NON-PASSIVE PARTICLE DISPERSION IN A DISPLACEMENT VENTILATED ROOM - A NUMERICAL STUDY

S. Holmberg[1], Y. Li[2]
[1] Dep. of Built Environment, KTH, Gävle, SWEDEN
[2] CSIRO, Building, Construction and Engineering, Highett, AUSTRALIA

ABSTRACT
Health effects caused by aerosol air pollutants in the breathing air is a main target for occupational health investigations. The effects of aerosol particles on health usually depend on the dose of particulate matter (PM) retained at various locations of the respiratory tract. Displacement ventilation has been proved to be an effective ventilation system for the removal of passive pollutants in many buildings. The question is often asked about the performance of non-passive particle removal in a room ventilated by displacement ventilation.

In the present paper, non-passive particle dispersion behaviour in a room ventilated by displacement ventilation is investigated numerically. The dispersion of particles is predicted by a drift-flux model where a settling term is added to the concentration equation, and the body force term in the momentum equation is treated using the principle of a Boussinesq approximation, similar to that in a thermal-buoyancy-driven flow. Turbulence effects in the air stream are modelled with a standard k-ε turbulence model. Some preliminary model validation work has been done by comparing numerically calculated results with those measured in an aerosol chamber. The main purpose of this study is to find out how particles of different sizes behave in a displacement ventilated room, and how different ventilation conditions change the exposure levels in the breathing zone.

KEYWORDS
CFD, particles, displacement ventilation, breathing zone, numerical methods

INTRODUCTION
Conventionally, concentrations of indoor contaminants are calculated by assuming that they fully follow the ventilation airflow in a room. Low velocity supply terminals at floor level continuously supply clean and cool air into the occupied region, while the outlets at the ceiling level remove the contaminated air out of the building. With non-passive particles, the downward settling velocity will work against the upward plume flows. The question is can displacement ventilation be applied in situations where non-passive particles need to be removed.

In this paper a non-passive particle model is suggested for use where indoor airborne particles do not always follow the main airstream. The model assumes that the settling velocity of each particle is sufficiently small, when compared to the inflow turbulence levels, so that the effect of the particles on turbulence can be neglected. This allows the turbulence to be treated as a one-way coupling between particles and the air. Any number of particle size groups can be accommodated. Two particle sizes and two different exhaust outlet arrangements are considered. Low particle settling velocities coupled with low particle volume fractions allow application of a drift-flux multi-phase model rather than a fully coupled multi-fluid model, Elghobashi (1994). The particle model has been preliminarily validated by comparing numerically calculated results with aerosol chamber measurements, Holmberg and Li (1998). Additional qualitative evaluation will be presented here.

METHOD

Governing equations

The governing general equation for continuity and transport is:

$$\frac{\partial(\rho u_j \varphi)}{\partial x_j} = \frac{\partial}{\partial x_j}(\Gamma \frac{\partial \varphi}{\partial x_j}) + S \quad (1)$$

where subscript j stands for coordinate directions. The equation components are given in Table 1. From Equation (1) the z direction momentum equation is given by:

$$\frac{\partial(\rho u_j w)}{\partial x_j} = \frac{\partial}{\partial x_j}(\Gamma \frac{\partial w}{\partial x_j}) + S + F_{\Delta\rho} + F_{\Delta T} \quad (2)$$

where body forces due to particle/fluid density differences ($F_{\Delta\rho}$) and thermal differences ($F_{\Delta T}$) are modelled using a Boussinesq approximation.

Particle settling velocity w_s is included in the concentration equation, giving the following equation for concentration calculations of non-passive particles in the air:

$$\rho(u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + (w+w_s)\frac{\partial c}{\partial z}) = \frac{\partial}{\partial x_j}(\Gamma \frac{\partial c}{\partial x_j}) \quad (3)$$

Boundary conditions

General boundary conditions for walls, inlets and outlets, including turbulence boundary conditions are given elsewhere, Holmberg and Li (1997). Specific boundary conditions for the case studied here are described in the next section.

