Displacement Ventilation

effects of movement and exhalation

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Publication date:
1997

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

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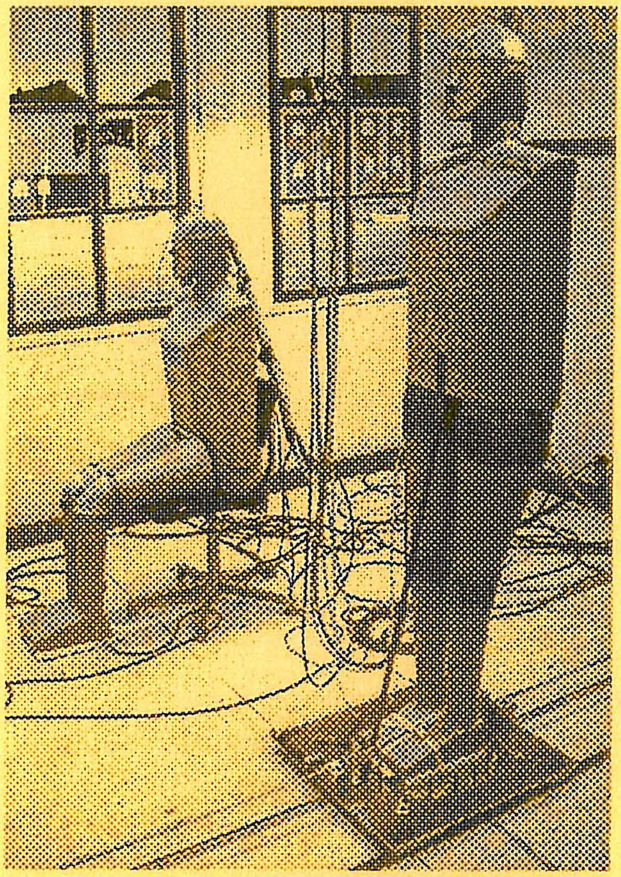

INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 70

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Printed at Aalborg University

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DISPLACEMENT VENTILATION - EFFECTS OF MOVEMENT AND EXHALATION

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ABSTRACT

Full-scale experiments were made in a displacement ventilated room with two breathing thermal manikins to study the effect of movements and breathing on the vertical contaminant distribution, and on the personal exposure of occupants. Concentrations were measured with tracer gas equipment in the room and in the inhalation of both manikins. Tracer gas was added in the heat plume above a sitting manikin, or in the exhalation through either the nose or the mouth. The other manikin moved back and forth at different speeds on a low trolley. The mentioned experimental conditions have a significant influence on contaminant distributions and personal exposures.

INTRODUCTION

Displacement ventilation has become popular in northern Europe, especially in the Scandinavian countries. The system is most suitable for removing heat loads, e.g. in offices or public assembly buildings, and will often improve air quality and energy efficiency compared with traditional mixing ventilation. Heat sources in the ventilated space are essential for the proper function of the system. The contaminant distribution is often described by a two-zone model, with a clean zone at the bottom of the room and a contaminated zone at the top. The natural convective boundary layer around a person has a positive influence: Usually the air quality is better than ambient air, so that a person can have the head placed in the upper, polluted zone and still inhale relatively unpolluted air. This is mainly the case if the contaminant sources are also heat sources. This is usually considered true of bioeffluents from people. For more details on personal exposure in connection with displacement ventilation, see (3).

This research focuses on some parameters which influence the air quality. The main objective is to observe the effect of movements and breathing on the contaminant distribution in a displacement ventilated room, and on the contaminant exposure of the occupants. These subjects have been investigated separately already by the authors of this paper (1,2,5,6,8,9), but combined effects of movements and breathing have not been investigated before, to our knowledge.

Previously, it has been observed that air exhaled through the mouth can be "locked" in a thermally stratified layer in breathing zone height, giving rise to enlarged personal exposure (1). The difference between exhaling through the mouth or the nose is also studied more closely (see also (2)), and compared with the contaminant distribution caused by the heat plume above a person. These phenomena are studied under the influence of different levels of physical activity, and the results are thus also intended to complement previous studies of movements in displacement ventilated rooms (5,6,8,9).

