CONTAMINANT DISPERSION NEAR A WORKER IN A UNIFORM VELOCITY FIELD

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INTRODUCTION

Information concerning the air flow pattern around a worker is essential when extracting contaminants from a nearby source. The level of exposure of a worker close to a contaminant source is dependent on:

- the properties of the source: strength and geometry;
- the distance from the worker and the initial velocity and direction of emission;
- the properties of the air flow pattern: directions, velocities and turbulence;
- the activity and the position of the worker in relation to the air flow pattern.

In many practical exhaust units, such as those installed in booths for spraying, grinding and painting, with suction extraction walls, air flows into the exhaust from behind the worker's back. In such cases, high exposure levels have been reported, although the exhausts appear to work efficiently (Flynn and Shelton 1990). When the supply air originates from behind the worker's back, reverse flow and upwardly-rising convection flow result, which transport the contaminant into the breathing zone (Kim and Flynn 1991; Johnson et al. 1996). This transportation of contaminant into the breathing zone reduces the effectiveness of the local ventilation.

Current knowledge of the effects of the worker on air flow is inadequate. In previous studies, laboratory tests have been made using heated and unheated mannequins. Further studies with heated mannequins and people are needed to provide information about how to combine local exhaust and the supply air flow pattern around the worker. More data concerning contaminant transport phenomena are needed to develop more effective control techniques and good work practices, in order to reduce the exposure of workers to air contaminants.

AIM

The aim of this study was to produce data which can be used as a basis for the control of factors affecting the concentrations of air contaminants in the breathing area of a worker, when the source of gaseous emission is handled by the worker. The experiments were focused on the effects of convection and reverse flows created by: the body of the worker, the position of the worker in relation to the main air flow field, the worker's activity, and the source configuration.

MATERIALS AND METHODS

Wind tunnel

Experiments were carried out in an open circuit, plastic wind tunnel with a section of 1.7 m x 2.2 m and a length of 3.0 m. Filter material was used downstream of two low velocity supply units (LVA315 from Halton) to produce a uniform flow field in the tunnel. The air flow rate was 1.146 m3/s. The corresponding nominal free-stream velocity was 0.31 m/s.

Source and work situations studied

Two different types of source were used for the experiments: a line source and a point source. In both cases the tracer gas was a mixture of acetone vapour in air. The line source was a 0.6 m long tube (⌀ 17 mm) with a 0.50 m long slit (width 8 mm). The tube was always oriented perpendicular to the main air flow direction and with the slit upward. The point source was a cylinder (⌀ 14 mm, height 14 mm) made out of a sintered glass filter (pore size G1) with tracer gas emitted from the casing and from one of the gables. The cylinder was oriented with its axis horizontal. The placement of the source is shown in Appendix 1. The amount of released acetone was approximately 3 mg/s and the total tracer gas flow was 35 l/min. The calculated nominal initial velocity of the point and line sources were 0.8 m/s and 0.1 m/s, respectively. The tracer gas was produced by bubbling air (0.5 l/min) through liquid acetone in a 30 ml glass bottle. In order to stabilise the temperature in the bottle, it was placed in a bucket with 2 l of water at room temperature. This flow of highly concentrated acetone in air was connected to a 3 l mixing glass bottle. The main air flow was connected to the same bottle. The concentration of acetone in the tracer gas was approximately 5000 mg/m3. To check the stability of the concentration of acetone in the tracer gas, a sample (1.0 l/min) was continuously taken from the main stream and diluted 20 times with air. The stability of the source flow rate was checked with the help of an orifice plate connected to a pressure gauge equipped with an analogue signal output. The stability of the system during a single experiment was good. The coefficients of variation for the concentration and air flow rate were typically 8 and 1 %, respectively. The point source or the line source either hung freely, or were placed on a table (0.585 m x 0.9 m) in front of the standing mannequin or worker. The worker stood close to the table. The height of the source was 0.94 m from the floor and the distance of the source from the body was 0.35 m.

Worker

A worker with a height of 1.75 m either stood still, or moved his arms in the geometry shown in Appendix 2 at approximately 10 cycles/minute at the centreline of the tunnel. A mannequin covered with the same overall and with a height of 1.75 m and a surface area of 1.72 m^2 was also used to simulate the worker. The mannequin was used in both the unheated (isothermal) and heated conditions, in which it was heated to a body surface temperature of 34-35°C. The corresponding surface temperature of the worker varied between 32 and 35°C. The distance between the supply air wall and the worker's back was 0.65 m.

