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Personal Exposure in Displacement Ventilated Rooms

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Personal exposure in a displacement ventilated room is examined. The stratified flow and the considerable concentration gradients necessitate an improvement of the widely used fully mixing compartmental approach. The exposure of a seated and a standing person in proportion to the stratification height is examined by means of full-scale measurements. A breathing thermal manikin is used to simulate a person. It is found that the flow in the boundary layer around a person is able to a great extent to entrain and transport air from below the breathing zone. In the case of non-passive, heated contaminant sources, this entrainment improves the indoor air quality. Measurements of exposure due to a passive contaminant source show a significant dependence on the flow field as well as on the contaminant source location. Poor system performance is found in the case of a passive contaminant released in the lower part of the room close to the occupant. A personal exposure model for displacement ventilated rooms is proposed. The model takes the influence of gradients and the human thermal boundary layer into account. Two new quantities describing the interaction between a person and the ventilation are defined.

Key words Personal exposure; Displacement ventilation; Exposure assessment; Contaminant distribution.

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Introduction

The fact that many people spend more than 90% of their time in a more or less artificial indoor environment (i.e., offices, factories, homes, transport vehicles, etc.) emphasizes the importance of a proper indoor exposure assessment.

When personal exposure in a ventilated room is to be determined, one may choose to perform a series of measurements or to use a model for calculation. Both approaches may lead to erroneous results if they are not treated properly. For instance Rodes et al. (1991) summarize various measurements from the literature and state that there may be considerable deviations between measurements using personal exposure monitors (PEM) and microenvironmental monitors (MEM). Typical PEM/MEM ratios were found in the interval from 1.58 to 13.40.

Exposure models usually treat the indoor microenvironments as well mixed compartments where the concentration of a certain component is found by a simple mass balance. When the ventilated room is addressed, the air is thus regarded as being fully mixed which implies that no concentration gradients exist.

In displacement ventilated rooms, subcooled air is supplied in the lower part of the room with a low momentum. The cool air fills the room from below while "old" air is displaced upwards (Breum, 1992; Nielsen, 1993). Assisted by the convective currents from the heat sources in the room, a stratified flow is created. A vertical temperature gradient will arise, facilitating removal of exhaust air at ceiling level several degrees above the temperature in the occupied zone. This allows an efficient use of energy.

If the contaminant sources also are heat sources, the displacement ventilation system can have a high ventilation effectiveness. In this case the stratified flow implies that the room is separated in a lower, cleaner part and an upper, more contaminated part. Consequently, it may be important to take concentration gradients into account when personal exposure in a displacement ventilated room is determined.

A person produces heat due to the metabolism and the surface temperature is usually several degrees above the ambient temperature level. In a state of thermal comfort the temperature of the human skin is about 33–34°C, depending on the activity level (Fanger, 1972). The clothing forms an insulating layer between the skin and the surrounding air and causes a drop in surface temperature. The temperature drop may be 5–8°C for persons standing relaxed wearing usual indoor clothing. The resulting excess surface temperature causes an upward airflow along the body which entrains air from the surroundings.

The thermal boundary layer around the person is able to entrain and to transport clean air as well as con-

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taminated air to the breathing zone which may cause an exposure to pollution in the room. Especially in a displacement ventilated room this may be important, as shown below.

Often the exposure is estimated from the concentration measured at the height of the breathing zone in a "neutral" place in the ventilated room. This may be a reasonable approximation in rooms with mixing ventilation, but when displacement is applied this may lead to erroneous exposures. The reason is the combined effect of the entrainment of room air into the human boundary layer and the concentration gradients in the displacement ventilated room. The transport of fresh air as well as contaminated air in the boundary layer may cause the concentration in the inhaled air to deviate considerably from the contaminant concentration outside the breathing zone.

In this paper the topics mentioned above are discussed and full-scale measurements are presented showing different aspects of personal exposure in a displacement ventilated room. First, measurements on the personal exposure at different stratification heights are presented and discussed. A personal exposure model for displacement ventilated rooms is proposed. The model takes the concentration gradients as well as the influence of the human thermal boundary layer into account. Secondly, the influence of a passive point contaminant source on personal exposure is discussed and measurements on the topic are presented.

Experimental Set-up

The measurements reported are performed in a displacement ventilated full-scale test room (see Figure 1).

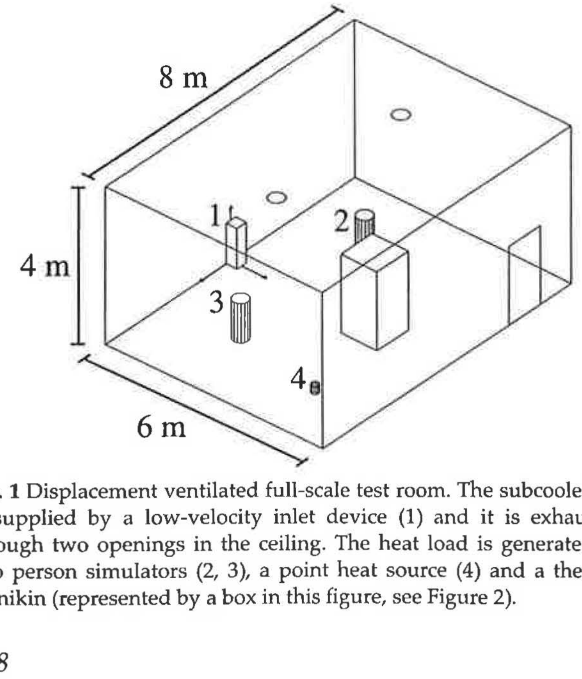


Fig. 1 Displacement ventilated full-scale test room. The subcooled air is supplied by a low-velocity inlet device (1) and it is exhausted through two openings in the ceiling. The heat load is generated by two person simulators (2, 3), a point heat source (4) and a thermal manikin (represented by a box in this figure, see Figure 2).

