PARTICLE FILTRATION IN A VENTILATED ROOM

G Einberg* and S Holmberg

Dept. of Building & Construction, Royal Institute of Technology, KTH Syd, Stockholm-Haninge, Sweden

ABSTRACT
Several studies based on analytical models and numerical simulations have shown that it is difficult to control airborne particle movements in a ventilated room. However, more knowledge and information on particle characteristics and particle movements, in combination with new numerical simulation tools, have recently made it easier to estimate particle patterns. In the present paper new information is used to evaluate the role of filtration and ventilation in the particle elimination process. Key parameters found include the particle aerodynamic diameter and the particle settling velocity governed by Stokes formula. Particle dispersion and settling are highly dependent on the ventilation airflow structure. Calculations with CFD (Computational Fluid Dynamics) show characteristic patterns of particle movements in rooms with displacement ventilation.

INDEX TERMS
Filtration, CFD, Simulations, Displacement ventilation, Breathing zone.

INTRODUCTION
In recent years ventilation of living and working spaces has been studied more then ever. Therefore different methods, i.e. analytical models and numerical simulations of airborne particle movements, are available in the design of efficient system solutions. Such systems are often designed for low ventilation flow rates and minimum energy consumption. Carefully placed and correctly designed air terminal devices (ATD) can significantly reduce ventilation flow rates. Correct ATD design in combination with filtration functions in the room should be used to decrease contaminant concentrations in the human breathing zone. The convective air plume around the human body brings fresh air into the breathing region with displacement ventilation. The convective air movements will, however, also attract contaminants into this zone. Especially particles near the floor (under the breathing zone) will easily follow the air streams into the breathing zone. Settled particle fronts are slowly brought into the human near field, where buoyancy forces attract them. One way to handle unwanted particle re-circulation in the room is to use local air filtration. The main idea with this paper is to discuss ventilation concepts where not only air movements but also particle movements and local filtration of particles are considered.

BREATHING ZONE EXPOSURES AND THE ROLE OF VENTILATION
The breathing zone concentration is dependent on both the chosen ventilation system and the particle characteristics. The contaminant (particle) sources in the room and outside the room are naturally important. Many contaminants originate from persons in the room and are thus directly generated into the buoyant heat plume around humans. Sometimes particle concentrations are higher indoors then outdoors, especially if we deal with homes with smokers (Wallace, 1996). This is often true for small particles. They stay airborne for a long

* Contact author email: gery.einberg@syd.kth.se
time, because of low settling velocity. With displacement ventilation gas contaminants and small particles are brought to an upper contaminated zone where they can be evacuated. However, concentration calculations with mass balance models for mixing ventilation (Jamrisko et al, 2000) are not practical in this case. Particles of different sizes are generated near the body (local heat source) in Figure 1. Some predicted dispersion patterns are shown in the figure. All particles below 20 micron are brought to the upper contaminated and mixed zone. Small particles (sub micron) and gas contaminants are evacuated in the upper zone, see particle pattern “1”. Super micron particles up to 5-10 micron show a ‘boomerang’ behaviour. They settle but are later again found in the breathing zone. The convective air plume attracts them while they are settling, (Holmberg et al, 2000). See particle pattern “2”. The largest particles have a ballistic behaviour and may be found deposited in corners or other hidden places. The preliminary results show that humans (convective heat sources) are causing increased contaminant concentrations in the breathing zone, see Figure 3 and 4. Settled particles are contamination sources. They should be eliminated by filtration or more efficient ventilation.

![Figure 1. Air and particle behaviour around a human body. Partly adapted from (Murakami et al, 1996)](image)

**THE ROLE OF PARTICLE FILTRATION IN THE ROOM**

The filtration of air is considered important as the air is contaminated from indoor and outdoor sources (Liddament, 2000). It has been shown that the ventilation alone cannot deal with all types of contaminants in the room. Local differences in contaminant concentrations can be observed when flow conditions are not fully mixed. This is the case with displacement ventilation. Particle fronts and regions with increased concentrations are presented in publication by (Holmberg et al, 2000). An important parameter is the particle aerodynamic diameter. The diameter dependent settling velocity $v_s$ is given by Stokes law and shown in
Equation 1 and Figure 2 below. This is a main variable in the modelling of particle dispersion and settling. See results from classroom simulations in Figure 3 and 4.

\[ v_s = \frac{\rho_p \cdot g \cdot d^2 \cdot c}{18\eta} \]  

(1)

Particle density is given by \( \rho_p \), \( g \) is the acceleration due to gravity, \( d \) is the particle aerodynamic diameter, \( c \) is the Cunningham’s slip correction factor and \( \eta \) is the dynamic viscosity of air.

The particle size and settling velocity can help us understand where different particle fractions may be found in a displacement ventilated room. Filtration of supply air is normally achieved by the air terminal device or in the duct system before the terminal. Particle filtration in the room is more complex and there are several different states to consider. The indoor thermal environment, ventilation flow rates and particle dispersion/deposition play a significant role. It is important to know where to locate filtration devices in a room. Preliminary results show that 10 \( \mu \)m particles can be evacuated/filtrated from lower elevations, see Figure 3 and 4. Air plume velocities of 0.26 m/s are normal in the buoyancy flow around persons with displacement ventilation, see Figure 1. This brings particles of different sizes into the upper zone. Coarse and middle-size particles will return from the upper zone into lower elevations by settling. Small particles follow the buoyant air streams to the upper zone and may be filtrated under the ceiling.

