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Improving the indoor / outdoor ratio of (ultra)fine particles in a school

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Abstract. Buildings located close to busy roads, industry or stock farms, are of risk of increased indoor particle concentrations, which negatively impacts the health of the building occupants. In order to reduce the exposure of the building occupants, it is important to take measures to reduce the concentration of particulate matter indoors. Solutions for existing buildings include application of improved filters in the air handling units, using local air cleaners and limit the use of operable windows. However, little is known about the overall effectiveness of these measures in existing buildings that are in use. The aim of our study was to quantify the effectiveness of particle reducing measures in buildings at high traffic locations. We performed a field study in a school in a neighbourhood between highways. In this school the effect of improved filters in the air handling unit, a HEPA filter at room level as well as the combination of both interventions on the particle concentrations indoors were studied. We quantified the effect of the interventions by momentary measurements of PM2,5 and ultrafine particles (≥4 nm). Moreover, PM2.5 was continuously measured outdoors and indoors. The ePM1 85% filters in the AHU seemed effective on the reduction of (ultrafine) particles (nearly 75% reduction of PM2,5). The use of a HEPA filter was not effective in our test situation.

Keywords. PM2.5, ultrafine particles, filter, classroom
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1. Introduction

Exposure to particulate matter over a longer period of time poses significant health risks. Exceeding the air quality guidelines for particulate matter of the World Health Organization (WHO) [1] can lead to acute and chronic health complaints, including throat and nose irritations, asthmatic complaints and (aggravation of) cardiovascular diseases [2].

Epidemiological studies show that no safe levels can be demonstrated at which no harmful health effects of particulate matter occur. This means that health benefits can be expected with any reduction in the particulate matter concentration (also indoors), regardless of the nature or composition of the particulate matter [3].

For ultrafine particles, there are no health-related guidelines yet. However, several epidemiological studies show a link between exposure to ultrafine dust and health effects, such as asthma, in children [4].

Exposure to particulate matter does not only occur outside: in particular, the small fractions of particulate matter (PM2.5 and ultrafine particles) that is present in the outside air can easily enter through cracks and seams in the façade and via ventilation. This is especially true for buildings located close to busy roads, air traffic, industry or stock farms.

It is important to take measures to reduce the exposure to particulate matter indoors. Solutions for existing buildings include application of improved filters in the air handling unit (AHU) and local air cleaners. However, little is known about the overall effectiveness of this kind of measures in a building that is in use.

The aim of our study was to quantify the effect of particle reducing measures in a school building at a high traffic location.

2. Research methods

2.1 location

We performed a field study in a primary school building located in a neighbourhood surrounded by highways. The study was caried out between April and October 2021. The school has two identical buildings next to each other. The distance from the road and the orientation of the windows was equal. Both buildings have their own ventilation system with CO_2-based demand-driven mechanical supply with a sensor for each classroom and (limited) mechanical exhaust. The maximum air change rate of the classrooms was approximately 950 m^3/h. The AHU's were both equipped with ePM2,5 70% filters. The classrooms on the second floor have a cooling system.

2.2 interventions

The following interventions were investigated:

I. Improved filters in the air handling unit (AHU). We replaced the standard ePM2.5 70% filters by ePM1 85% filters in one of the school buildings.

II. HEPA filter at room level. We used two Camfil City M units with H14 filters with an efficiency of 99.995% for particles between 0,1 and 0,25 μm. The maximum capacity of the unit is 433 m3/h (level 6). In the experiments, we used the filter at level 4 (127 m3/h) due to noise. The rooms in which the filters were tested have a floor area of ±50 m2 and a volume of ±140 m3. The circulation rate of the unit was around 0.9. The filter was turned on continuously throughout the test period. This situation was tested in combination with the standard ePM2.5 70% filter and both with open and closed windows.

III. Combination of intervention I and II. This situation was tested only with open windows.

2.3 momentary measurements

The effect of the interventions was quantified by means of momentary measurements in empty classrooms. We first explored the baseline situation in both buildings. Then, the interventions were tested simultaneously with the baseline situation. This was possible since the school has two identical buildings.