Table 1. General transport parameters for Equation (1). The pressure component is given by p, temperature by T, laminar Prandtl number (Schmidt number) by σ, fluid viscosity by μ and density by ρ. Subscripts c, i and t indicate particle concentration, coordinate direction and turbulence, respectively.

EQUATION	φ	Γ	S
Continuity	1	0	0
Momentum	u_i	$\mu + \mu_t$	$-\partial p/\partial x_i$
Particle concentration Energy	c T	$\mu/\sigma + \mu_t/\sigma_c$ $\mu/\sigma + \mu_t/\sigma_t$	0
Turbulent kinetic energy	k	$\mu + \mu_t/\sigma_k$	$P_k - \rho\varepsilon$
Dissipation of k	ε	$\mu + \mu_t/\sigma_\varepsilon$	$\varepsilon(C_{\varepsilon 1}P_k - C_{\varepsilon 2}\rho\varepsilon)/k$
$P_k = \mu_t(\partial u_i/\partial x_j + \partial u_j/\partial x_i)\partial u_i/\partial x_j$, $\mu_t = C_\mu \rho k^2/\varepsilon$, $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $\sigma = 0.72$, $\sigma_c = 0.9$, $\sigma_t = 0.9$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$			

NUMERICAL INVESTIGATION

Test chamber

The geometry and dimensions of the numerical test chamber, as well as the general flow pattern in the investigated room segment, are shown in Figure 1. An equally spaced grid of 40 x 20 x 40 was used for all calculations. Two rectangular blocks 0.18 m x 0.36 m x 1.68 m were designed to represent two standing persons. Both blocks have a free surface area of 1.67 m^2, giving a constant heat flux of 50 W to the surrounding air. No other heat sources are present in the room and the total heat load of 100 W was appropriate to provide a reasonable room mean air temperature and a vertical temperature gradient. Similar heat loads per square metre may be found in schools. Such environments are of certain interest from particle dispersion and efficient ventilation point of view. The selected roof height of only 2.4 m is a low-energy choice for which the function of the displacement ventilation system is evaluated.

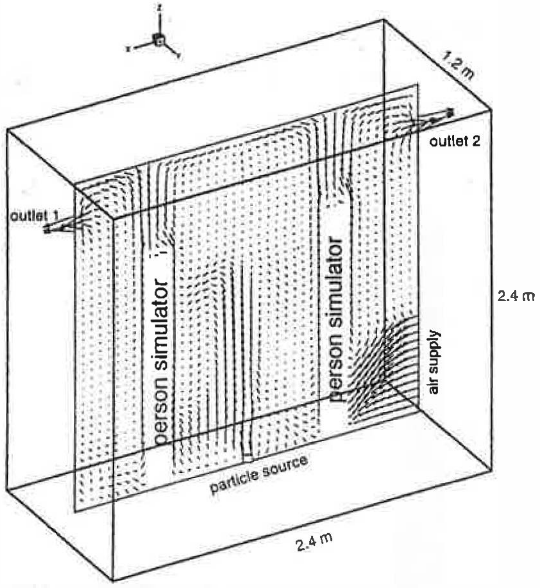

Figure 1. Numerical test chamber for particle dispersion and concentration evaluations in the breathing zone. Room configuration, geometries and positions for air and particle supply/evacuation are shown.

Adiabatic wall conditions are used for all wall boundaries. The supply air is 17°C, with an incoming velocity of 0.1 m/s and turbulence intensity of 4 %. The 0.24 x 0.72 m^2 air terminal for fresh air supply has a capacity of about 7 nominal air changes per hour. Another small air supply was connected to the particle supply. Two exhaust outlet positions are shown in Figure 1. Each outlet is 0.18 x 0.24 m^2 and centred 2.1 m above floor level.

Particles and particle supply

A size distribution of indoor air aerosols shows a wide variation in particle diameter from ultra fine particles to big particles with totally different aerodynamic behaviour in the air. Several epidemiologic studies have given evidence that small particles may be of highest concern for health protection, Hauck (1996). However, this is not fully clear and other researchers state the opposite considering big particles most dangerous. Here two particle sizes are considered, i.e. 0.3 μm and 20 μm. A unit particle density of 1000 kg/m^3 is used.