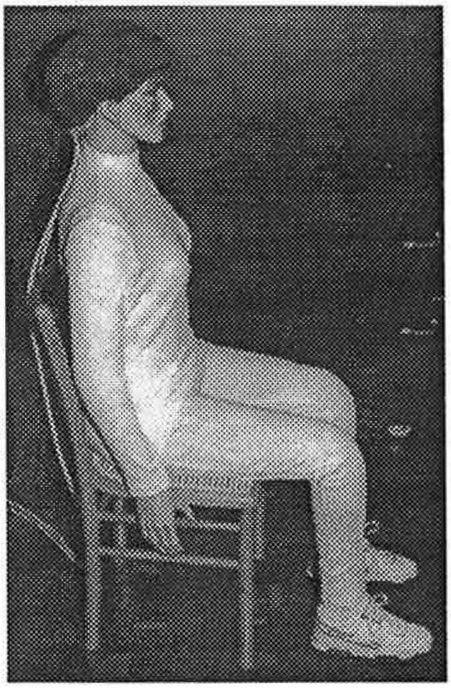


Fig. 2 Thermal manikin used to measure personal exposure. The manikin is separated in 16 individually controlled parts of the body, each with the same surface temperature and heat output as people in thermal comfort. The manikin has an artificial lung to simulate breathing

Three different heat sources are used: a point hea source consisting of heated coils mounted on an iron base surrounded by a 0.2 m high tube ø 0.15 m; a person simulator in the shape of a 1.0 m high black-painted closed cylinder ø 0.4 m, heated by four light bulbs; and finally, a thermal manikin acting as a heat source.

To be able to measure the personal exposure properly the thermal manikin seen in Figure 2 is used. The manikin is shaped as a 1.7 m high average-sized woman. The tight-fitting clothes have an insulation value of 0.8 clo The manikin consists of a fibre-armed polyester shell wound with nickel wire that is used sequentially both for the heating of the manikin and for measuring and controlling the skin temperature. The skin temperature and the heat output correspond to people in therma comfort.

The exposure measurements are performed with the thermal manikin by means of an artificial lung able to simulate the respiration either through the mouth or through the nose. It is possible to adjust both the frequency of respiration (number of inhalations per minute) and the pulmonary ventilation (litres per minute).

Since the manikin is controlled to obtain the same heat output and the same skin temperatures as a human being, the results should approach the personal exposure of a real person. Certain limitations are discussed later.

Two kinds of contaminant source are examined, a passive source and a non-passive source. The non-passive source is simulated by nitrous oxide injected through an upward pointing tube, ø 0.01 m. The tube is located above a heat source at an elevation of 2 m (see Figure 4). The passive contaminant source is simulated by a neutral density mixture of nitrous oxide and helium injected through a porous foam rubber ball, ø 0.1 m.

The tracer gas concentration is measured by photo-acoustic spectroscopy (uncertainty ±2%). The temperatures are measured by thermocouples, type k (uncertainty ±0.2°C). The velocities are measured by temperature-compensated hot sphere anemometers (uncertainty ±0.02 m/s).

Definitions

Ventilation Effectiveness

To describe the efficiency of an air distribution system, different quantities are commonly used. The ventilation effectiveness in the occupied zone, ε_{oc}, is given by

$$\varepsilon_{oc} = \frac{c_R}{c_{oc}} \tag{1}$$

where c_R is the concentration in the return opening and c_{oc} is the mean concentration in the occupied zone. In this paper the occupied zone is defined as the area up to 1.8 m above floor level.

The local ventilation index, ε_p, is defined as

$$\varepsilon_P = \frac{c_R}{c_p} \tag{2}$$

where c_p is the concentration at a point in the room.

A new ventilation effectiveness is defined, the personal exposure index, designated ε_e

$$\varepsilon_e = \frac{c_R}{c_e} \tag{3}$$

where c_e is the concentration of inhaled contaminant. The personal exposure index expresses the effectiveness actually experienced by a person in the ventilated room. The new quantity and its use is discussed in more detail below.

Equations (1) to (3) assume that the supply air is uncontaminated.

Concentration, Exposure and Dose

Before the topic "personal exposure" is further discussed, it may be convenient to clarify the differences between the concepts of concentration, exposure and dose.

Exposure requires, strictly speaking, the simultaneous occurrence of two events: a pollutant concentration at a particular place and time, and the presence of a person at that place and time (Sexton and Ryan, 1988). Expressed in another way, exposure is defined as the event