Measurements of the PM2.5 mass concentration were carried out using a TSI Sidepak personal aerosol monitor (TSI AM520). At each measuring location, the mass concentration of these particles was measured for 10 minutes with an interval of 1 second.

Measurements of the ultrafine particles were performed using a TSI Condensation Particle Counter (TSI 3775). The device measures particles of 4 nm in diameter and larger in a bandwidth of 0 to 107 particles per cubic centimeter of air. The measurements were carried out over a period of 10 minutes with a set interval of 10 seconds.

These measurements were performed successively indoors and outdoors. During the momentary measurements the air change rates in the classrooms were comparable: the CO_2-based demand-driven ventilation system in the school was overruled, so the classrooms were all ventilated at maximum capacity. The HEPA filter was in operation for at least one hour before the measurements.

The table below shows the number of measurement series per intervention.

Table 1 – Overview of measurements

Situation	Number of locations	
	PM2,5	Ultrafine
Baseline	10	10
Intervention I	9	9
Intervention II	5	5

2.4 continuous measurements

The PM2.5 concentration was been monitored continuously during the research period. These measurements were performed simultaneously indoors in multiple rooms (Siemens QSA2700 room sensors) and outdoor at the air intake of the AHU (Siemens QSM2100 duct sensor). An interval of 5 minutes has been used.

2.5 data analysis

The impact of the interventions was evaluated by comparing the indoor/outdoor (I/O) ratios during the different situations. The I/O ratio was calculated using the measured particle concentration in the building divided by the concentration outside.

For the momentary measurements, the average PM2.5 concentration and ultrafine particle concentration were calculated per measurement location, indoors and outdoors, over the measurement period of 10 minutes. For the PM2.5 measurement the standard deviation was calculated as well. Only measurements performed with outdoor PM2.5 concentrations above 5 $\mu g/m^3$ were included in the analysis.

With an unpaired t-test, it was investigated whether the average I/O ratios in a situation with improved filters (intervention I) differ significantly from the situation without intervention. A p-value <0.05 was considered to be statistically significant. The static analyses were performed in Microsoft Excel version 2102. The data of the other interventions could not be statistically tested, due to the limited number of momentary measurements.

Continuous measurements were used to underpin the findings of the momentary measurements. The hourly average on schooldays of both concentrations and I/O ratios were visually presented in graphs.

3. Results

3.1 improved filters in the AHU

The I/O ratio in the situation with an ePM1 85% filter is compared with the standard ePM2.5 70% filter (Figure 1). The median of the average I/O ratios of all measurements was 0.27 in the situation with an improved filter, which is significantly lower (p=0.026) than with a standard filter (0.38). With an improved filter, the average of all measurements was between 0.24 and 0.30. With a standard filter, this was between 0.27 and 0.82.

The median I/O ratios of the ultrafine particle concentration were comparable (0.28 vs 0.26) (Figure 2). The range of the I/O ratio is wider for the standard filter; the P75 for the standard filter is 0.55 whereas it was 0.28 for the improved filter. The difference is not significant (p=0.104).

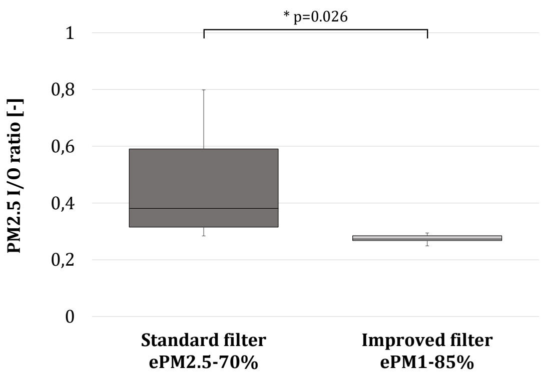

Fig. 1 – Boxplot of the average I/O ratio of PM2.5 comparing the situation with a standard filter (n=8) and a classroom with an improved filter (n=5).

