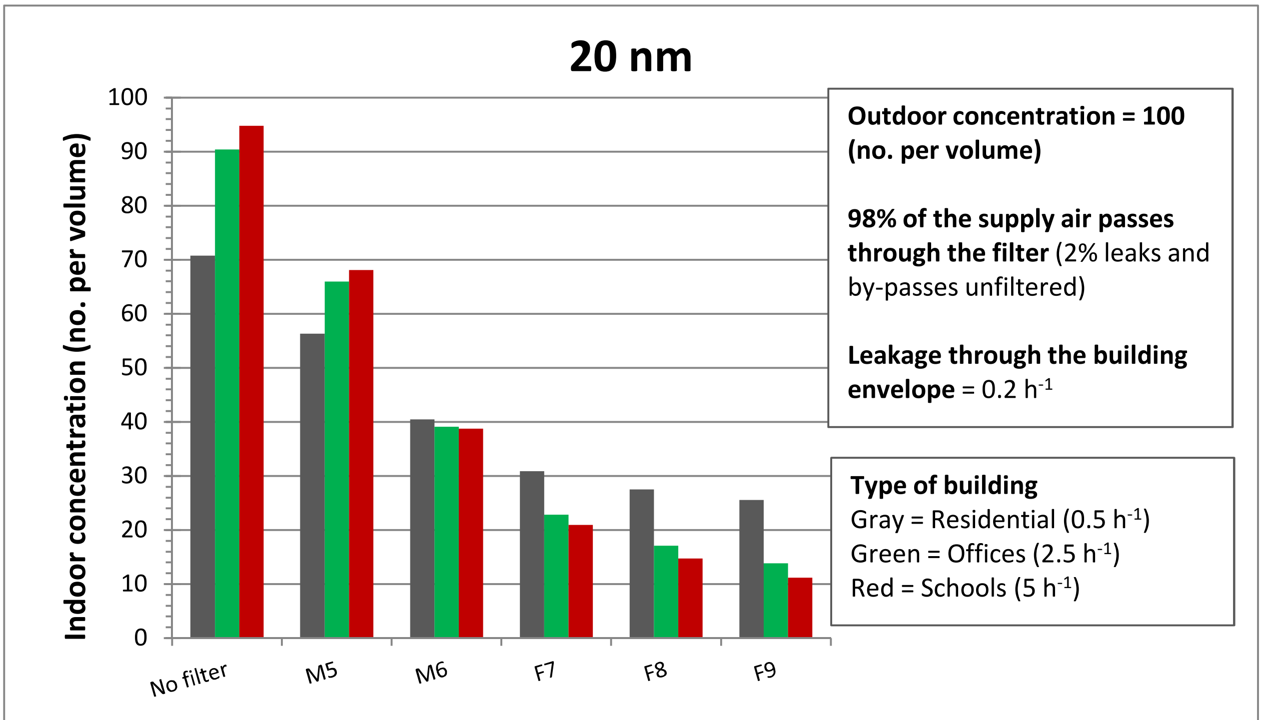
26. Hanley, J.T., Ensor, D.S., Smith, D.D., Sparks, L.E., 1994. Fractional Aerosol Filtration Efficiency of in-Duct Ventilation Air Cleaners. Indoor Air-International Journal of Indoor Air Quality and Climate, vol. 4, no. 3, pp. 169-178.

27. SS-EN 1822:2009, Högeffektiva luftfilter (EPA, HEPA och ULPA), del 1-5 (standard for high efficiency air filters in Sweden).

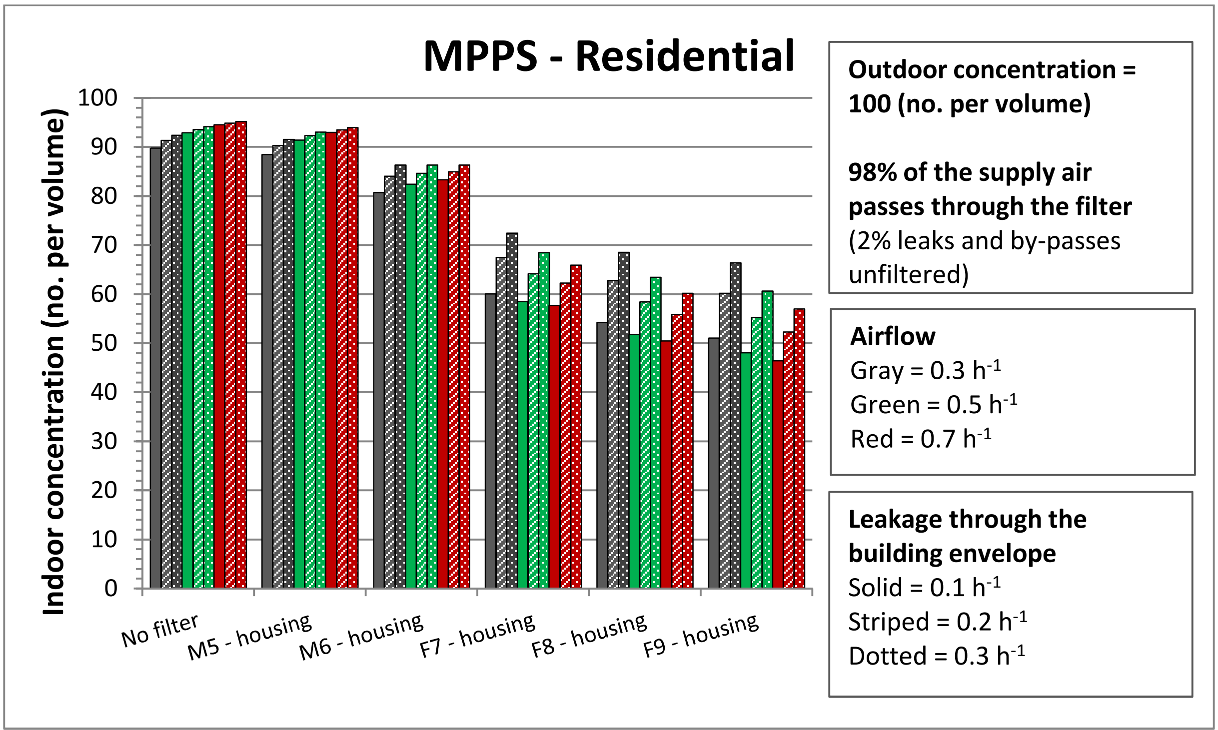
28. El Orch, Z., Stephens, B., Waring, M.S. (2014) Predictions and determinants of size-resolved particle infiltration factors in single-family homes in the U.S., Building and Environment 74, pp. 106-118.

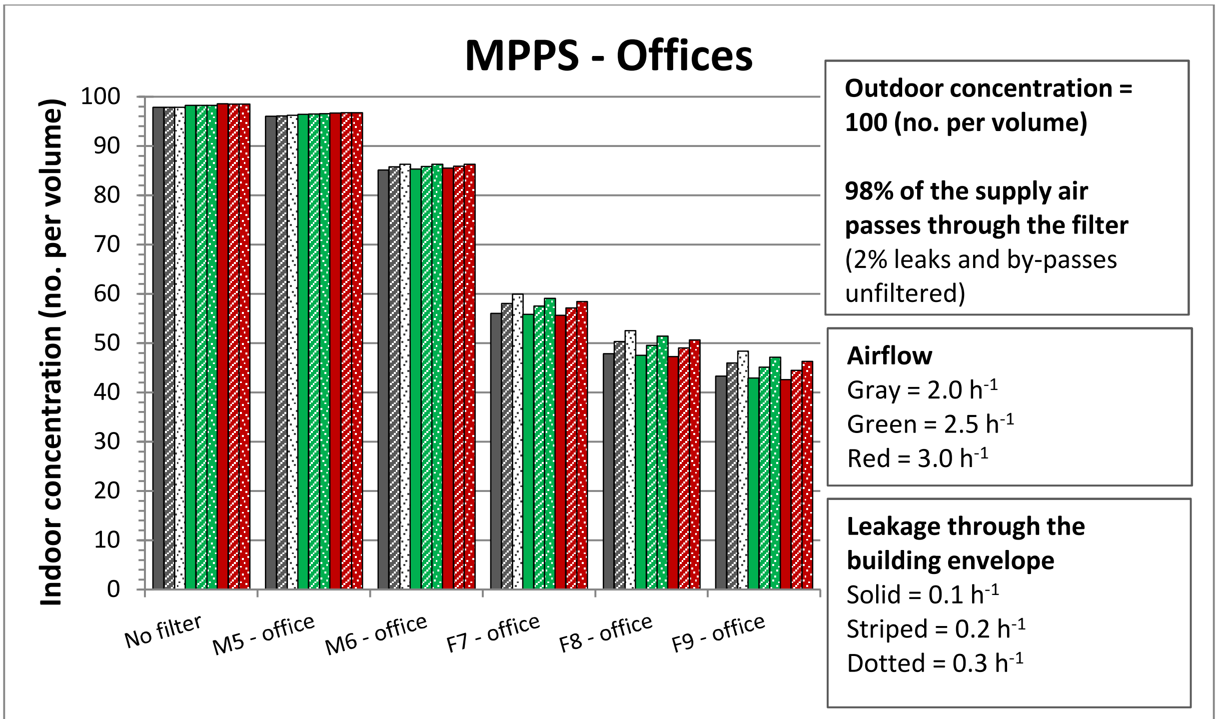
Appendix 1. Indoor particle concentration for different types of buildings and glass-fiber filters of different classes

