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The Effect of Particle Source Position and Air Supply Location on Contaminant Dispersion in Displacement Ventilation Systems

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Abstract

The aim of this paper is to investigate the effect of the particle source location on contaminant distribution in a displacement ventilation system with varying air supply settings. This study investigates two different supply locations (perforated floor and wall diffuser) and two supply air flow rates (40 m³/h and 250 m³/h) with three different particle source locations at a buoyant source (bottom, top, overall). Contamination dispersion patterns and ventilation effectiveness were evaluated by means of computational fluid dynamics.

The results indicate that the particle source location has no significant impact with a suitable combination of diffuser location and supply volume flow rate. In this case, efficient removal of contaminants is achieved with both positions of the supply diffuser. However, the supply location has significant impact when the air is supplied through wall-diffusers at a high volume flow rate. The air flow pattern around the source is influenced, resulting in a polluted occupied zone and thus in a poor ventilation effectiveness.

Keywords - displacement ventilation; particle dispersion; ventilation effectiveness; particle source position, air supply location

1. Introduction

A displacement ventilation system assures good air quality in the occupied zone. Fresh, cool air is supplied at floor level. A buoyancy-driven volume flow results at heat sources. If these heat sources are also contamination sources, the contaminants are carried to the ceiling region, from where they are extracted from the room. In this way, displacement ventilation is characterized by the formation of layers of air with different qualities: a layer of supply air with low levels of contamination, and a layer of exhaust air with high levels.

Literature sources [1], [2] provide calculation rules for thermal plumes above heat sources. These rules are accompanied by a number of assumptions regarding the development of the models, such as a background environment which is at rest. In most cases, if the displacement ventilation system has been designed properly, one can assume that there are low flow velocities and therefore that the environment is nearly at rest. Yet this becomes a critical point when the warm contaminants are introduced at the floor region. If the supply air is introduced from the side at high velocities, the contaminants can be transported along with the volume flow and lead to a contamination of the supply air layer.

The focus of this study is therefore the effect of the particle source location on contaminant distribution in a displacement ventilation system with varying air supply locations. The influence of three different particle source locations at a buoyant source (top, bottom, overall), two different supply locations (wall-diffuser, perforated floor) and two supply air flow rates (40 m³/h, 250 m³/h) on ventilation effectiveness indices are investigated by validated computational fluid dynamics analysis.

2. Methods

a. Indices

Ventilation effectiveness is split into two classes: indices representing the ability of a system to exchange the air in the room (air change efficiency) and indices representing the ability of a system to remove air-borne contaminants (contaminant removal effectiveness). The latter is examined as part of this study and therefore presented below.

The contaminant removal effectiveness is a means of defining how effectively airborne contaminants are removed from a room. Equation (1) shows the global contaminant removal effectiveness and Equation (2) the associated local contaminant removal effectiveness with C_e as the concentration in the exhaust air, $\langle C \rangle$ the mean, and C_p the local concentration in the indoor air. Alternatively, for uniformly distributed sources, the contaminant removal effectiveness can be defined as the ratio between the nominal time constant τ_n and the turnover time for contaminants (local mean age of the contaminant in the exhaust) τ_t^c.

$$\varepsilon^c = \frac{C_e}{\langle C \rangle} = \frac{\tau_n}{\tau_t^c} \quad (1)$$

$$\varepsilon_p^c = \frac{C_e}{C_p} \quad (2)$$

The location at which particles are introduced is of central importance and has significant influence on the local contaminant removal effectiveness in the room. The contaminant removal effectiveness increases ($\varepsilon^c > 1$) when particles are removed from the room effectively and there is little mixing with the surrounding room air. Conversely, contaminant sources in stagnation areas can lead to increased levels of particle concentration, which causes the contaminant removal effectiveness to decrease. With ideal mixing ventilation, the concentration is homogeneously distributed throughout the room, leading to a contaminant removal effectiveness of ε^c=1.

b. Geometry

Experiments regarding displacement ventilation by Mundt [2] were used as validation. The test stand used in these experiments is shown in Figure 1 and consists of a room (3.6 m x 3.6 m x 2.4 m) which is ventilated by means of displacement ventilation with wall-diffusors (0.4 m x 0.4 m) and a volume flow of 150 m³/h. This achieves an air exchange rate of 5 per hour. A cylindrical heat source with a diameter of 0.4 m, a height of 1 m and a heat output of 100 W is placed in the centre of the room.

