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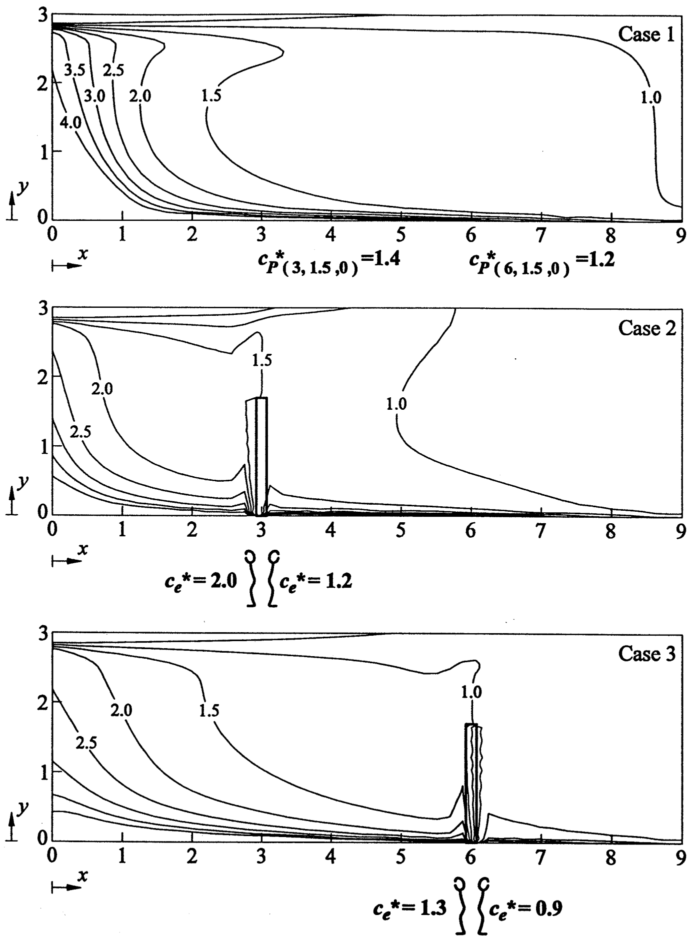

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CFD SIMULATION OF PERSONAL EXPOSURE TO CONTAMINANT SOURCES IN VENTILATED ROOMS

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ABSTRACT
In this study Computational Fluid Dynamics (CFD) is used to predict the personal exposure to contaminant sources in a ventilated room. A CFD model of a person is located in a displacement ventilated room as well as in a mixing ventilated room. The personal exposure to different contaminant sources is simulated, taking both the concentration gradients and the local influence of the person into account.

The results show that the personal exposure is highly dependent both on the kind of source as well as on the ventilation system. The simulations show that it is not sufficient to know the local concentration in an empty room, the local impact of a person is distinct and should be considered in the personal exposure assessment.

INTRODUCTION
When a person is located in a ventilated room where concentration gradients prevail, the local concentration field may be changed significantly and thus the personal exposure. The reason is the local change in the flow field caused by the presence of the person, e.g. due to:

- the excess surface temperature of the human body that generates a convective ascending air current along the body.

- a person may locally act as an obstacle to the general flow field.

- movements, etc.

Numerous measurements demonstrate that erroneous results may be obtained if the local effect of the person is neglected when the personal exposure is assessed (Rodes et al., 1991; Brohus and Nielsen, 1996a).

METHOD
The steady-state, three-dimensional, non-isothermal flow field is simulated by means of a numerical solution of the continuity equation, the Navier-Stokes equations and the energy equation. Turbulence is modelled by means of the k - ε turbulence model. Contaminant transport is simulated by means of a concentration equation. Standard wall functions are applied on all surfaces.

Computer Simulated Person
The Computer Simulated Person (CSP) applied in the simulations is a simple model of an average sized woman where the clothing has an insulation value of 0.8 clo (Brohus and Nielsen, 1996b).

The CSP is a heated cuboid with a height of 1.7 m, an aspect ratio of the width and the depth of approximately two, and a surface area of 1.62 m^2, see Table 1. The heat transfer boundary condition is a convective heat flux of 25 W/m^2, which corresponds to an activity level of a person standing relaxed, i.e. approximately 1 met.

Table 1. Geometry of the Computer Simulated Person (CSP).

