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Publication date:
1994

Document Version
Publisher's PDF, also known as Version of record

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INTRODUCTION

The fact that many people spent more than 90% of their time in a more or less artificial indoor environment (i.e. office, factory, home, transport vehicles etc.) stresses the importance of a proper indoor exposure assessment.

When the 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 C.E. 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 a ventilated room concentration gradients will occur if a contaminant source is present. The order of magnitude of the gradients is determined by the effectiveness of the air distribution system and large differences are found between the different types of ventilation systems as well as between different designs of the same type (P.V. Nielsen, 1992).

This paper deals with personal exposure in rooms with concentration gradients and persons present. Results from case studies including a breathing thermal manikin in a displacement ventilated room and in a wind channel are presented.

PERSONAL EXPOSURE

The reason for determining the personal exposure is to enable the prediction of health effects. In order to do so one must assess both the level of exposure and the corresponding human response. Besides the health effects the perceived air quality may be determined when the exposure is known.

The instantaneous exposure, the dose rate, is expressed by (P.O. Tjelflaat, 1992) as

$$\dot{m}_e(t) = \dot{m}_{vp}(t) \quad c_e(t) \tag{1}$$

where $\dot{m}_e$ is the dose rate of the inhaled contaminant (kg/s), $\dot{m}_{vp}$ is the pulmonary ventilation (kg/s) and c_e is the concentration of the inhaled contaminant (ppm). The pulmonary ventilation is found to be proportional to the metabolic rate which is expressive of the activity level of a person (P.O. Fanger, 1972). This results in the instantaneous exposure being proportional to the activity level.

The integrated exposure, the dose m_{ed} (kg), from the time t_s to t_e is

$$m_{ed} = \int_{t_s}^{t_e} \dot{m}_{vp}(t) \; c_e(t) \; dt \tag{2}$$

If the integrated exposure is modelled the time integral may approximately be devided into N finite time steps Δt_i

$$m_{ed} = \sum_{i=1}^{N} \dot{m}_{vp,i} \, c_{e,i} \, \Delta t_i \tag{3}$$

where the pulmonary ventilation and the concentration of the inhaled contaminant are regarded as constants for each time step. When equation (3) is applied the integrated exposure is divided into a series of steady state conditions. This implies that $c_{e,i}$ can be obtained from a steady state model or from measurements. In this paper the results all come from steady state conditions and the main emphasis is laid on determining the concentration of inhaled contaminant c_e - in the subsequently designated "exposure".

<u>Fully mixed conditions</u>

The homogeneous concentration throughout the room $c = \Sigma s/q$ where s is the contaminant source strength (kg/s) and q is the air flow rate (kg/s). Since there is no concentration gradients the concentration at a certain location c_P equals the homogeneous concentration and the exposure c_e as well as the concentration in the return opening c_R. If the concentrations are made dimensionless we get

$$c_e/c_R = c_e^{*} = c_P^{*} = 1 \quad (\textit{fully mixed}) \tag{4}$$

To describe the efficiency of the air distribution system in the occupied zone the ventilation effectiveness in the occupied zone $\varepsilon_{oc} = c_R/c_{oc}$ is commonly used where c_{oc} is the mean concentration in the occupied zone defined as the area up to 1.8 m above floor level. The inhalation effectiveness is defined as $\varepsilon_e = c_R/c_e$ (H. Brohus and P.V. Nielsen, 1994). Equation (4) implies that

$$\varepsilon_e = \varepsilon_{oc} = 1 \quad (\textit{fully mixed}) \tag{5}$$

<u>Concentration gradients</u>

In ventilated rooms with contaminant sources there will exist gradients. Pronounced gradients are found for instance in displacement ventilated rooms and in the vicinity of contaminant sources. When personal exposure in rooms with gradients is assessed two different approaches can be chosen, depending on whether the local effects of the persons present are considered or not. If not, the exposure c_e is usually estimated from the concentration c_P in the height of the breathing zone

$$c_e^{*} = c_P^{*} \neq 1 \quad (\textit{gradients}) \tag{6}$$

$$\varepsilon_e \neq \varepsilon_{oc} \quad (\textit{gradients}) \tag{7}$$

Equation (6) expresses that the dimensionless exposure may differ from 1, obviously the exposure may also equal 1. As seen from the measurements below the dimensionless exposure can be smaller and larger than 1. Equation (7) indicates the the inhalation effectiveness may differ from the effectiveness in the occupied zone in case of gradients.

