ENERGY EFFICIENT REDUCTION OF FINE AND ULTRA-FINE DUST IN A NURSERY

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Keywords: Ultrafine dust, particle classes, electrostatic filter, Infiltration, Ventilation model

SUMMARY
An intervention study with a decentral electrostatic filter has been carried out in a nursery. The field study shows that it is possible to reach a reduction up to 80% of ultra-fine (<0.1 µm) and up to 68% for the PM₁ and PM₂.₅-PM₁ fractions at a relatively low energy consumption. These particle fractions were mostly determined by the outdoor concentration. Neither the children nor other indoor sources constituted a dominant source of particles. This does not hold for the courser dust (PM₂₀-PM₂.₅), the indoor concentration of these particles can be up to a factor 10-50 higher than the outdoor concentration. That infiltration can be a significant contributor is illustrated by the fact that during the research the outer door of the playroom was opened for several hours. This increased the infiltration coefficient for PM₂.₅-PM₁ and PM₁ by a factor of three.

INTRODUCTION

Fresh air is important. Children spend a significant part of their time indoors, and a large part of that in a day-care centre. In the Netherlands more than half of the children below 12 years are attending the childcare. In 2008 an investigation in 60 Dutch nurseries showed that especially the air quality during the heating season, noise due to mechanical ventilation systems and the temperature in the summer cause problems (Versteeg, 2009). The recommendations of this measurement campaign are to improve the ventilation provisions and the use of them and to apply sun and heat protecting measures in existing nurseries.

However, simply pumping in outdoor air or opening windows for ventilation can also have negative consequences, since together with the ventilation air fine dust is introduced into the building. Especially the very fine particles (ultrafine dust, <0.1 µm), which in an urban environment originate mostly from (diesel)traffic, are thought to have a negative impact on health. Recently the World Health Organisation (2012) has indicated that diesel exhaust gases cause cancer with human. This should not be a reason not to ventilate, but rather a reason to purify the ventilation air. This can be done either by cleaning the air before it enters or by recirculating and cleaning the air indoors. Janssen (2002) suggests that central air conditioning significantly modifies the effect of PM₁₀ on hospital admissions, especially for Cardio Vascular Diseases. This may either be caused by less fresh air supply in case of air conditioning through open windows, or the effect of the filtering of the recirculation air.

Since there are no internal sources of ultrafine dust in day-care centres and due to rather high ventilation rate, cleaning the incoming air seems the obvious choice. The aim of the study was
to show the possibility to reduce fine dust in an energy efficient way in an existing nursery. And to experimentally determine the reduction of fine dust in both the bedrooms and the playrooms for different particle classes: $< 0.1 \, \mu m$, $< 1 \, \mu m$, $1 – 2.5 \, \mu m$ and $> 2.5 \, \mu m$. Our goal was further to investigate the effects of filter efficiency, external sources (via cracks, open windows/doors) and internal sources and to use these data to set up and to validate a simple simulation model.

**METHODOLOGIES**

The intervention study has been carried out in an existing nursery which contains 10 bedrooms and 8 playrooms. The nursery is located near a busy road in a residential area. Figure 1 shows for two bed/playrooms the ventilation system. Outside air is directly blown into the bedroom by an energy efficient low pressure fan developed during the RESHYVENT project (Jacobs and de Gids, 2003). The air flows from the bedroom to the playroom through an overflow opening with an acoustic damper. All air of the 8 playrooms flows to the entrance hall were at about 10 m height an exhaust fan is placed. More information about this ductless ventilation system and the intervention study can be found in Jacobs (2011, 2012).

![Figure 1. Schematic of the air flows through the nursery.](image)

Two identical bedrooms have been selected which have their air inlet at the same façade. In the ‘Sheep’ bedroom the ventilation air delivered by the supply fan was filtered with a newly installed electrostatic filter (VFA, Aspra XS), see figure 2.