Particles were supplied into the room together with incoming air from a small 0.12 x 0.12 m^2 source in the middle of the test chamber floor. Figure 1 shows velocity vectors for a mid-plane y-z cut. Both the main fresh air supply and the mid-room particle/air supply source are visible. Mean velocity, turbulence intensity and temperature of the particle-ladden air supply are respectively 0.1 m/s, 20 % and 30°C. This particle spread pattern could perhaps be compared to the spread of particles from a vacuum cleaner filter with reduced function. Steady state average particle concentration in the room was kept at a constant level of around 100 $\mu g/m^3$. This is achieved by suppling particles at a rate of 4.7 g/h. Personal (breathing zone) particle exposures are investigated numerically taking particle dimensions and different ventilation exhaust outlet arrangements into account.

RESULTS

Two particle sizes (0,3 μm and 20 μm) and two exhaust outlet configurations (outlet 1 and outlet 1 + outlet 2) were used in the present numerical investigation. Because of their characteristic aerodynamic behaviour, the small 0.3 μm particles were expected to behave in a similar manner as passive gas contaminants. This provides an additional opportunity to validate the simulated results against gas contaminant measurements in laboratory. Figure 2 shows predictedted 0.3 μm particle concentrations in the test chamber. Breathing zone concentrations are circled in the upper part of the person simulators (thermal manikins). Room particle concentrations are normalized against the emitted steady state concentration. It is obvious that the particles are entrained into the vertical plume of the thermal manikins, which in turn determines the breathing zone concentrations. It is therefore to be expected to have particles concentrated close to and in the breathing zone.

From the unity exhaust outlet concentrations in the two outlets (outlet 1 + outlet 2) it seems reasonable to assume that almost all emitted particles are transported through the outgoing air stream. This simulation was also performed with only one active outlet (outlet 1) in the numerical test chamber. More or less identical particle concentrations were achieved in the room. This shows that different locations and number of exhausts did not change the particle concentrations in the breathing zone for the small 0.3 μm particles.

The particle dispersion pattern for 0.3 μm particles in Figure 2 can be compared with passive tracer gas measurements in Figure 3, Stymne et al (1991). A complete comparison is not possible because of different physical conditions (standing/sitting manikin), but the dispersion pattern and (relative) local concentration variations are comparable. The comparison shows resonable agreement.

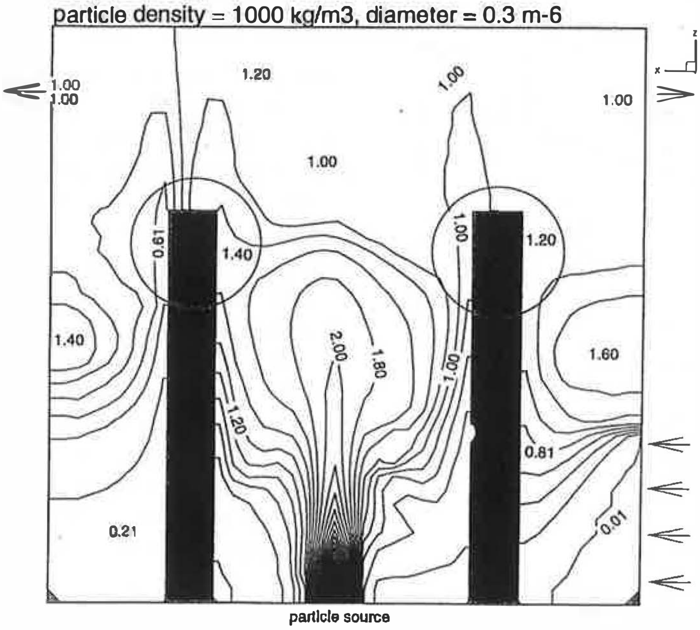

Figure 2. Dispersion of 0.3 μm particles from a floor-located particle source in the middle of the test chamber. Normalized breathing zone concentrations are circled on the upper part of the two manikins. An altered exhaust outlet arrangement with only one outlet (outlet 1) did not change the breathing zone concentrations.