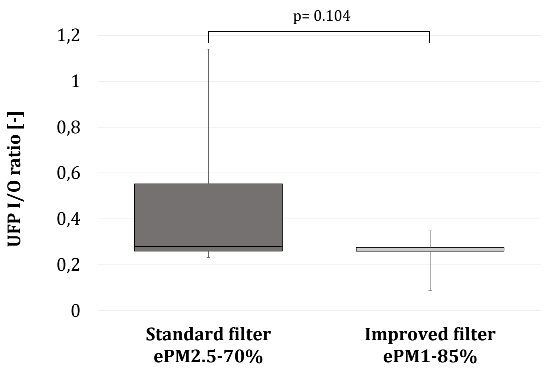

Fig. 2 – Boxplot of the average I/O ratio of ultrafine particles comparing the situation with a standard filter (n=8) and a classroom with an improved filter (n=5).

The continuous measurements showed a clear difference between the concentration and I/O ratio in classrooms in the building with the standard filter and the building with the improved filter (Figure 3). Remarkably, we also found differences between classrooms within the same building (Figure 4). These differences were observed between the classrooms on the ground floor (higher indoor concentrations) and the first and second floor (lower indoor concentrations).

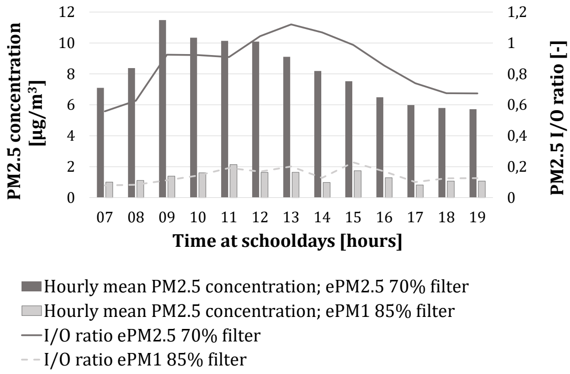

Fig. 3 – Continuous measurements comparing a classroom with a standard filter (ePM2.5 70%) and a classroom with an improved filter (ePM1 85%).

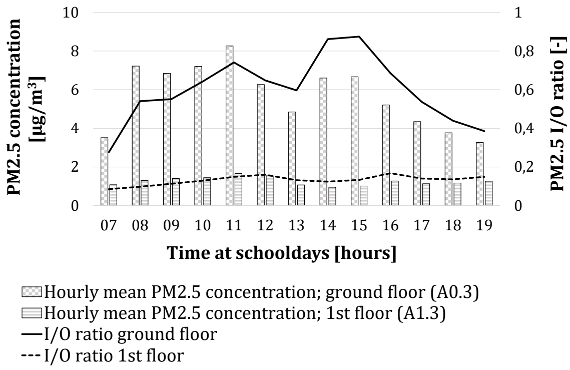

Fig. 4 – Continuous measurements comparing two classrooms with an improved filter (ePM1 85%); one on the ground floor and one on the first floor.

3.2 HEPA filter at room level

The average I/O ratios were 0.75 and 0.82 without HEPA filter and 0.63 and 0.75 with HEPA filter in the room in a situation with closed windows (Figure 5). The difference was not significant (p=0.158).

With open windows, the average I/O ratios were 0.67 and 0.84 without HEPA filter and 0.75 and 0.78 with HEPA filter in the room (Figure 5).

The measurements of ultrafine particles (Figure 6) show a comparable trend.

In line with these observations, no differences were observed based on the continuous measurements in two in adjacent classrooms with and without a HEPA filter during school hours (Figure 7). However, it is clear that the PM2.5 concentrations are lower in the rooms with a HEPA filter in the evening and at night, when the ventilation system is turned off and the room is not occupied.

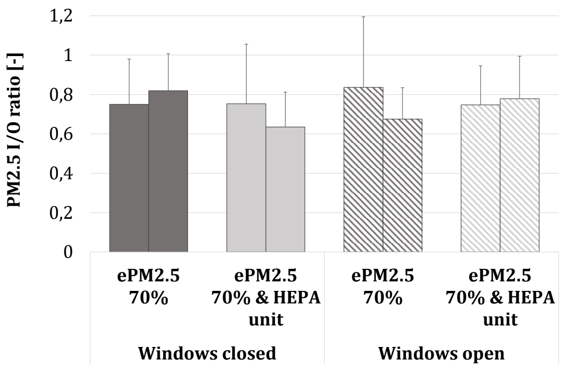

Fig. 5 – Bar diagram of the I/O ratio of PM2.5 (average and standard deviation) for the intervention with a HEPA filter at room level.

