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Brohus, Henrik

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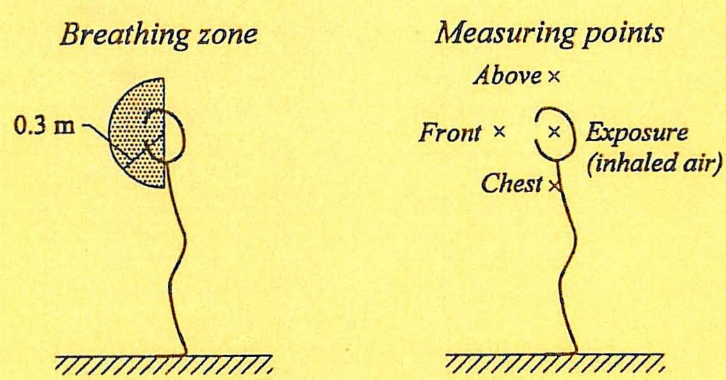

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MEASUREMENT OF PERSONAL EXPOSURE USING A BREATHING THERMAL MANIKIN

by Henrik Brohus

Aalborg University
Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark
E-mail: i6hb@civil.auc.dk Fax: +45 9814 8243 Phone: +45 9635 8539

ABSTRACT

When a person is located in a contaminant field with significant gradients the contaminant field will be modified locally due to the entrainment and transport of contaminated air in the human boundary layer as well as due to the effect of the person acting as an obstacle to the flow field, etc.

In this paper personal exposure measurements are performed by means of the Breathing Thermal Manikin. Contaminant concentration is measured in a number of locations in the breathing zone and in the inhaled air. Two cases are investigated: exposure to different contaminant sources in a displacement ventilated room and in a uniform flow field.

The measurements show a significant local modification of the contaminant field close to the person affecting the personal exposure. The results also show that significant concentration differences can be found throughout the breathing zone.

INTRODUCTION

When a person is located in a contaminant field with significant gradients the contaminant distribution is modified locally due to the entrainment and transport of room air in the human convective boundary layer as well as due to the effect as the person acting as an obstacle to the flow field, etc. The local modification of the concentration distribution may affect the personal exposure significantly (Brohus and Nielsen, 1996; Rodes et al., 1991).

Thus, it is important to consider the local influence of persons when the personal exposure is measured in a ventilated room where concentration gradients prevail. This may be done by means of occupants wearing personal monitors or by means of measurements including a proper model of a human being. In this paper personal exposure measurements using a Breathing Thermal Manikin (BTM) are presented, see Figure 1.

METHOD

In the subsequent the personal exposure index will be used among other quantities. The personal exposure index, ε_e, is defined as (Brohus and Nielsen, 1996)

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

where c_R is the concentration in the return opening and c_e is the concentration of inhaled contaminant, i.e. the personal exposure. The personal exposure index expresses the ventilation effectiveness actually experienced by a person in the ventilated room.

Breathing Thermal Manikin

The Breathing Thermal Manikin (BTM) shown in Figure 1 is developed at Technical University of Denmark. The BTM is shaped as a 1.7 m high average sized woman, developed from an anatomically correct female display manikin consisting of a fibreglass-armed polyester shell. The shell is wound with nickel wire used sequentially both for the heating of the manikin and for measuring and controlling the skin temperature. The BTM is controlled to obtain a skin temperature and a heat output corresponding to people in thermal comfort (Tanabe et al., 1994).

The BTM is wearing tight-fitting clothes with an insulation value of 0.8 clo. Respiration is simulated by means of an artificial lung. In this study 10 min^{-1} is chosen as the frequency of respiration and 10 litre/min as the pulmonary ventilation. The respiration is performed through the mouth. The dispersion and transport of contaminant is modelled by means of tracer gas, see Figure 1.

Experimental set-up

Two different set-ups are examined: exposure to contaminant sources in a displacement ventilated room and in the uniform flow field of a wind channel. The geometry is shown in Figures 2 and 3. In each case the contaminant concentration is measured at three different locations in the breathing zone as well as the concentration of inhaled contaminant, see Figure 4. The tracer gas concentration is measured by means of photoacoustic spectroscopy (uncertainty ± 2%).

RESULTS

Personal exposure in displacement ventilated room

Two different kinds of contaminant sources are examined, a warm source and a passive source, see Figure 1. In case of the warm source the characteristic two-zone concentration distribution is generated with a lower, cleaner zone and an upper, more contaminated part of the room. Three cases are examined for the BTM in seated and standing position, see Table 1. The corresponding vertical concentration distributions are shown in Figure 5. Table 2 summarises the exposure measurements.

Table 1. Specification of three cases examined in the measurements. q is the supply air flow rate, n is the air change rate, Φ is the heat load, t_O is the supply air temperature, t_R is the return air temperature.