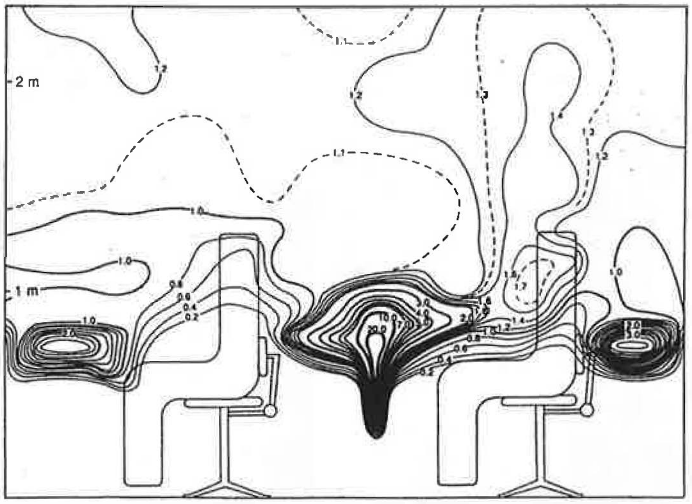

Figure 3. Concentration map showing the dispersion of passive (gas) contaminants emitted from a heated source, Stymne et al (1991).

The dispersion pattern of the 20 μm particles was different to what has been observed for the small 0.3 μm particles. The relatively high settling velocity of the large particles plays an important role in establishing a settling region behind the second person, which is remote from the supply inlet. In the settling region, the air velocity is relatively low. The same phenomena were observed in a mixing ventilation room in our earlier studies, Holmberg and Li (1997). It was obvious that the outlet arrangement had some influence on the breathing zone concentrations as well as on particle settling.

Figure 4 shows the floor region with the main settling zone. From this zone, particles were re-entrained into the convective plume of a thermal manikin resulting in relatively high breathing zone concentrations. Figure 5 shows simulated results with 20 μm particles and one exhaust outlet (outlet 1). Settled downstream particles re-entrained into the thermal plume of the thermal manikin next to the settling zone, resulting in a relatively high breathing zone concentration. The three other breathing zone concentrations as well as the upper-zone concentrations were relatively low.

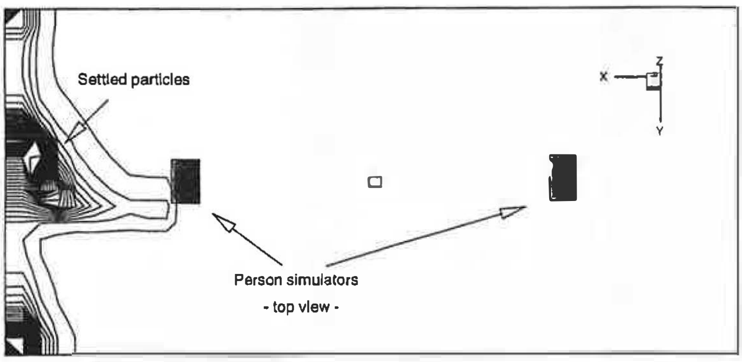

Figure 4. Settled 20 μm particles in the floor region acted as a secondary source for re-entrainment into the convective plume of a thermal manikin.