Height	1.7 m
Width	0.3 m
Depth (aspect ratio of the width and the depth ~ 2)	0.16216 m
Surface area (average sized woman, clothing insulation 0.8 clo)	1.62 m^2
Convective heat flux (activity level ~ 1 met)	25 W/m^2
Note 1: The surface area is the "exposed" area, i.e. the part of the surface in contact with the surrounding air (this implies that the area in contact with the floor is not included).	
Note 2: The first grid line is located at a distance of 1 cm corresponding to a grid node distance of 0.5 cm from the surface.	

In order to determine the concentration of inhaled contaminant, i.e. the personal exposure, the simplified model for the inhalation shown in Figure 1 is used to estimate from what volume the air is drawn. By assuming inhalation from a hemisphere in front of the mouth/nose and a "capture velocity" of 0.25 m/s volumes between 2 cm^3 and 30 cm^3 are obtained for activity levels corresponding to rest and moderate work, respectively. In the present simulations the personal exposure, c_e, corresponds to the contaminant concentration in the nearest cell along the CSP (~ 10 cm^3) at a height of 1.5 m.

Experimental set-up

Two different set-ups are examined: exposure to contaminant sources in a displacement ventilated room and in a mixing ventilated room. The geometry is shown in Figure 2 for the displacement ventilated room and in Figure 3 for the mixing ventilated room.

RESULTS

Personal exposure in displacement ventilated room

Boundary conditions for the displacement ventilation case are summarised in Table 2.

Table 2. Boundary conditions for the CFD simulation of the displacement ventilation room. q is the air flow rate and t is the temperature, see Figure 2.

Parameter	Location	Value
q_0 (m^3/h)	Supply	145
t_0 (°C)	Supply	14.67
t_{Floor}	$y = 0$ m	22.63
$t_{Ceiling}$	$y = 4$ m	23.70
t_{Front}	$x = 6$ m	23.22
t_{Back}	$x = 0$ m	22.87
t_{Side}	$z = 4$ m	22.17
Heat sources	**Convective heat output**	**Implementation in CFD simulation**
Person simulator	50 W	Obstacle with prescribed surface heat flux
Point heat source	225 W	Transparent volume source
CSP	25 W/m^2	Obstacle with prescribed surface heat flux

The flow field is illustrated by means of vector plots from three different planes in Figure 5.

Two different contaminant sources are applied. First, a warm point contaminant source simulated by a small transparent volume source (0.1 m x 0.1 m x 0.1 m) located above the point heat source in a height of 2 m above the floor (see Figure 2). The combination of the point heat source generating an ascending plume of warm air and the contaminant source located above causes a transport of the contamination to the upper part of the room. The dimensionless concentration distribution in the room and the corresponding personal exposure are shown in Figure 6.

Secondly, a passive constantly emitting planar contaminant source in shape of the floor is applied. The dimensionless concentration distribution and personal exposure are shown in Figure 7.

Personal exposure in mixing ventilated room

The mixing ventilated room is a test case described by Nielsen (1990) which has been used as part of the International Energy Agency, Annex 20 work, see Figure 3.

In Case 1 the flow is isothermal, and in Case 2 and 3 the only heat source is the CSP with a surface heat flux of 25 W/m^2, see Figure 4. The walls are adiabatic and surface friction is included by means of standard wall functions.

The flow field is shown as vector plots for the vertical symmetry plane in the three cases, see Figure 8.

A passive constantly emitting planar contaminant source in shape of the floor is applied. The dimensionless concentration distribution in the room and the personal exposure are shown in Figure 9. For the empty room the contaminant concentration at the location of the breathing zone is shown in stead of the personal exposure.

DISCUSSION

Personal exposure in displacement ventilated room

Close to the inlet the dense subcooled air is directed towards the floor where it spreads out radially, see Figure 5. An ascending convective boundary layer is generated along the CSP together with a significant plume. In major part of the room the flow direction is horizontal. Only close to sources of momentum, like the inlet and the heat sources, considerable non-horizontal movements prevail.

In Figure 6 the concentration distribution and the personal exposure are shown in case of the warm source. The results indicate a stratified flow with horizontal isoconcentration curves increasing in level for increasing height. Close to the CSP the concentration field is significantly modified due to the convective transport in the boundary layer. The cleaner air in the lower part of the displacement ventilated room is entrained and transported to the breathing zone. This causes a high ventilation effectiveness locally around the person and thus a personal exposure which is lower than the corresponding concentration in the surroundings. A dimensionless personal exposure $c_e^* < 1$ indicates a higher ventilation effectiveness than in case of fully mixing, where $c_e^* = 1$.