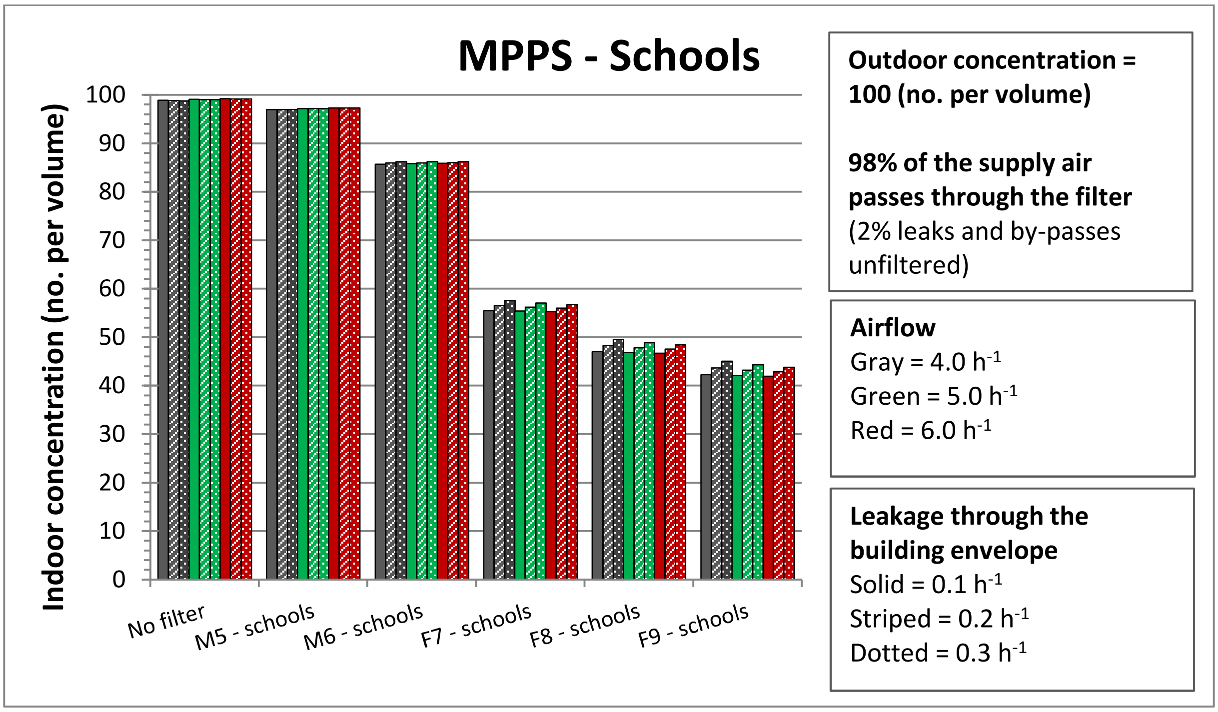


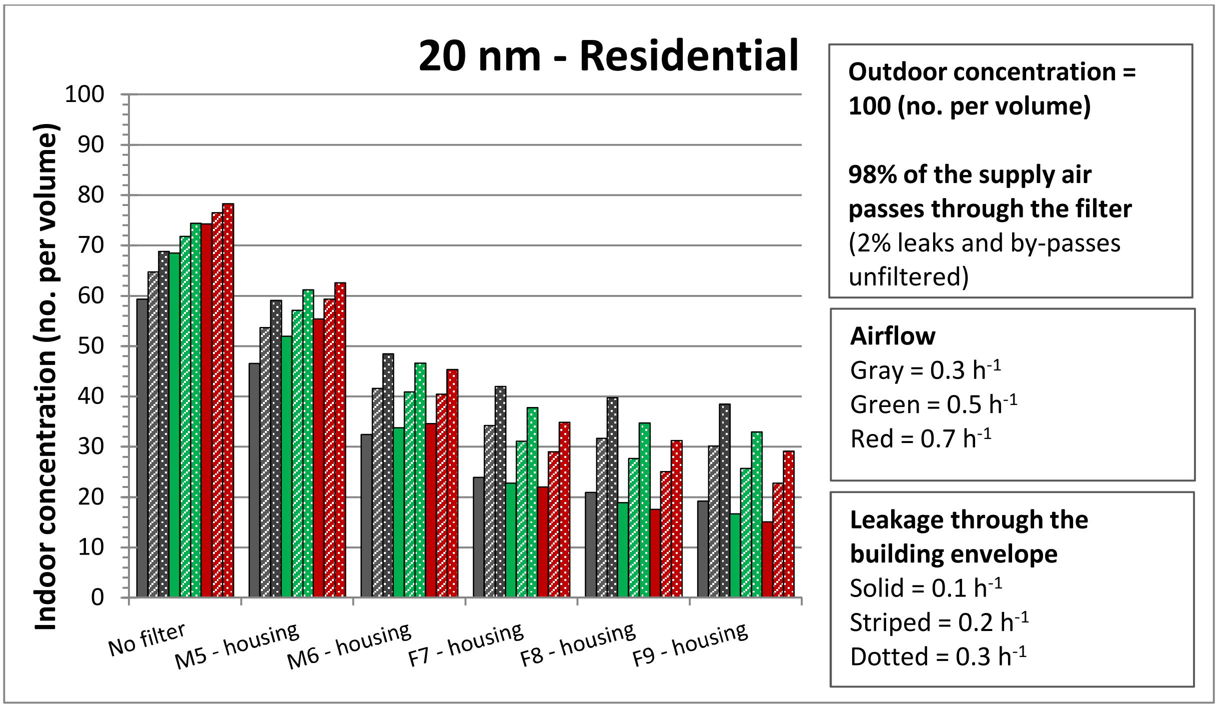


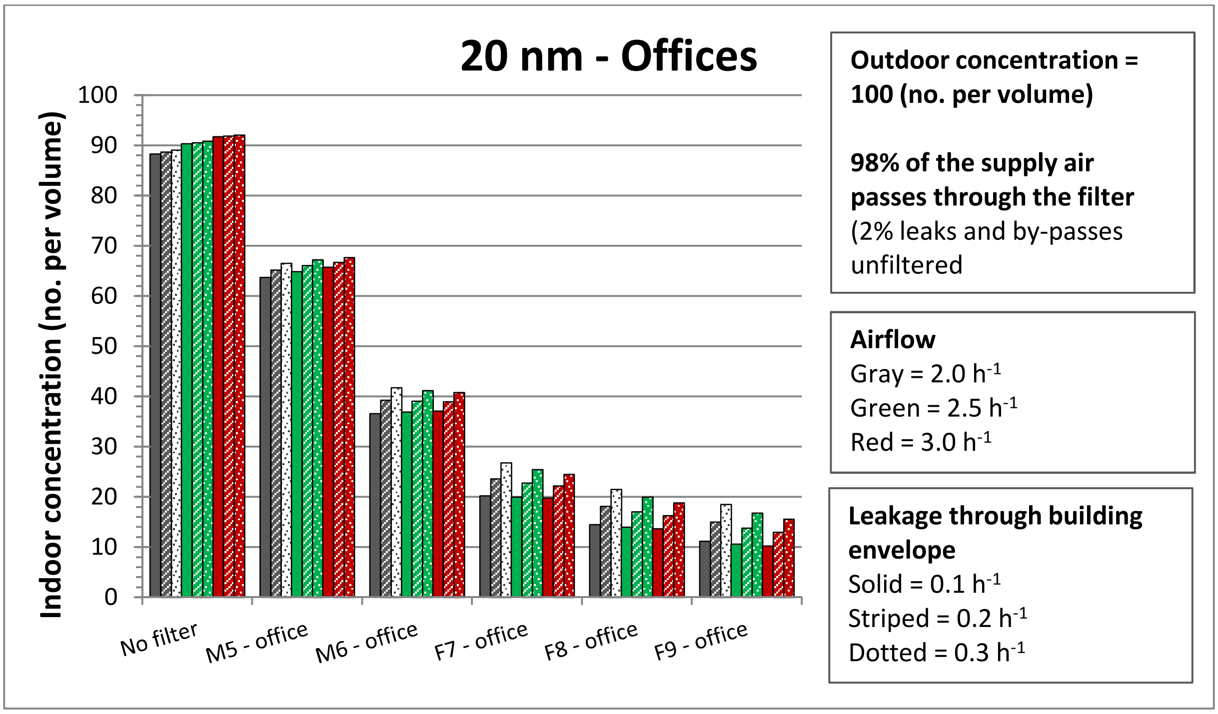
Appendix 2. Indoor particle concentration for different types of buildings, with different air change rates and leakage through the building envelope

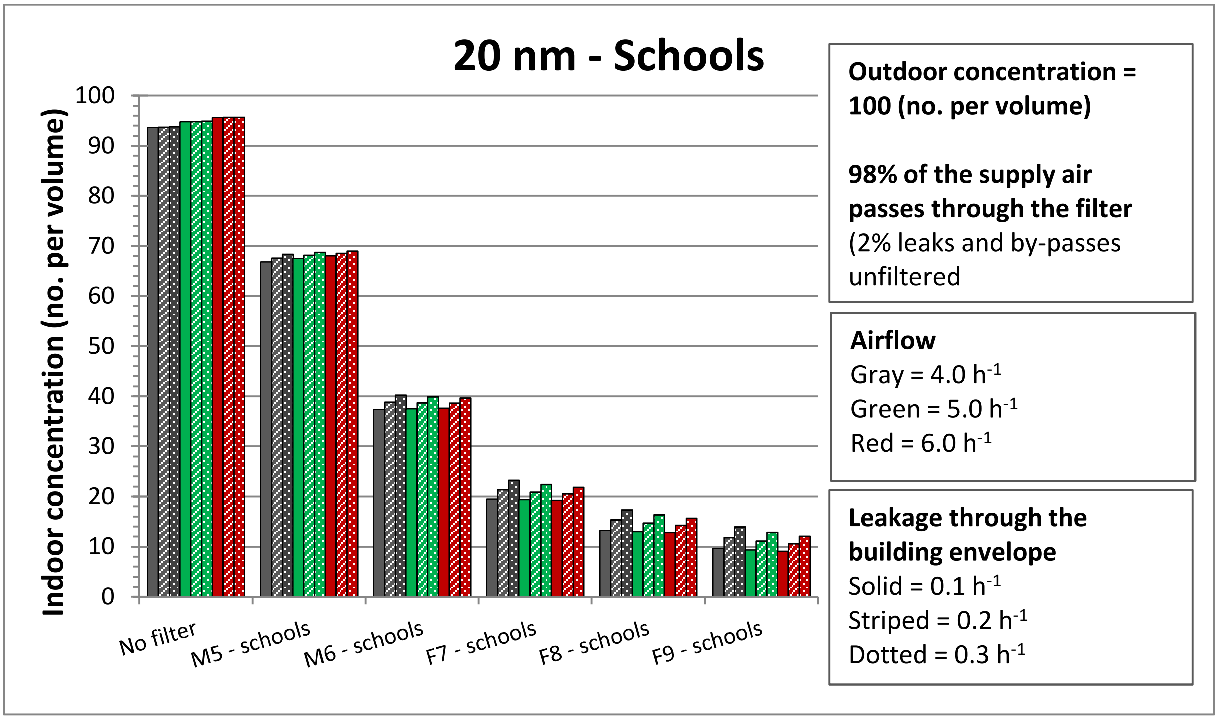




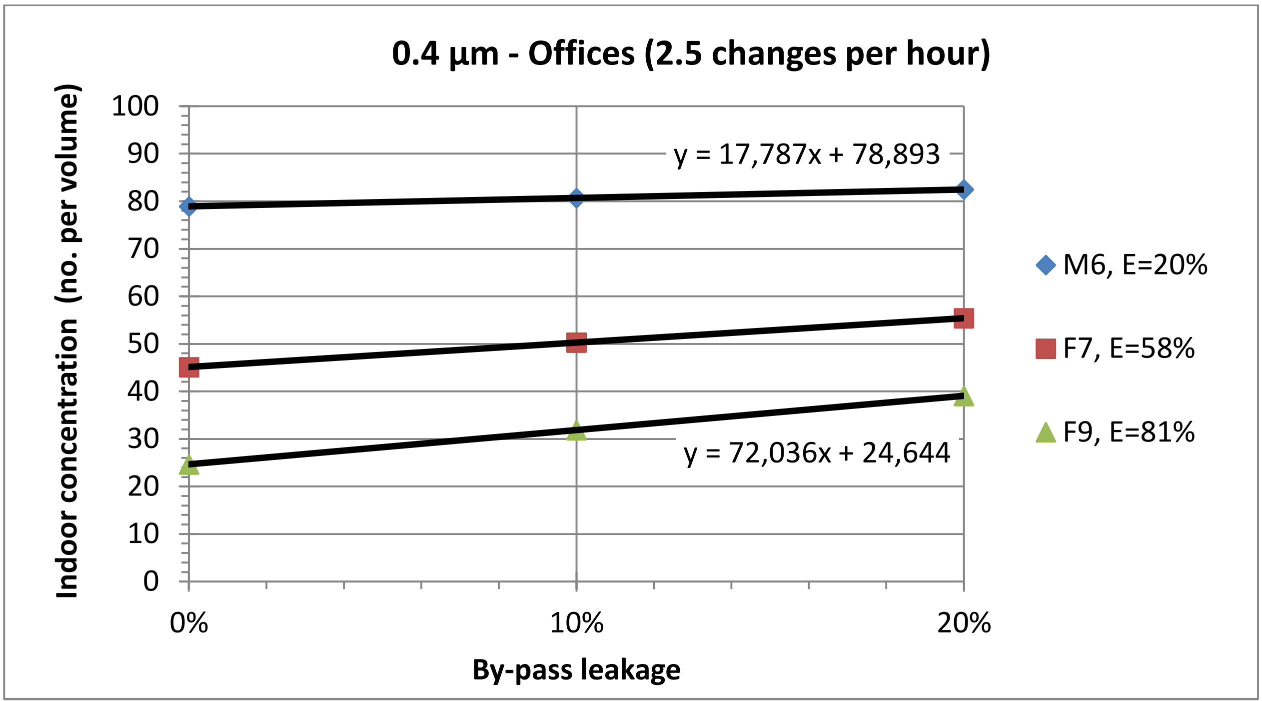

MPPS - Schools
Indoor concentration (no. per volume)
100
90
80
70
60
50
40
30
20
10
0
No filter
M5 - schools
M6 - schools
F7 - schools
F8 - schools
F9 - schools
Outdoor concentration = 100 (no. per volume)
98% of the supply air passes through the filter
(2% leaks and by-passes unfiltered)
Airflow
Gray = 4.0 h-1
Green = 5.0 h-1
Red = 6.0 h-1
Leakage through the building envelope
Solid = 0.1 h-1
Striped = 0.2 h-1
Dotted = 0.3 h-1

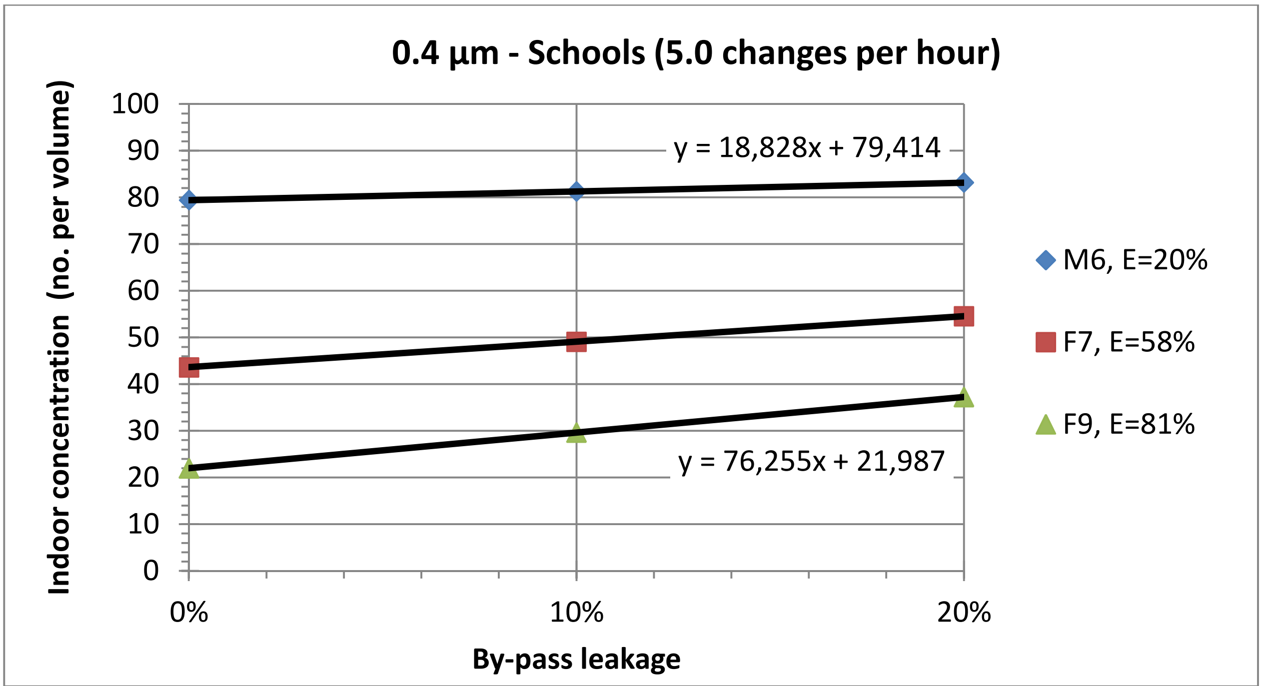

20 nm - Residential
Indoor concentration (no. per volume)
100
90
80
70
60
50
40
30
20
10
0
No filter
M5 - housing
M6 - housing
F7 - housing
F8 - housing
F9 - housing
Outdoor concentration = 100 (no. per volume)
98% of the supply air passes through the filter
(2% leaks and by-passes unfiltered)
Airflow
Gray = 0.3 h-1
Green = 0.5 h-1
Red = 0.7 h-1
Leakage through the building envelope
Solid = 0.1 h-1
Striped = 0.2 h-1
Dotted = 0.3 h-1


20 nm - Offices
Indoor concentration (no. per volume)
100
90
80
70
60
50
40
30
20
10
0
No filter
M5 - office
M6 - office
F7 - office
F8 - office
F9 - office
Outdoor concentration = 100 (no. per volume)
98% of the supply air passes through the filter
(2% leaks and by-passes unfiltered
Airflow
Gray = 2.0 h-1
Green = 2.5 h-1
Red = 3.0 h-1
Leakage through building envelope
Solid = 0.1 h-1
Striped = 0.2 h-1
Dotted = 0.3 h-1


20 nm - Schools
Indoor concentration (no. per volume)
100
90
80
70
60
50
40
30
20
10
0
No filter
M5 - schools
M6 - schools
F7 - schools
F8 - schools
F9 - schools
Outdoor concentration = 100 (no. per volume)
98% of the supply air passes through the filter
(2% leaks and by-passes unfiltered
Airflow
Gray = 4.0 h-1
Green = 5.0 h-1
Red = 6.0 h-1
Leakage through the building envelope
Solid = 0.1 h-1
Striped = 0.2 h-1
Dotted = 0.3 h-1

Appendix 3. Effect of leakage by-passing the filter





Appendix 4. Measurements in test chamber

This section reports the results of particle measurements in a test chamber. The tests were conducted in January 2016. The purpose of the tests was to verify the results of calculations.

