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Air flow and particle control with different ventilation systems in a classroom

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Abstract
Most ventilation and air conditioning systems are designed without much concern about how settling particles behave in ventilation air flows. For displacement ventilation systems, designers normally assume that all pollutants follow the buoyant air flow into an upper zone, where they are evacuated. This is, however, not always true. Previous studies show that high concentrations of settling respirable particles can be found in the breathing zone, and that the exposure rates can be a health hazard to occupants. The emphasis here is on how ventilation systems should be designed to minimise respirable airborne particles in the breathing zone. The supply and exhaust conditions of the ventilation air flow are shown to play an important role in the control of air quality. Computer simulation programs of CFD (Computational Fluid Dynamics) type are used. Particle concentrations, thermal conditions and modified ventilation system solutions are reported.

Key words: Displacement ventilation; Mixing ventilation; Particles; System solutions; CFD; Classroom.

Practical Implications
Gravitational settling of airborne particles influences the design of ventilation systems.

An important question is whether one should design ventilation systems so that particles settle to the floor (or other surfaces) and then clean the floor carefully, or whether one should design the ventilation systems to keep contaminants airborne and then evacuate them by the exhaust air. Probably a combination of these two techniques is the best choice. For this purpose we need better ventilation design guidelines. This caper compares concentrations of 10 µm (aerodynamic diameter) particles in a classroom with different ventilation methods.

Introduction
A previous paper by Holmberg and Li (1998a) dealt with particle characteristics and the classification of airborne particles. A model to simulate the dispersion and settling of particles in ventilated rooms was presented. In this paper the model is applied to illustrate airborne particle behaviour and new ventilation design.

Particle concentrations in classrooms vary on average between 50 and 200 $\mu g/m^3$. The dominating source for particle fractions with diameters less than 1 µm is the outdoor air, and that for particle fractions greater than 1 μm is indoor activities (Jansson, 2000). The risk of bacteria and virus attacks is normally higher in environments with a high relative humidity (Gertis, 1999), but with particles (dust) in the air even dry environments may represent a health hazard. The dry particle mass may cause an imbalance in the mucous membrane humidity, with resulting irritation. Outdoor air in Scandinavia contains around 10 $\mu g/m^3$ particles (PM_{10}). Higher concentrations, up to 50 $\mu g/m^3$, mean an increased risk for sensitive persons, 100 $\mu g/m^3$ can result in hospital care for airway problems, and over 100 $\mu g/m^3$ represents an increased mortality risk (Åhmansson et al., 1996). Good particle control is therefore important. A preliminary model for particle settling was developed (Holmberg et al 2000) to show the ratio of settled particles as a function of the total flow rate with displacement ventilation. The aim of this project is to carry out further investigations of suitable strategies for controlling air flows and particle concentrations in ventilated rooms. Particles movements in a displacement ventilated room is illustrated in Figure 1.

Figure 1.

Modelling of particle dispersion

To be able to solve the problems with poor indoor environments and contamination, it is important to identify the potential sources of indoor particles and to understand their dispersion patterns. Indoor environments consist of low particle volume fractions and relatively small particle diameters. The particles in the model used here are therefore treated as a continuum. A drift-flux model for particle movements in turbulent air flows is used. This means that the governing equations are similar to the Navier-Stokes equations with some extra source/sink terms. To be able to use the Eulerian approach for particle dispersion, some kind of continuum criteria must be justified. For this approach to be valid, each computational element should contain a sufficient number of particles for statistically averaged properties to be assumed. Also, the particle size should be significantly smaller than the Kolmogorow microscale. The momentum equation can be expressed in vector form as

$$div(\rho w \mathbf{u}) = div(\mu_{eff}\ grad\ w) + S_w \tag{1}$$

where the first term is the convection term and the second term is for diffusion. The relative influence of particle settling is strong in low velocity regions where both convection and diffusion influence particle movements. The central differencing scheme (accurate to second-order) is here employed. A negative buoyancy term is included in the source term S_w. This is for the vertical (z) momentum equation to deal with particle concentration (density) variations in the carrier air. Turbulence in air is modelled with a standard k-ε model (Launder and Spalding, 1974). A settling vector $\mathbf{u}_s$ can then be added to the convection part of the particle concentration equation to deal with the particle settling

$$div(\rho c (\mathbf{u}+\mathbf{u}_s)) = div(\frac{\mu_{eff}}{\delta_c}\ grad\ c) + S_c \tag{2}$$

A more detailed description of the different components is given in the reference by Holmberg and Li (1998a). Particle movements in a room originate from supply air inertia, natural convection and diffusion, pressure and temperature gradients, human activity, etc. These macro movements affect the particle dispersion in the room. Both concentration and turbulence gradients influence the particle flux. The gravitational settling velocity of the particles is derived by Stokes equation, demonstrated in Holmberg et al (2000).