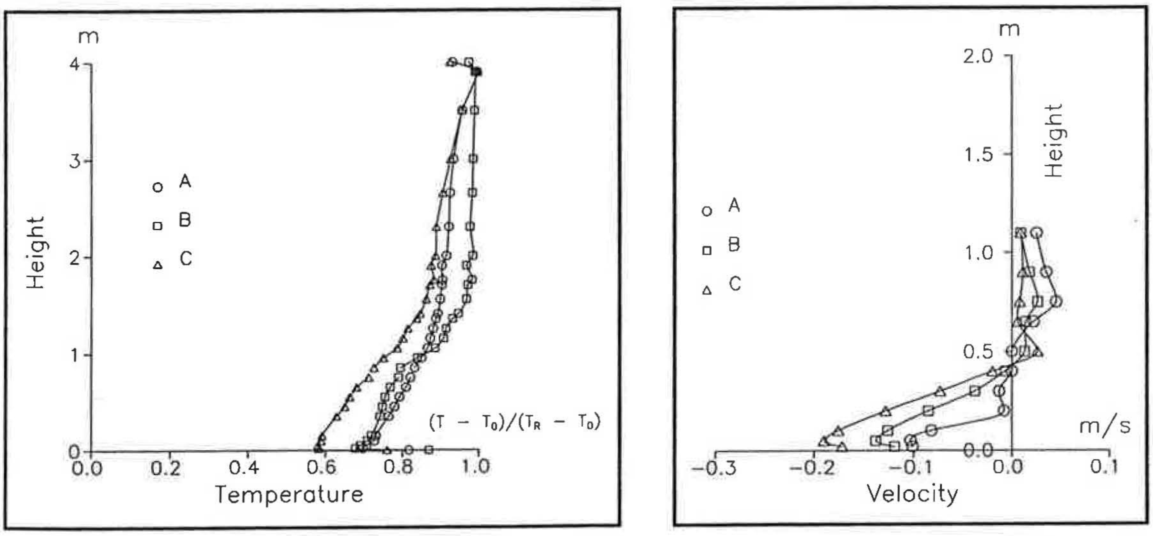
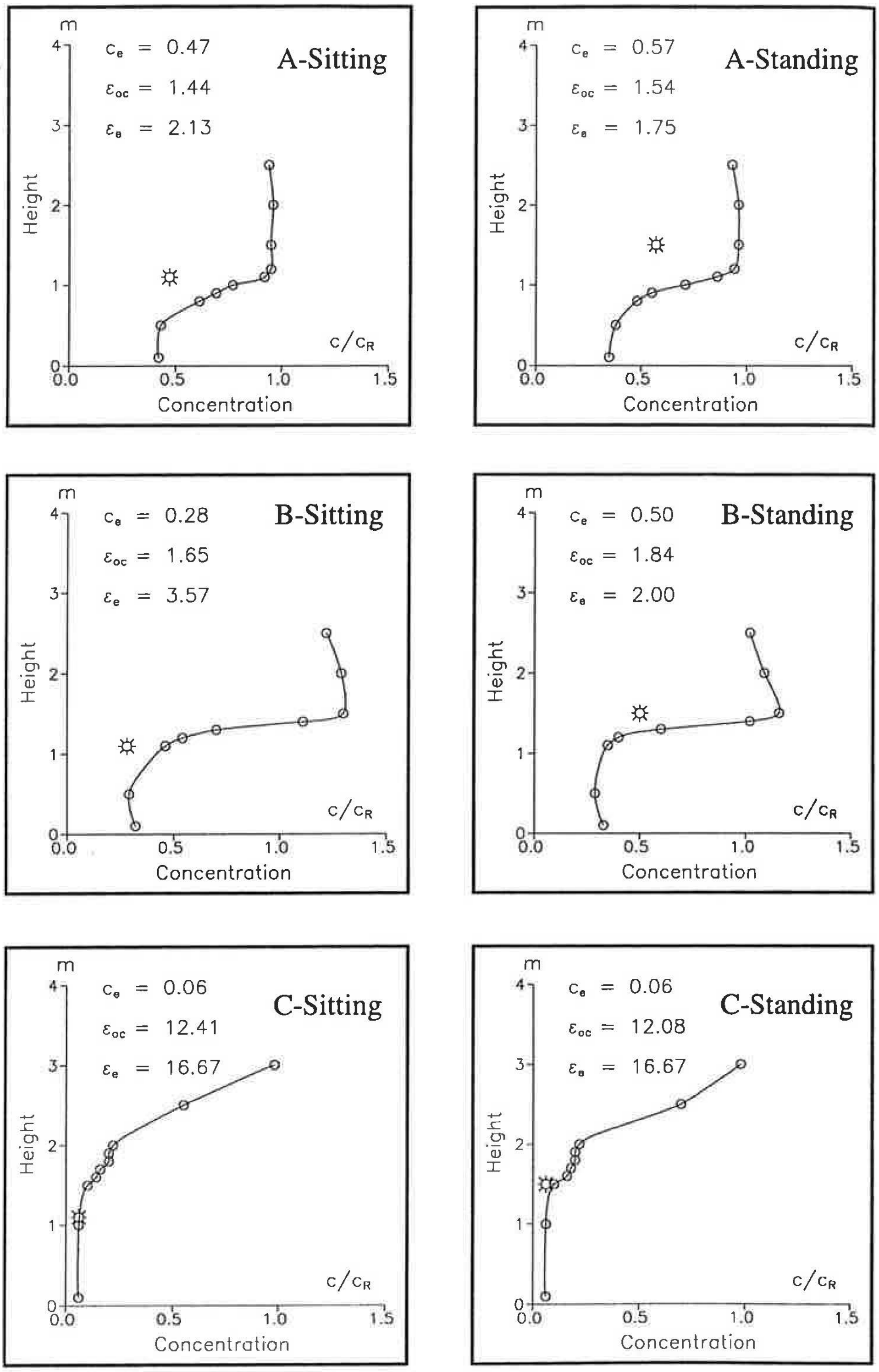


Fig. 3 Temperature and velocity profiles. The measurements correspond to the concentration measurements in Figure 4. The velocity profiles are measured 4 m from the inlet device at the same location as the thermal manikin. q is the airflow rate, Φ is the heat load, T_0 is the inlet temperature and T_R the return temperature. y_{st} is the stratification height.
Please note the different ordinate axis heights.
Case A: y_{st}=1.00 m, q=145 m^3/h (0.8 h^{-1}), Φ= 771 W, T_0 = 14.7°C, T_R=24.4°C
Case B: y_{st}=1.35m, q=290 m^3/h (1.5 h^{-1}), Φ=376 W, T_0= 17.6°C, T_R=22.6°C
Case C: y_{st}=2.25 m, q=395 m^3/h (2.1 h^{-1}), Φ= 781 W, T_0= 15.8°C, T_R=23.4°C.