Method

The test chamber was located at Camfil AB in Trosa, Sweden. The interior surfaces of the chamber were made of polished stainless steel and had the dimensions $2.49 \times 3.35 \times 2.36$ m. The interior volume was therefore 19.7 m^3. An air handling unit (AHU) was used to ventilate the chamber that supplied air from the laboratory hall where the chamber was placed. Measurements were made without filters and with filters of different classes. The filters were bag filters with glass-fiber media in quarter-sized modules. A small fan located inside the chamber carefully mixed the air in the chamber.

In addition to the supply air, a small flow of unfiltered air was supplied from the laboratory hall to simulate the leakage of outdoor air through untight parts of the building envelope. This air was provided through a hose with an interior diameter of 38 mm. The supply airflow and exhaust airflow were determined by measuring the pressure drop over the calibrated measurement flanges.

Particle concentrations were measured with two TSI particle counters, model AeroTrak. The counters were calibrated simultaneously and the particle count measured on one instrument was approximately 3% lower for particles 0.3 µm to 0.5 µm in diameter. The test results were adjusted for this deviation. One of the particle counters was used to measure the particle concentration outside the test chamber by the air intake for the AHU. The other particle counter was used to measure the particle concentration in the supply air and inside the chamber.

Results

Table B4.1 summarizes the measurement results outside the chamber and in the supply air, without filters and with filters of different quality mounted in the AHU. The test results were used to calculate the penetration through the filters and the efficiency of the filters.

Table B4.1. Results of particle measurements before and after the supply air system. The results are for particles 0.3 µm to 0.5 µm in diameter.

Case	Penetration		Efficiency
	Average value	Standard deviation	
Without filter	105%	4%	-
Filter A	99%	7%	1%
Filter B	77%	3%	23%
Filter C	75%	4%	25%
Filter D	45%	3%	55%
Filter E	13%	1%	87%

A series of measurements was made without filters, with a supply airflow corresponding to 1.0 air changes per hour and without a flow of leaking air. The quotient between the indoor concentration inside the chamber and outside (the I/O quotient) stabilized at 0.83. The particle concentration in the chamber was therefore 83% of the outside concentration.

According to the theory described in the main section of this report, the particle concentration in the chamber, based on the conditions described above, will be 92% of the outside concentration, or 9 percentage points higher than what the measurement showed. This figure is valid on the assumption that the particle deposition rate in the chamber is k_{dep}= 0.08 h^{-1}. If we assume instead that the deposition rate is k_{dep}=0.18 h^{-1}, the estimate will be completely in agreement with the measurement result, meaning that the estimated particle concentration in the chamber will be 83% of the outside concentration. As noted in the report under the subheading *Deposition of particles indoors*, the deposition rate can vary considerably between different rooms and the obtained measurement result is therefore completely reasonable. Measurements without filters indicated that the deposition rate in the test chamber was 0.18 h^{-1}.

Table B4.2 shows the results of six more series of tests using different combinations of filters, air change rates and leakage airflows. The “air leakage” created in the test chamber had a concentration of particles 0.3 µm to 0.5 µm in diameter that was 89% of the particle concentration outside the test chamber. As shown in Table B4.2, the difference between the measured and estimated results was 7 percentage points at the most.

Table B4.2. Results of particle measurements inside and outside the test chamber, together with the estimated results. The calculations were based on a deposition rate set at k_{dep} 0.18h^{-1}. The results are for particles 0.3 µm to 0.5 µm in diameter.

Case	Measured I/O quotient*		Estimated I/O quotient	Difference between measurement and estimate
	Average value	Standard deviation		
Without filter Ventilation = 2.5 h^{-1} Leakage = 0.2 h^{-1}	88%	3%	92%	4 percentage points
Filter B Ventilation = 2.5 h^{-1} Leakage = 0.2 h^{-1}	67%	3%	73%	6 percentage points
Filter D Ventilation = 2.5 h^{-1} Leakage = 0.2 h^{-1}	38%	2%	45%	7 percentage points
Filter E Ventilation = 2.5 h^{-1} Leakage = 0.2 h^{-1}	20%	1%	18%	2 percentage points
Filter E Ventilation = 1.0 h^{-1} Leakage = 0 h^{-1}	12%	1%	12%	0 percentage points
Filter E Ventilation = 1.0 h^{-1} Leakage = 0.3 h^{-1}	20%	2%	20%	0 percentage points

**Concentration in test chamber in relation to the outside concentration, expressed as a percentage.*

Appendix 5. Calculation results for cases with return air

The following diagrams show the results of calculations with the equation (1) that were made on the assumption that return air is used. In the calculation used for Figure B5.1, the deposition rate k_{dep} and the infiltration rate q_{leak} have both been set at zero. This is therefore a theoretical case in which no particles are deposited indoors and there is no air leakage through the building envelope. The supply airflow (the sum of outdoor air and return air) is constant. Under these conditions, the diagram will be valid for any supply air flow rate, as long as it is constant. The estimates are for a case in which the return airflow and outdoor airflow are mixed and filtered in a single bank of filters, see Figure 5. The result will be the same if the outdoor airflow and return airflow are filtered separately – as long as both banks of filters contain filters of the same efficiency.

With 0% return air, there is no return airflow, in which case the supply airflow consists of 100% filtered or unfiltered outdoor air. The indoor concentration of particles, in relation to the outdoor concentration, will therefore have the same value as the filter's efficiency. With 100% return air, the entire supply airflow will consist of filtered or unfiltered indoor air. Since the outdoor airflow is zero and the calculation model only has to take into account the particles supplied from outdoors, the particle concentration will be zero, regardless of the filter's efficiency.

With 50% return air, the return airflow will be as large as the outdoor airflow. The particle concentration in the indoor air is determined by the balance between the number of particles supplied from outdoors and the number of particles captured by the filter.

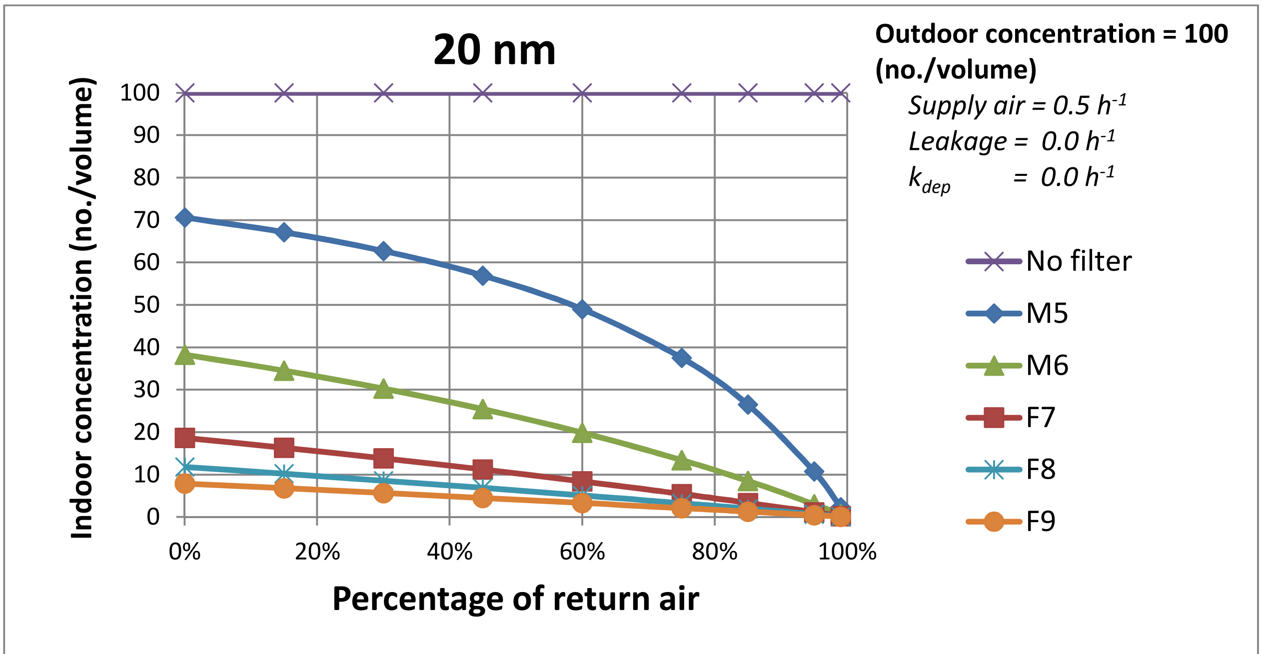


Figure B5.1. The indoor particle concentration as a function of the percentage of return air. The diagram is based on the assumption that the indoor particle deposition rate and air filtration rate through the building envelope are zero (k_{dep} = 0 and q_{leak} = 0). The outdoor particle concentration has been set at 100 particles per unit volume of air.

In the following diagrams, the particle deposition rate has been set at $k_{dep} = 0.25\ h^{-1}$. Calculations have been made for two levels of air leakage through the building envelope. In the one case, the air leakage corresponds to 0.1 air changes per hour, and in the other case, it is 0.3 air changes per hour ($q_{leak}/V = 0.1\ h^{-1}$ and $0.3\ h^{-1}$).

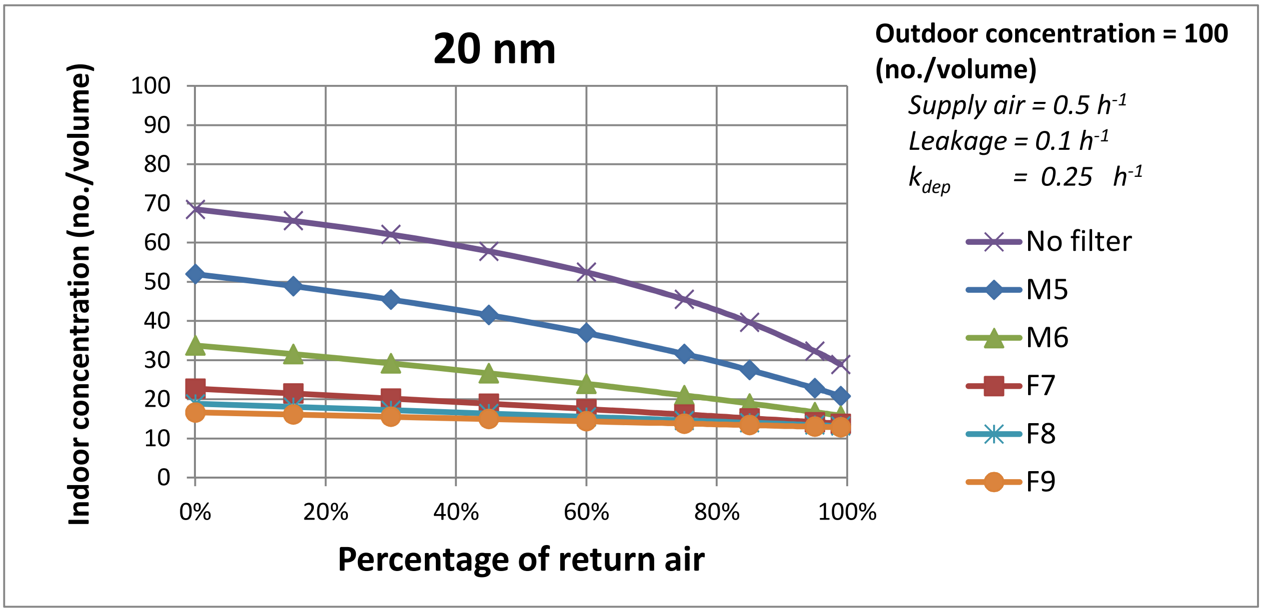


Figure B5.2. The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 0.5 air changes per hour. The particle deposition rate has been set at $0.25\ h^{-1}$ and air leakage corresponds to 0.1 air changes per hour.