Figure 7 shows the exposure and the concentration distribution in case of the floor acting as a contaminant source. The results show how the clean, subcooled air from the inlet device is gradually more and more polluted during the flow throughout the floor. At the walls the flow is deflected and a secondary opposing flow occurs above the primary flow. This causes a complex local concentration distribution around the CSP resulting in a dimensionless personal exposure of approximately 1.

Personal exposure in mixing ventilated room

The simulated flow field in the mixing ventilated room is presented in Figure 8. The flow field in the empty room (Case 1) shows a typical recirculating flow field. When a person in shape of the CSP is located in the room (Case 2 and 3) the flow field is significantly affected both in general and, especially, close to the person.

Figure 9 shows the concentration distribution in the mixing ventilated room in case of a constantly emitting planar source in shape of the floor. The concentration distribution in Case 1 is also simulated by Nielsen (1981) using a two-dimensional CFD calculation, and a very good agreement is found.

It is seen how the concentration level increases towards the lower left part of the room and how the CSP modifies the distribution for the two different locations. When the exposure levels are compared an important influence of location and orientation of the person is found. It is also found that $c_P \neq c_e$.

CONCLUSION

In this study personal exposure to contaminant sources in ventilated rooms is examined by means of a simple CFD model of a person applied in the numerical simulation of the flow field and the contaminant distribution. In that way it is possible to estimate the personal exposure in ventilated rooms where concentration gradients prevail and the local influence of the person is included regarding the convective boundary layer and the effect as an obstacle to the flow field.

The results show that the personal exposure depends highly on the kind of contaminant source as well as the ventilation system. It is also found that the local effect of a person in a flow field with concentration gradients exerts a significant influence on the personal exposure. The simulations show that it is not sufficient to know the local concentration level of an empty room, the local impact of a person is distinct and should be considered in the personal exposure assessment.

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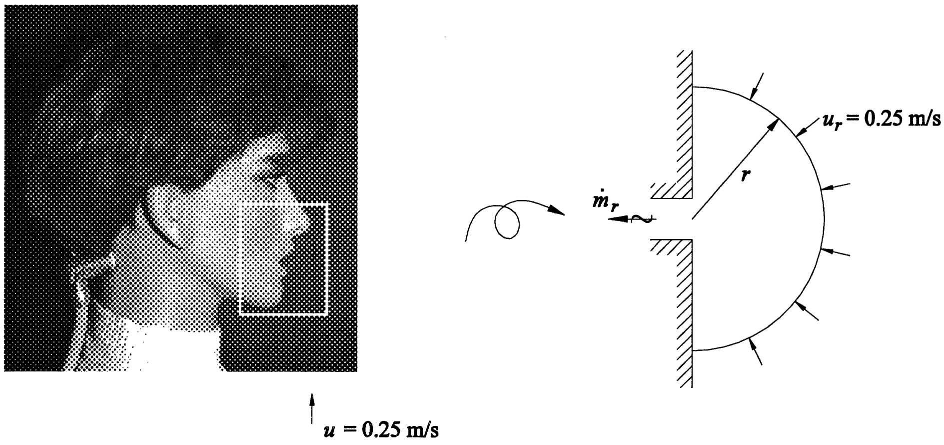

Figure 1. Simplified model of the inhalation from a person to estimate from what volume the air is drawn. The necessary capture velocity is assumed to be 0.25 m/s. $\dot{m}_r$ is the exhaust air flow, r is the distance from the opening (radius in a hemisphere) and u_r is the velocity in the distance r.