Fig. 4 Personal exposure (☼) and concentration distribution (o) measured for the three stratification heights 1.00 m (A), 1.35 m (B) and 2.25 m (C) for seated (left) and standing (right) manikin. Exposure, c_e, ventilation effectiveness in the occupied zone, ε_{oc} and personal exposure index, ε_e. The personal exposure is measured at 1.1 m for the seated manikin and at 1.5 m for the standing manikin. In Case A and Case B the tracer gas is supplied above the heat source (3) in Figure 1. In Case C the tracer gas is supplied above the heat source (4) in Figure 1.



during which a person comes into contact with a pollutant.

Dose occurs when the pollutant actually crosses the physical boundary of a person. Consequently, there can be an exposure without a dose but there cannot be a dose without an exposure (Ott, 1985). This implies that persons exposed to the same level may receive different doses if the pulmonary ventilation varies due to different activity levels (Brohus and Nielsen, 1994b).

The concentration of inhaled contaminant, c_e, corresponds to the exposure of a person. It represents the event during which a person – here, in the shape of a thermal manikin – is in contact with a pollutant. Subsequently c_e is designated "exposure" as well as "concentration of inhaled contaminant".

To compare the exposure and the concentration, c_p, easured at a "neutral" point at the breathing zone ight, both quantities should in theory be measured at e same location, but in the case of c_p without the local fluence of the person (movements, convective bound- y layer flow, etc.). In this way the difference between and ε_p is due solely to the person's presence. The im- rtance of making this distinction will appear clearly the following discussion.

In practice, c_p is measured at the breathing zone ight outside the thermal boundary layer some dis- nce away from the person. Alternatively, the person in estion is temporarily moved while measuring c_p at e point of interest.

esults and Discussion

xposure in Proportion to Stratification Height

xposure measurements are carried out with respira- on through the mouth. In the present measurements o significant difference between respiration through e mouth and respiration through the nose was found. he present measurements were performed under teady-state conditions.

In Figure 4 the exposure of a seated and a standing anikin is shown. The measurements are performed at hree different stratification heights, y_{st}. The corre- ponding temperature and velocity profiles are found in igure 3. Supply flow rates, supply temperatures and eturn temperatures are also shown in Figure 3.

Figure 4 shows the dimensionless concentration pro- ile and the exposure at the three stratification heights .00 m, 1.35 m and 2.25 m. The exposure, c_e, the effec- iveness in the occupied zone, ε_{oc}, and the personal ex- osure index, ε_e, for the three cases are shown. In all hree cases the thermal manikin (approximately 75 W), he two person simulators (2×100 W) and the point heat ource (100 W or 500 W) constitute the heat load in the oom.

Due to the uninsulated walls there is a slight heat ransfer between the room and the surrounding laboratory. The difference between the mean room air temperature and the mean surface temperature is less than .5°C. Nevertheless, due to the temperature gradient, there will be a heat gain in the lower part of the room and a heat loss in the upper part. At the walls this causes a slight upward convective flow on the lower surfaces and a slight downward convective flow on the upper surfaces. The net effect is presumably of no significant importance in this context, a conclusion that is confirmed also by smoke tests.

As seen in Figure 4, the effect of entrainment and transport of room air from the lower and cleaner zone to the breathing zone is distinct, which is also pointed out by Holmberg et al. (1990) and Stymne et al. (1991), among others. This means that the concentration of inhaled contaminant is smaller than the corresponding concentration at the same height at a "neutral" place in the room. In this case the entrainment provides a better indoor air quality in the displacement ventilated room than in a room with mixing ventilation.

The figure shows also that the effectiveness in the occupied zone is higher than in the case of mixing ventilation, where ε_{oc} approaches 1 in the ideal case. As expected, the effectiveness increases with increasing stratification height. In all cases the personal exposure index, ε_e, exceeds ε_{oc}, indicating that the quality of the inhaled air exceeds the mean indoor air quality in the occupied zone.

Personal Exposure Model for a Displacement Ventilated Room

The exposure depends among other things on the concentration in the lower zone of the room. At the same stratification height this concentration may vary from case to case, depending on the inlet device, the air temperature differences, the heat and contaminant source configuration, room surface temperatures, etc. To be able to take the concentration in the lower zone into account, a new quantity is defined: the effectiveness of entrainment in the human boundary layer, designated η_e

$$\eta_e = \frac{c_P - c_e}{c_P - c_f} \tag{4}$$

where c_f is the concentration at the floor that typically corresponds to the concentration in the lower, cleaner zone of the displacement ventilated room (see Figure 5).

The effectiveness of entrainment in the human boundary layer, η_e expresses the ability to supply (fresh) air from the floor area to the breathing zone. It expresses the utilized fraction (c_p–c_e) of the possible concentration difference (c_p–c_f).