Validation of the model

Results from measurements with turbulent flow conditions and a sensitive aerosol detection technique, Byrne et al (1995), have been used for validating the numerical calculations. A cubic aluminium test chamber of 8 m^3, where turbulent flow conditions were generated with a rotating fan, was used for the measurements. Air velocities, turbulence levels and average aerosol deposition velocities on all surfaces were measured for particles of various mono-disperse particle sizes. Numerical simulations were designed to fully follow the experimental work, Holmberg and Li (1998a). The agreement between measured and modelled particle settling velocities was good. Numerical simulations of flow patterns and thermal conditions were compared to measurements in a full-scale room, Holmberg and Einberg (2002). The agreement was acceptable.

Ventilation simulations in a classroom – room details and boundary conditions

Monodisperse particles 10 μm in diameter were brought into the room by the ventilation supply air at a concentration of 100 μg/m^3. The displacement system was later modified by adding a low-zone exhaust terminal and the evaluation repeated. Finally a low-zone supply device (slot) was used to replace ordinary air supply diffusers.

Displacement ventilation

A numerical study was carried out in order to investigate airborne particle concentrations, and to find some general ventilation requirements for a ventilated classroom with 25 persons. Figure 2 shows the modelled classroom, 2.5 m high and with 56 m^2 of floor area. A relatively coarse computational grid (36 x 36 x 27) gave fast results and acceptable numerical accuracy. Twenty-five rectangular blocks, each 0.34 x 0.2 x 1.4 m^3, represented the persons in the room. The height of the persons (1.4 m) was selected as a compromise between standing and seated persons. The blocks had a free surface area of 1.6 m^2, which gave a constant convective heat flux of 60 W to the surrounding air. No other heat sources were present and this total heat load of 1500 W provided a suitable mean air temperature and vertical temperature gradient in the room. Adiabatic wall conditions were assumed, which meant no heat exchange with wall, floor and ceiling surfaces. The reference value for the particle concentration in the room was 100 μg/m^3. The incoming fresh air supply rate was 0.250 m^3/s (10 litres/s per person). Two supply air terminals for displacement ventilation were modelled (based on FMK-03, ABB Ventilation Products AB). The supply air was evenly distributed over the area of the terminals, which resulted in an average supply velocity of 0.3 m/s. An initial turbulence intensity of 10% was given to the supply air at 19°C. An exhaust terminal (0.40 × 0.30) m^2 was centred on the exhaust wall 2.1 m above floor level. Method specific boundary conditions are given in Holmberg and Li (1998a, 1998b).

Figure 2.

Conventional displacement ventilation is based on the assumption that heat sources in the room bring contaminants to an upper zone where they are evacuated. A number of investigations, including laboratory measurements, have shown this is true for gas phase contaminants. Both industry and university laboratory measurements (Mattsson, 1999) have been checked within the frames of this work. However, there is currently no method available for assessing the movements of airborne particles with displacement ventilation systems.

Mixing ventilation
A mixing ventilation example was introduced in order to have reference exposures. Both mixing and displacement systems used the same exhaust terminal. The mixing system had a supply terminal on the wall opposite the exhaust, with the same size and geometry as the exhaust terminal. A supply jet with negative buoyancy was formed, from the supply device to the middle of the floor. The supply air velocity and temperature were set to 0.87 m/s and 19°C respectively. All other conditions, including personal heat loads, were identical to the displacement example.

Modified displacement ventilation

Particle accumulation in the breathing zone has been observed with different displacement ventilation arrangements (Holmberg and Li, 1998b; Holmberg et al., 1999). A reorientation of supply/exhaust devices was here expected to improve the evacuation of particles in the room.

Low-zone exhaust
Particle settling is a natural form of air cleaning, and thus a positive process as long as particle accumulation in the air can be avoided. This has been tried here by an additional exhaust arrangement designed to evacuate settling particles in the low-zone, below the breathing level. The system thus has a low-zone exhaust in addition to the high-zone exhaust for conventional displacement ventilation.

Low-zone exhaust with low-zone slot supply

This system forces ventilation air and contaminants in a certain direction (*x*-direction) for evacuation. A low horizontal wall slot replaced the two diffusers (Figure 2).
The idea here is to create an efficient and systematic transport of ventilation air and contaminants in the main flow direction of the ventilated space. Three zones have been defined. A low zone for air flow and contaminant control, which consists of the air supply terminal and the low-zone exhaust (in addition to the high-zone exhaust) of air and settled particles. A human near zone (including breathing zone) with buoyant convective air movements around persons, and finally an upper zone with separate exhaust. It is expected that the flow conditions in the low zone are important for the control of particle contaminants.