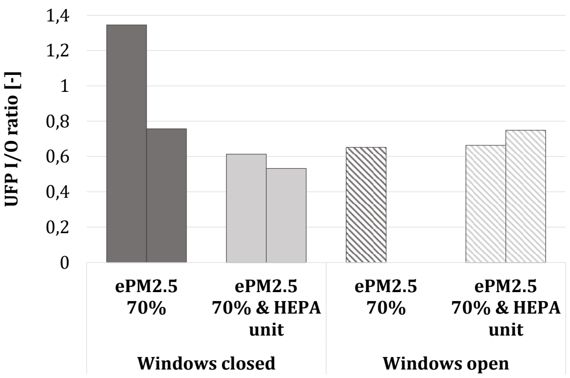

Fig. 6 - Bar diagram of the I/O ratio of ultrafine particles (average) for the intervention with a HEPA filter at room level.

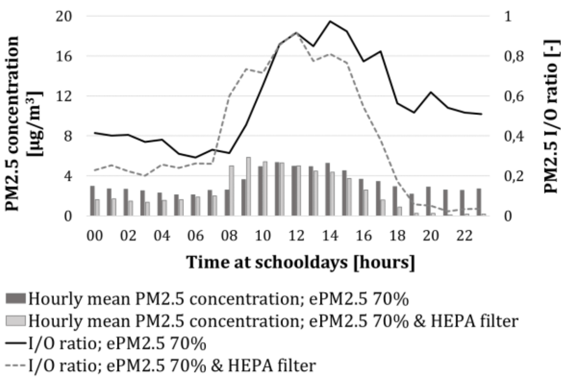

Fig. 7 - Continuous measurements comparing a classroom with a standard filter only and a classroom with a standard filter and HEPA filter.

3.3 improved filters and HEPA filter

The average I/O ratios were 0.30 and 0.33 when the AHU is provided with an improved ePM1 80% filter and 0.32 and 0.37 when the classroom additionally is provided with a HEPA filter; both in a situation with windows open (Figure 8). The combination of an improved filter and a HEPA filter did not reduce the indoor concentration as compared to the situation with only an improved filter.

Similarly, the results of the ultrafine particles (Figure 9) show no impact of the HEPA filter when combined with an improved filter in the AHU.

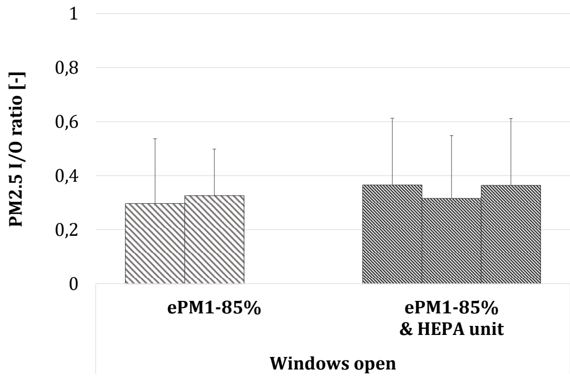

Fig. 8 - Bar diagram of the I/O ratio of PM2.5 (average and standard deviation) for the intervention with both improved filters and a HEPA filter.

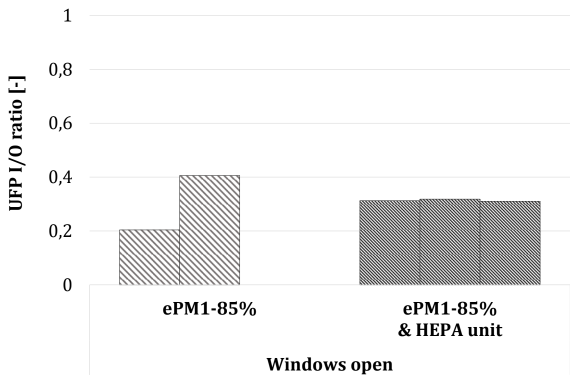

Fig. 9 - Bar diagram of the I/O ratio of ultrafine particles (average) for the intervention with both improved filters and a HEPA filter.

