Mixing and displacement ventilation compared in classrooms; distribution of particles, cat allergen and CO_2

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ABSTRACT
Mixing ventilation and displacement ventilation were compared in an intervention study in classrooms. Particles, cat allergen and CO_2, were measured in classroom air at different levels above the floor, during regular lessons. With mixing ventilation, the particle concentration tended to decrease with height, with a stronger gradient occurring for larger particles. With displacement ventilation, the particle concentration increased with height, except for particles >25 µm. The displacement system thus tended to have a slight upward displacement effect on most of the particles. Significant correlations were found between concentrations of cat allergen and particles in the size fraction 1–10 µm. The particle and cat allergen concentration at breathing height did not, however, differ significantly between the two ventilation systems. CO_2 was about 10% lower with displacement ventilation. A fairly high level of physical activity of the pupils is believed to have had significant dispersing effect on the airborne contaminants.

INDEX TERMS
Mixing ventilation; Displacement ventilation; Particles; Cat allergen; Schools

INTRODUCTION
When aiming at reducing concentrations of airborne allergens in schools, the choice of ventilation supply air principle is likely to be important. Many previous studies have indicated that displacement ventilation is more efficient in extracting indoor-generated gaseous contaminants from the room air than is mixing ventilation. The displacement system tends to displace the gaseous contaminants to the upper part of the room and to create a fairly clean lower zone (Stymne *et al.*, 1991; Brohus and Nielsen, 1994; Mundt, 1996; Mattsson, 1999). Indications of similar effects have been noted also for particulate matter in laboratory studies (Mattsson, 2002) and at CFD calculations (Holmberg *et al.* 2000; Raimundo *et al.*, 2002). Little is, however, known about the performance in the field. Indications of less asthma symptoms, better perceived air quality and positive physiological effects when using displacement ventilation in schools have been reported (Smedje and Norbäck, 2000; Smedje *et al.*, 1997 and Wålinder *et al.*, 1998, respectively), but control for several influential factors (e.g. ventilation rate) has then not been optimized. The present work is an intervention study, where displacement and mixing ventilation are compared in classrooms according to a cross-over design.

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METHODS

The measurements were performed in four adjacent classrooms of a Swedish elementary school, 'Bergaskolan', centrally situated in the town of Uppsala. The pupils (111 in total, 11–12 years old) had their ordinary lessons while the measurements were carried out during two 3-week periods in February to March 2002. The classrooms had an average floor area and room height of 60.4 m^2 and 3.28 m, respectively, with small differences between the classrooms. Each classroom was originally equipped with two displacement supply air diffusers (Halton ABF-200-1200) along the wall at the 'teacher-side' of the room, and with one exhaust air terminal on or close to the ceiling on the other side of the room. In order to perform the ventilation interventions, two mixing supply air diffusers (Polman P01b) were mounted on the ceiling, about 3.5 m from the 'teacher-side' wall. Ventilation ducts and dampers were connected to the existing air supply ducts, so that switching between displacement and mixing ventilation could be done while the ventilation rate was kept constant. Average total supply and exhaust ventilation rates were 302 l/s and 335 l/s, respectively (±5%, measured through transversing Prandtl-tube and tracer gas decay respectively). The supply air was filtered through an F7 (=EU7) filter and its temperature at the diffuser was maintained at 19.3 ± 0.2°C. Each displacement diffuser had a total free supply area of 997 cm^2 and a perforation degree of 9.25%. Corresponding values for the mixing diffusers were 314 cm^2 and 12.5%, respectively. Each mixing diffuser spread the supplied air two-ways in opposite directions, forming two wide air jets, directed ~30° below the horizontal plane into the occupied zone. During the first measurement period, mixing ventilation was applied in two of the classrooms and displacement ventilation in the other two. During the second period these arrangements were shifted. Cleaning of the classrooms was performed during every lunch-brake, when the floors were wet-mopped (occasionally the windowsills were dusted).