METHODS

This was an experimental study, carried out in an well insulated, office sized test room, ventilated by the displacement principle (see figures 1 + 2 for dimensions and setup).

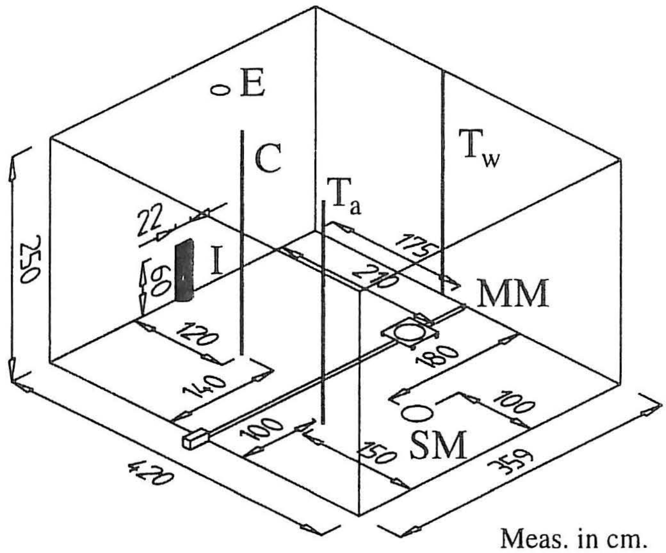

Figure 1: Test room with experimental setup. Location of inlet (I), exhaust (E), sitting manikin (SM), moving manikin (MM), measurement of concentrations (C), air temperatures (Ta), wall temperatures (Tw).

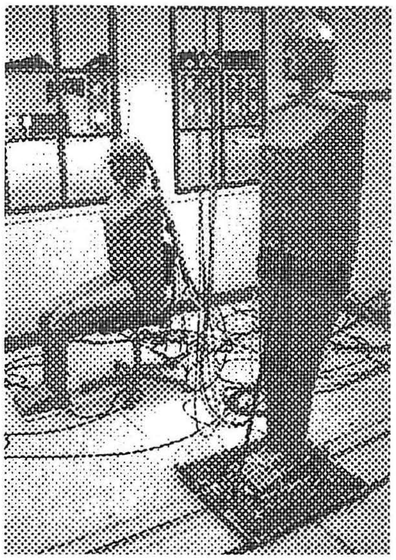

Figure 2: Moving manikin on trolley (right) and sitting manikin (left).

People were simulated by two life-sized thermal manikins, and contaminant was simulated by using N_2O as tracer gas. Both manikins were equipped with a breathing mechanism, see (2) for details. One of the manikins was placed sitting on a chair, while the other manikin could move back and forth in the room standing on a low trolley (see figures 1 + 2). The sitting manikin acted as contaminant source in all experiments. Personal contaminant exposure was measured in the inhalation of both manikins. The above mentioned trolley was equipped with a mechanism that rotated the manikin, so it always moved forward. The trolley was pulled by a conveyor belt, connected to an electric motor placed outside the test room. Speed, acceleration and amplitude of the movements were controlled by a computer program. The amplitude (horisontal span of the movement from one side of the the room to the other) was 2.50 m in all cases. At each pass through the room, the manikin was accelerated constantly from zero until maximum velocity, which was kept for as long as possible, and then decelerated constantly until zero velocity. The following combinations of maximum velocity and acceleration were used:(0.2 m/s , 0.45 m/s^2), (0.4 m/s, 0.4 m/s^2), (1.0 m/s, 0.72 m/s^2). At maximum velocity 1.0 m/s, the above mentioned rotating device caused too much load on the system, and was put out of function, so the manikin moved backwards half of the time.