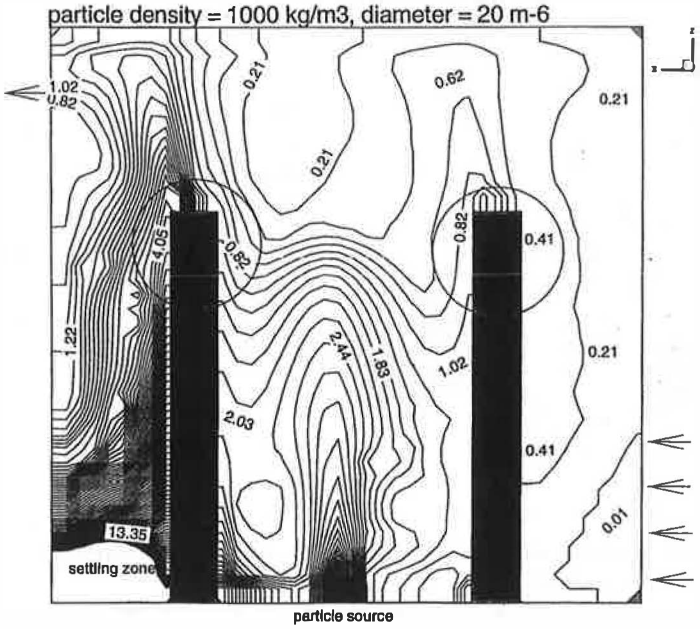

Figure 5. Dispersion of 20 μm particles in the numerical test chamber with displacement ventilation. The single exhaust outlet (outlet 1) used here evacuated 94 % of the particles. Re-entrainment from settled particles increased breathing zone concentration locally.

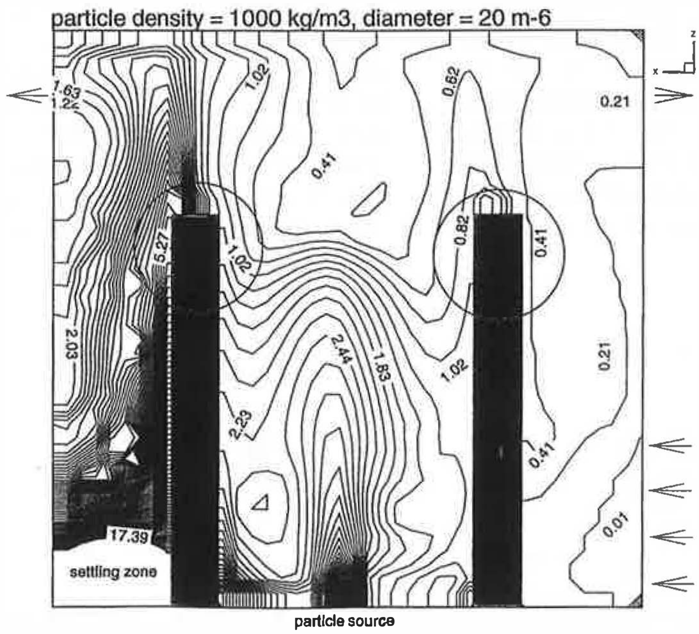

Figure 6. Dispersion of 20 μm particles with two ventilation exhaust outlets (outlet 1 + outlet 2). Approximately 82 % of the emitted particles were evacuated. Relatively high down-stream and upper-zone concentrations were achieved.

The above described simulation with 20 μm particles was repeated with two exhaust outlets (outlet 1+outlet 2) and the results are shown in Figure 6. It seems that the downstream particle concentrations including breathing-zone concentrations around the left person is higher in Figure 6 than that in Figure 5. A weaker main air flow direction through the room (with two outlets) is a possible reason.

It is clearly shown in both Figure 5 and Figure 6 that the thermal plumes can no longer bring all the large particles upward into the upper zone, where the concentration is no longer homogeneous. The gravity current (incoming air) tends to prevent the formation of local settling zones at floor level. In this situation, settling zones tend to be formed behind solid objects and in corners where the velocity is low, compare Figure 4.

DISCUSSION AND CONCLUSIONS

A drift-flux model (Eulerian type) for non-passive particle dispersion has been described and demonstrated by simple examples. Realistic indoor air particle characteristics have been chosen for the 3D numerical predictions. Promising results show that the model can be useful for providing practical particle dispersion information in the design of modern ventilation systems.

The new model is expected to give a better total understanding of relationships between room geometries, ventilation air flow rates and ventilation principles on the one hand, and pollutant characteristics and concentration levels on the other. Simulations can be used to find optimal ventilation strategies to eliminate harmful indoor air particles. The particle behaviour and local concentrations in the human near-body zone are of particular interest from an occupational health point of view.

With homogeneous contaminant levels without specific local sources displacement ventilation has a good chance to bring fresh air into the breathing zone and the contaminant concentration here will stay below average room concentrations, Kato et al (1996). If, on the other hand, relatively strong local sources located below the breathing zone are influencing the particle concentration in the room, particle entrainment into the breathing zone is hard to avoid. The thermal plumes that surround persons in the room control the vertical air movements and will attract particles from the source into the breathing zone.

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