Influence from persons

The presence of persons may modify the effectiveness of the air distribution both in general and locally. The effects of persons which affect the air distribution can be divided into at least six points: Excess surface temperature, respiration, obstacle, movement, heat emission and contaminant emission.

Usually the surface temperature of a person exceeds the temperature of the surroundings giving rise to an upward airflow along the body. This convective airflow entrains and transports air from the surroundings to the breathing zone where it may alter the concentration of inhaled contaminant c_e from the concentration c_p in the undisturbed surroundings at the same height

$$c_e^* \neq c_p^* \qquad (gradients\ and\ persons) \tag{8}$$

Respiration enables the exposure on account of the inspiration. The expiration forms one (mouth) or two (nose) jets penetrating the boundary layer locally. It is found (C.E. Hyldgård, 1994) that no short circuit takes place between the expiration and the inspiration at usual conditions. Thus the personal exposure appears to be unaffected by the expiration.

In a ventilated room the persons constitute obstacles which may influence and modify the airflow locally. Behind an obstacle in a uniform flow field a wake is generated which may influence the personal exposure. When people move through a room air velocities are generated around them. An attempt to examine this effect is made by placing a thermal manikin in a wind channel. Apart from the above-mentioned effects people act as heat and contaminant sources (bioeffluents, CO_2 etc.) which may influence the exposure indirectly.

MEASUREMENTS AND DISCUSSION

Two different cases are examined in order to study the importance of the various parameters determining the personal exposure level when concentration gradients prevail. In the first case measurements are performed in a displacement ventilated full-scale test room (lenght x width x height = 8 x 6 x 4 m). In the second case measurements are performed in a wind channel with a uniform velocity field and different concentration distributions.

In both cases a breathing thermal manikin is used to model a person (see fig.1). The manikin consists of 16 individually controlled parts of the body, each with the same surface temperature and heat output as people in thermal comfort. An artificial lung provides for the breathing.

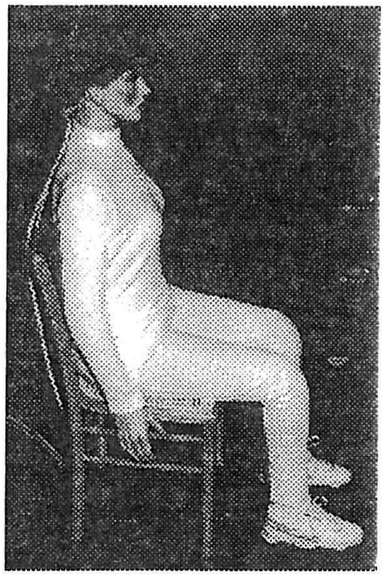


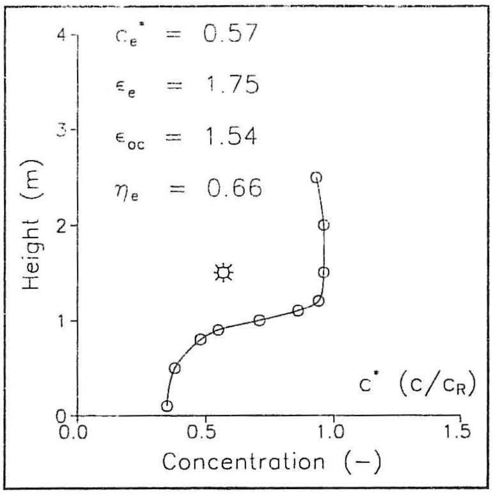
Fig.1 Thermal manikin.

Displacement ventilated room

Air change rate, heat load etc. in the displacement ventilated room are chosen to lie in the range of thermal comfort to obtain a realistic condition. In fig.2 the dimensionless concentration distribution in the displacement ventilated room is shown for a stratification height of 1.0 m. The corresponding exposure c_e^* for the standing manikin is shown by ☼.

The room is thus, characteristic of displacement ventilation, separated in a lower, cleaner part and a more contaminated upper part.

As seen in fig.2 the exposure 0.57 is considerably smaller than the concentration in the corresponding height c_p^* which equals 1 in the present case.



This shows that the exposure is influenced by entrainment in the human boundary layer. The transport of cleaner air from the lower part of the room to the breathing zone results in a lower exposure and an improved indoor air quality. Results from corresponding measurements are found in (H. Brohus and P.V. Nielsen, 1994).