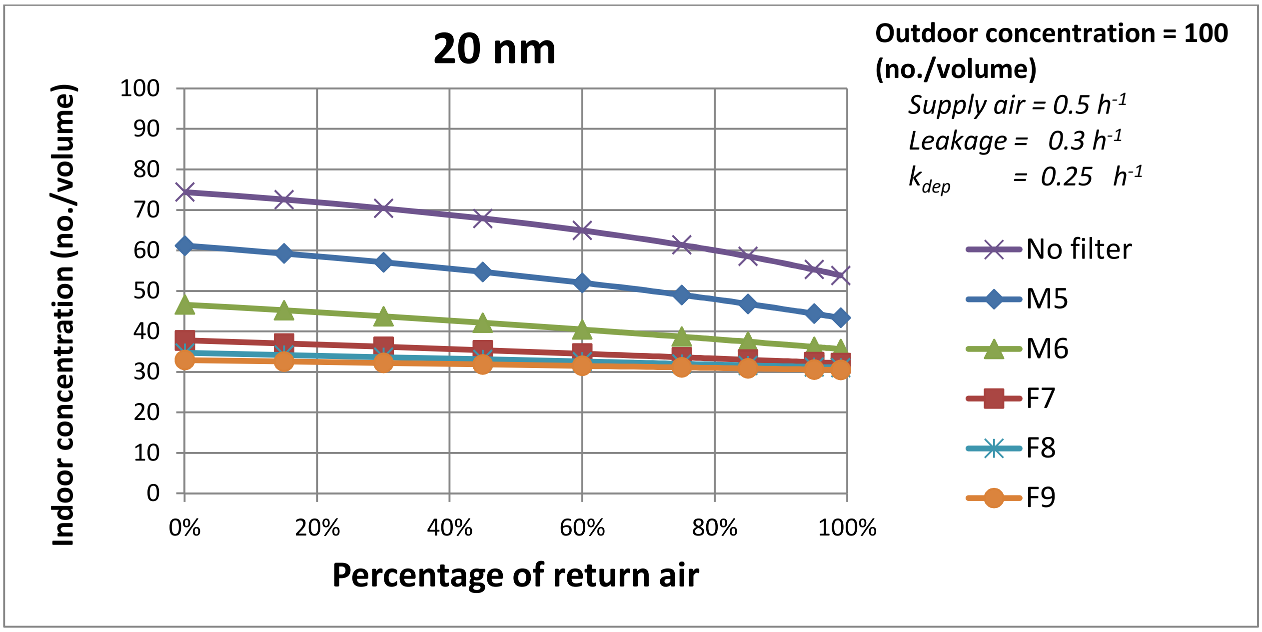


Figure B5.3. The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 0.5 air changes per hour. The particle deposition rate has been set at $0.25\ h^{-1}$ and air leakage corresponds to 0.3 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

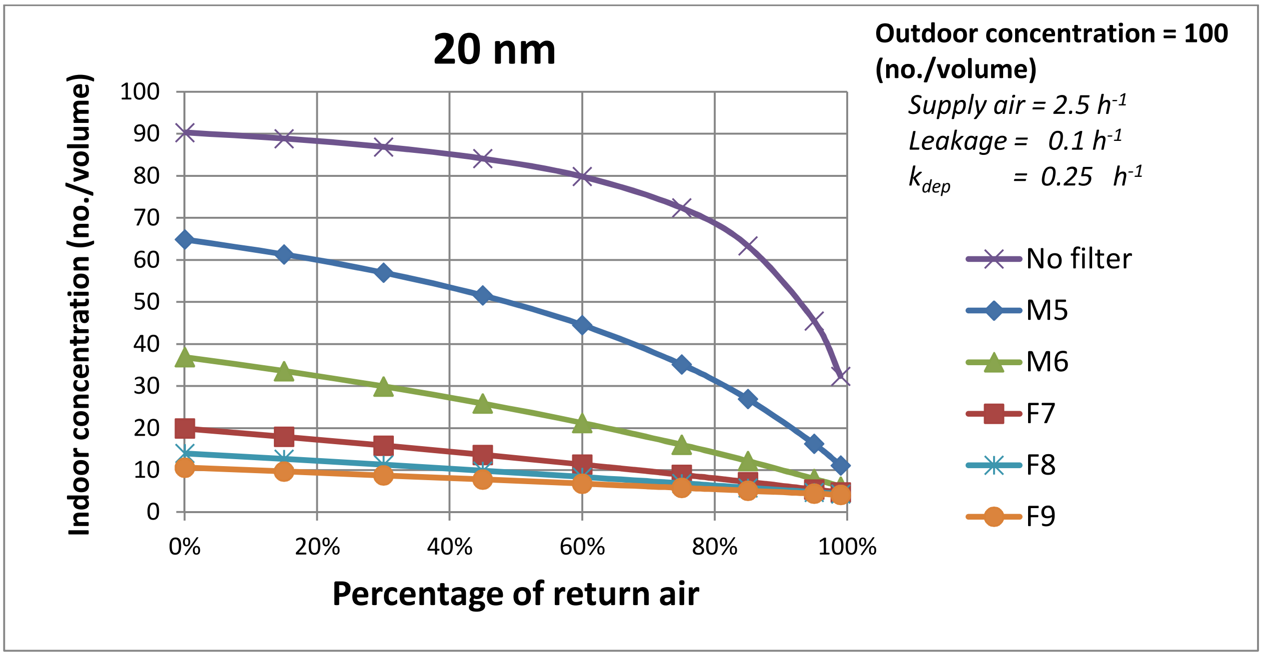


Figure B5.4. The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 2.5 air changes per hour. The particle deposition rate has been set at 0.25 h^{-1} and air leakage corresponds to 0.1 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

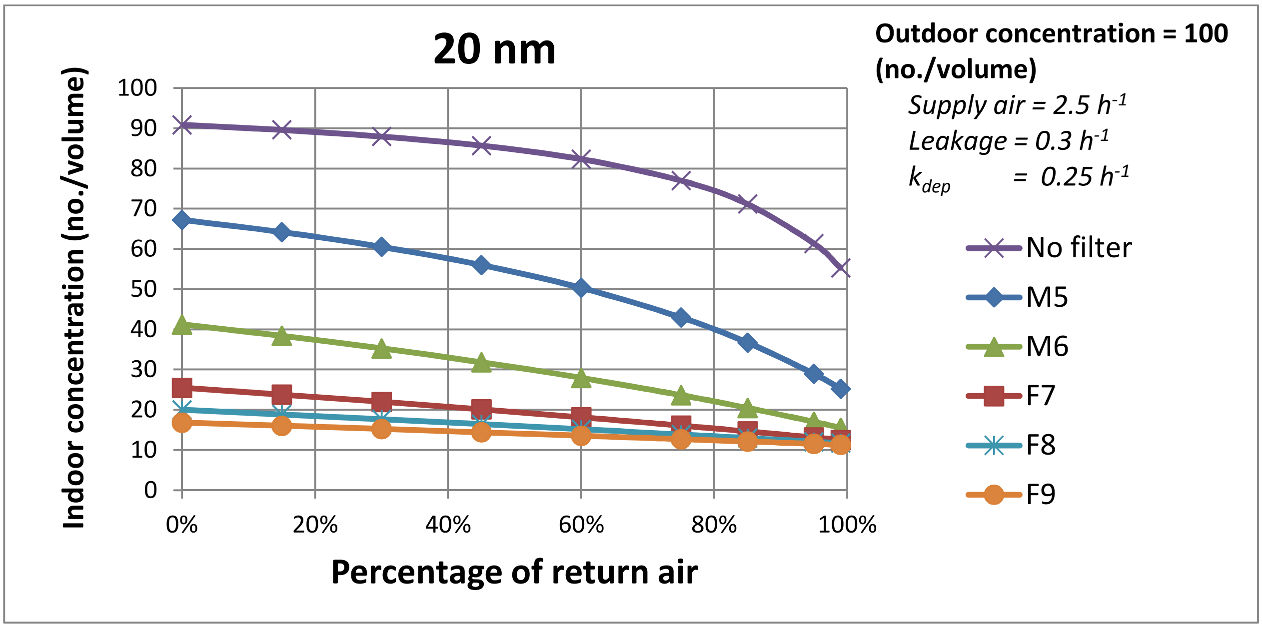


Figure B5.5. The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 2.5 air changes per hour. The particle deposition rate has been set at 0.25 h^{-1} and air leakage corresponds to 0.3 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

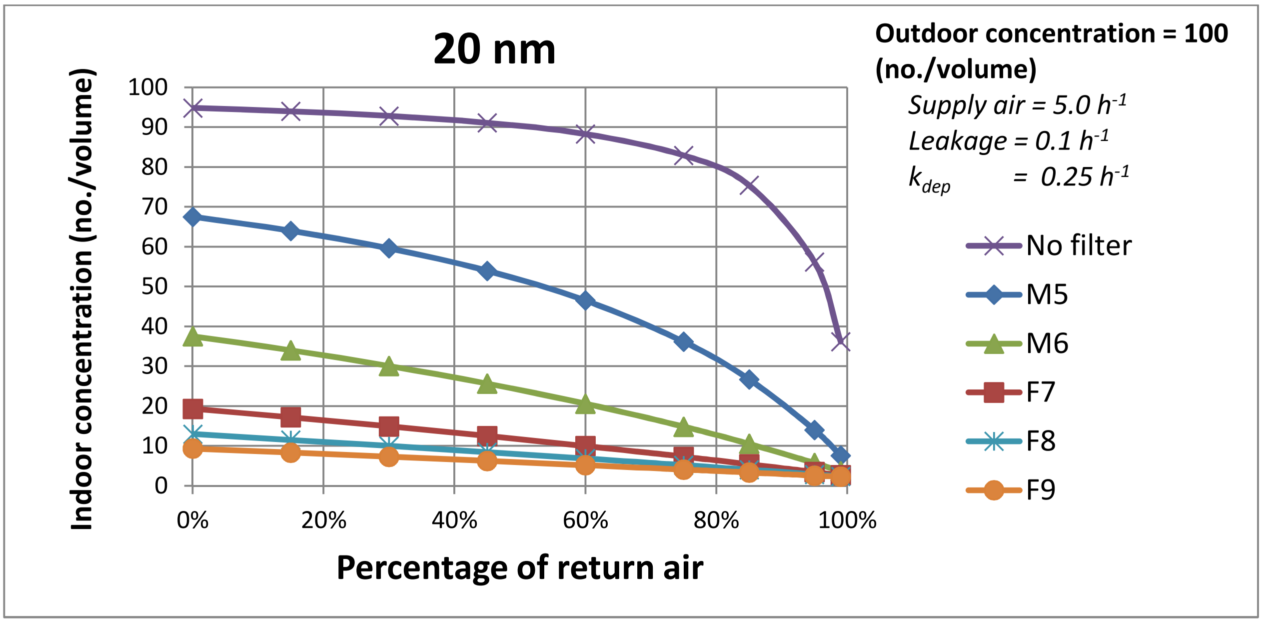


Figure B5.6. The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 5.0 air changes per hour. The particle deposition rate has been set at 0.25 h^{-1} and air leakage corresponds to 0.1 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

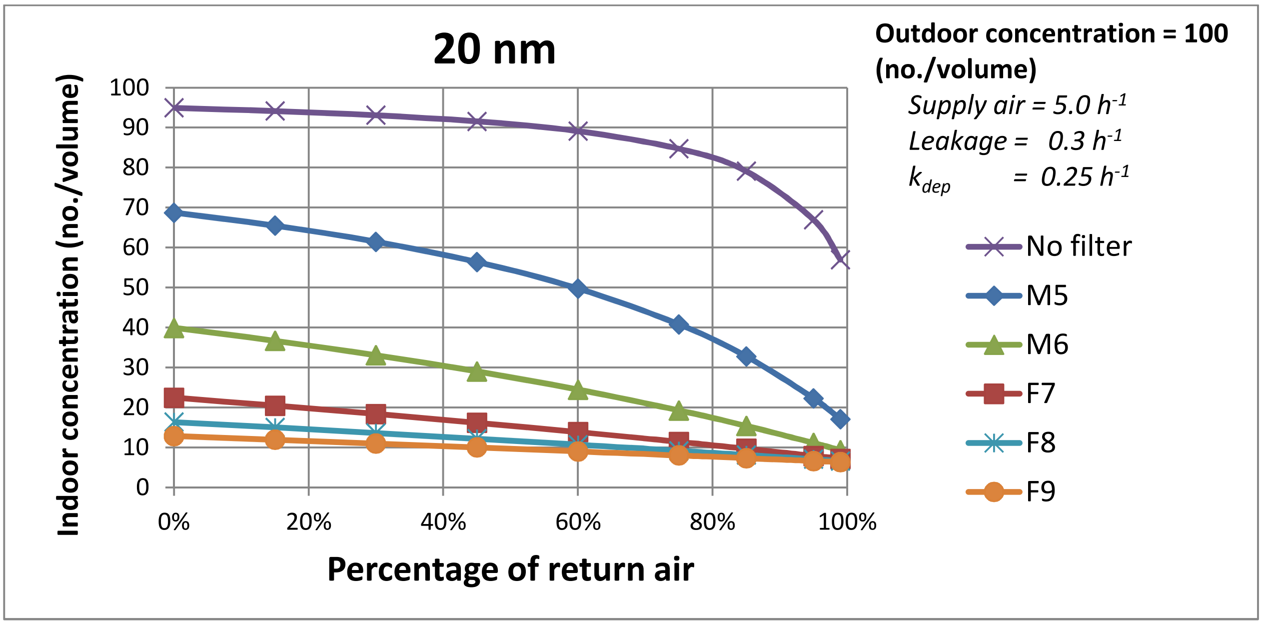


Figure B5.7. The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 5.0 air changes per hour. The particle deposition rate has been set at 0.25 h^{-1} and air leakage corresponds to 0.3 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