When η_e=1, all the inhaled air comes from the lower zone and c_e equals the concentration at the floor, c_f.

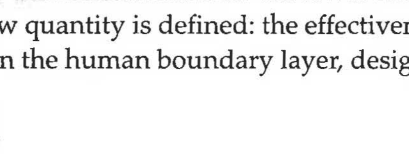


Fig. 5 Virtual concentration distribution in a displacement ventilated room. y_e is the breathing zone height and y_{st} is the stratification height. c_e is located in between c_P and c_f due to the effect of entrainment in the human boundary layer.

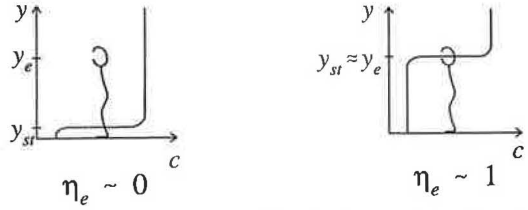


Fig. 6 Effectiveness of entrainment in the human boundary layer, η_e. When the stratification height, y_{st} decreases, the effectiveness decreases. When the stratification increases to the breathing zone height, y_e, the effectiveness of entrainment in the human boundary layer approaches 1.

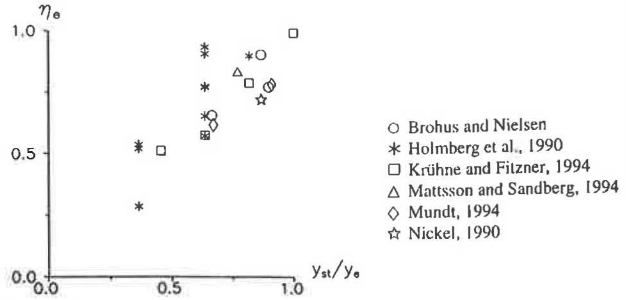


Fig. 7 Effectiveness of entrainment in the human boundary layer, η as a function of the dimensionless height, y_{st}/y_e.

When η_e=0 the exposure equals the concentration c_p at the breathing zone height, i.e. no particular effect because of the convective transport in the human boundary layer (see Figure 6).

In the case of complete mixing, as well as in displacement ventilation with a stratification height located above the breathing zone, η_e is not defined. In these cases c_e equals the homogeneous concentration in the room or the concentration in the lower zone, respectively. This implies that $\eta_e \equiv 1$ for $c_p = c_f$.

One advantage of using η_e is the independence of the concentration in the lower zone that may vary in different cases. This enables and improves the comparison of results from different test rooms and different experimental set-ups.

From the results in Figure 4, η_e is calculated for Case A-Seated (0.91), Case A-Standing (0.66) and Case B-Standing (0.78), where it is defined. It illustrates the extent to which the inhaled air is supplied from the lower and cleaner zone. In Case A-Seated, almost all air comes from the lower zone, while in Case A-Standing, only somewhat more than half of the air arises from the lower zone. The reason why η_e is lower in the Case A-Standing is that the breathing zone is located at a higher level. This implies that more contaminated air is entrained in the boundary layer before it reaches the breathing zone where it is inhaled.

If c_e is expressed by means of the new quantity, we get the following equation

$$c_e = c_p - \eta_e (c_p - c_f) \quad (5)$$

i.e. the concentration of inhaled contaminant is expressed as a function of the concentration at the breathing zone height unaffected by a person present (c_p), the concentration at the floor, and the effectiveness of entrainment in the human boundary layer. If η_e is known, equation (5) can be used to estimate the personal exposure in a displacement ventilated room.

In the expression for η_e, the stratification height must be considered due to the significant influence of this parameter. If we furthermore want to incorporate the height of the breathing zone, y_e, the dimensionles height y_{st}/y_e may be used. This quantity attains th value from 0 to 1 when the stratification height ir creases from the floor to the breathing zone heigh which is the range of interest in this context. Conse quently, if the effectiveness of entrainment in the hu man boundary layer is expressed as a function of y_{st}/y we may expect that η_e ranges from 0 to 1 when y_{st}/y_e ir creases from 0 to 1 (see Figure 6). In Figure 7 the effe tiveness of entrainment in the human boundary laye versus y_{st}/y_e is plotted.

The results shown in Figure 7 come from η_e calcu lated from the measurements presented in Figure 4 an corresponding results from different references. Her the effectiveness and the dimensionless height are ca culated on the basis of the various full-scale measure ments performed in displacement ventilated room Holmberg et al. (1990) have made measurements wit tracer gas and paraffin oil particles (<2 µm) in a roor with heated cylinders as well as persons. The measure ments were performed at different stratification heigh for persons sitting perfectly still and for seated person with natural movements. Krühne and Fitzner (199 performed measurements at different stratificatio heights with a heated cylinder. Mattsson and Sandber (1994) performed measurements with a heated cylinde continuously moved back-and-forth as well as standin still. Here, the results from the "standing still" situatio are used. Mundt (1994) has made measurements in displacement ventilated room with a person sitting an a person walking around, respectively. Nickel (199 performed measurements with a heated cylinder.

Although different "models" of a person are used i different experimental set-ups, the quantity η_e and th relation y_{st}/y_e seem to establish a way of expressing th various results more generally.

If we make a linear equation fit on the plot in Figure to obtain the coefficients of the equation η_e=A+B (y_{st} y_e), we find that A=0.22 and B=0.73 with a coefficient c determination R^2=0.58. This reveals that A is close t zero and that B is close to one.