Case	Parameters				
	q (m^3/h)	n (h^{-1})	Φ (W)	t_O (°C)	t_R (°C)
A	145	0.8	771	14.7	24.4
B	290	1.5	376	17.6	22.6
C	395	2.1	781	15.8	23.4

Table 2. Personal exposure measurements in the displacement ventilated room in case of a warm contaminant source. c_P^* is the dimensionless concentration measured at a point in the breathing zone, c_e^* is the dimensionless personal exposure and ε_e is the personal exposure index. The breathing zone height is 1.1 m and 1.5 m in seated and standing position, respectively. See Figures 4 and 5.

Case	BTM position	$c_{P,Chest}^*$	$c_{P,Front}^*$	$c_{P,Above}^*$	c_e^*	ε_e
A	Seated	0.39	0.43	0.55	0.47	2.13
	Standing	0.39	0.97	0.79	0.57	1.75
B	Seated	0.26	0.30	0.38	0.28	3.57
	Standing	0.35	0.85	0.57	0.50	2.00
C	Seated	0.06	0.06	0.06	0.06	16.67
	Standing	0.06	0.14	0.08	0.06	16.67

In Figure 6 the dimensionless vertical concentration distribution is shown for two different locations of the passive point contaminant source in the displacement ventilated room. The corresponding exposure measurements are mentioned in Table 3.

Table 3. Measurements in case of a high and a low location of a passive point contaminant source . c_P^* is the dimensionless concentration measured at a point in the breathing zone, c_e^* is the dimensionless personal exposure and ε_e is the personal exposure index. See Figures 4 and 6.

Case	Source location	$c_{P,Chest}^*$	$c_{P,Front}^*$	$c_{P,Above}^*$	c_e^*	ε_e
1	High	0.93	2.93	1.28	1.17	0.85
2	Low	1.87	1.11	1.50	1.74	0.57

Personal exposure in a uniform flow field

The measurements performed in the wind channel on personal exposure to a passive point contaminant source in a uniform flow field are shown in Figures 7 - 9. The three figures show the measured contaminant concentrations for different vertical locations of the point contaminant source as a function of the flow direction, the velocity level and the source location relative to the BTM.

DISCUSSION

Personal exposure in displacement ventilated room

In Figure 5 and Table 2 the vertical concentration distribution and the personal exposure measurements are shown in case of a warm contaminant source in the displacement ventilated room. The concentration level in the inhaled air is found to be significantly lower than in the "neutral" surroundings. The improved air quality is caused by entrainment and transport of room air in the human convective boundary layer.

If the personal exposure, c_e^*, is compared with the three concentrations measured in the breathing zone it is found that $c_{P,Chest}^*$ is slightly lower than the exposure. $c_{P,Front}^*$ is found to approach the exposure well in seated position, whereas in standing position considerable deviations occur. This fact is due to the differences in the boundary layer generated in front of the BTM in the two different positions. $c_{P,Above}^*$ is found to be higher than c_e^* but lower than the concentration in the surroundings, which is also expected due to the plume of the BTM supplying cleaner air from the lower part of the room to the measuring point located above the head.

ε_e is found to be significantly higher than 1 indicating that the air quality in the displacement ventilated room is improved compared with mixing ventilation, where ε_e equals 1 in the ideal case.

Figure 6 and Table 3 present results from measurements on exposure to a passive point contaminant source in the displacement ventilated room. In this case the influence of the ascending air current along the BTM is also distinct. In Case 1 the boundary layer flow protects against the exposure and in Case 2 the boundary layer flow deteriorates the air quality. Relatively large differences are found between c_e^* and the concentration measured at the three different locations in the breathing zone. Here, $c_{P,Above}^*$ is closer to c_e^* than $c_{P,Chest}^*$. $c_{P,Front}^*$ shows considerable deviations from the personal exposure.

Personal exposure in a uniform flow field

Figures 7 - 9 present the results on personal exposure to a passive point contaminant source in a uniform flow field. The flow field is generated in the wind channel shown in Figure 3, but the uniform field may also represent the local flow field around a person located in a mixing ventilated room.

In Figure 7 a distinct influence of the location relative to the wind direction and the contaminant source is found. In Case 1 no exposure takes place when the source is below 1 m. When the source is raised above 1 m the level increases to a maximum value around the breathing zone height after which it decreases again. In Case 2 exposure occurs for almost every source location, and the location for maximum exposure is found at a lower level.

A good correspondence is found between the personal exposure and $c_{P,Chest}^*$ as well as $c_{P,Front}^*$, both regarding the shape of the curves and also the location and the level of the maximum concentration. $c_{P,Above}^*$, however, shows considerable deviations.