Appendix 6. Diagrams with filter classifications according to ISO/FDIS 16890 – cases without return air

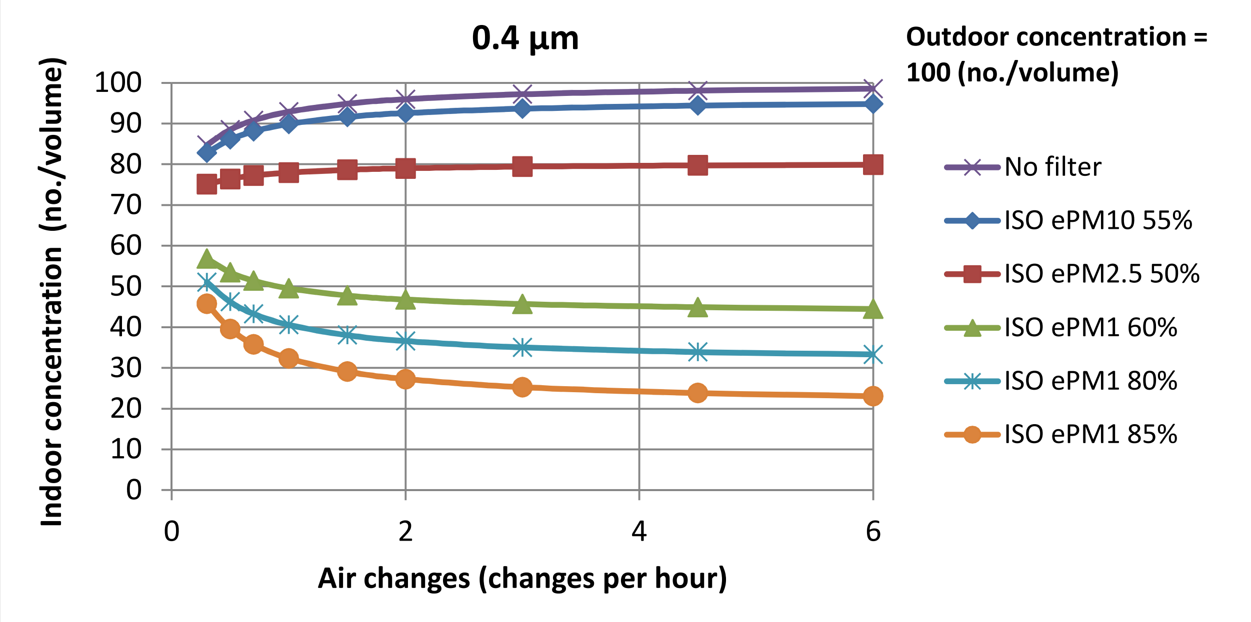


Figure B6.1 *(Figure 6 in the main section of the report).* The calculation of the concentration of 0.4 µm particles in the indoor air was made on the assumption that the outdoor concentration has a value of 100. Air leakage through the building envelope has been set at 0.2 air changes per hour and 2% of the outdoor airflow is assumed to leak by the filter without being cleaned. The efficiencies of the filters are for the glass-fiber filters listed in Table 1a.

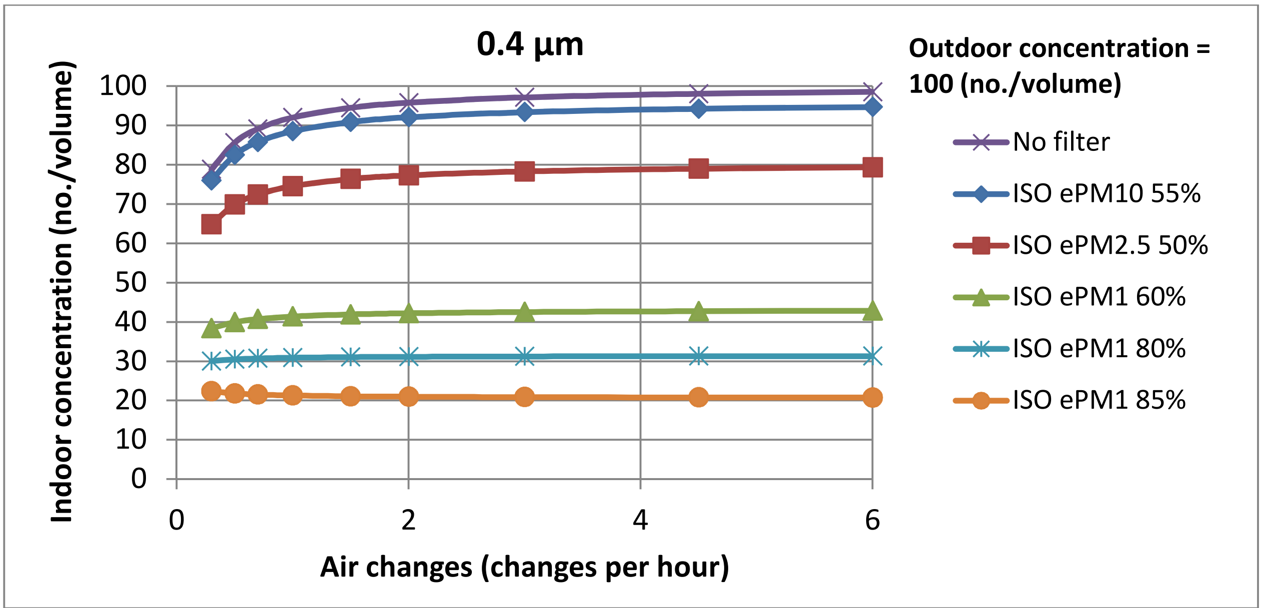


Figure B6.2 *(Figure 7 in the main section of the report).* The calculation of the concentration of 0.4 µm particles in the indoor air was made on the assumption that the outdoor concentration has a value of 100. The calculation is for a very tight building. Air leakage through the building envelope has been set at 0.03 air changes per hour and 2% of the outdoor airflow is assumed to leak by the filter without being cleaned. The efficiencies of the filters are for the glass-fiber filters listed in Table 1a.

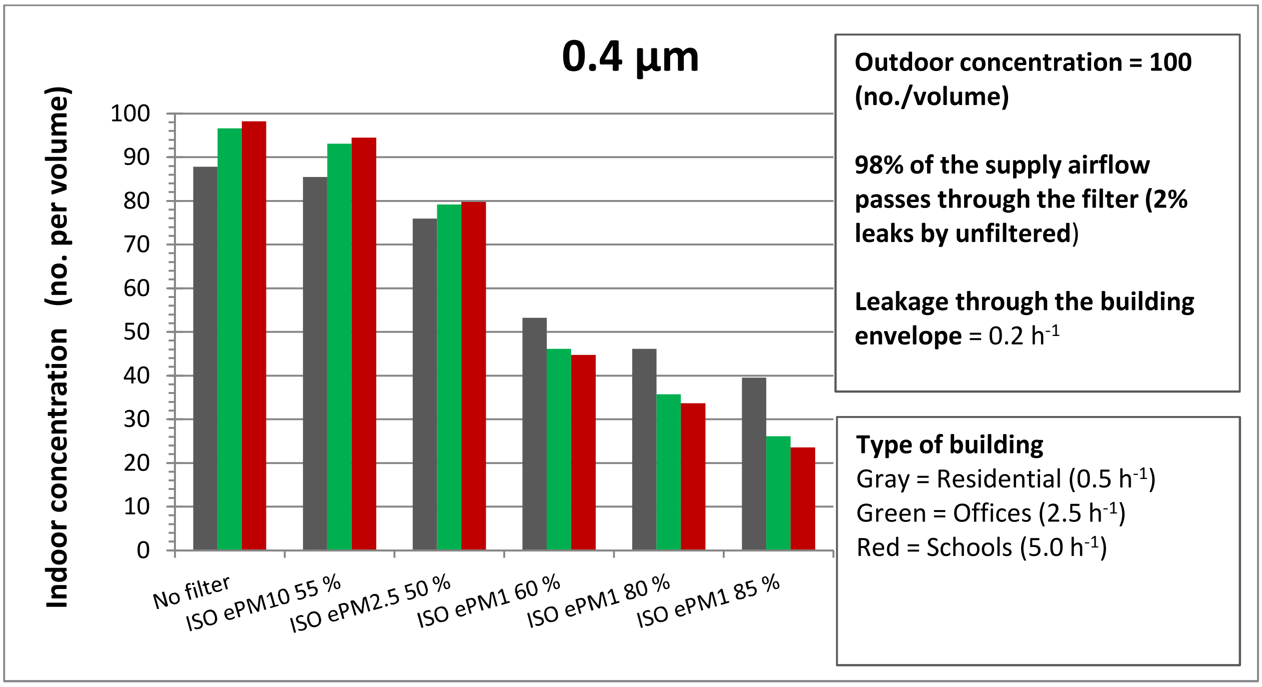


Figure B6.3 *(Figure 8 in the main section of the report).* The calculation of the concentration of 0.4 µm particles in the indoor air was made on the assumption that the outdoor concentration has a value of 100. Data are reported for residential buildings (0.5 changes/hour), offices (2.5 changes/hour) and schools (5.0 changes/hour). Air leakage through the building envelope has been set at 0.2 air changes per hour for all three building types and 2% of the outdoor airflow is assumed to leak by the filter without being cleaned. The efficiencies of the filters are for the glass-fiber filters listed in Table 1a.

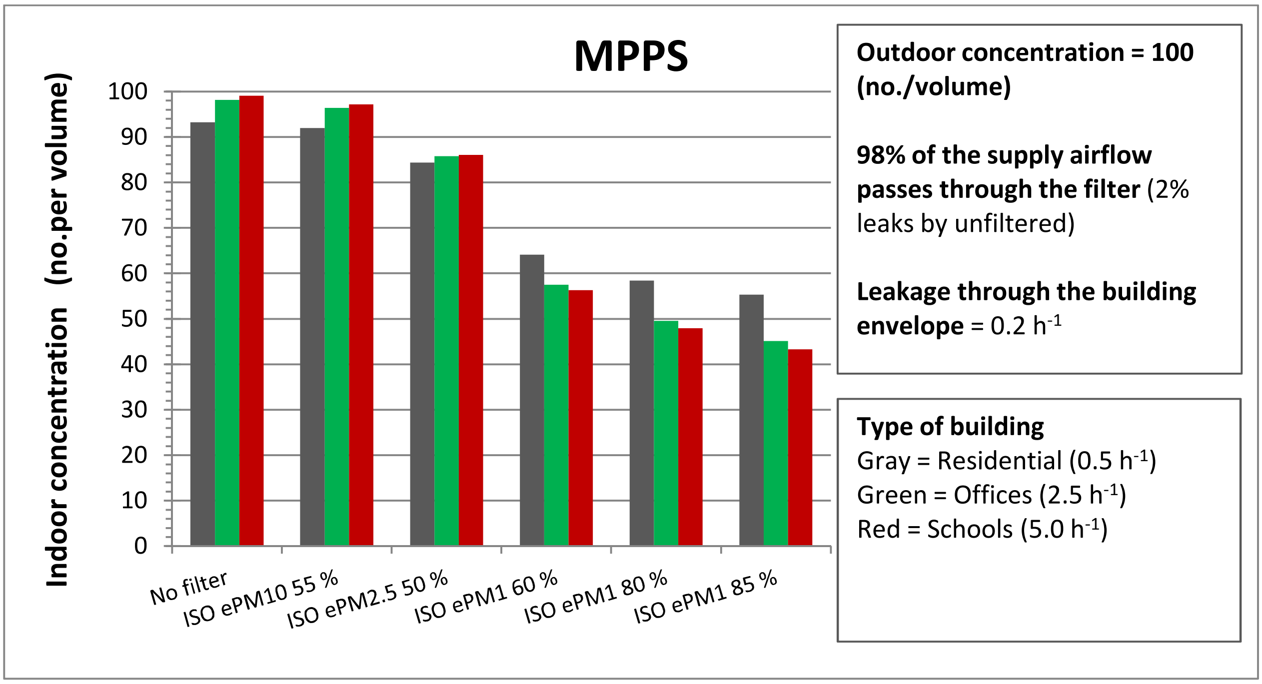


Figure B6.4 *(Top figure in Appendix 1).* The indoor concentration of MPPS is calculated for the different types of buildings with glass-fiber filters of different classes. The conditions are the same as those in Figure B6.3.