With a power equation fit, the following relation $\eta_e=C(y_{st}/y_e)^D$ is obtained. Here the coefficients C=0.95 and D=0.75 are found with $R^2=0.62$.

These results suggest an almost linear relationship between η_e and y_{st}/y_e with a starting point close to origo and with the effectiveness of entrainment in the human boundary layer approaching 1 when the relative height approaches 1.

For practical engineering purposes and without considerable loss of accuracy, one may use the simple relation

$$\eta_e = \frac{y_{st}}{y_e} \tag{6}$$

By inserting the above expression in equation (5) we obtain a model for the personal exposure in a displacement ventilated room.

This exposure model may also be obtained in another way by means of a zonal model approach. If it is assumed that the concentration of inhaled contaminant is a mixture of the concentration in the lower, cleaner part of the displacement ventilated room and the upper, more contaminated part, we may get the following expression if the two parts of the room are assumed to contribute with an amount proportional to the height occupied by the person, i.e.

$$c_e = \frac{y_{st}c_f + (y_e - y_{st})\,c_p}{y_e} \tag{7}$$

Hence,

$$c_e = c_p - \left(\frac{y_{st}}{y_e}\right)(c_p - c_f) \tag{8}$$

Comparing equations (5) and (8) reveals that η_e is expressed as y_{st}/y_e which in fact is the approximate relation (6) found empirically from Figure 7.

Further analysis of the human boundary layer may show a nonlinear dependence of η_e on y_{st}/y_e and relations where more parameters are considered may be found, but still the above expression may serve as a reasonable approximation for practical engineering use in the case of an exposed subject in a displacement ventilated room.

One limitation of the model is the effect of persons' movements. Since the basic results arise mainly from cases where a "still" model of a person is used, the equation (8) is not valid when the person is making violent movements or when the person is walking fast through the ventilated room. This topic is discussed in greater detail below.

Another limitation may be the influence of an obstacle in front of the person. If the boundary layer is disturbed or partially destroyed, the effect of entrainment and transport is obviously reduced.

If, for instance, a person is sitting (or standing) very close to the edge of a table, the thermal boundary layer is locally interrupted and the convective transport of air from below the table is significantly limited. The effect of this limitation depends to a great extent on the horizontal distance between the person and the obstacle. If the distance between the table and the person exceeds the boundary layer thickness, there will presumably be no reduction in the entrainment and transport in the human boundary layer. According to Homma and Yakiyama (1988), the thickness of the thermal boundary layer in front of the chest of a standing person is 0.07–0.15 m. Although the boundary layer thickness in a seated position is greater, the order of magnitude suggests that even relatively small gaps between the person and the table will enable convective mass transfer to take place. More research on this subject is needed.

The Effect of Movements on Personal Exposure

The measurements shown in Figure 7 represent mainly cases where the model of a person is sedentary or standing still. This fact raises the question as to the effect of movement on personal exposure.

One extreme is a sedentary person or a person standing still. Here, equation (8) provides a reasonable model for personal exposure in a displacement ventilated room. The second extreme is the case of a person walking quickly through a ventilated room. Here, the concentration of inhaled contaminant, c_e, obviously approaches the neutral concentration in the breathing zone height, c_p, due to the considerable horizontal velocity generated around the breathing zone. This case corresponds to $\eta_e=0$. The actual case may be found somewhere between the two situations, depending on several parameters, for example the type of work, activity level, etc.

This point is supported by measurements of Holmberg et al. (1990) where η_e changed from 0.94 to 0.66 when the persons present changed from motionless to natural motion in a seated position.

Measurements of Mattsson and Sandberg (1994) with a moving heated cylinder may serve as another illustration. From these measurements the effectiveness η_e is calculated and shown in Figure 8 for three different velocities of the heated cylinder continuously moved back-and-forth in a displacement ventilated room. Even though Figure 8 is an example involving only one heated cylinder in "systematic motions" at one stratification height, it clearly illustrates that the effectiveness, η_e decreases when the movements increase as mentioned above.

Measurements and smoke tests with a thermal manikin in a wind channel confirm that the thermal bound-

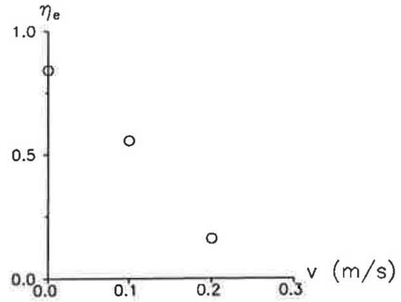


Fig. 8 η_e as a function of the velocity relative to a moving cylinder. Measurements from Mattsson and Sandberg (1994) with a heated cylinder continuously moved back-and-forth in a displacement ventilated room.

ary layer is considerably affected at uniform velocities above 0.05–0.10 m/s (Brohus and Nielsen, 1994b; Hyldgaard, 1994).

Although the measurements mentioned previously from Holmberg et al. (1990) show a decrease in η_e, there is still a significant effect of entrainment in the human boundary layer during "natural motion" in a seated position. This point is supported by Mundt (1994) reporting measurements where the concentration is found close to the nose of a person walking around in a displacement ventilated room. Here, the exposure is significantly below the corresponding concentration in the surroundings.

An improvement of the personal exposure model suggested above may be obtained by including the relative velocity, v, or the movements of the exposed person, e.g.

$$\eta_e = f\left(\frac{y_{st}}{y_e}, v\right) \tag{9}$$

Exposure in Proportion to Location of a Passive Point Contaminant Source

The above conclusions assume that the contaminant sources are also heat sources, generating the characteristic two-zone concentration distribution in the displacement ventilated room.