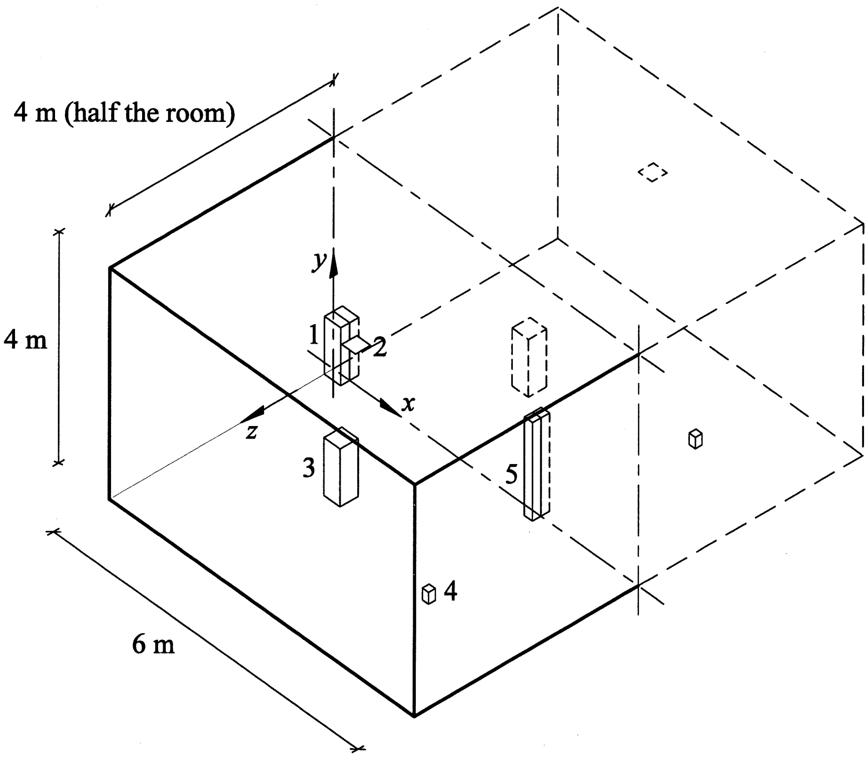

Figure 2. Geometry of the CFD simulated displacement ventilated room. Only one half of the symmetric room is simulated. The subcooled air is supplied through the inlet device (1) and exhausted through a return opening in the ceiling (2). The heat load is generated by a person simulator (3) located at $(x,z) = (2,2)$, a point heat source (4) located at $(x,z) = (4.5,2.5)$, and the Computer Simulated Person (5) located at $(x,z) = (4,0)$.

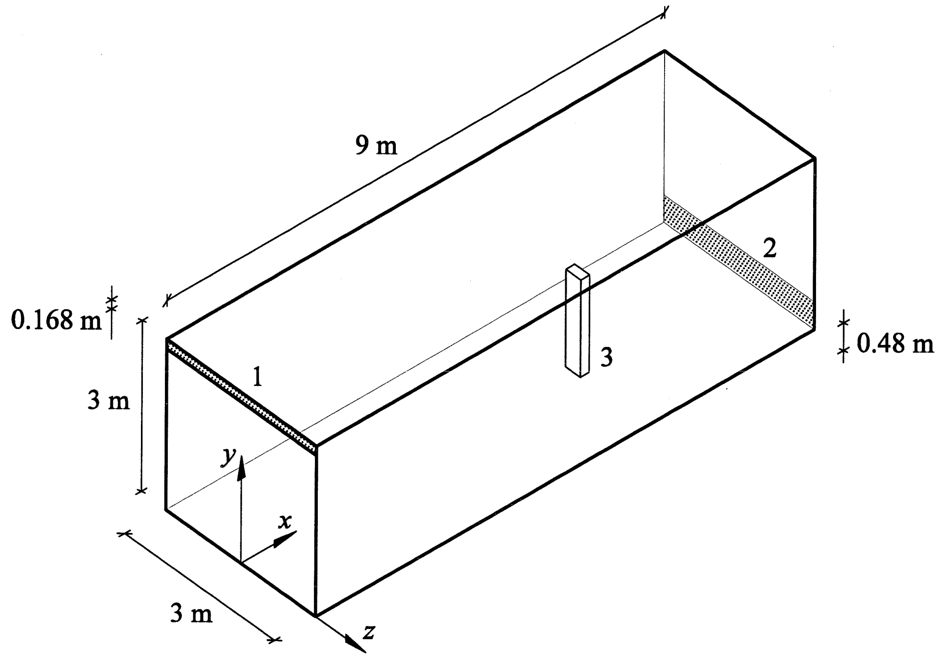

Figure 3. Geometry of the CFD simulated mixing ventilated room. The air is supplied by the inlet (1) located close to the ceiling, and the air is exhausted by the return opening (2) located close to the floor in the opposite end. The Computer Simulated Person (3) is located in the symmetry plane, $z = 0$ m