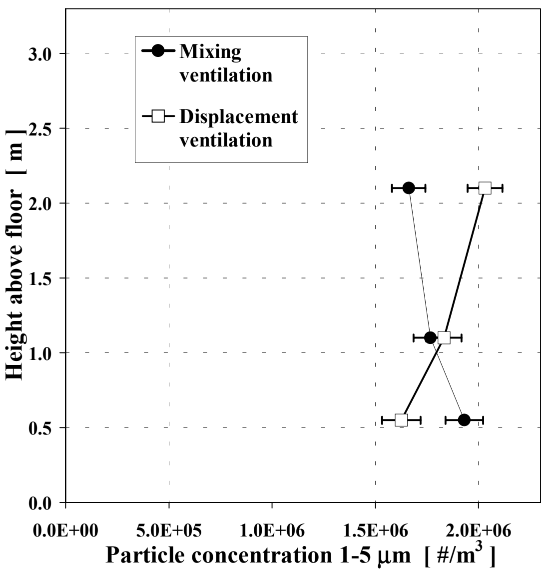
The measurements took place during the last 2 weeks of the two intervention periods. Two of the classrooms, always having different ventilation supply systems, were selected for detailed measurements of particles, CO_2 and temperature during two days of each period. Measurements were then made at three different heights, 0.55, 1.10 and 2.10 m above floor, at one horizontally central position of the classroom. An optical particle counter (CI-500), placed on a computer-controlled elevator, was programmed to sample consecutively at the different heights. The counter selected particles into six different size fractions in the range 0.3 to >25 μm. Sample air entered the counter through an 'isokinetic' sample probe, mounted directly onto the counter's inlet nozzle, with the 10.8 cm^2 opening vertically oriented. The sampling flow rate was 1.00 ft^3/min and the sample volume at each sample 10 l. The time lag was 2 min 15 s for a measurement cycle, during which one sample was taken at each height. CO_2 was measured at the same heights and in the exhaust air terminal using a BrüelandKjaer 1302, compensating for humidity. The time lag for a measurement cycle was 4 min 29 s.

Also, cat allergen was measured at the three heights mentioned above, employing a luminescence immunoassay of the allergens on air sampling filters (Holmquist and Vesterberg, 1999). This was done in all four classrooms, 2–4 days every period, with separate samples every day. Sampling flow rate was 2 l/s. The teachers and the pupils were asked to keep classroom doors and windows closed as much as possible. During days of detailed measurements, an experimenter was present in the classroom most of the time, to check instruments and to log the coming and going of the pupils. The number of pupils in each class ranged between 26 and 29. Often, there were also one or two assisting apprentices in the classrooms. The breathing height of the seated pupils was at approximately 1.1 m above the floor. The pupils left their outdoor clothes and shoes in the corridor right outside their classroom before coming in.

RESULTS

The particle measurements revealed that the pupils, as they entered their classroom, caused a manifold increase in particle concentration, of all size fractions except the smallest fraction, 0.3–0.5 µm, which appeared to be virtually unaffected. Simultaneous particle measurements outdoors, indoors and in the supply air indicated that the proportion of the indoor air particles that entered the classrooms through the supply air was 90–100% for the smallest fraction, 19–29% for the fraction 0.5–1 µm and 1–4% for the larger fractions. The large particle fractions were hence generated in the classrooms.

In the following, the presented data are selected from the time periods when the pupils were inside their classroom. The number concentration of the particles decreased rapidly with particle size. Figure 1 shows the number concentration of particles in the 1–5 µm size fraction. The depicted statistics represent estimated values after adjusting for the CO_2 concentration in the exhaust air; the values were obtained running ANCOVA with CO_2 concentration as a covariate. The rationale for using this covariate is that it is related to the number of pupils and to some extent to their physical activity; both in relation to the ventilation rate. Thus, some correction for variations in these quantities between the measurement occasions is obtained. The error bars indicate the 95% confidence interval *of the mean* in order to illustrate the significance of mean differences. Figure 2, showing cat allergen concentrations, is constructed in the same way; this figure will be discussed later. The difference in particle concentration at the different heights depicted in Figure 1 is fairly representative for all size fractions larger than 1 µm. That is, at the highest level (2.10 m) there were significantly more particles (10–22%) with displacement ventilation; at the middle height (1.10 m) there were slightly (insignificantly) more particles (–2 to 7%) with displacement ventilation; and at the lowest level (0.55 m) there were significantly more particles (10–25%) with mixing ventilation. For the smallest size fractions, 0.3–0.5 and 0.5–1 µm, there were significantly more particles (10–40%) at all heights with displacement ventilation. This might have been due to the fact that the outdoor levels happened to be higher during days with displacement ventilation.



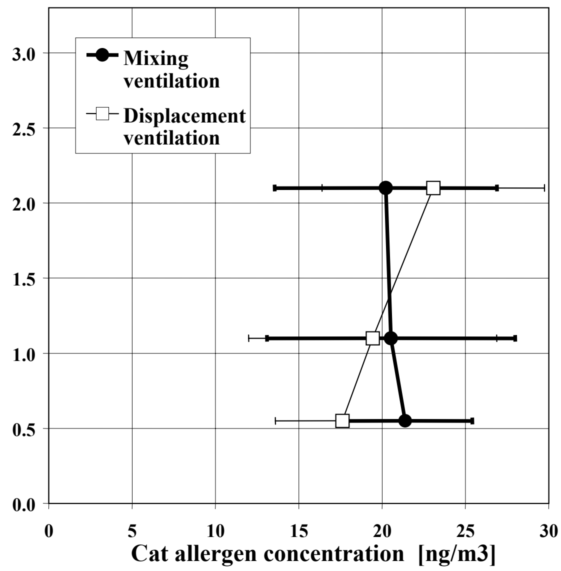


Figure 1 Particle concentration for the fraction 1–5 µm. Means and their 95% CI ($N \approx 400$ for each statistic).