If the contaminant sources are passive, e.g. from building materials and other "cold" sources, the concentration distribution may be changed radically, affecting personal exposure.

A passive point contaminant source is defined as a pollutant source without any significant initial momentum or buoyancy, i.e. the pollution is supplied with a very low velocity at room air temperature and at room air density.

In Figure 9 the exposure of the standing thermal manikin is found in the case of a "high" and a "low" location of a point contaminant source. Figure 9 shows the effect of the two different concentration distributions corresponding to the different point source locations. In the case of high location of the source, c_e is 1.17 (Case 1) which must be considered rather low compared with the concentration peak at the height of the breathing zone. However, in the case of low location of the source, the exposure amounts to 1.74 (Case 2) while the concentration at the height of the breathing zone approaches 1.

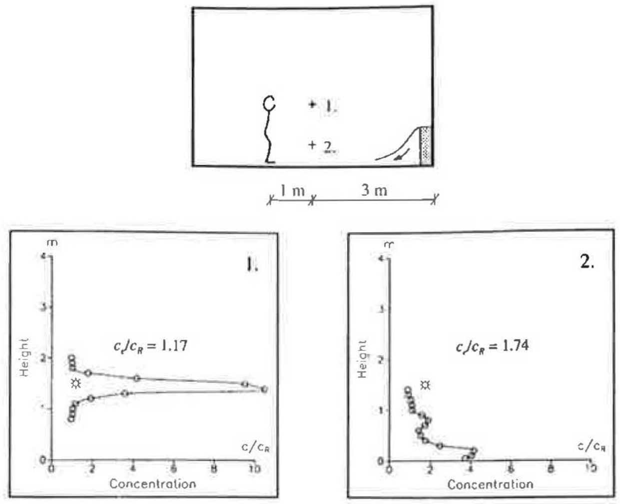


Fig. 9 Personal exposure (✡) at concentration profiles (o) corresponding to a high (Case 1) and a low (Case 2) location of a point contaminant source in the displacement ventilated room. The concentration profile is measured 0.9 m from the manikin and 0.1 m from the source. The measurements are performed under conditions corresponding to Case B (see Figure 3). Neutral density tracer gas N_20 mixed with He is supplied through a porous foam rubber ball.

This reveals the advantage and the disadvantage of entrainment and transport in the human boundary layer. In Case 1 the boundary layer transports fresh air to the breathing zone and only a slight influence from the high local concentration in the breathing zone height is seen. In Case 2 the boundary layer obviously transports contaminated air to the breathing zone even though no particularly high concentration is found at the breathing zone height at a distance of 0.9 m.

Personal exposure as a function of the point source height and the point source location is further examined in Figure 10. Two different cases are investigated. Case 1: the manikin standing facing the inlet device. Case 2: the manikin standing reversed as shown in the figure.

Figure 10 shows how the exposure clearly varies with the elevation of the point source in the room. Both improved as well as deteriorated indoor air quality compared to the case of complete mixing is found. A distinct dependence on the flow field stresses the importance of convective mass transfer when pollutant dispersion is addressed (Brohus and Nielsen, 1994a).

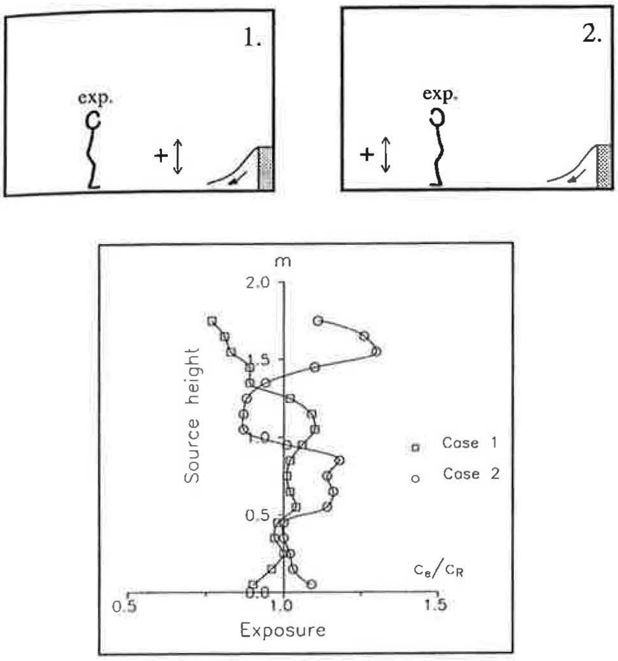


Fig. 10 Personal exposure, c_e, as a function of point contaminant source height in the displacement ventilated room. The horizontal distance between the source and the manikin is 1.5 m. Case l, manikin facing inlet device (k) and Case 2, manikin reversed (o). The measurements are performed under conditions corresponding to Case B (see Figure 3). Neutral density tracer gas N_2O mixed with He is supplied through a porous foam rubber ball.

In Case 2 where the manikin, still facing the source located 1.5 m away, is turned around, the exposure is almost opposite to Case 1, as if mirrored in the ordinate axis of Figure 10. In the one case the horizontal convective flow removes or dilutes the contamination, either giving rise to improved conditions ($c_e<1$) or somewhat "mixed" conditions ($c_e \sim 1$) in the lower zone. In the other case the horizontal convective flow transports the contamination directly against the manikin where a fraction is entrained in the boundary layer, giving rise to enhanced exposure ($c_e>1$). Actually, this result may to some extent be expected when the stratified flow is considered with a main flow at the floor, reverse flow above, etc.