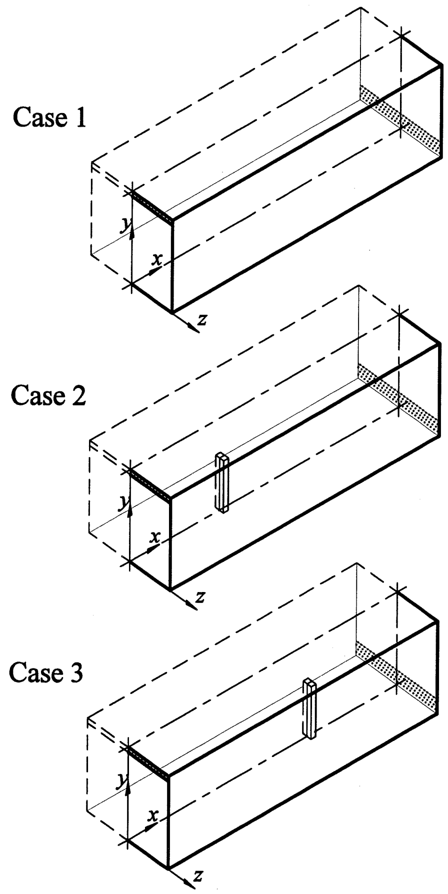

Figure 4. Only one half of the symmetric mixing ventilated room is simulated. Case 1: Empty room, Case 2: CSP located at $(x,z) = (3,0)$, and Case 3: CSP located at $(x,z) = (6,0)$.

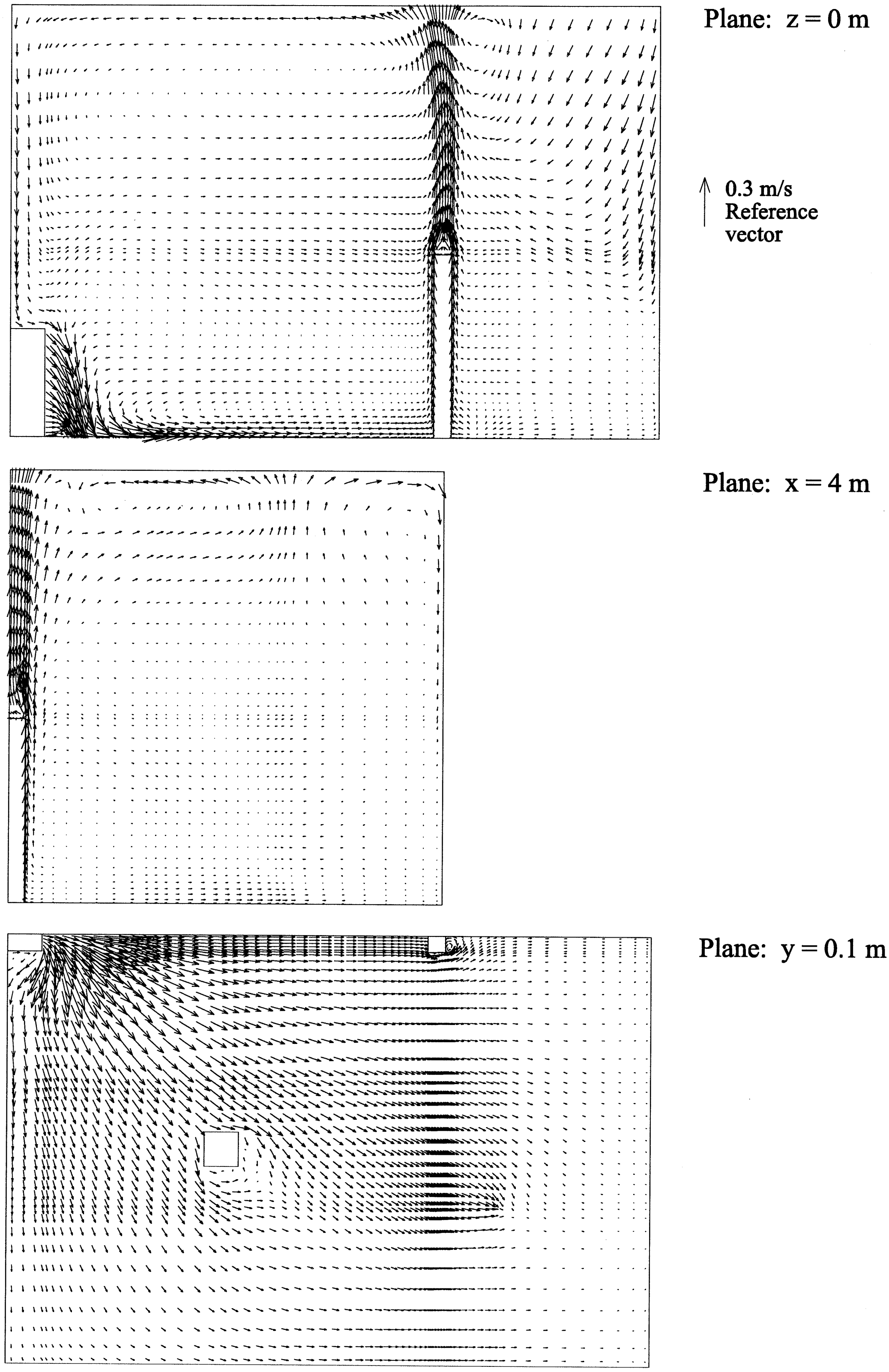

Figure 5. Vector plots from the displacement ventilated room for the three planes: z = 0 m (vertical symmetry plane), x = 4 m (vertical section through Computer Simulated Person) and y = 0.1 m (horizontal plane 0.1 m above the floor).