The combined effect of the improved filters and the HEPA filter was evaluated using the continuous measurements. The hourly average concentration during the day in the building with the improved filter in the AHU is comparable in the situation with and without mobile HEPA filter (figure 10). In contrast to the situation where the HEPA filter was combined with a standard filter (figure 7), no lower PM2.5 concentrations were observed in the evening or night.

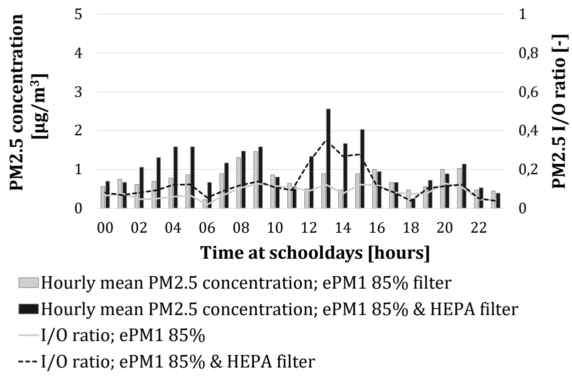

Fig. 10 – Continuous measurements comparing a classroom with an improved filter only and a classroom with an improved filter and HEPA filter.

4. Discussion

4.1 methodology

The field study was carried out to get a better understanding about particulate reducing measuring in a school in use. Thereby confounding factors such as opening windows were explored. Because of that numerous combinations were possible leading to limited number of momentary measurements for each situation. This makes it difficult to prove the effectiveness, since the power is too small to statistically compare the situations. Especially when the impact of the intervention is small, effects are not clearly visible.

In this field study we had to cope with changing outdoor conditions, like outdoor particle concentrations and wind speed and direction, affecting the I/O ratio. Low outdoor concentrations (<5 μg/m^3) during the momentary measurements reduced the number of valid measurements. In the continuous measurements we only compared classrooms with identical orientations to minimize the effect of the outdoor situations.

For the continuous measurements we used the PM2.5 room sensors connected to the building management system. Unfortunately, the range of these sensors seemed too broad, making the results unusable for this study. The sensors were replaced, but data from a vast period of the study is missing.

4.2 effect improved filters

The measurement data show a clearly improved I/O ratio in the building where the improved filter (ePM1 85%) is placed in the AHU compared to the building with the standard filter (ePM2.5 70%). This is in line with the required performance of the filters: the improved filter should reduce the outdoor concentration by 85% while the standard filter is only rated on the efficiency for PM2.5 which should be reduced by 70%.

Although the overall findings are clear, we found remarkable differences between classrooms within the same building, as illustrated by the results in figure 4. The I/O ratio in the classrooms on the ground floor (I/O on average 0.45) seemed much higher than on the 1st and 2nd floor (I/O average 0.20). This is, to some extent, expected: Traffic related particles are known to distribute at lower altitudes. As a result, the outdoor air at ground level is more polluted than on the first floor. Though, the difference could also be explained by the different settings of demand-driven ventilation in combination with the opening of windows. All rooms are equipped with demand-driven ventilation based on the CO_2 concentration. When conducting the measurements, we noticed that the windows were often open, especially in the classrooms on the ground floor. This ensures that the ventilation system in classrooms on the ground floor may not be switched on much or not at all, because sufficient air exchange already takes place through open windows (natural ventilation). Probably, these rooms were regularly ventilated with unfiltered air, leading to higher I/O ratios. Moreover, in some rooms on the 1st floor, the ventilation settings were disturbed and air is continuously supplied at a fixed (maximum) flow rate. These classrooms always receive filtered air, whether the windows are open or not.

In order to gain more insight into the effect of demand-driven ventilation, the ventilation system was overruled for several weeks and the results of continuous measurements in the period with and without demand-driven ventilation were compared.

Table 2 – Statistics of the I/O ratios (7-19h) for two measurements periods: average ± stdev.