In fig.2 the effectiveness of entrainment in the human boundary layer η_e is shown. This quantity is defined by (H. Brohus and P.V. Nielsen, 1994) as

$$\eta_e = \frac{c_p - c_e}{c_p - c_f} \tag{9}$$

Fig.2 Concentration distribution (○) and personal exposure level (☼) in a displacement ventilated room. Concentrations and effectiveness are defined in the text.

In (9) c_f is the concentration at the floor. η_e expresses the ability to supply (fresh) air from the floor area to the breathing zone. The effectiveness of entrainment in the human boundary layer is not defined when the stratification height is located above the breathing zone. If η_e equals 1 all the inhaled air comes from the lower cleaner zone.

Wind channel (moving person)

To examine the effect of movements and the effect of a uniform velocity field measurements are performed with the manikin placed in a wind channel. In this way the movements are equivalent to a uniform velocity field. In fig.3 the exposure is shown as a function of the contaminant source height. The contaminant source consists of a porous foam rubber ball ø 0.1 m through which tracer gas is supplied. The standing manikin is located 1.2 m from the source at a uniform velocity of 0.15 m/s.

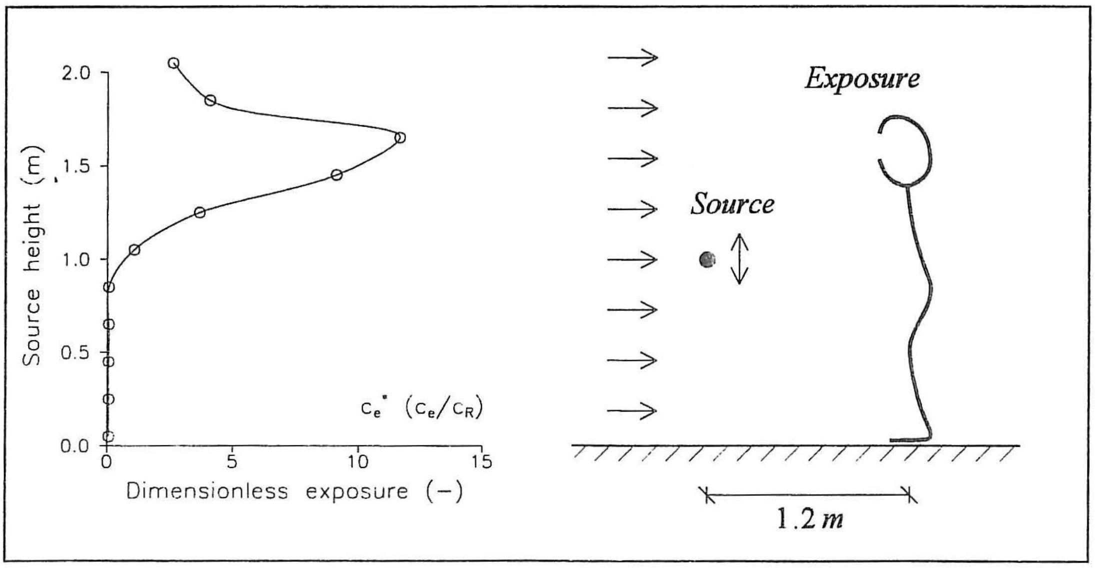


Fig.3 Dimensionless exposure as a function of point contaminant source height in a uniform 0.15 m/s velocity field.

As fig.3 indicates the exposure is highly dependent on the source height and with it the contaminant distribution. Fully mixed conditions would result in the dimensionless exposure 1 at all source heights in contrast to the present measurements where the gradients and the influence of the person increase the exposure level more than 10 times with the source located at breathing zone height.

Measurements in fig.2 show a distinct influence of the convective transport in the human boundary layer on account of the excess surface temperature. This effect is not pronounced in the case illustrated in fig.3 where the peak exposure is found in the breathing zone height 1.5 m. The uniform velocity field directed against the front of the manikin seems to wash away the boundary layer which implies that $c_e \approx c_p$. Other measurements and smoke visualisation confirm this effect already at uniform velocities from 0.05 - 0.10 m/s.

If the manikin is turned around with the back against the velocity field the generated wake is now located in front of the manikin. In that case a significant influence of the excess surface temperature is found. This phenomenon may be illustrated by measuring the concentration at the back of the manikin in the close proximity of the skin surface with the heating turned on and off (see fig.4).