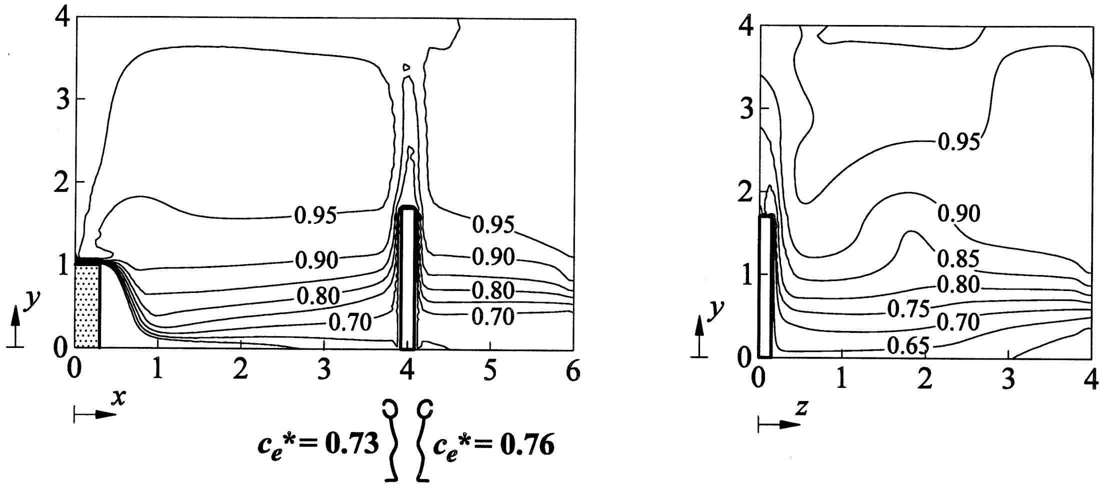

Figure 6. Dimensionless contaminant concentration distribution in the displacement ventilated room in case of a warm contaminant source. *Left*: Vertical symmetry plane, z = 0 m. *Right*: Vertical section through Computer Simulated Person, x = 4 m. The dimensionless personal exposure, c_e^*, is mentioned for the different orientations of the CSP. The concentrations are made dimensionless by dividing by the return concentration, i.e. $c^* = c/c_R$.

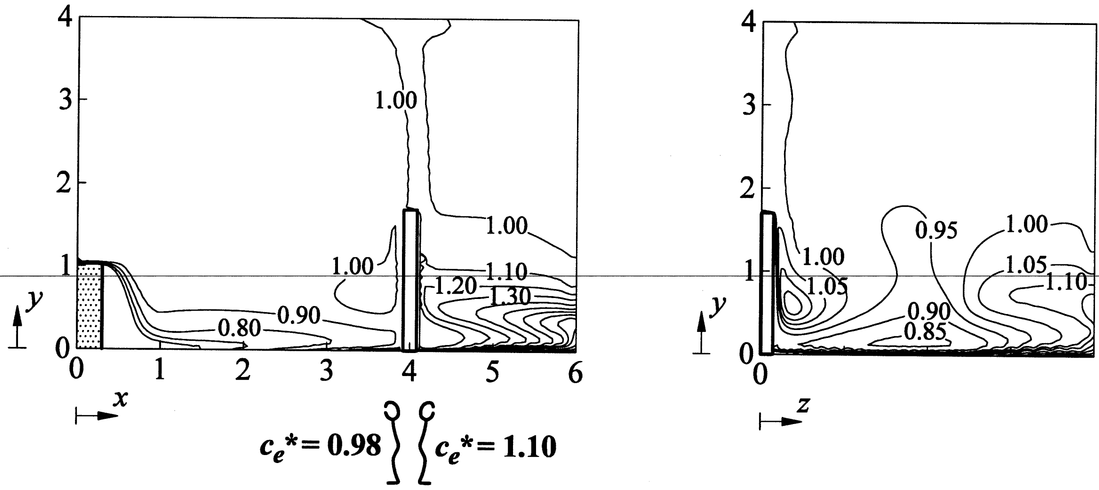

Figure 7. Dimensionless contaminant concentration distribution in the displacement ventilated room in case of the floor acting as a planar contaminant source with a constant emission rate. *Left*: Vertical symmetry plane, z = 0 m. *Right*: Vertical section through Computer Simulated Person, x = 4 m. The dimensionless personal exposure, c_e^*, is mentioned for the different orientations of the CSP. The concentrations are made dimensionless by dividing by the return concentration, i.e. $c^* = c/c_R$.