Figure 2 Cat allergen concentration. Means and their 95% CI ($N = 8$–9 for each statistic)

Figure 3 pictures the vertical profiles of the mean particle number concentration for the different particle size fractions. The concentrations are given relative to the concentration at 2.10 m. At mixing ventilation it appears that the particle concentration tends to be higher the lower the level above the floor, with the gradient getting stronger the larger the particles. This is presumably an effect of gravity. At displacement ventilation, the gradients tend to point in the other direction, except for the smallest and the largest particles. For the largest particles it is likely that these are significantly affected by gravity. For the smallest particles their homogeneous concentration is probably due to negligible gravitational forces and their source being the ventilation supply air. Overall, the vertical variations are however marginal.

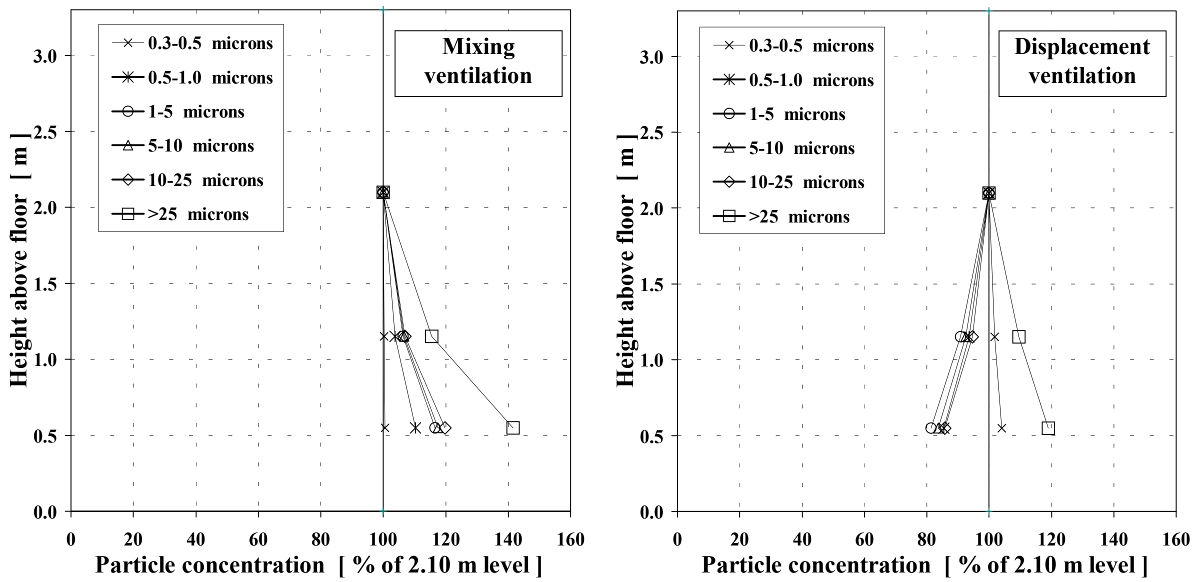


Figure 3 Particle profiles at mixing ventilation (left) and displacement ventilation (right).

The measured cat allergen concentrations showed considerably greater variation in the vertical concentration profile than the mean particle concentrations did. A possible explanation for this could be that most of the airborne cat allergen was concentrated to rather a few allergen-carrying particles. In constructing Figure 2 the two measurement occasions exhibiting the most extreme variations were omitted. Data from all four classrooms were included. The depicted statistics are estimated values obtained running ANCOVA with ‘number of cat owners in the classroom’ as a covariate. There is a notable resemblance between the allergen profiles in Figure 2 and the particle profiles in Figure 1. None of the mean differences in Figure 2 are, however, significant. Correlating allergen data with simultaneous mean particle data yielded a fairly significant correlation between the concentrations of allergens and particles of the size fractions 1–5 and 5–10 μm ($R = 0.55$, $p = 0.016$ and $R = 0.53$, $p = 0.020$, respectively), but not of the other fractions. The fact that particles smaller than 1 μm to a great extent entered through the supply air is, however, likely to have reduced the correlations for these particles. Hence it cannot be ruled out that a significant correlation existed between *indoor-generated* small particles and cat allergen.