In Figures 8 and 9 a systematic investigation is performed on the exposure as a function of the uniform velocity level and the vertical point source location. This is done for two horizontal locations of the contaminant source relative to the BTM. The two cases show that the personal exposure depends strongly on both the source location and the velocity level. Dimensionless exposure levels exceeding 30 are found.

$c_{P,Chest}^*$ is found to be a reasonable approximation for the personal exposure. $c_{P,Front}^*$ shows some deviation for the results presented in Figure 9, where the contaminant source is located in front of the BTM. At low velocities and a high location of the source $c_{P,Front}^*$ deviates significantly from c_e^*. This is due to the fact that the source is located relatively close to the measuring point and also due to the distinct effect of the human boundary layer. The measuring point above the head, $c_{P,Above}^*$ should not be used to estimate the personal exposure.

CONCLUSION

The results of the full-scale exposure measurements by means of the Breathing Thermal Manikin show the importance of a proper tool for the assessment of personal exposure in ventilated rooms where concentration gradients prevail. The human convective boundary layer is found to affect the local concentration distribution considerably together with the effect of the person acting as an obstacle to the general flow field.

Comparisons between the concentration of inhaled contaminant and the concentrations measured at three different locations in the breathing zone show substantial deviations when the measuring point is located above the head and in front of the head, whereas the measuring point located at the chest show a good agreement with the personal exposure.

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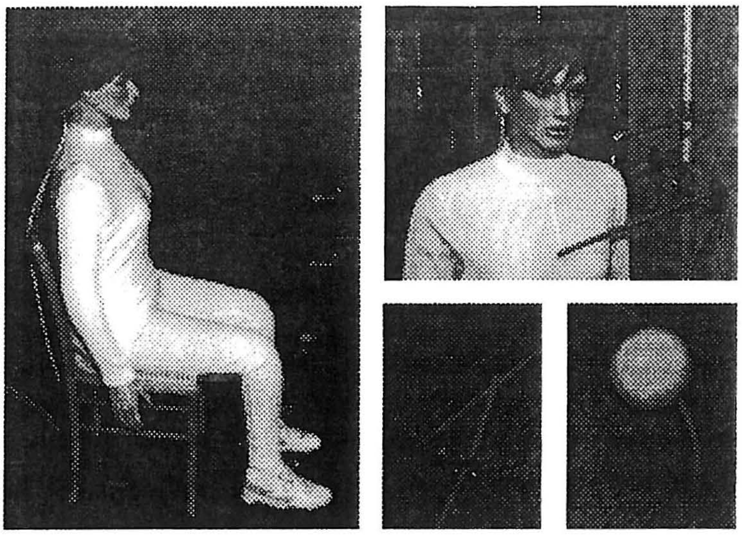

Figure 1. *Left and top, right*: Breathing Thermal Manikin (BTM) used to measure the personal exposure. The BTM is separated in 16 parts, each with the same surface temperature and heat output as people in thermal comfort. Height 1.7 m, clothing insulation 0.8 clo. *Bottom, right*: Contaminant sources used for injection of the tracer gas N_2O. 1) Upward pointing tube, ø 0.01 m, located above a heat source (warm). 2) Porous foam rubber ball, ø 0.1 m, N_2O mixed with He (passive).