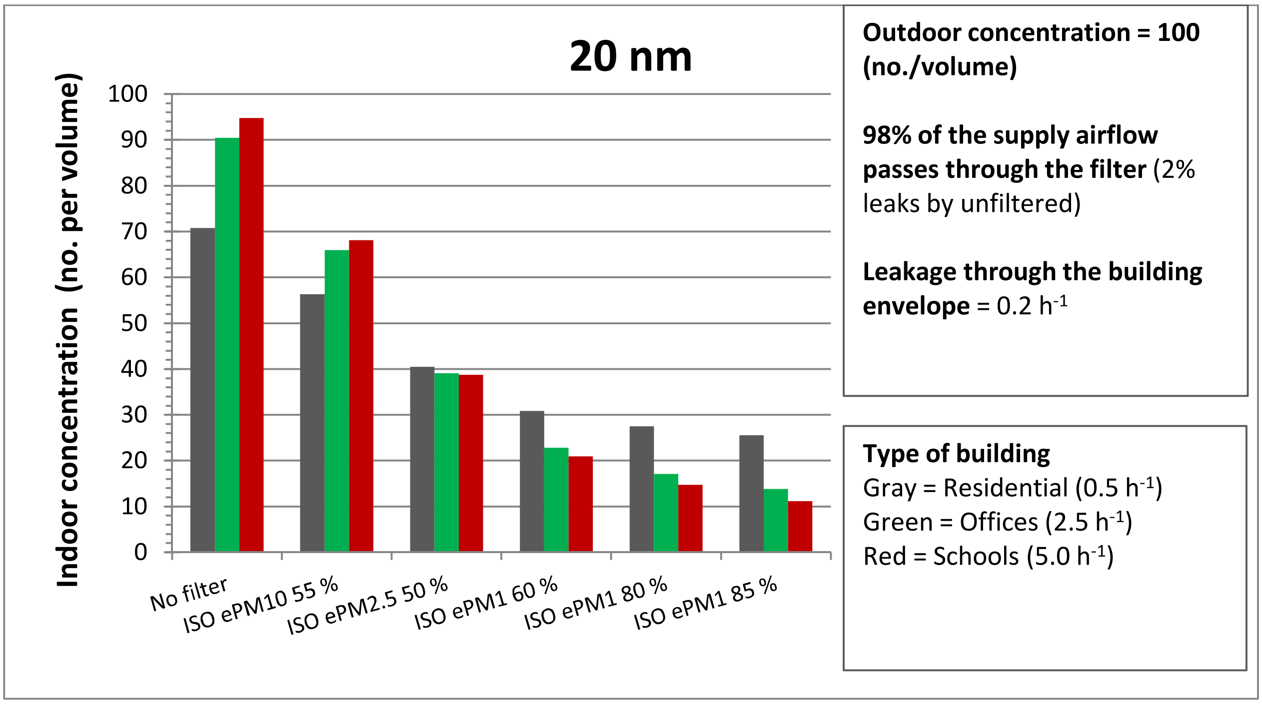


Figure B6.5 *(Bottom figure in Appendix 1).* The indoor concentration of 20 nm particles is calculated for the different types of buildings with glass-fiber filters of different classes. The conditions are the same as those in Figure B6.3.

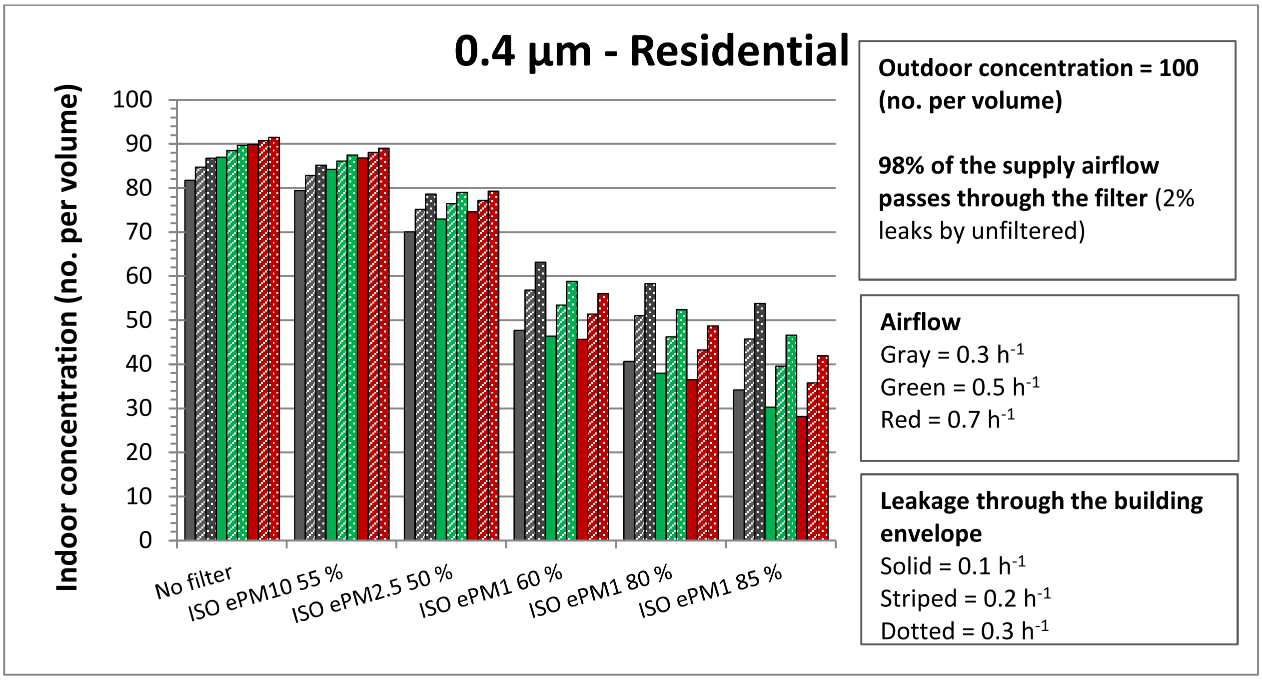


Figure B6.6 *(Figure 9a in the main section of the report).* The particle concentrations in residential buildings are calculated for ventilation airflows corresponding to 0.3 to 0.7 air changes per hour and for different amounts of air leakage through the building envelope (between 0.1 and 0.3 air changes per hour). The efficiencies of the filters are for the glass-fiber filters shown in Table 1a.

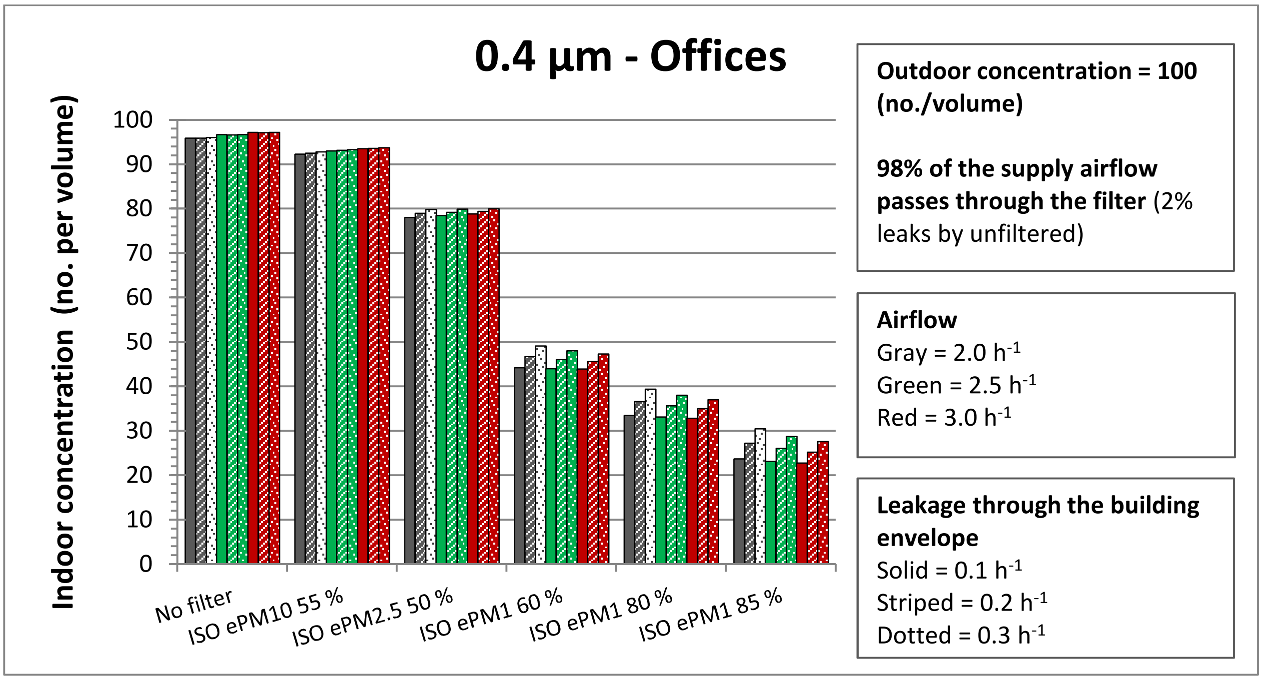


Figure B6.7 *(Figure 9b in the main section of the report).* The particle concentrations in offices are calculated for ventilation airflows corresponding to 2.0 to 3.0 air changes per hour and for different amounts of air leakage through the building envelope (between 0.1 and 0.3 air changes per hour). The efficiencies of the filters are for the glass-fiber filters listed in Table 1a.

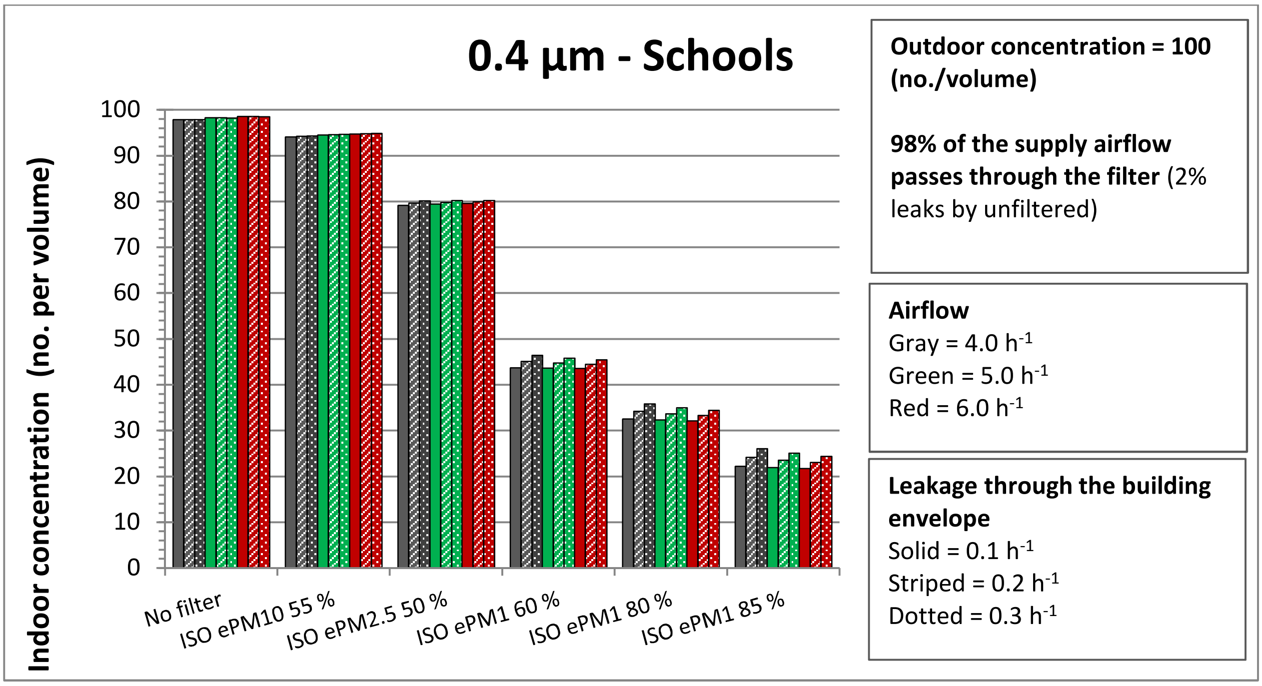


Figure B6.8 *(Figure 9c in the main section of the report).* The particle concentrations in schools are calculated for ventilation airflows corresponding to 4.0 to 6.0 air changes per hour and for different amounts of air leakage through the building envelope (between 0.1 and 0.3 air changes per hour). The efficiencies of the filters are for the glass-fiber filters listed in Table 1a.

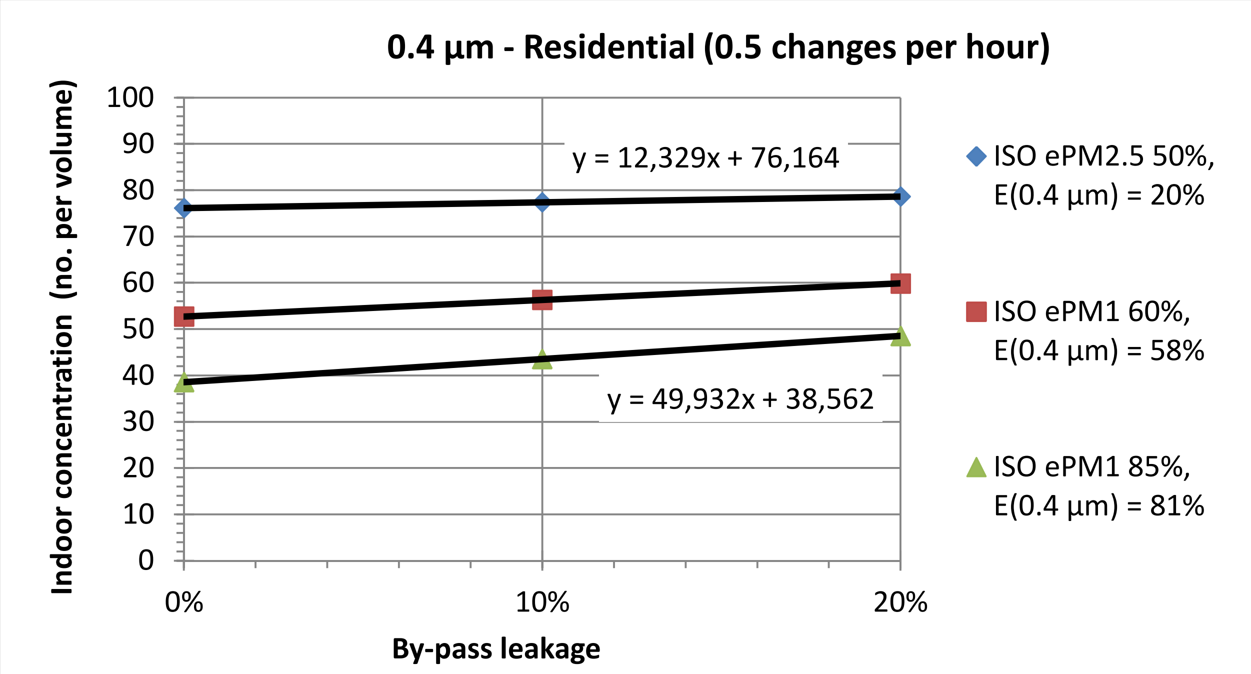


Figure B6.9 *(Figure 10 in the main section of the report).* The concentration of 0.4 µm particles in residential buildings is calculated as a function of the leakage by-passing the filter.