![Figure 2. Installation of decentral electrostatic filter (white part) on the low pressure fan.](image)
In the ‘Dolphins’ bedroom no filter was installed, this served as a reference. The flow rates of both bedrooms have been measured with an Acin Flowfinder and adjusted to 35 dm$^3$/s during daytime. The air exchange in the bedrooms and in the playrooms was 5 and 1.3 ACH respectively. Between 18.00 and 7.00 hour the ventilation and electrostatic filter were turned off. One week after the installation of the filter the ultrafine dust concentration was measured for a day in the bedrooms with two TSI 3007 CPC’s and compared to outside measurements made with a Philips Nanotracer. After the experiment all three measurement devices have been placed in the same bedroom. Based on this measurement the signals were scaled with correction factors towards the CPC used in the Dolphins bedroom. Thereafter during two weeks 0.5 – 20 μm particle fine dust measurements have been made with Osiris particle counters placed in the Sheep and Dolphin bed and playrooms. Further one Osiris was placed on the roof to measure the outside air. These measurements are reported in particle mass. The Osiris monitors are not calibrated to mass according to reference methods. However before and after the experiment they were all placed in the same room. Based on these comparative measurements the signals of the Osiris were scaled with correction factors towards each other. During the second week apart from the air cleaner on the ventilation inlet of the Sheep bedroom also an identical electrostatic filter has been placed in the corresponding Sheep playroom. This filter cleans the indoor air in a recirculation mode at a flow rate of 55 dm$^3$/s during the same time period (7 – 18 hour). The number of children and staff members present in the bed and playrooms has been logged with a logbook. Further in all rooms CO$_2$ concentration and temperature have been logged with a 5 minute interval.

A ventilation model has been set up based on the Multizone model COMIS (1990) for the playroom.

RESULTS AND DISCUSSION

Energy consumption
The pressure drop of the electrostatic filter was 30 Pa, which is much lower than that of conventional F9 (250 Pa) or HEPA (500 Pa) filters. This not only reduces energy consumption, but due to the low sound pressure also enables a decentralized air supply, often an advantage in existing situations. The energy consumption of the low pressure supply fan amounted 8 W including the resistance of the electrostatic filter. The Specific Fan Power (SFP) is 0.23 kW/(m$^3$/s). Including the energy consumption of the electrostatic filter (5 W) and one tenth of the exhaust fan ($50/10 = 5$ W) the SFP of the whole air conditioning system is 0.51 kW/(m$^3$/s). This is typically a factor 5 lower than modern air handling units (Railio, 2007).

Occupancy
In the Sheep group the age of the children was between 1.5 and 3 years. At maximum 16 children and 3 adults were present in the Sheep playroom. The maximum number of children in the bedroom was 13. In the Dolphin group, which served as reference, the age of the children was between 0 and 4 years. At maximum 11 children and 2 adults were present in the Dolphin playroom. The maximum number of children in the bedroom was 6. In general the occupancy of the Sheep bed and playroom was higher than the Dolphin’s. Therefore it can be assumed that the internal dust generation in the Sheep group was higher than in the Dolphin group. Therefore the reported reductions in the Sheep group compared to the reference Dolphin group can be considered as conservative.
Ultra-fine dust

Figure 3 shows the results of the ultra-fine dust measurement in the Sheep bedroom with electrostatic filter in comparison with the Dolphin bedroom and the outside concentration measured at the roof of the nursery. The capricious pattern for the outside concentration is caused by passing vehicles and fluctuating airflows. It is also partly caused by the different measurement principle of the Nanotracer compared to the CPC’s. The peaks in the outside air arrive about 15 minutes later in the Dolphins bedroom. The total exposure (concentration x time) seems sometimes even higher than at the roof. This may be caused by dilution by eddies on the flat roof. The concentration in the Sheep bedroom also follows the outside concentration peaks. However due to the presence of the electrostatic filter it is 80% lower than in the reference Dolphins bedroom.