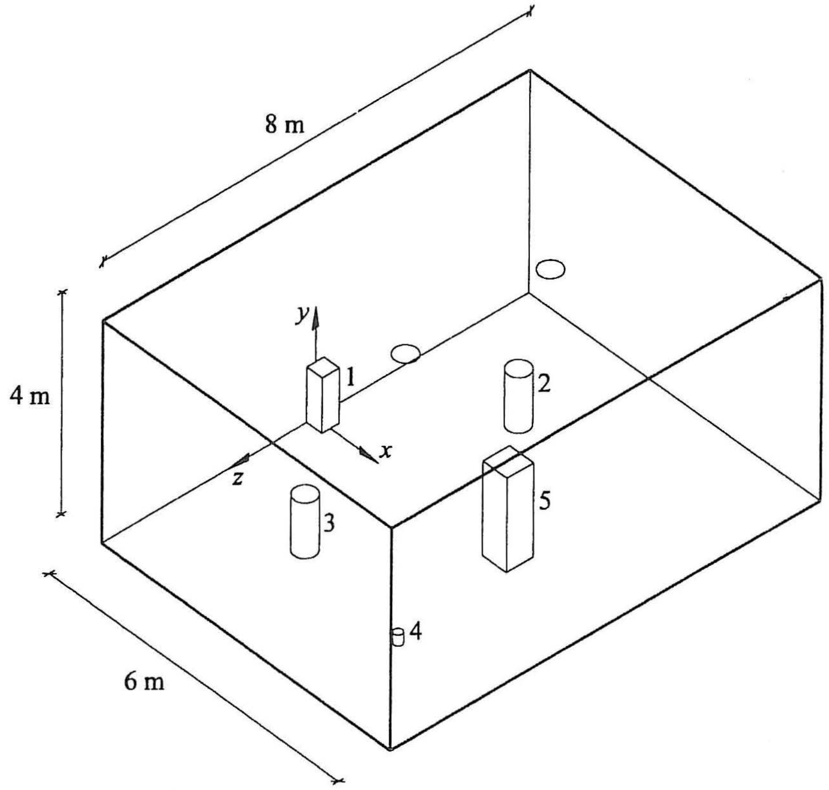

Figure 2. Geometry of the displacement ventilated room. Subcooled air is supplied by the inlet device (1) and exhausted through two openings in the ceiling. The heat load is generated by two person simulators (2,3), located at $(x,z) = (2,\pm2)$, a point heat source (4) located at $(x,z) = (4.5,2.5)$ and the BTM (5) located at $(x,z) = (4,0)$, represented by a box (see Figure 1).

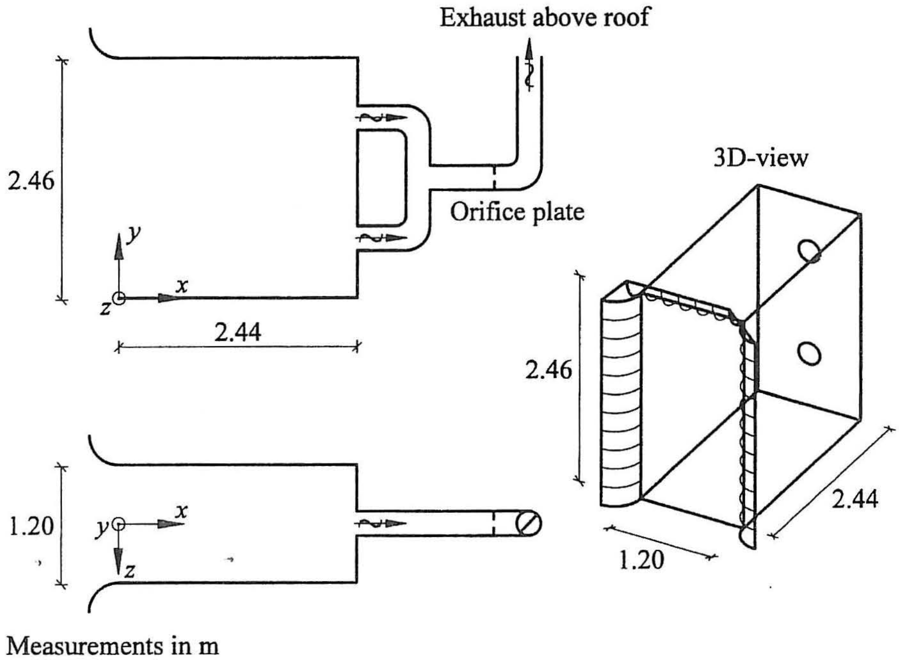

Figure 3. Geometry of the wind channel used in the full-scale measurements on the BTM standing in a unidirectional flow field. The flow field is generated by extracting air through two exhaust openings, each ø 0.25 m. The rounded inlet opening is applied to reduce turbulence generation at the edges.

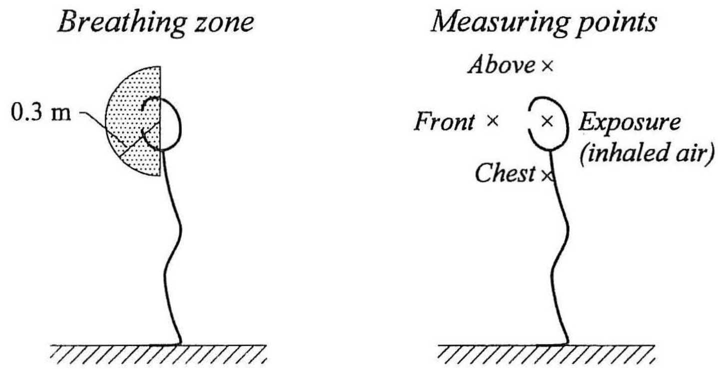

Figure 4. *Left*: The breathing zone of a person is frequently defined as a hemisphere with a radius of 0.3 m and the virtual centre located in the middle of the head, between the ears. *Right*: Location of the measuring points. Three measuring points are located on the edge of the breathing zone in a distance of 0.3 m from the virtual centre. They are designated "chest", "front" and "above", respectively. Furthermore, the concentration of inhaled contaminant, i.e. the personal exposure, is measured by means of an artificial lung providing the respiration through the mouth of the BTM.