Figure 4 shows the vertical distribution of mean CO_2 concentrations. As in Figure 3 the values have been normalized with the value at the measurement height 2.10 m in order to facilitate profile comparison. Data represented by the grey dashed lines were obtained using the absolute recorded values, whereas the solid lines were obtained after subtracting the background (outdoor) concentration (•385 ppm). The latter ought to be of most interest since it better represents all other human-generated gaseous bio-effluents, for which the background concentration is negligible. The CO_2 data of the exhaust air terminal are included in Figure 4 although that sampling location was not on the same horizontal position as the other sampling locations. The figure indicates increasing CO_2 concentration with height for both ventilation systems, although the gradient is quite weak at mixing ventilation, as could be expected. When comparing Figures 4 and 3, focusing on background-subtracted data, the graphs suggest that the lower levels in the room (the occupied zone) were held cleaner as to human-generated *gaseous* contaminants than as to *particulate* ones. Running ANCOVA with background-subtracted CO_2 values (ppm), and using 'number of persons in the classroom' as a covariate, rendered an estimated mean CO_2 concentration at 1.10 m height that was 10% lower with displacement ventilation than with mixing ventilation. At 0.55 m height it was 45% lower with displacement ventilation ($p < 0.001$ for both differences)

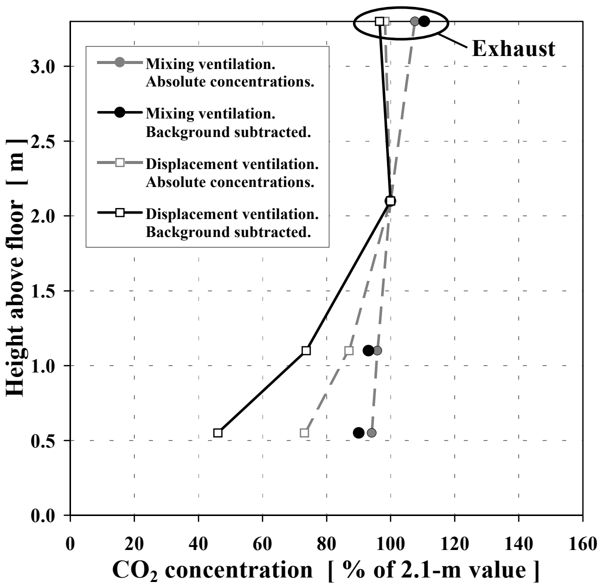


Figure 4 Mean CO_2 concentration. Values relative to the concentration at 2.1 m. ($N \approx 200$ for each statistic).

DISCUSSION

The results of this study indicate no big differences between the two ventilation principles as regards the contaminant concentrations at breathing height. It has, however, been shown (see e.g. Stymne *et al.*, 1991; Brohus and Nielsen, 1994; Mattsson, 1999; Bjoern and Nielsen, 2002) that, particularly at displacement ventilation, the air reaching the breathing zone is to a large extent brought up from lower levels in the room, via free convection currents around the human bodies. The fact that the measurements showed somewhat lower contaminant concentrations at the lowest measurement level when using displacement ventilation, suggests that the quality of the *inhaled* air might well have been slightly better with displacement ventilation. The CO_2 measurements suggest that this applies particularly to heat-associated gaseous contaminants, like human bio-effluents or emissions from, e.g. computers.

It is often assumed that the upper part of ventilated rooms is fairly well mixed due to substantial convection currents from people and other heat sources. Furthermore, it is usually the case that practically all airborne contaminants escape the room through the exhaust air terminal close to the ceiling. In the present case, one could, therefore, assume that the measured contaminant concentrations at the highest measuring point (at 2.1 m) were reasonably representative for the concentrations in the exhaust air, and hence also representative for the emission rate of the contaminants. The fact that the particle concentrations were higher with displacement ventilation than with mixing ventilation at 2.1 m could consequently mean that the particle emission rate happened to be somewhat higher during the displacement ventilation tests. Thus, for displacement ventilation the recorded particle concentrations might be over-estimated, relative to those of mixing ventilation. However, we cannot be sure that the concentrations at the highest measurement point actually were representative of the exhaust concentrations and the emission rate, especially for particulate contaminants. For these there are also deposition mechanisms involved, which might work differently at the different ventilation systems.

On the whole, however, the vertical contaminant concentration differences proved to be moderate. The experimenter attending the classes noted a fairly high level of physical activity of the pupils, teachers and assistants during the lessons. The practised pedagogic involved much individual work and work in groups, allowing a great deal of moving around. Plausibly this activity resulted in significant mixing of the room air, also when displacement ventilation was applied. In classrooms with less activity it is likely that the displacement system functions better.

CONCLUSION AND IMPLICATIONS

In classrooms where pupils are fairly active physically there seems to be no substantial difference between mixing and displacement ventilation, as to the efficiency in extracting particulate contaminants from the room air. For heat-associated gaseous contaminants, the displacement system seems to be somewhat more efficient.

ACKNOWLEDGEMENTS

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