The ventilation effectiveness was determined through the use of tracer gas measurements during the experimental studies. The tracer gas source was positioned directly above the top of the heat source, and the vertical concentration in the room profiled at the positions A to D and P according to Figure 1. The concentration at the exhaust e was also recorded. A detailed description of the experimental setup and the implemented procedures can be found in [2].

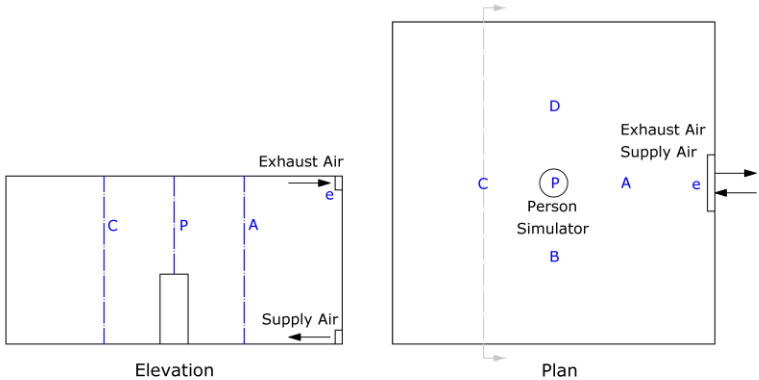

Fig. 1. Elevation and Plan of test stand (3.6 m x 3.6 m x 2.4 m) according to Mundt [2]

c. Numerical Approach

The numerical simulations are performed with STAR-CCM+ (CD-adapco, 2013, Melville, NY USA, Version 10.04.009-R8).

The conversion equations for mass, impulse and energy build the foundation for the mathematical models and are discretized on the basis of the finite volume method. The flow is handled as steady state, with friction, and in three dimensions. Heat transfer is implemented through conduction, convection and radiation. The ideal gas equation is utilized as the thermal state equation. The turbulent oscillatory movements must be modelled since room air flows are generally turbulent by nature. The standard k-e model with the two layer approach according to Xu [3] is applied for static modelling (RANS (Reynolds-Averaged-Navier-Stokes)).

Table 1 shows an overview of the utilized boundary conditions for the validation case. The simulated person is modelled as a heated cylindrical form with a constant heat flow of 100 W emanating from its surface. In order to examine the ventilation effectiveness, a contamination source with a particle volume flow is implemented as the cover of the cylinder. Air is used as the contamination medium, since particles behave approximately like gasses [4]. Therefore, an additional transport equation needs to be solved. The contamination in the cross section of the exhaust air duct is based on the local concentration in the room air and leads to the local ventilation effectiveness according to Equation (2). The global ventilation effectiveness is determined as in the experiment through the age of the air according to Equation (1). To achieve this, a passive scalar ξ is introduced into the entire solution domain as a source ($S_{\zeta}=\rho\cdot 1$). An additional conservation equation is solved for the scalar. The scalar-free supply air displaces the more highly concentrated room air, through which a distribution of the scalar results for the steady state, corresponding to the local age of the air.

Table 1. Boundary conditions of validation test-case

Boundary	Properties
Supply Air	Wall diffuser: 0.4 x 0.4 m² Constant velocity, corresponding to Flow rate: 150 m³/h Turbulence Intensity: 5 % Temperature: 22 °C
Exhaust Air	Pressure Outlet
Walls	Adiabatic, No-slip
Person Simulator	Cylinder shaped Heat Source: 100 W Diameter: 0.4 m Height: 1 m Contamination source: Airborne particles (medium air) at cylinder cover

The solution domain is established as an unstructured polyhedral mesh. The boundary layer is meshed with prism layers down to the viscous lower layer in order to show the temperature and velocity boundary layers. In order to ensure a mesh dependent solution, a mesh study according to [5] is carried out with 3 meshes and a refinement factor of r=1.5. A mesh with 800000 cells results.