Measurement arrangement

Temperatures

Surface, supply air and ambient air temperatures were controlled with Graftemp-thermistor probes (accuracy ±0.3°C). Air temperatures in the wind tunnel were measured using 10 Dantec 54N10 sensors simultaneously at different heights and by a traversing system from point to point.

Velocities

Free-stream velocities were measured simultaneously using 10 Dantec 54N10 hot sphere anemometers at different heights. Velocities were measured along 3 longitudinal lines (the centreline and two sidelines) by traversing the anemometer system from point to point. Velocities were measured at 280 points. At each point the mean velocity and its standard deviation was calculated over a duration of 1 minute.

Concentrations

Ten photo-ionization (PID) instruments (SI-12, EAK Tallinn, Estonia) were used. One of them was connected to the diluted side stream of the tracer gas. A vertical sampling grid with nine sampling points was placed at the centreline of the tunnel. The grid covered a vertical rectangular area with one corner located at the nose of the mannequin/person, and with the opposite diagonal positioned close to the source, Appendix 1. The vertical and horizontal distances between adjacent grid points were 0.3 and 0.15 m, respectively. The nine PID instruments were placed on top of the wind tunnel. Teflon tubes were used to transport samples from the points studied to the instruments. All PID-instruments were calibrated by connecting them to a gas sampling bag filled with acetone in air. This was repeated twice a day to check the stability of the instruments. All ten instruments were connected to a data logger (AAC, Intab, Stenkulla, Sweden) and data were stored every second during the whole experiment. The absolute concentration of acetone vapour in the tracer gas was determined by weighing the glass bottle with acetone before and after each experiment. Data concerning the source air flow rate and the elapsed time were also used in the calculations.

Experimental design

The effects of the following factors on the concentration profiles were studied: 1) the presence of a worker, unheated mannequin, heated mannequin, stationary person, and moving person; 2) the main air flow direction - from the back, from the side, and from the front of the worker; 3) the presence of a work table; and 4) the source type - a line source or a point source. The first series of experiments was designed principally to establish the result of heating the mannequin, and of the main air flow direction. The second series of experiments focused on the effect of the worker (except for the unheated mannequin), the work table, and the source type on concentration profiles. This provides 12 possible combinations. All experiments were repeated twice and the total was therefore 24 experiments, performed in a random order. Sampling of concentration data was started after allowing the system to stabilise for approximately two minutes after the source flow was initiated. In total, ten minutes of data were stored. The air flow field downstream of the mannequin/person was checked immediately after concentration measurement was finished.

RESULTS

Air flow field in the tunnel

The space average of all free-stream mean velocities (N=840) was 0.31 m/s and the standard deviation of all mean velocities was 0.04 m/s. From these data, together with the velocities and standard deviations at the source height (Appendix 3), and the fact that all other velocities at different heights were similar, it can be concluded that the free-stream velocity field was quite uniform.

Temperature distributions

The surface and the air temperatures during the experiments were quite stable. Their variations during all experiments are given in Table 1.

Measuring point	Temperature, °C
Supply air	19.1-20.9
Air in wind tunnel -empty tunnel -with worker	 19.9 20.8-20.9
Ambient air outside the wind tunnel	19-21
Ceiling	21
Floor	19-20
Walls	20-21

Table 1. Surface and air temperatures during the experiments

Dependence of concentrations on main air flow direction and heating of the mannequin

These experiments were performed using both heated and unheated mannequins in three different orientations in relation to the air flow field. The mannequin was located at the centreline of the wind tunnel with either the back or face oriented towards the air flow direction. The mannequin was located at the left wall side of the wind tunnel with the side oriented toward the air flow direction. The results clearly showed that the only case in which the released acetone vapours reached the breathing zone was when the mannequin was placed with the main air stream coming from the back side. The warm mannequin produced twice the acetone concentration in the breathing zone compared with the unheated (isothermal) mannequin.

Effect of worker, use of a table and source type on concentrations.

These experiments were performed with a heated mannequin and a moving person, or a person standing still with his back towards the air flow. The source was a point or a line source hanging freely or lying on the table. The results are summarised in Table 2. The concentration data from the nine measuring points have been normalised by dividing them with the source concentration measured at the same time. All data presented here are therefore expressed as concentration per mil. Each result in Table 2 represents the geometrical mean of data collected during 10 minutes of experiment, which was repeated twice. Since the sampling rate was 1 s^{-1}, the total number of data points from which the mean was obtained was 1200.