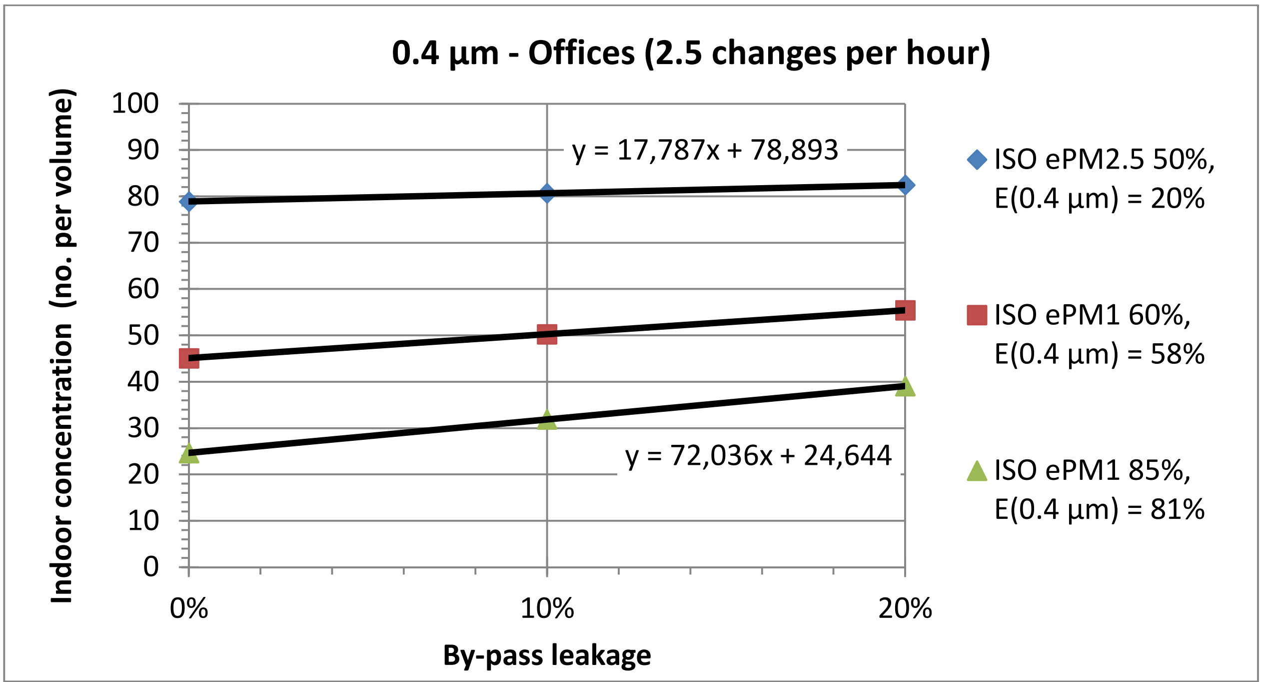


Figure B6.10 *(Top figure in Appendix 3).* The concentration of 0.4 µm particles in offices is calculated as a function of the leakage by-passing the filter.

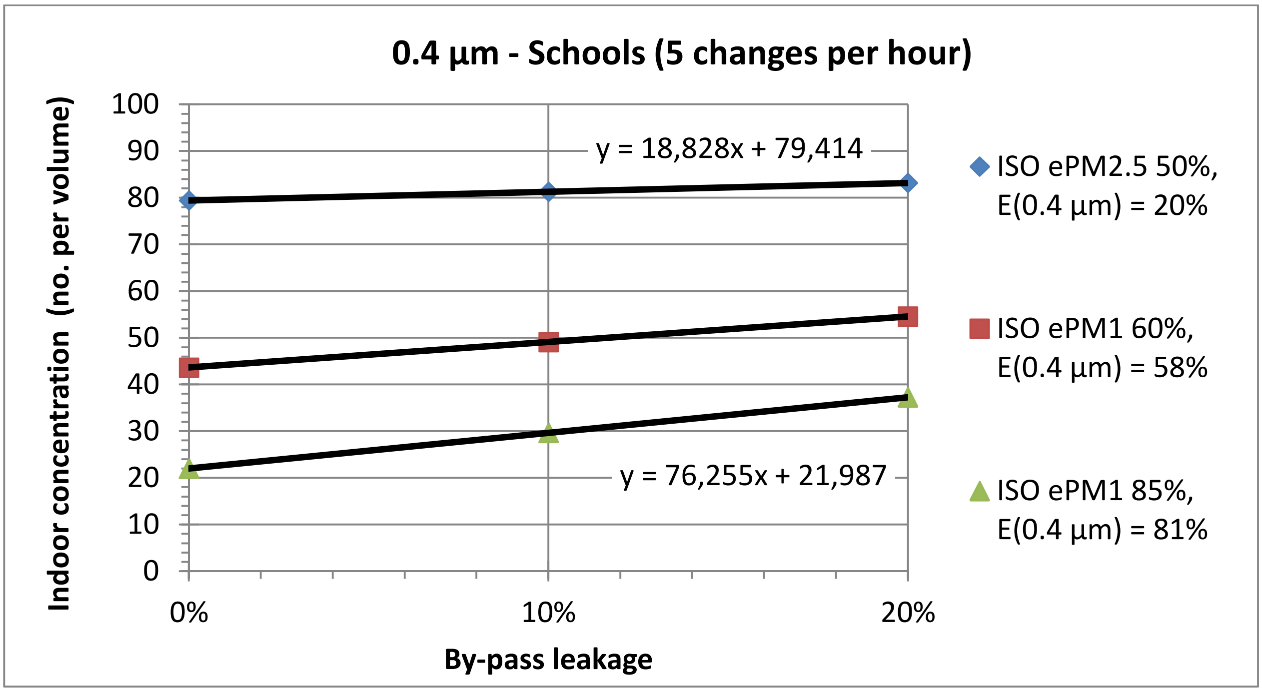


Figure B6.11 *(Bottom figure in Appendix 3).* The concentration of 0.4 µm particles in schools is calculated as a function of the leakage by-passing the filter.

Appendix 7. Diagrams with filter classifications according to ISO/FDIS 16890 – cases with return air

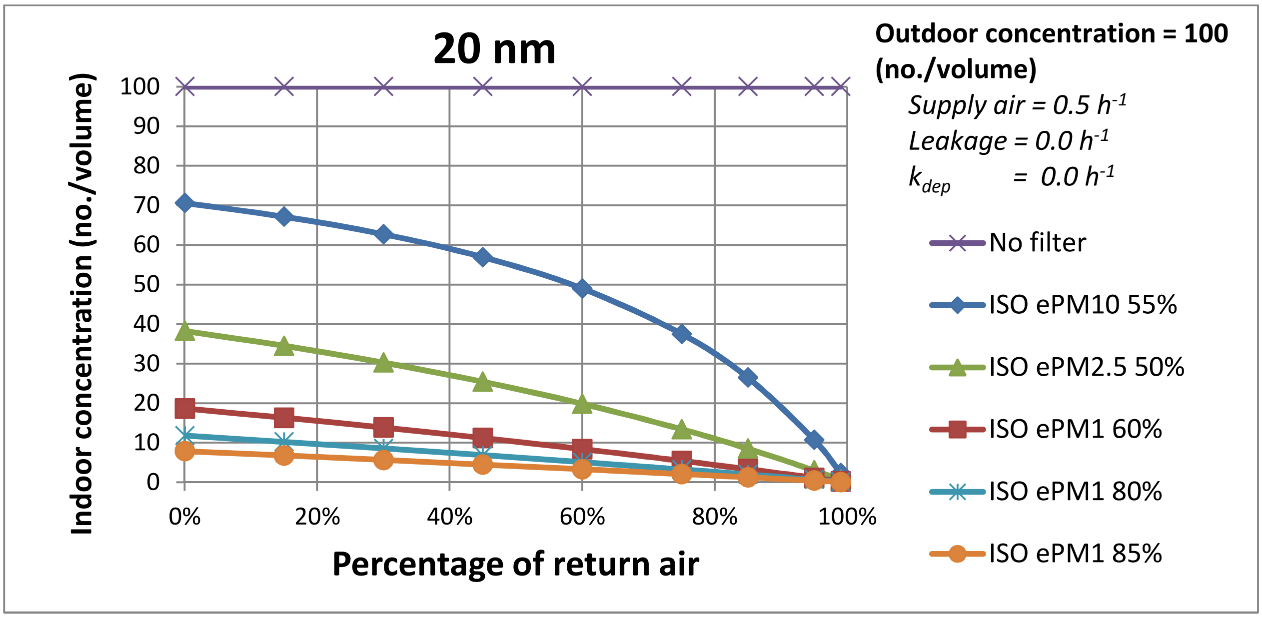


Figure B7.1 *(Figure B5.1 in Appendix 5)***.** The indoor particle concentration as a function of the percentage of return air. The diagram is based on the assumption that the indoor particle deposition rate and air filtration rate through the building envelope are zero (k_{dep}= 0 och q_{leak} = 0). The outdoor particle concentration has been set at 100 particles per unit volume of air.

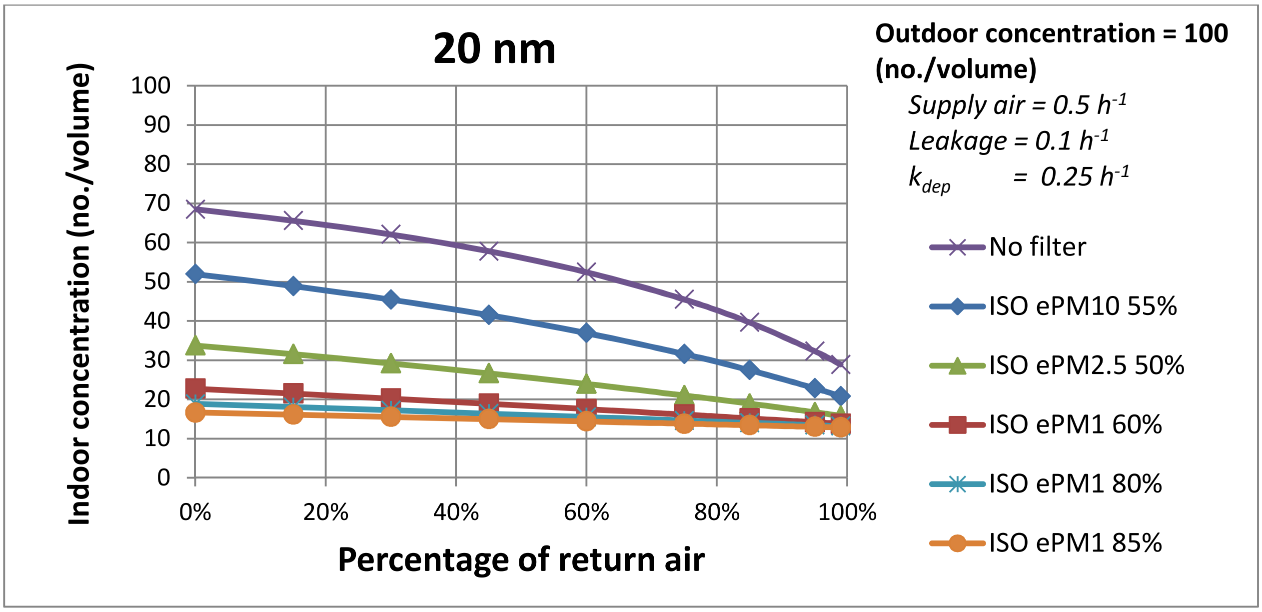


Figure B7.2 *(Figure B5.2 in Appendix 5)***.** The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 0.5 air changes per hour. Particle deposition has been set at 0.25 h^{-1} and air leakage is 0.1 air changes per hour.