d. Model validation

Table 2. Validation results

Parameter	Mundt [2]	Simulation	Deviation
Temperature Gradient (K/m)	0.60	0.66	10%
Temperature Diff. Out-In (K)	2	2	-3%
Convective Flow Rate, 40 cm (l/s)	40	35.2	-12%
Convective Flow Rate, 120 cm (l/s)	68	65	-5%
v_{max}, 40 cm (cm/s)	18.6	19.8	6%
v_{max}, 120 cm (cm/s)	17.9	15.2	-15%
R, 40 cm (m)	0.26	0.24	-8%
R, 120 cm (m)	0.35	0.37	5%
Global contaminant removal effectiveness (-)	116%	102%	-12%
Local air quality index at B/D in height			
0 m (-)	700%	700%	0%
1 m (-)	700%	700%	0%
1.4 m (-)	700%	700%	0%
1.8 m (-)	167%	142%	-15%
2.2 m (-)	88%	92%	5%
Local air quality index at A in height			
0 m (-)	700%	700%	0%
1 m (-)	700%	700%	0%
1.4 m (-)	700%	700%	0%
1.8 m (-)	171%	121%	-29%
2.2 m (-)	89%	69%	-22%

Table 2 shows a comparison of the results from the simulation and the experiment. Overall, the comparison shows very similar results. The temperature and velocity fields were modeled with sufficient accuracy in the simulation. Differences in the global ventilation effectiveness as well as the local ventilation effectiveness near the ceiling can be seen in the comparisons of the results for the ventilation effectiveness. Differences between the models used for the experiment and the simulation might be the cause for these differences. In the experiment, tracer gasses were measured, which are influenced by changes in density. In the simulation, the contamination was modeled to be airborne. In addition, the walls of the room used for the experiment have leaks, which, when compared with the simulation, increases the ventilation effectiveness. Furthermore, the global ventilation effectiveness was only determined based on measurements near the exhaust air duct, while in the simulation it was determined based on the average value in the cross section of the exhaust air duct.

The presented model will be used for further studies since the indoor airflow, temperature distribution and the local particle distribution in the room all correspond quite well with the measured values.

e. Case description

Table 3 summarizes the investigated test cases. The source location at which the air was introduced (wall-diffuser, perforated floor), position at which particles are introduced at the source (top, bottom, overall) and the supply air volume flow (40 m³/h, 250 m³/h) are varied in the 12 cases. The minimum flow satisfies the hygienic requirements for the minimum outside air volume flow [6]. The maximum volume flow is determined in such a way that the calculated height of the supply air layer (approximation according to Skistad [1]) is outside of the room.

Table 3. Summary of test cases

Test Case Nr.	Diffuser	Source Location	Flow Rate, m³/h
1	Wall-mounted	Top	250
2	Wall-mounted	Bottom	250
3	Wall-mounted	Overall	250
4	Perforated Floor	Top	250
5	Perforated Floor	Bottom	250
6	Perforated Floor	Overall	250
7	Wall-mounted	Top	40
8	Wall-mounted	Bottom	40
9	Wall-mounted	Overall	40
10	Perforated Floor	Top	40
11	Perforated Floor	Bottom	40
12	Perforated Floor	Overall	40

3. Results and Discussion

The results of the study are depicted in Figure 2. When a layered airflow is implemented, suitable positioning of the supply air ducts based on the supply flow rate is essential in order to achieve the correct operating conditions.

With a suitable combination of supply location and volume flow rate, no lateral transport of contaminants is observed. In those cases, a pool of fresh air with low contamination level develops near the floor. The pool of fresh air extends to the height at which the supply air volume flow equals the buoyancy flow at the heat source. Thereby, the ventilation effectiveness shows only minor changes in response to a varying distribution of the particle output on the surface of the person simulator. These changes are only evident in the region directly above the cylinder. This effect is unchanged when the air is introduced at high flow rate through a perforated floor.

However, a significant difference appears when air is supplied through wall diffusers with increasing supply air flow. In this case, the lateral flow impulse leads to a horizontal transport of the contamination, causing a portion of these contaminants to escape the buoyancy flow and therefore not be carried directly to the exhaust air layer near the ceiling. This effect is especially evident when compared with the case where particles are introduced at the bottom of the heat source.

Version 4 shows an example of this effect: the fresh air pool is contaminated by the lateral transport of contaminants with a high supply air volume flow. In the region far away from the supply air wall-diffuser, the ventilation effectiveness drops significantly. In contrast to the case with supply air introduced through the perforated floor, now even the air in the lower region of the room has a quality equivalent to that of the exhaust air. The supply air layer near the floor is still contaminated when the particles are not introduced exclusively in the region of the floor, rather at the cover of the cylinder or evenly distributed over the surface of the cylinder. Yet in those cases, the ventilation effectiveness, even in the cases of high supply flow rate, is higher than the academic case of the ideal mixing ventilation (ε_c=1).