To illustrate the route of the contaminant in the boundary layer, measurements are performed on the contaminant concentration at the chest and the contaminant concentration at the back in proportion to the point source height (see Figure 11). The conditions are otherwise the same as in Figure 10, Case 2.

The concentration at the two points in Figure 11 are measured at the same height in the room. If the manikin was not present they would be approximately the same, while in the actual case there is a significant difference. What makes the difference is the presence of a person and the entrainment and transport of the contaminant as well as the fresh air in the boundary layer.

If the concentration at the chest is compared with the exposure in Figure 10, Case 2, a very good correspondence is seen. This is due to the fact that the main part of the inhaled air comes from the boundary layer in front of the person, anyhow, in the case of an almost motionless person, unaffected by obstacles in a room, where the velocities from the air distribution system are sufficiently low to avoid draught and to ensure thermal comfort.

The measurements show a significant influence of the person's orientation relative to the flow field and relative to the passive point contaminant source. If the manikin is turned around to face the inlet, the exposure may presumably be reduced by 25% in the present case.

If a contaminant source (passive as well as non-passive) is located close to a person, e.g. in the occupant's hands or on the desk top, very high exposures may be obtained. In this case, personal exposure depends to a large extent on local flow phenomena around the person and the source (Brohus and Nielsen, 1995).

Personal Exposure Index in Displacement Ventilated Rooms

In the figures shown above, all concentrations are made dimensionless by dividing by the return concentration, c_R. Consequently, the personal exposure index, ε_e, is easily obtained as the inverse of the dimensionless exposure.

If the room air is fully mixed, both the exposure and the personal exposure index equal 1. When the expo-

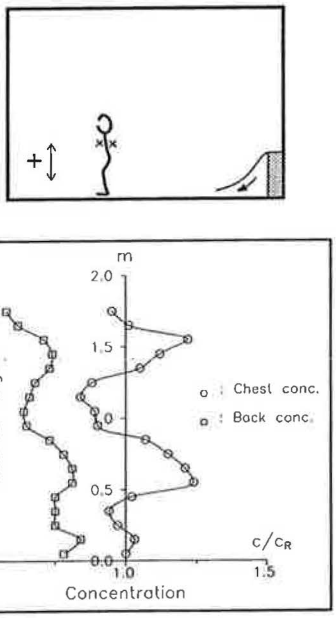


Fig. 11 Concentrations measured at the chest (o) and at the back (k) at a distance of 0.3 m from a virtual point between the ears of the person. The concentrations are found as a function of the point contaminant source height. The conditions are otherwise the same as in Figure 10, Case 2.

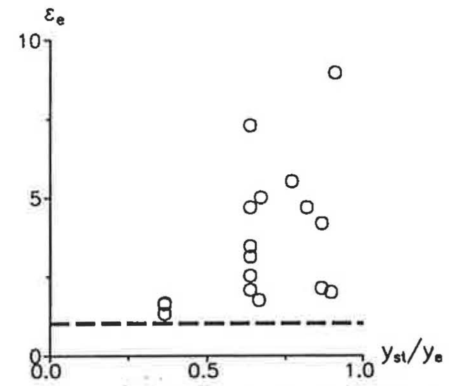


Fig. 12 Personal exposure index, ε_e, as a function of the dimensionless height, y_{st}/y_e. The results correspond to those shown in Figure 7. The personal exposure index in the case of complete mixing is indicated by the dotted line, i.e. ε_e=1.

sure decreases due to improved indoor air quality, ε_e exceeds 1. This is the typical case in displacement ventilated rooms (see Figure 12).

In Figure 12, ε_e is plotted as a function of y_{st}/y_e for the measurements corresponding to Figure 7. The dotted line indicates complete mixing. The results show how the displacement principle improves the air quality compared to dilution ventilation. In practice, the results will appear less significant due to persons' movements and other disturbances in a displacement ventilated room as discussed previously.

One of the advantages of using ε_e, compared to for example the ventilation effectiveness in the occupied zone, is that the personal exposure index relates to what is actually experienced by a person and not just a kind of "mean" air quality.

If ε_e is known, we may, as a first step, treat the ventilated room as fully mixed. The personal exposure index is then used to convert the "fully mixed exposure" into "actual exposure" when the mean concentration is divided by ε_e.

Conclusions

Personal exposure in a displacement ventilated room is examined. The stratified flow and the considerable concentration gradient necessitate an improvement of the widely used fully mixing compartmental approach.

The exposure of a seated and a standing person as a function of the stratification height is examined. It is found that the flow in the boundary layer around a person is able, to a great extent, to entrain air from below the breathing zone, thus improving the quality of the inhaled air.

Persons' movements cause the air quality to decrease due to the disturbance of the human boundary layer which promotes the high air quality transporting fresh air to the breathing zone.

A personal exposure model is proposed. The m
takes the concentration gradient and the influenc
the human thermal boundary layer into account.

Entrainment of air in the human boundary laye
usually an advantage but measurements show also
possible disadvantage when passive contamir
sources are present. In this case the convective curr
around the person transport contaminated air to
breathing zone, giving rise to increased exposure.

Two new quantities are defined: the personal ex
sure index, ε_e, which expresses the concentration o
haled contaminant relative to the return concentrat
and the effectiveness of entrainment in the hur
boundary layer, η_e, which expresses the ability to s
ply (fresh) air from the floor area to the breat
zone.

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