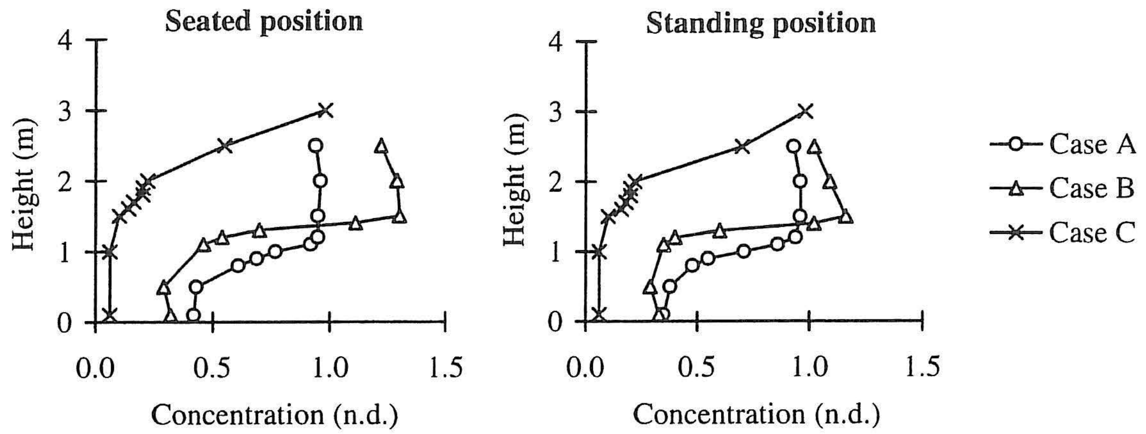

Figure 5. Dimensionless vertical concentration distribution in the displacement ventilated room Case A, B and C for the BTM in seated and standing position, respectively (warm source). The measurements are performed at $(x,z) = (3,-1)$.

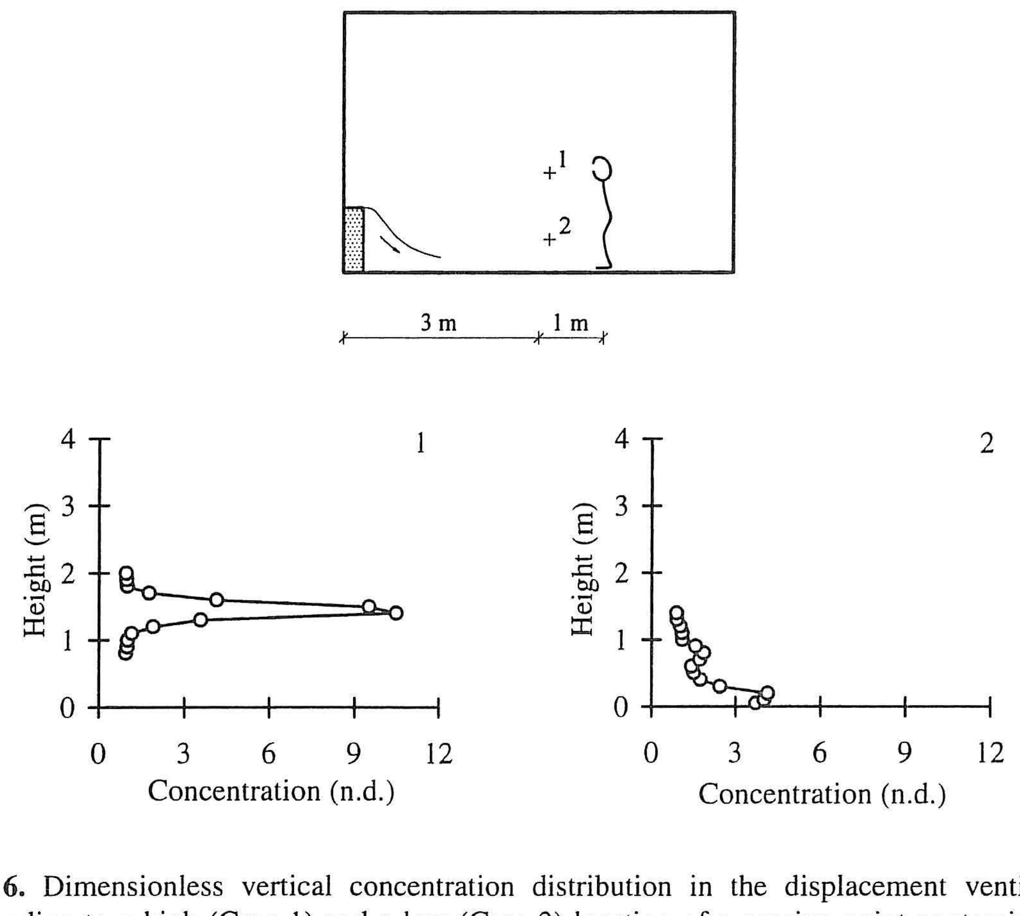

Figure 6. Dimensionless vertical concentration distribution in the displacement ventilated room corresponding to a high (Case 1) and a low (Case 2) location of a passive point contaminant source. The profile is measured 0.9 m from the BTM and 0.1 m from the source. The measurements are performed under conditions corresponding to Case B, Table 1.