Results and discussion

The various supply diffuser locations that have been used are shown in Figures 2. A total ventilation flow rate of 250 l/s (10 l/s/person) was used. The total heat load (1500 W) from the person simulators was constant in all comparisons.

System assessment
An assessment of the ventilation function was performed by parameter comparisons close to the simulated students in the classroom. Variations in the ventilation flow rate and in the size of airborne particles are not considered in this work. Such variations influence the absolute values of the above results but leave the tendencies unchanged, within certain limits. For estimations of particle exposures a slice cut through an inner student line along the *x-z* plane was chosen. Vertical temperature gradients were investigated in the middle of the classroom by another slice cut through the *y* co-ordinate. The assessments thus include:

- particle control
- vertical temperature gradient values for thermal comfort considerations

The results for particle control are shown in Figure 3.

Figure 3.

The continuous settling of particles during transport in the main flow direction (x-direction) leads to an accumulation of particles that are brought into the breathing zone by the human convective heat sources. The exposures are increased by distance from supply wall with displacement ventilation. Low zone evacuation of air and particles improves the conditions.

Vertical temperature gradients in the middle of the classroom are shown in Figure 4. Acceptable thermal climate conditions are obtained with mixing and displacement ventilation. With forced (low zone supply/exhaust) displacement ventilation, steep temperature gradients are obtained below the breathing zone. Recent measurements indicate that temperature conditions in the room as a whole have a greater effect on thermal comfort than the actual temperature gradient does (Holmberg et al, 2000). Thus in a warm room such as in Figure 4, the cooling effect at foot level may be regarded as pleasant. The air supply temperature is a control parameter.

Figure 4.

Conclusions

Previous research (Luoma and Batterman, 2001) has demonstrated that occupant-related emissions of 1-25 μm particles significantly elevate the exposure levels in a person's microenvironment. Thatcher and Layton (1995) showed that occupants significantly affect the concentration of airborne particles > 5 μm. Here has been shown that displacement ventilation systems modified with a low-zone particle exhaust can decrease particle concentrations in the breathing zone.

Particle settling is a natural cleaning of ventilation air. On the other hand, if particles settle towards the floor and particle fronts (with increased concentration locally) are created, contamination can arise in the breathing zone.

Particles may be carriers of carcinogenic, allergic and irritant substances, Indoor Environment and Health (1999). It is known that a large quantity of specific allergens and many organic particles can give risk to allergic and other hypersensitivity reactions. The particle content in indoor air should therefore be kept at a low level by good ventilation. Measured data provide evidence of significant indoor generation (re-suspension) of particles larger than 1μm, Fisk et al (1999). The numerical results presented here indicate that when settling (re-suspended) particles occur in the room they can easily be brought into the breathing zone by the strong convective heat plumes around persons. Our results indicate that an additional exhaust outlet below the breathing zone can control high particle concentrations in the breathing zone.

However, such modifications to a ventilation system must be properly designed and tested. Good overall function is required, including the general requirements of efficient ventilation and acceptable thermal comfort.

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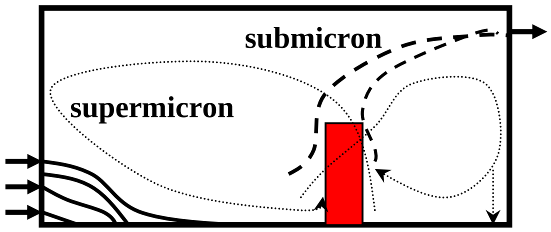


Figure 1. Particle behaviour with displacement ventilation close to a simple rectangular human model. Small particles follow the ventilation air flow while larger particles may behave differently and settle. Internal re-circulation of such particles into the human convective heat source may increase particle exposures in the breathing zone.