4. Conclusion

The effect of particle source location at a buoyant source, supply air positions and supply volume flow rate on contaminant distribution in a displacement ventilation system was investigated by means of validated computational fluid dynamics.

When a layered flow is implemented, the particle source position at a buoyant source has no significant impact when supply air enters through a perforated floor. When lateral air supply through wall-diffusers is implemented with a low supply volume flow, the same results are achieved. However, the ventilation effectiveness decreases significantly with a high supply air volume flow through wall-diffusers. In this case, especially poor results are obtained in the case where particles are introduced in the floor region near the heat source. This leads to horizontal transport of contaminants, resulting in an undesired contamination of the fresh air pool. Overall, a proper diffusor design is crucial in order to avoid lateral contaminant dispersion and to assure high ventilation effectiveness in the occupied zone.

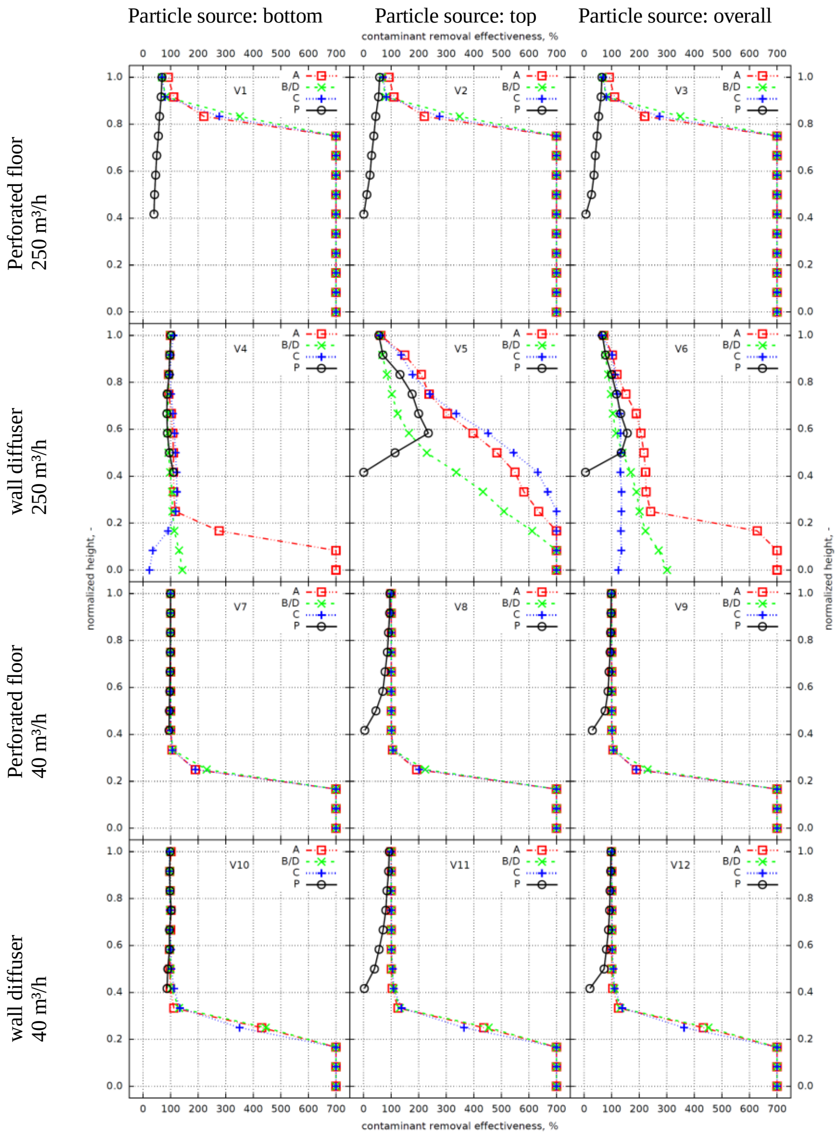

Fig. 2. Local contaminant removal effectiveness of the cases examined

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