	Period 1 (1- 20 sept) Demand-driven	Period 2 (22 sept - 4 oct) Overruled	Delta Period 1 - period 2
Ground floor A0.1	0,62 ± 0,17	0,08 ± 0,04	0,54
Ground floor A0.2	0,60 ± 0,16	0,07 ± 0,04	0,52
Ground floor A0.3	0,65 ± 0,22	0,26 ± 0,15	0,39
1st floor A1.1	0,19 ± 0,04	0,06 ± 0,03	0,13
1st floor A1.3*	0,13 ± 0,02	0,04 ± 0,02	0,09
1st floor A1.5	0,14 ± 0,05	0,03 ± 0,02	0,12
2nd floor A2.1	0,24 ± 0,06	0,09 ± 0,03	0,15
2nd floor A2.3	0,22 ± 0,07	0,05 ± 0,02	0,17

** continuously overruled*

The results of these measurements (table 2) show that the I/O ratios of the PM2.5 concentrations in the rooms on the ground floor are significantly lower (average Δ=0.48) when the ventilation system is continuously switched on (overruled) compared to the situation with demand-driven ventilation. Also in the other classrooms a small improvement was observed.

Further research is required to learn more about the effect of operable windows on particle concentrations in buildings.

4.3 effect HEPA filter

The HEPA filter has a higher efficiency than a ePM1

80% filter, and it theory may therefore be a more effective solution than the installation of improved filters in the AHU. Moreover, the unit should be able to filter particles entering the room through open windows (in schools opening windows is very important for passive cooling), in contrary to a filter in the AHU. However, we found that the relative contribution of the local HEPA filter was too small to achieve a clear reduction of particulate matter.

Measurements near the outlet of the filter proved that the HEPA filter is effective. Measured values of PM and UFP at the outlet of the unit are lower than the average concentrations in the room. The limited effectiveness of the HEPA filter can be explained by the flow rate of the unit. At the setpoint used, 127 m3 of air is filtered per hour (circulation rate of approx. 0.9). The mechanical ventilation system, on the other hand, supplies approximately 950 m^3 of filtered air per hour (ventilation rate of approx. 6.8 h^{-1}). This means that filtration via the HEPA filter is more than a factor of 7 lower than by the mechanical ventilation system. The filter unit needs a higher flow rate to become effective. With the risk of an increased noise level as a result, which is unacceptable during lessons.

4.4 effect improved filters and HEPA filter

We expected that the HEPA filter could further reduce the exposure to (ultra)fine particles when windows were opened. Though, we didn't see any effect of the presence of the HEPA filter in combination with improved filters in the AHU.

5. Conclusions

Application of an improved filter in the air handling unit seemed the most effective measure to reduce the number of particles coming from outdoors to the indoor environment compared to a HEPA filter in the classrooms.

In the building with an improved filter (ePM1 85%) the I/O ratios were significantly lower as compared to the building where the standard filter (ePM2.5 70%) was used.

Local air cleaning by a HEPA filter in the room seemed ineffective in a school. Both with the windows open and closed. And independent from the type of filter in the AHU (ePM2.5 70% or ePM1 85%). The HEPA filter does remove contaminants from the air, but since the ventilation flow rate in classrooms is about 7 times higher than the circulation flow rate of the HEPA filter, it is fighting a running battle. At a higher flow rate, the noise level of the filter unit becomes critical.

The results imply that the particulate concentration in schools can significantly be reduced using adequate filters. Still, other pollutants in polluted areas can negatively impact the indoor air quality. Moreover, children are also exposed when playing outside. Therefor the most important measure to reduce exposure to traffic related pollutants is to pay attention on the outdoor air quality when choosing a location to build new schools.

6. Acknowledgements

The study was funded by TVVL and VCCN. The interventions are sponsored by Camfil. Siemens installed PM2,5 sensors for continuous monitoring in the school. We are grateful that the school allowed us to perform this study in their buildings.

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Data Statement

The datasets generated during and/or analysed during the current study are not publicly available because the project is privately funded. The data that support the findings of this study are available from the corresponding author, and with permission of TVVL/VCCN, upon reasonable request.