![Figure 3](image_url)

Figure 3. Corrected particle number concentrations, the Sheep bedroom is provided with an electrostatic filter, the Dolphins bedroom is the reference room.

PM$_{2.5}$ and PM$_{1}$

Figure 4 shows that the PM$_{2.5}$-PM$_{1}$ and PM$_{1}$ concentration in the Dolphin and Sheep bedrooms are strongly correlated with the concentration on the roof (outside concentration). Based on linear regression infiltration coefficients have been derived, see table 1. In the Sheep bedroom with the electrostatic filter room the infiltration coefficient is 66% lower for PM$_{1}$ and 68% lower for the PM$_{2.5}$-PM$_{1}$ fraction compared to the Dolphin bedroom. The PM$_{2.5}$-PM$_{1}$ concentration shows more scattering around the trend line compared to the PM$_{1}$ fraction. Also data points above the diagonal are visible, this indicates the presence of internal sources. These data points are associated with the wake up and go to bed of the children.

Figure 5 again shows that for the Sheep playroom the PM$_{2.5}$-PM$_{1}$ and PM$_{1}$ concentration are strongly correlated with the concentration on the roof (outside concentration). In the figure the data is presented in three subsets. During the second measurement week a recirculating electrostatic filter in the playroom has been installed, these data points are indicated with:
**stand alone.** As the outside concentration is relatively low during this period and comparable with internal sources no infiltration coefficient has been derived. By comparison of fine dust concentration ratio of the Sheep/Dolphin playroom with and without stand alone it is estimated that the stand alone resulted in a reduction of about 30%. Further, derived from the logbook on one afternoon the outside door of the Sheep playroom had been opened, these data points are indicated with: *open door*. This increased the infiltration coefficient for PM$_{2.5}$-PM$_1$ and PM$_1$ with about a factor three. This shows that, at least regarding fine dust, opening a door does not necessarily bring in fresh air.

Figure 4. Correlation between the concentration on the roof and the concentration in the Dolphin and Sheep bedrooms during the day period.

Figure 5. Correlation between the concentration on the roof and the concentration in the Sheep playrooms during the day period.

Also for the Dolphins playroom and the Central hall infiltration coefficients have been derived, see table 1. The infiltration coefficient in the Dolphins playroom and also in the central hall is lower than in the Dolphins bedroom. This decrease can be explained by absorbance of fine dust to walls and floors while the outside air flows through the building.
Table 1. Infiltration coefficients for all measured rooms, including 95% confidence interval.

<table>
<thead>
<tr>
<th>Room Type</th>
<th>PM$_{2.5}$-PM$_1$</th>
<th>PM$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheep Bedroom</td>
<td>0.23 ± 0.02</td>
<td>0.23 ± 0.01</td>
</tr>
<tr>
<td>Playroom</td>
<td>0.23 ± 0.01</td>
<td>0.27 ± 0.01</td>
</tr>
<tr>
<td>Playroom with open door</td>
<td>0.80 ± 0.08</td>
<td>0.76 ± 0.10</td>
</tr>
<tr>
<td>Dolphins Bedroom</td>
<td>0.72 ± 0.02</td>
<td>0.68 ± 0.01</td>
</tr>
<tr>
<td>Playroom</td>
<td>0.49 ± 0.02</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>Central hall</td>
<td>0.39 ± 0.02</td>
<td>0.42 ± 0.01</td>
</tr>
</tbody>
</table>

The reduction in the fine dust concentration in this study is significantly larger than the 11%-30% reduction determined by Dijkema (2011) in a previous study, which tested ventilation systems with F7-F9 filters in a classroom. Based on the filter efficiency for PM$_1$ a reduction of 85 – 95% should be expected. However, infiltration might play a large role here as the ventilation systems were CO$_2$ controlled. Due to the CO$_2$ control before and up to about 15 minutes after the children enter the ventilation system does not run. During that time infiltration of outside air can occur. The CO$_2$ control reduces the effect of the installed filters.