### CFD modelling of particle settling

A numerical test room (9.0m x 6.0m x 2.7m) simulates a real classroom in Figure 3. The simulated students were represented by rectangular heat sources. The air was supplied from two simulated low velocity air - terminal devices and one exhaust grille was located near the ceiling. The average particle concentration in the simulated room was 100 \( \mu \)g/m\(^3\). Particles
were generated close to the students. The particle size was 10 micron. The used total ventilation flow rate was 0.25 m$^3$/s. The results of the simulations can be observed in Figure 3. They indicate that the particles tend to accumulate in the corners of the room. All the calculations and governing equations are based on numerical modelling in previous work (Holmberg and Li, 1998) and (Holmberg et al, 2000). It is obviously not simple to implement boundary conditions that fully are in agreement with the real conditions. Turbulence modelling with two equation models is always difficult close to solid surfaces. This experience we share with (Brohus, 1997) and several others.

Figure 3. Test facility and particle concentration (lower figure) in the simulated room. Settling takes place in the corners of the room (opposite the air terminals). Concentrations that exceed twice (>200 $\mu$g/m$^3$) the room average concentration are visible in the figure.

**Location of filtration devices**
- All types of particles can be filtrated above convective heat plumes. This filtration should be completed before dispersion and sedimentation of particles from this region takes place.
• Middle size particles re-circulate in the room and should be filtrated in the breathing zone. Personal filtration equipment is an effective solution.
• Coarse particles shown in Figure 3 should be filtrated in corners to avoid re-circulation of particles into the room. Stationer filtration equipment is a possible solution.

PARTICLE REMOVAL EFFICIENCY
The relative air quality in the breathing zone can be expressed by the particle removal efficiency $\varepsilon_{b.z}$. This efficiency gives a relative comparison between particle concentrations in the exhaust outlet and the breathing zone. The following definition is used by referring to behaviour in Figure 1:

$$\left(\varepsilon_{b.z}\right)_{1-3} = \left(\frac{c_{\text{exhaust}}}{c_{b.z}}\right)_{1-3}$$  (2)

$c_{\text{exhaust}}$ – measured (calculated) concentration in exhaust air
$c_{b.z}$ – measured (calculated) concentration in the breathing zone
1-3 - particle size index used in this paper, see Figure 1

Particle removal efficiency with an ideal mixing system is unity (1.0). Higher values (>1.0) indicate improved indoor air quality conditions in the breathing zone (Behne, 1999). This may be arranged by properly designed displacement ventilation in combination with room air filtration. The breathing zone can be defined as the air layer near the human head 1.5 – 2.0 m over floor level. To determine the extension of the breathing zone in the horizontal pane is difficult. When the plume has changed direction in the upper zone, some of the particles will return to lower zones by settling. Equation (2) is useful in designing the ventilation airflow in such a way that the concentration in the breathing zone is low for particle fractions (1-3). By filtration in the room particle re-circulation can be reduced and particle removal efficiency increased. The particle behaviour is highly dependent on the ventilation airflow. Previous investigations have indicated that the concentration of 2.5 $\mu$m particles is increasing near the human body (Holmberg et al, 2000). When local air flows in the room are low and the buoyant flows around persons dominate, contaminants may be attracted into the heat plumes around persons.

The positions of exhaust grilles in displacement ventilation should be considered carefully. Contaminants do not follow the air streams to the outlet. They behave differently and they settle. Similar deposition occurs in smooth ventilation ducts in laminar airflows. Later they become sources that generate particles into the air stream (Lai and Nazaroff, 2000) and (Hwu et al, 1997). From the results in Figure 4 we can observe increasing concentrations in the breathing zone. Concentration near the ceiling was rising when tracer gas CF$_6$ was used (Mattsson,1999). Figure 4 proves that a convective heat source attracts contaminants into the breathing zone at 1.5 m height. Therefore local air filtration should be considered as a possible solution to avoid this problem.

CONCLUSION AND IMPLICATIONS
A new concept to evaluate particle movements in a ventilated room is presented. Air borne particles do not always behave like the main air streams. They tend to have behaviour of their own, see Figure 1. In this concept particles are divided into three categories. The three groups are based on the particle aerodynamic diameter. Presented results give an indication of where filtration devices could be located. The floor region is both a sink and a source for particle contamination in the room. Different particle sizes should be investigated in the future. We
have observed that thermal plumes are elevating contaminants into breathing zone. Improved validation requires more measurements and numerical simulations.

Figure 4. Settling particles are re-entering convective air plumes (left). Measured gas concentrations and simulated particle concentrations (non-dimensionalized by exhaust concentration) in the human near field (right). Compare to Figure 3.

REFERENCES
Brohus H. 1997. Personal Exposure to Contaminant Sources in Ventilated Rooms, PhD-thesis, December 1997, Department of Building Technology and Structural Engineering Aalborg University, Denmark
Mattsson M. 1999. On the Efficiency of Displacement Ventilation with Particular Reference to the Influence of Human Physical Activity, Doctoral thesis KTH, Centre of Built Environment, Royal Institute of Technology, Gävle, Sweden