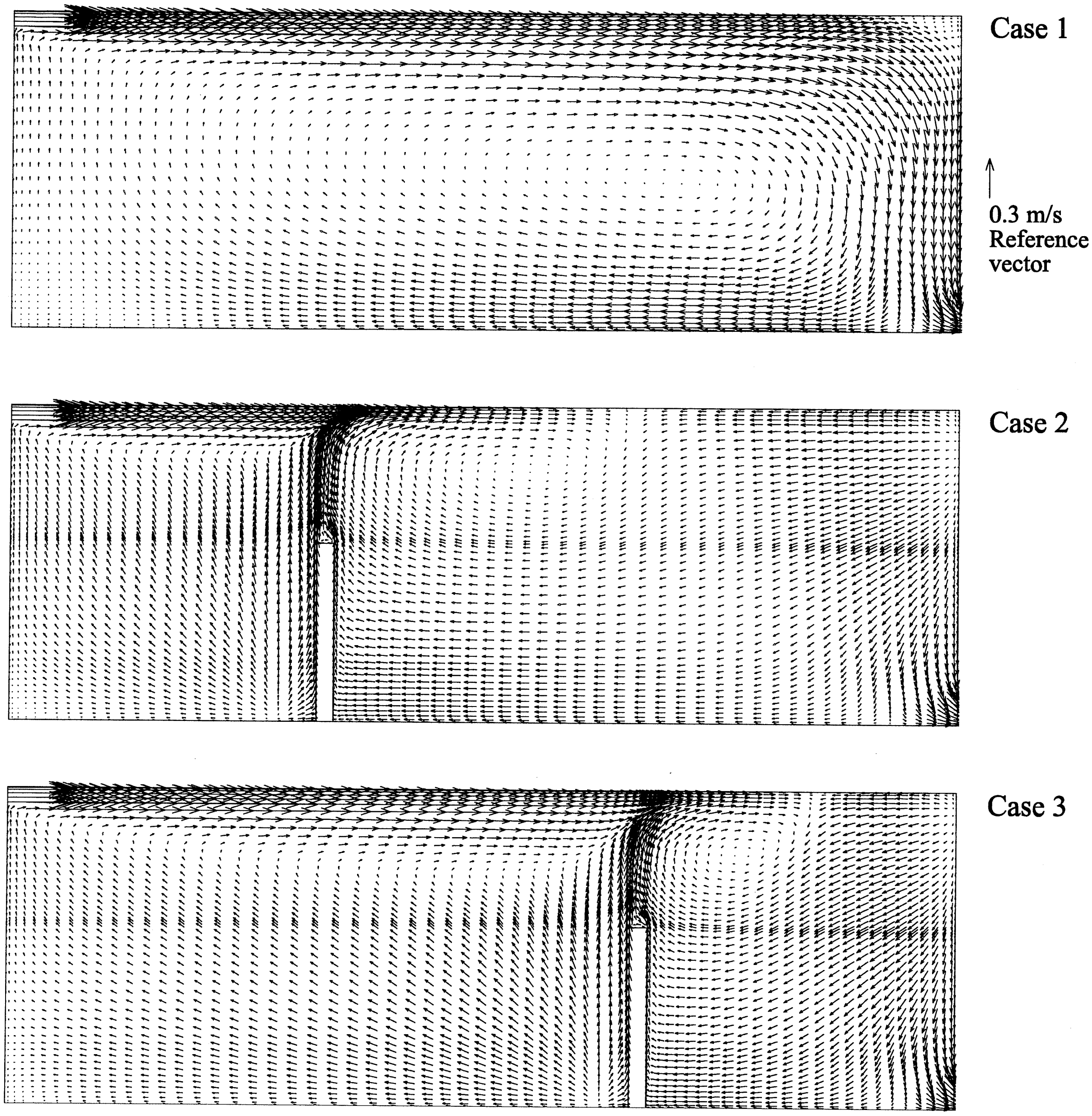

Figure 8. Vector plots from the mixing ventilated room Case 1, 2 and 3. Plane: z = 0 m (vertical symmetry plane). See Figure 4.