**PM$_{20}$ – PM$_{2.5}$**

As shown in Figure 6 the coarse dust fraction clearly correlates with the concentration CO$_2$ in the Sheep bedroom. The joint bedtime around 12.30 and rise again around 15.00 hour is clearly visible. Peaks up to 1200 µg/m$^3$ occur while the PM$_{20}$ – PM$_{2.5}$ concentration outside during the whole measurement never came above 170 µg/m$^3$. Also in the Dolphin bedroom and in both playrooms (graphs not shown) the concentration of course dust corresponds with peaks in CO$_2$ concentration. The concentrations in these rooms are lower.

Figure 6. Course dust fraction (PM$_{20}$ – PM$_{2.5}$) and the CO$_2$ concentration in de Sheep bedroom compared to the outside concentration during the second measurement week.

In the Dolphins bedroom the concentration is lower probably because not all children go to bed at the same time. In the play rooms the concentrations are lower, probably due to the absence of bed clothes. All absolute concentrations mentioned in this section are indicative as
the Osiris monitors are not calibrated to mass according to reference methods and can only be used to derive infiltration coefficients and relative reductions.

Simulation model for ventilation and infiltration

Figure 7 shows the effect of pressure hierarchy. In figure 7a the particle concentration in time is shown in case of natural supply and mechanical exhaust is applied. In that case due to the under pressure outside air infiltrates through cracks and an end concentration of 2000 particles/cm³ is reached. This is twice as high as the same filter is applied with a mechanical supply and natural exhaust, see figure 7b. In figure 7c the effect of an open door is modelled. This drastically increases the indoor concentration. As mentioned earlier opening the outside door during the intervention study increased the infiltration coefficient by a factor three. Based on the temperature logged the temperature difference between indoor and outdoor amounted 14 K. By cracking a door open at 10 cm an exchange flow of 45 dm³/s is generated, which is of the same order as the ventilation flow rate. To prevent this exchange flow the supply air flow should amount 135 dm³/s. Another manner to mitigate the effects of an open window is to apply recirculation mode air filter. Figure 7d shows that it requires relative large air flows to approach the theoretical particle concentration based on the filter quality.

Figure 7. Effect of ventilation concept and infiltration on particle concentration. An outside concentration of 1000 particles/cm³ and a filter efficiency of 90% is assumed.

a. Mechanical exhaust: 8 Pa under pressure  b. Mechanical supply: 4 Pa overpressure

c. Mechanical supply, open door/window  d. Open door/window with recirculation filter
It also requires relative large air flows to counteract internal sources of dust. Dorizas (2013) reports daily averaged PM$_{10}$ values in Greek class rooms of 245 µg/m$^3$. Alves (2013) reports significant positive relations between CO$_2$ and PM$_{2.5}$ confirming that the human presence and related activities represents an important source of particles. This coincides with the finding of Scheepers (2011) that air cleaning units are much more effective during weekends than on schooldays. Polidori (2013) reported reductions between 87 and 96% for Black Carbon, Ultra-fine dust and PM$_{2.5}$. He used high flow rates in the order of 0.4 – 0.8 m$^3$/s resulting in 6 - 11 air changes per hour (ACH).

CONCLUSIONS

This study shows that electrostatic filters can effectively reduce the ultra-fine, PM$_1$ and PM$_{2.5}$ fine dust fractions originating from outside in an energy efficient way. However in nurseries and in schools the contribution of internal sources for the coarser fractions above PM$_{2.5}$ are often much higher than the outside contribution. It requires relative large air flows to filter these internal sources of fine dust. This provides a challenge for suppliers to deliver noise free, low maintenance and inexpensive solutions. It may be logical to combine these solutions with active and passive temperature control measures because then the windows will be kept closed which minimizes infiltration.

ACKNOWLEDGEMENT

I would like to thank Vincent Vons from VFA for the use and the installation of the electrostatic filter and his help with the data processing.

REFERENCES