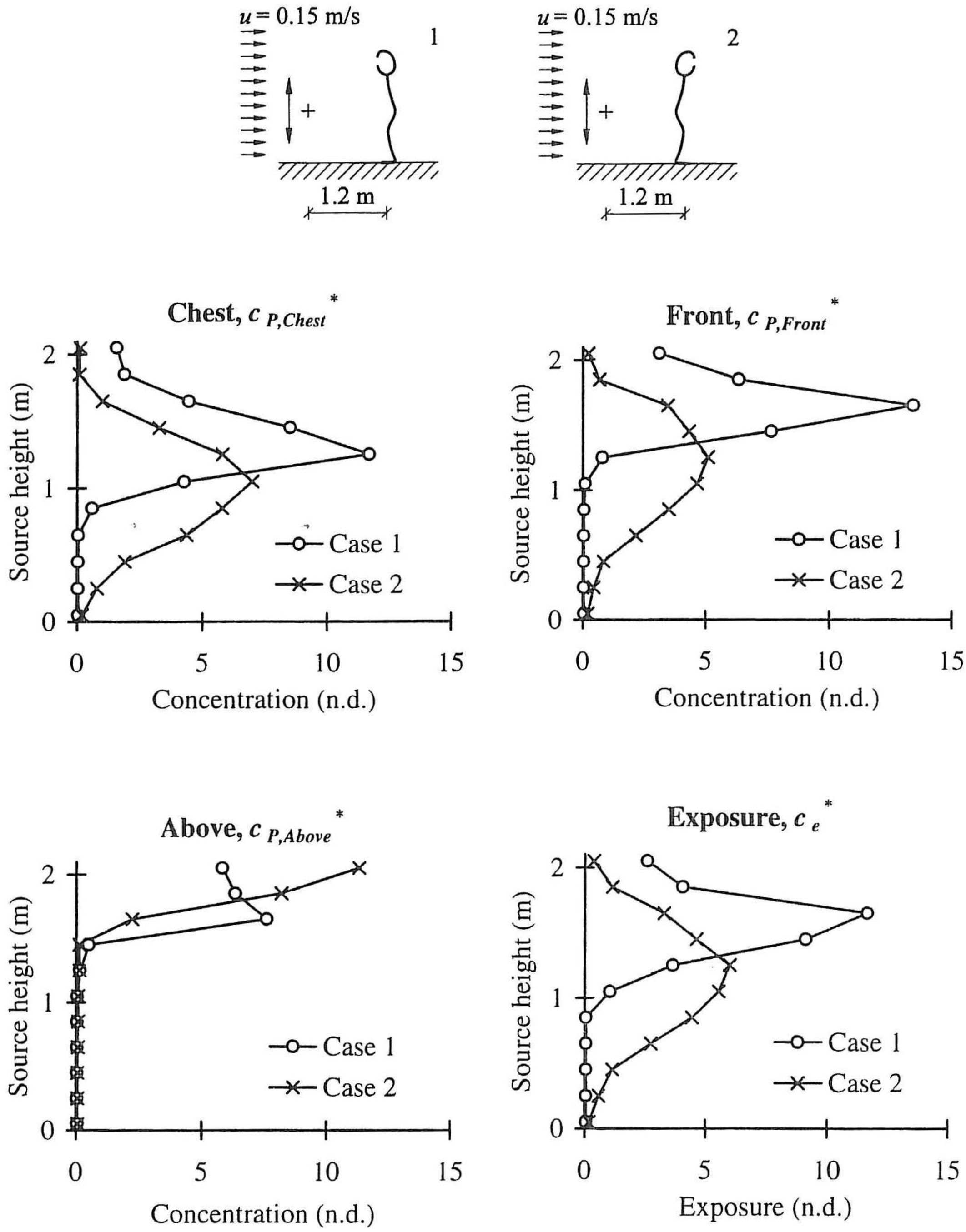

Figure 7. Dimensionless concentration, c_P^*, measured at three different locations in the breathing zone (see Figure 4) and the dimensionless personal exposure, c_e^*, of the BTM standing in a unidirectional flow field at a velocity of 0.15 m/s. Case 1: BTM facing wind direction. Case 2: BTM facing opposite direction. The horizontal distance between the centre of the BTM, $(x,z) = (1.2,0)$, and the centre of the point contaminant source, $(x,z) = (0,0)$, is 1.2 m. The vertical location of the point contaminant source is ranging from 0.05 m to 2.05 m. The results are made dimensionless by dividing by the contaminant concentration measured in the return opening of the wind channel.