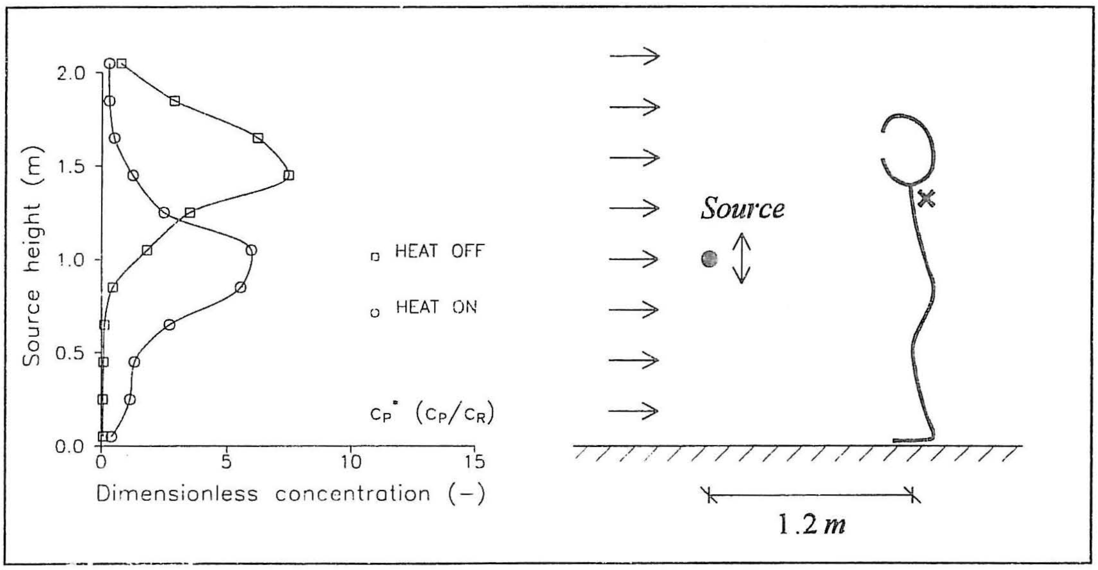


Fig.4 Dimensionless concentration at the back (×) as a function of point contaminant source height and heating. Uniform 0.15 m/s velocity field.

When the heating is turned off the concentration peak is found approximately at the height of the sampling point (×), whereas the heated manikin modifies the result. On account of entrainment and upward convective transport the peak is now found when the source is about 1 m above the floor. If the contaminant source is raised further the concentration decreases on account of the supply of uncontaminated air from below the source height.

Personal exposure modelling

When the personal exposure is modelled the compartmental - fully mixing - model may not be adequate when gradients are present in the ventilated room. For instance at a workplace in a factory such a model may predict erroneous exposures.

The first step to predict the exposure more accurately is knowing the concentration distribution in the ventilated room. This may be accomplished by using simple models, full/small-scale measurements or by using the somewhat more comprehensive Computational Fluid Dynamics (CFD) which solves the Navier-Stokes flow equations numerically.

When the concentration distribution is known the exposure may be determined by letting c_e be equal to c_p. This approach, however, does not consider the local influence from the persons present. If this influence, which is shown to be important in various cases, is considered the above-mentioned models have to be improved.

A possible way to improvement is the development of an exposure model implemented in a CFD subroutine which on the basis of the calculated local temperature, velocity and concentration fields in the vicinity of the person is able to predict the personal exposure. The subroutine should also be able to work separately outside the CFD programme if the data are obtained from measurements.

CONCLUSIONS

The effectiveness of the ventilation system and the local transport processes in the vicinity of a person are important factors which, to a great extent, determine the personal exposure.
Often, ventilation systems cannot establish fully mixed conditions although this is usually presumed. Consequently, concentration gradients frequently occur in rooms with contaminant sources. When gradients are present the exposure depends on the location of the person in the room.

The exposure of a standing person in a displacement ventilated room is examined. It is found that the flow in the boundary layer along the person to a great extent entrains air from below the breathing zone and affects the personal exposure.

Different locations of the contaminant source and orientation of the person relative to the flow field are examined in a wind channel. It is shown that both the location of the source and the flow field in the vicinity of the person have significant influence on the exposure.

Major errors may occur in estimating the personal exposure if considerations for the concentration gradients and the presence of the persons are neglected.

ACKNOWLEDGEMENTS

This research was supported financially by the Danish Technical Research Council (STVF) as a part of the research programme "Healthy Buildings", 1993-1997.

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