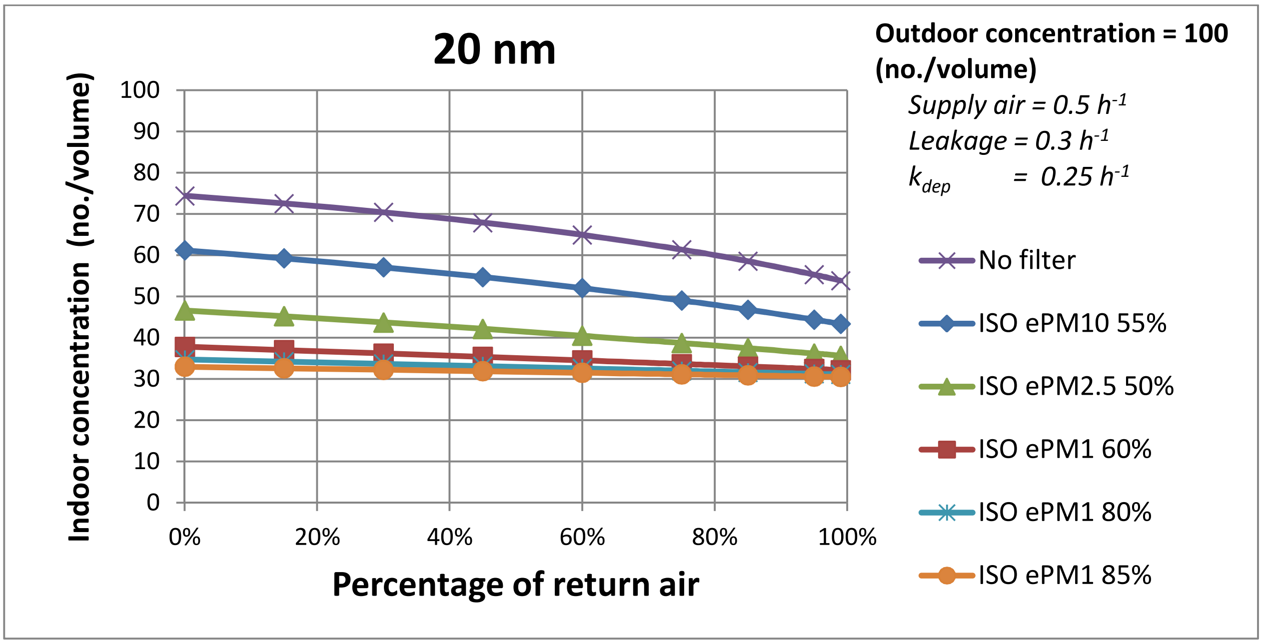


Figure B7.3 *(Figure B5.3 in Appendix 5).* The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 0.5 air changes per hour. Particle deposition has been set at 0.25 h^{-1} and air leakage is 0.3 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

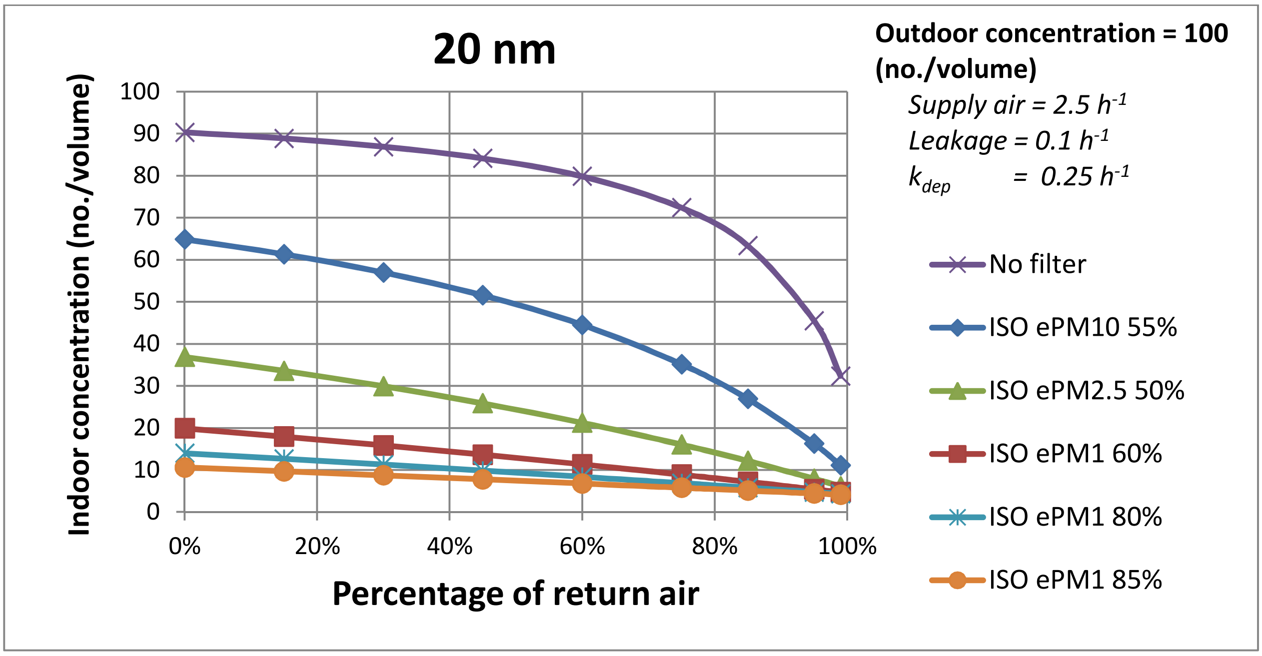


Figure B7.4 *(Figure B5.4 in Appendix 5).* The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 2.5 air changes per hour. Particle deposition has been set at 0.25 h^{-1} and air leakage is 0.1 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

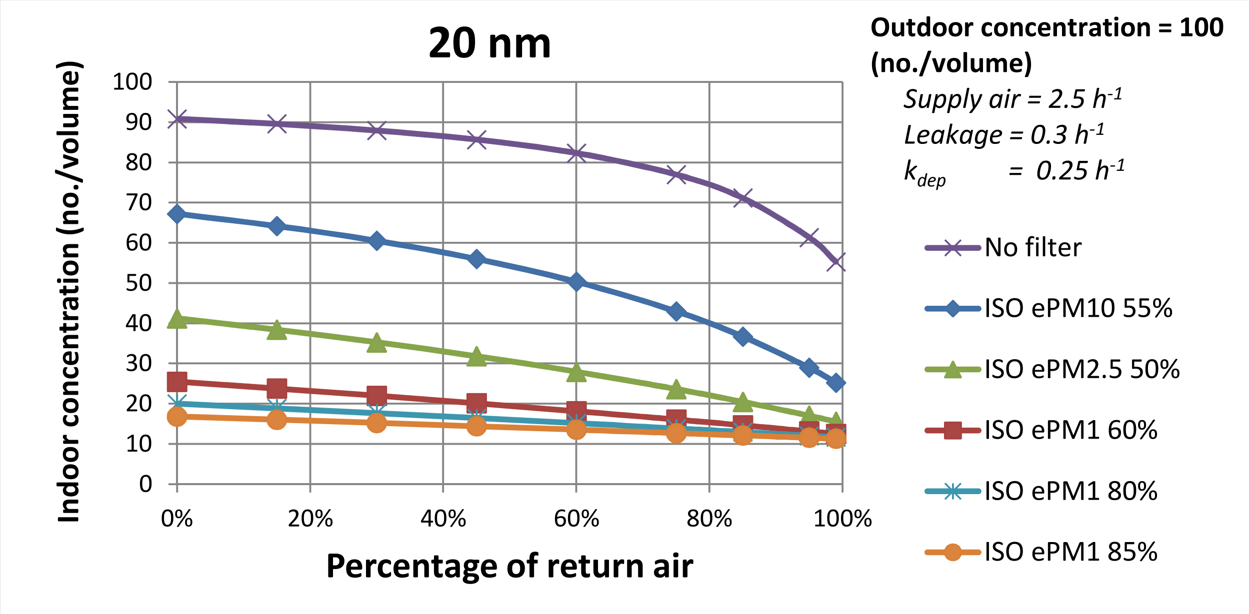


Figure B7.5 *(Figure B5.5 in Appendix 5).* The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 2.5 air changes per hour. Particle deposition has been set at 0.25 h^{-1} and air leakage is 0.3 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

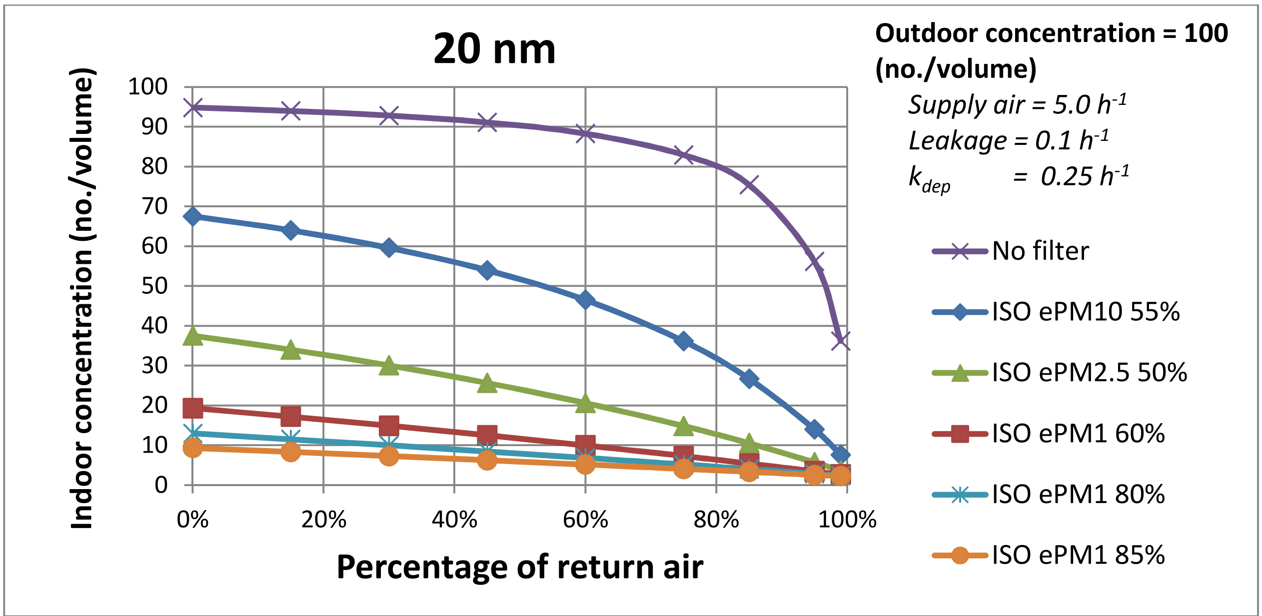


Figure B7.6 *(Figure B5.6 in Appendix 5).* The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 5.0 air changes per hour. Particle deposition has been set at 0.25 h^{-1} and air leakage is 0.1 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.

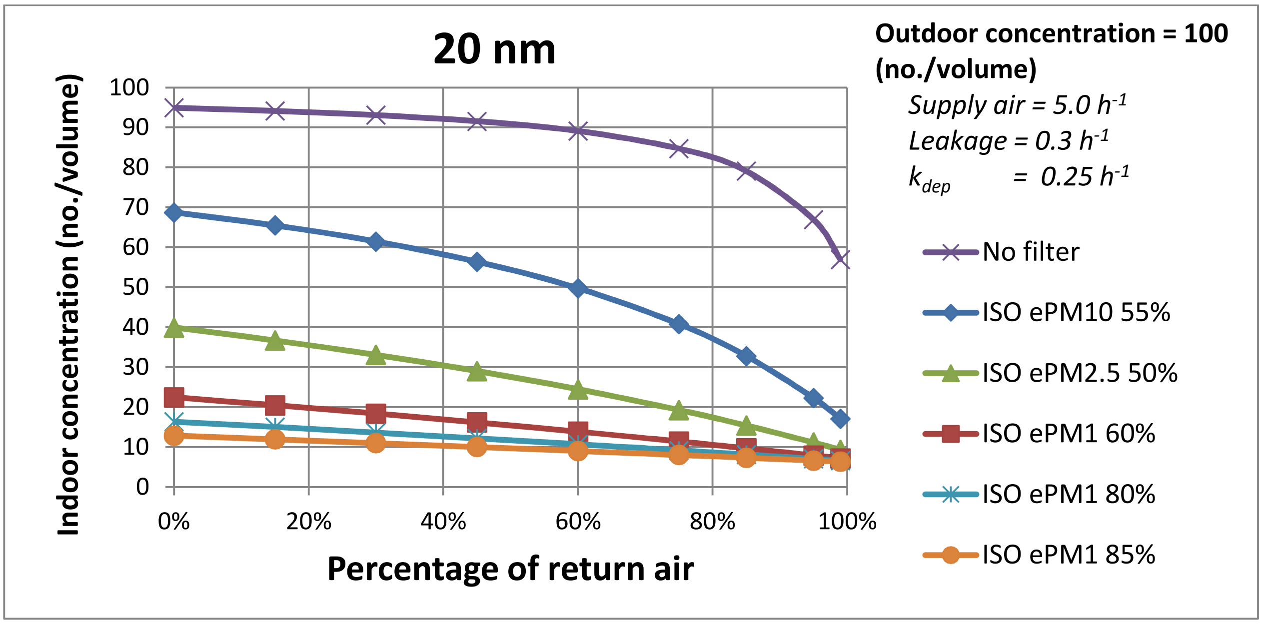


Figure B7.7. *(Figure B5.7 in Appendix 5).* The indoor particle concentration as a function of the percentage of return air with a supply airflow corresponding to 5.0 air changes per hour. Particle deposition has been set at 0.25 h^{-1} and air leakage is 0.3 air changes per hour. The outdoor particle concentration has been set at 100 particles per unit volume of air.