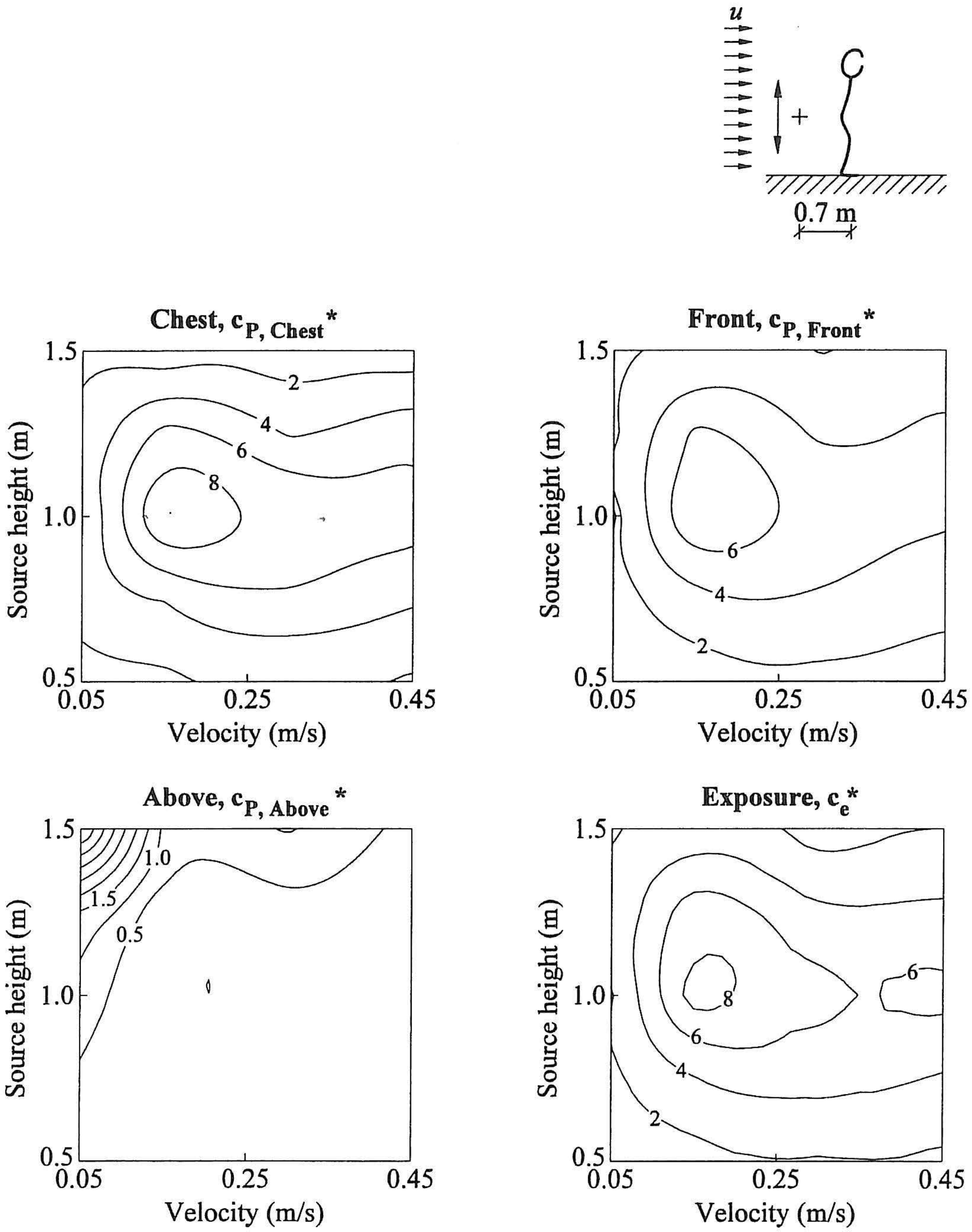

Figure 8. Dimensionless concentration, c_P^*, and dimensionless personal exposure, c_e^*, of the BTM standing in a uniform velocity field as a function of the velocity level (0.05 m/s - 0.45 m/s) and the vertical point source location above the floor (0.5 m - 1.5 m). The horizontal distance between the centre of the BTM, $(x,z) = (0.7,0)$, and the centre of the contaminant source, $(x,z) = (0,0)$, is 0.7 m. The locations of the measuring points are found in Figure 4. The results are made dimensionless by dividing by the contaminant concentration measured in the return opening of the wind channel. They are converted into isopleths by using a computer programme incorporating Kriging for the interpolation.