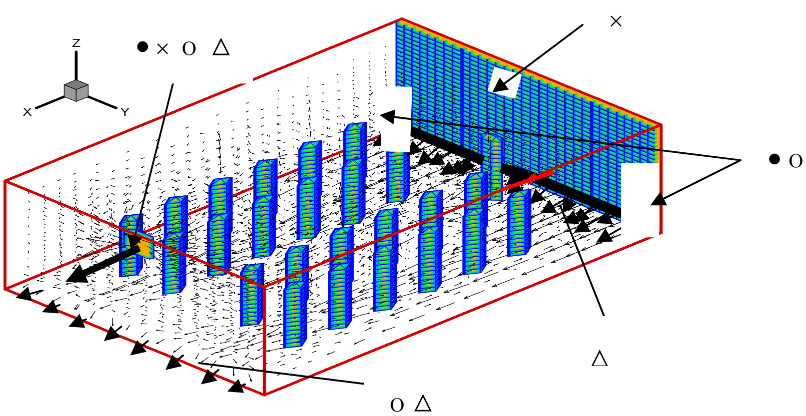
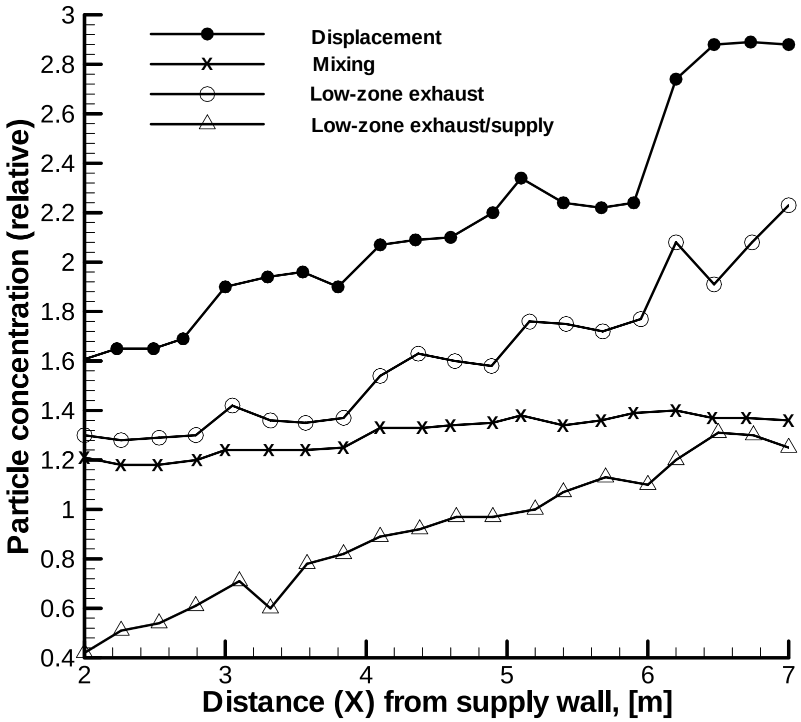
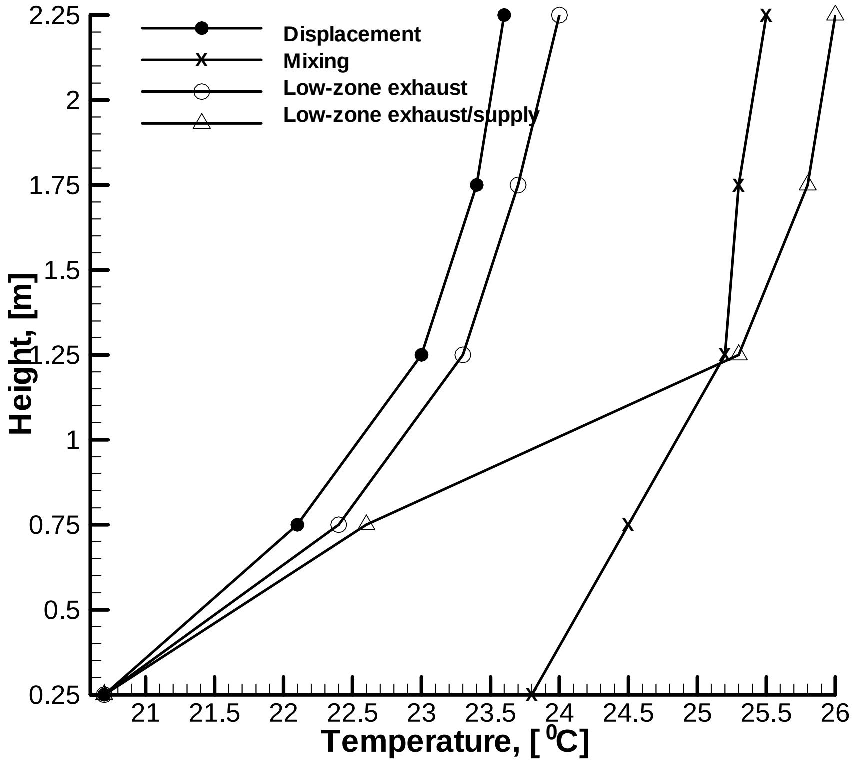


Figure 2. Numerical test chamber (classroom) for displacement ventilation, •, displacement ventilation with an additional low-zone exhaust, o, mixing ventilation, ×, and low-zone slot supply, △, with exhaust at two levels on the opposite wall (active in the figure). The supply and exhaust slots in the last example are 0.2 and 0.1 m above floor level respectively. Particle concentrations and temperature conditions are compared with the different supply/exhaust arrangements.

(•, ×, o, △ = supply/exhaust device indicators)



of supply air) inlet. Different ventilation forms (displacement/mixing) and supply/exhaust conditions were used. The particle diameter was 10 μm.



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