Three different ways of adding contaminant were used: In the plume 1-2 cm above the sitting manikin, and in the exhalation through either mouth or nose. When exhaling through the mouth, air leaves the body in a horizontal circular jet. When exhaling through the nose, air leaves the body in two seperate jets with 45° downward inclination and 30° mutual inclination. Previous measurements (1,2) have indicated that these differences in adding contaminant are important for the contaminant distribution. The temperature of air exhaled through the mouth was kept at 34°C, air exhaled through the nose was 33°C - these are both maximum temperatures, since the temperature pulsated up and down. Both the chosen exhalation temperatures and the pulsating behaviour are very realistic according to (4). The pulmonary ventilation rate was chosen at 6 liter/min, the respiration frequency was 10 min^{-1}, corresponding to a person at a low activity level. The volume flow of the respiration pulsated in a sinusoidal fashion. The amount of N_2O added was appr. 160 ml/min. The height of respiration was 1.18 m for the sitting manikin and 1.58 for the standing manikin. In the experiments involving exhalation through the mouth, the sitting manikin faced in 4 different directions: 0° (back facing inlet), 90°(right side facing inlet), 180°(front facing inlet), and 270°(left side facing inlet). In the other experiments, only 0° orientation was used, as the orientation seemed to be of no great significance.

All experiments were performed at a constant air change rate of 2 h^{-1}. This equals 10.5 liter/sec fresh air per "person". The total heat effect of the manikins was kept constantly at 100 W for each manikin. Lighting was supplied by four fluoerescent tubes placed close to the ceiling with a total effect of 145 W. The vertical contaminant distribution in the test room was measured in seven points at one location (see fig.1). The tracer gas analyser was a Binos 1.2 with an accuracy of appr. ±1%. The main air movements in the room were visualized with smoke tests. The vertical temperature distribution was measured on one of the walls and in the room air at one location (see fig.1). Inlet and exhaust temperatures were measured. All temperatures were measured with thermocouples type T, accuracy appr. ± 0.1°C.

RESULTS

With no movement, and with contaminant added to either plume or nose, the typical 2-zone distribution is observed (fig. 3 + 4). Concentrations are made dimensionless by dividing with the return concentration c_r. There is an obvious influence of a moving person on the vertical contaminant distribution: Higher speed means less stratification. At a speed of 1.0 m/s, the contaminant distribution is close to the completely mixed situation. At low speed (0.0 - 0.2 m/s), there is some difference between the three ways of adding contaminant, but at higher speeds (0.4 - 1.0 m/s), the distributions are very much alike.

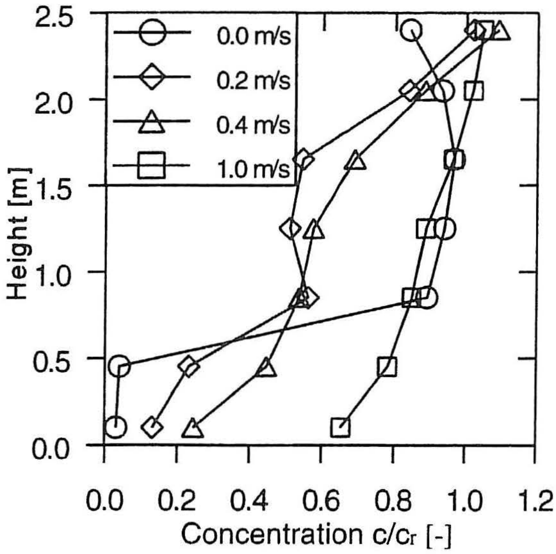

Figure 3: Contaminant added to heat plume above head of sittting manikin. Dimensionless concentration profiles for different speeds of moving manikin.

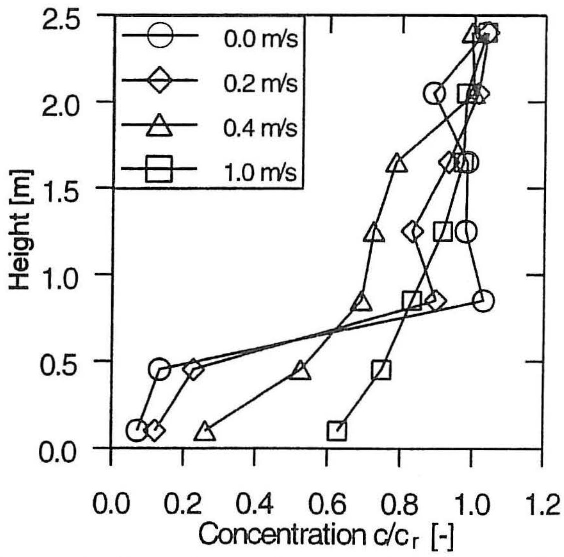

Figure 4: Contaminant added to exhalation (nose) of sitting manikin. Concentration profiles for different speeds of moving manikin.