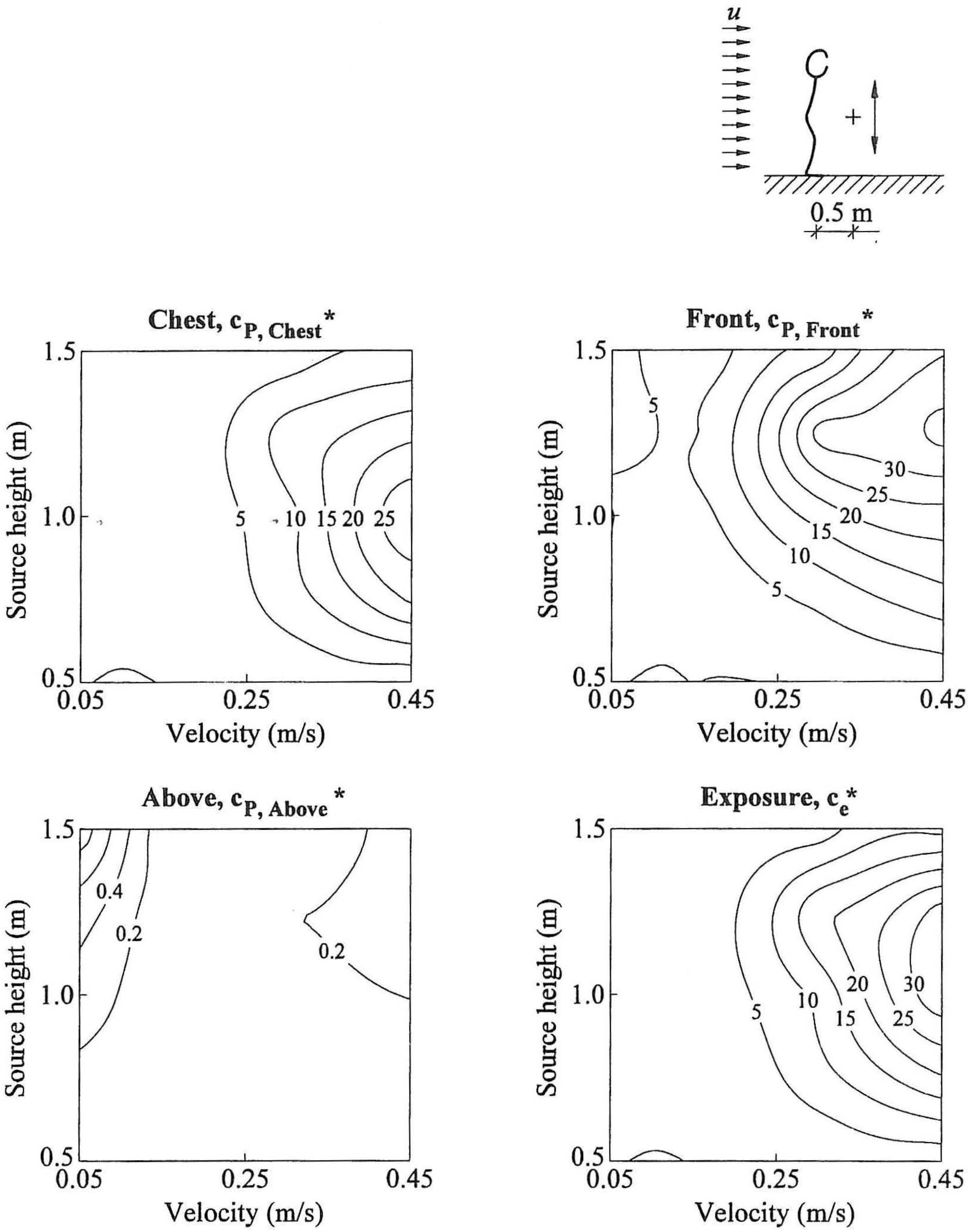

Figure 9. Dimensionless concentration, c_P^*, and dimensionless personal exposure, c_e^*, of the BTM standing in a uniform velocity field as a function of the velocity level (0.05 m/s - 0.45 m/s) and the vertical point source location above the floor (0.5 m - 1.5 m). The horizontal distance between the centre of the BTM, $(x,z) = (0.7,0)$, and the centre of the contaminant source, $(x,z) = (1.2,0)$, is 0.5 m. The locations of the measuring points are found in Figure 4. The results are made dimensionless by dividing by the contaminant concentration measured in the return opening of the wind channel. They are converted into isopleths by using a computer programme incorporating Kriging for the interpolation.

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Department of Building Technology and Structural Engineering
Aalborg University, Sohngaardsholmsvej 57. DK 9000 Aalborg
Telephone: +45 9635 8080 Telefax: +45 9814 8243