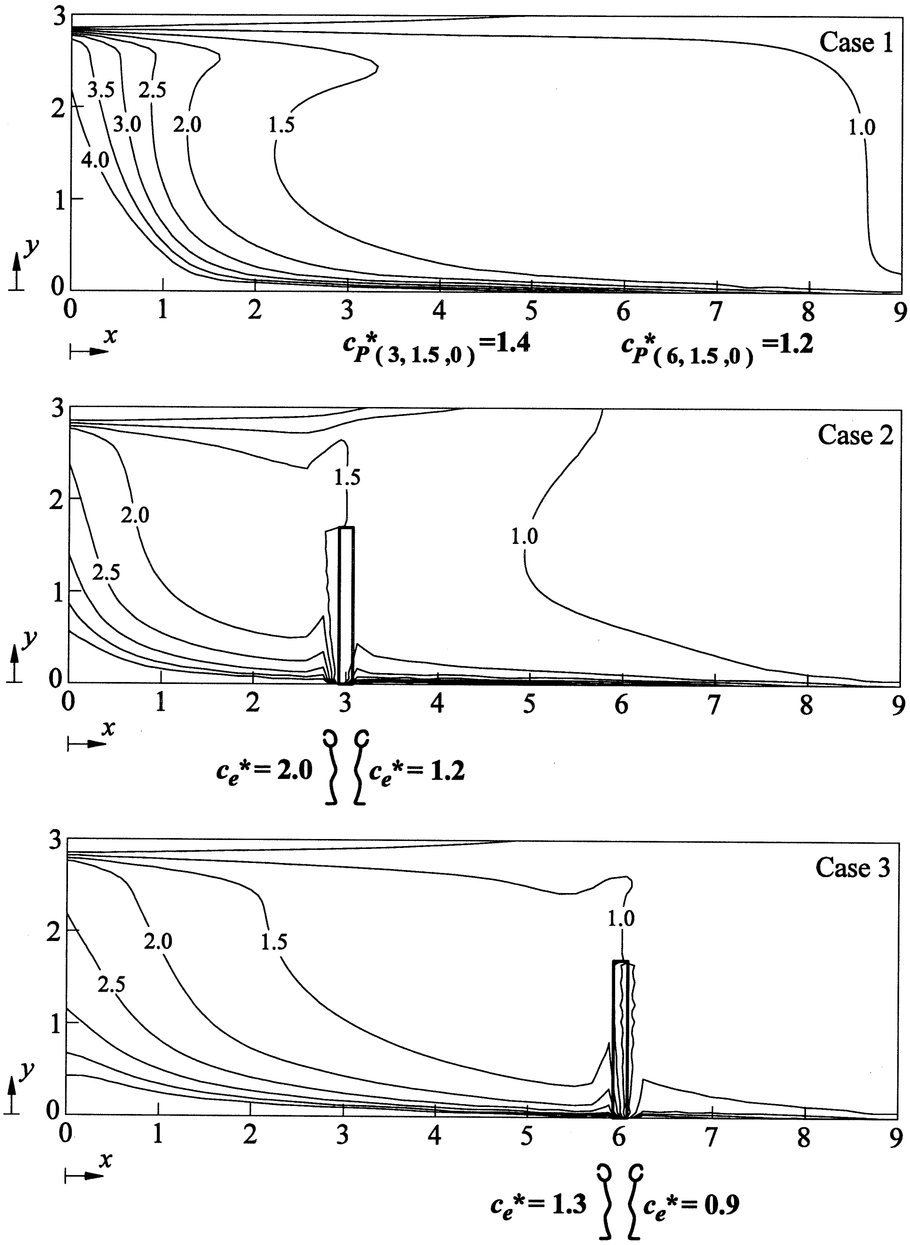

Figure 9. Dimensionless contaminant concentration distribution in the vertical symmetry plane, $z = 0$ m, of the mixing ventilated room. The floor is a planar source with a constant emission rate. The dimensionless personal exposure, c_e^*, (c_P^* in Case 1) is mentioned for the different locations and orientations of the Computer Simulated Person, see Figure 4. The concentrations are made dimensionless by dividing by the return concentration, i.e. $c^* = c/c_R$. The corresponding velocity field is shown in Figure 8.