With exhalation through the mouth, a layer of high concentration is observed at a height of appr. 1.2 m (fig.5) when there is no movement. This is consistent with measurements in (1). The measured concentration level in this layer is much dependent on the orientation of the sitting manikin. However, this stratified layer is disrupted as soon as movement begins. At all three speeds (0.2 - 0.4 - 1.0 m/s), the vertical concentration distributions are very alike regardless of orientation of the sitting manikin, so only 0° orientation is shown (fig.6).

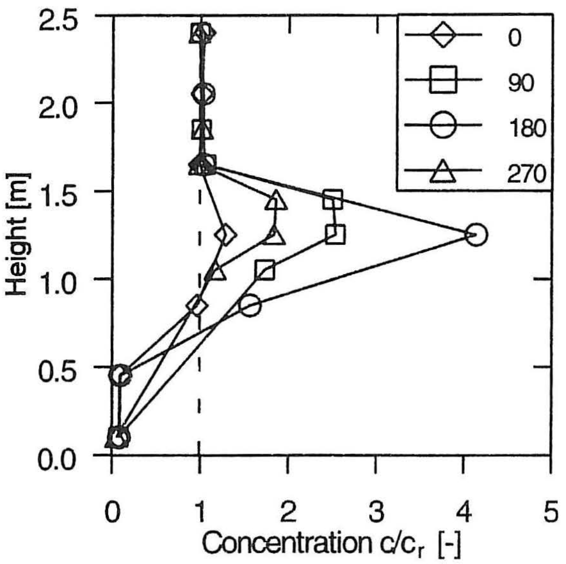

Figure 5: Contaminant added to exhalation (mouth). Concentration profiles for different orientations of sitting manikin. Moving manikin is standing still.

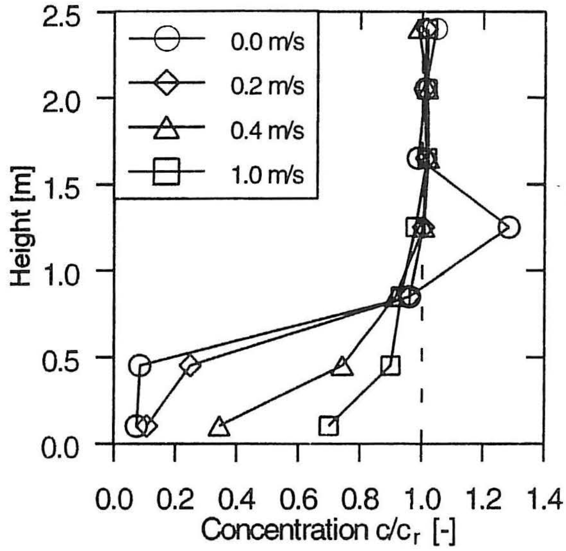

Figure 6: Contaminant added to exhalation (mouth). Concentration profiles for different speeds of moving manikin. Orientation of sitting manikin is 0°.

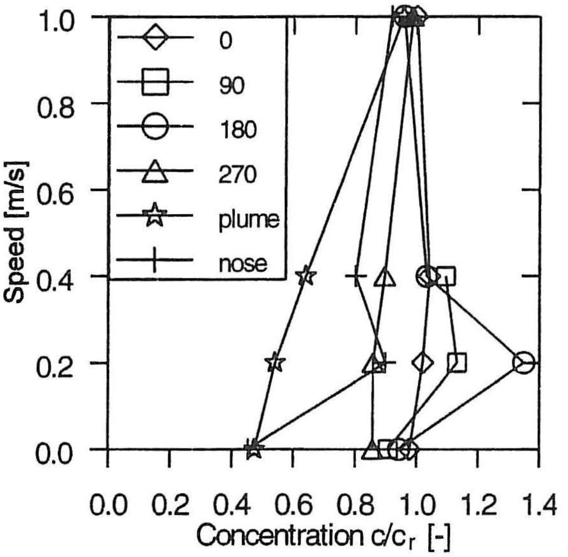

Figure 7: Personal exposure of moving manikin with different ways of adding contaminant: Mouth of sitting manikin at 4 different orientations, plume, and nose.

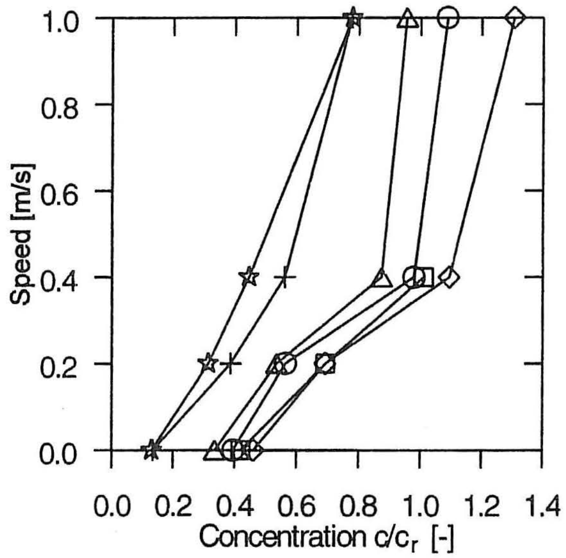

Figure 8: Personal exposure of sitting manikin in all experiments. Regarding nomenclature, see fig. 7.

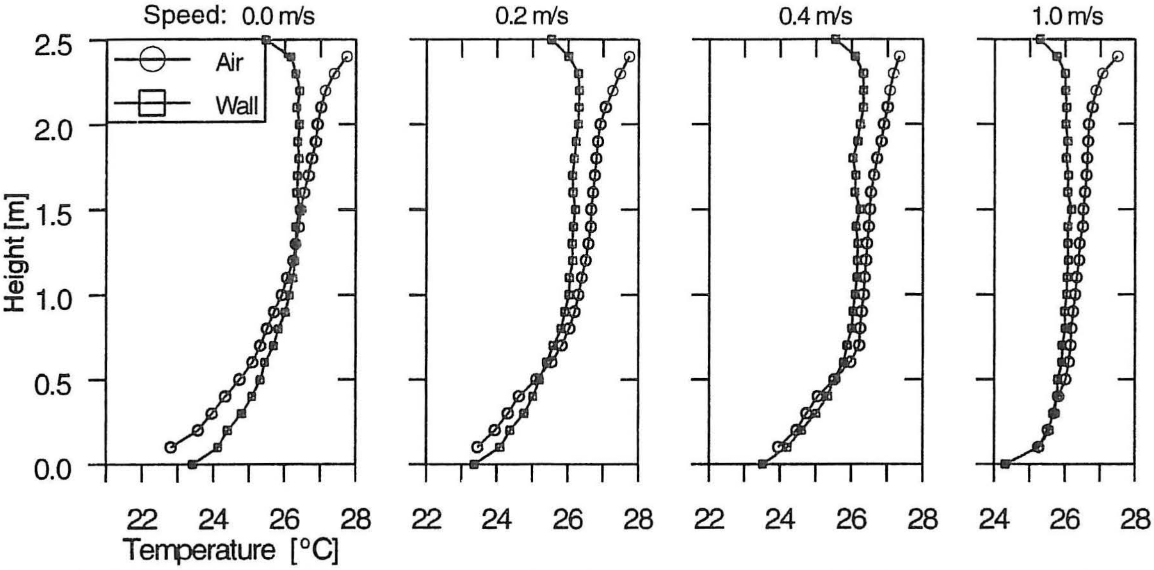

Figure 9: Typical vertical temperature profiles at different speeds of moving manikin, from experiments with exhalation through nose of sitting manikin. Inlet temperature was 16.7°C, exhaust temperature 27.3°C.

DISCUSSION

Plume above the sitting manikin acts as contaminant source: The concentration at breathing height is lower at moderate speeds (0.2 - 0.4 m/s) than at zero speed. This phenomenon has been observed before, and is discussed in (5,8,9). Consequently, the personal exposure of the moving person (fig.7☆) is not increased dramatically by the movement, even if the protecting convective boundary layer close to the body is "blown away" because of the relative speed of the ambient air caused by the movement (we know this is the case because the inhaled air has the same concentration as the ambient air in the same height). In the case of the sitting person (fig.8☆), the personal exposure is increased proportionally with the speed of the moving manikin. This must be due to polluted air being mixed downwards into the lower part of the room, where the air is entrained into the convective boundary layer of the sitting person. However, there is still some protection from the convective boundary layer, since the inhaled concentration is always lower than the ambient air in breathing height. See also (3). At high speed (1,0 m/s), the dimensionless personal exposure for the moving manikin is close to 1.0, which is the same as the ambient air. At 1.0 m/s, the exposure of the sitting manikin is still only 0.8. This means that the situation is never worse than the completely mixed situation. These results are consistent with the results reported in (5,9).

Exhalation through the nose of the sitting manikin acts as contaminant source: The situation is rather similar to the "plume case", but at low speeds (0.2 - 0.4 m/s) contaminat levels at breathing height are somewhat higher, resulting in higher personal exposure of the moving manikin (fig.7+). The reason for these differences are not made quite clear by the present experiments, but it is possible that some of the contaminant in the exhalation actually "breaks free" of the boundary layer flow, even if this was not obvious in the smoke tests.

Exhalation through the mouth of the sitting manikin acts as contaminant source: A significantly larger exposure is observed, especially when the main direction of exhalation is towards the other person (fig.7○). This is not surprising considering the vertical contaminant distributions in these cases, with large concentrations in breathing zone height. This was also confirmed by smoke visualisations. The stratified layer of exhaled air, which can be observed at zero velocity, is dissolved even at a very low speed (0.2 m/s) of the moving manikin (fig.6), but at low speeds the concentration in breathing zone height is still higher than if the contaminant is added to the plume or the nose (comp. fig.6◇ w. fig.3+4◇). There is an interesting effect of contaminant in exhalation together with large speeds of the moving person: when the oriention is 0°, higher personal exposures than 1,0 are observed for the sitting manikin (fig.8◇). This must be due to "short circuiting" of the exhaled air, since the main air movements in the room are directed towards the moving manikin (air is sucked into the wake behind the moving manikin), i.e. exhaled air is blown into the face of the sitting manikin by the disturbances caused by the movement.

When studying the temperature distribution (fig.9), one can observe the effect of the moving manikin mixing air downwards from the upper part of the room into the lower part. This has the interesting effect that the room air is generally warmer than the wall at high speed, whereas at low speed the lower part of the wall is warmer than the room air. This effect will create a downdraft at the walls which will move contaminant from the upper part of the room into the lower part, thus enhancing the mixing effect.

There are some limitations regarding the interpretation of the results, since some potentially interesting parameter variations have not been performed. When people indulge in physical activity, their pulmonary ventilation rate and heat effect will rise. To be able to predict the influence of physical activity precisely, the amount and type of activity should be correlated to the heat effect and the pulmonary ventilation rate, and these factors should be incorporated into the experiments. The total heat effect emitted in the room together with the fresh air rate will influence both temperature and concentration gradients. With regard to the exhalation as contaminant source, it might make a difference if the "source" person is sitting or standing. The geometry of the room, especially the room height, might also be of some importance. All these matters need to be investigated more closely before general rules can be established.

ACKNOWLEDGEMENTS

This research was supported financially by the Danish Technical Research Council (STVF) as part of the research programme "Healthy Buildings", 1993 - 97.

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