Source type	*Worker*	*Table*	*A1*	*A2*	*A3*	*B1*	*B2*	*B3*	*C1*	*C2*	*C3*
point	sp	no	6.8	5.5	5.0	15.9	12.1	7.8	83.7	152.7	57.3
line	sp	No	9.9	7.1	5.7	20.6	20.9	10.1	29.4	16.8	317.6
point	man.	No	9.7	7.4	6.3	13.1	15.2	12.5	32.0	40.3	36.8
line	man.	No	11.5	8.3	6.4	16.9	22.0	16.6	29.9	30.0	142.4
point	sp	yes	6.0	5.2	4.6	14.5	11.7	7.4	49.1	62.5	115.2
line	sp	yes	6.8	5.5	5.0	15.9	12.1	7.8	83.7	152.6	57.3
point	man.	Yes	6.2	4.9	4.3	12.8	17.0	10.9	50.2	50.4	101.1
line	man.	Yes	8.6	6.2	5.4	13.2	16.6	15.8	94.0	168.4	52.0
point	mp	no	4.7	5.0	3.5	13.2	8.2	3.9	29.8	31.3	34.9
line	mp	no	5.8	4.8	3.7	11.7	7.4	4.9	27.6	35.5	25.5
point	mp	yes	7.3	6.8	5.0	17.6	11.4	6.9	37.0	45.0	80.2
line	mp	yes	8.0	7.0	5.3	17.8	11.4	7.7	46.7	57.9	45.3

Table 2. Acetone concentration measurements (of source concentration) at points A1-C3 (see Appendix 1): sp denotes a standing person, mp denotes a moving person and man. denotes a heated mannequin.

The results have been treated statistically as two series of experiments according to a two-level factorial design model (4). The factorial design has been used to fit a response surface model to the experimental results. Every response (average concentration at the nine measured points) therefore has a surface model which accounts for the average, all main effects, and all two-factor interactions. The three-factor interactions have been calculated by using:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + e$$

where y is the concentration at the point, β_0 is the average concentration, β_i are the coefficients for each factor and xi are the factors. Factor 1 was the source type (line = 1, point = -1), and factor 3 was the table (yes = 1, no = -1). In the first series, factor 2 was a mannequin or stationary person (1 or -1), and in the second series a moving person or a stationary person (1 or -1). e is the experimental error which was estimated to be less than 14 % (coefficient of variation) of the average response. The results showed a clear reduction in concentrations at the nose level of standing person and mannequin, when a table was used. The average reduction at point A1 was 30%. This is the only significant ($p < 0.05$) effect of any single factor (5). The table also reduced the concentrations at chest level (15 % at point B1), when the worker was standing still, and (at point B) when the mannequin was used. There were also a clear, but not statistically significant, increase in concentrations at source level (55 % at point C1), when the table was used.

The line source resulted in higher concentrations at the nose and chest levels compared with the point source (15-20% at point A1).

Movement of the worker reduced the concentrations at all points, when the table was not used. This effect is relatively small in the breathing zone (17% at point A1), but was larger closer to the source (28% at point C1). When the table was used the movements increased the concentrations at nose, chest and source levels.

DISCUSSION

The finding that when the worker is oriented with his back towards the main air stream direction, high concentrations are obtained, is in agreement with data obtained elsewhere (Flynn and Ljungqvist 1995, Flynn and Dennis 1991, Flynn et al. 1996, Kulmala et al.). However, this may not be true with lower air velocities or with a different source type (Kim et al. 1992, Carlton et al. in press).

Heating of the mannequin is important since it causes an upwardly-directed airflow around the worker. This air flow is one of the two major factors which explain the transportation of the contaminant from the source to the breathing zone. The other factor is the reverse air flow, opposite to the main air stream, downstream of the body. This second factor is responsible for the first part of this transportation of the contaminants towards the breathing zone. When the contaminant has reached the lower part of the body the convection flow of the body takes over transportation to the breathing zone.

In order to reduce concentrations in the breathing zone, these transmission paths should be blocked. This effect is clearly illustrated with the table placed close to the worker. Even though the presence of the table resulted in significantly higher concentrations close to the source and lower part of the worker's body, transportation up to the breathing zone was smaller. (The relative decrease in contaminant concentration from measuring points C1 to A1 is 12.7 with the table, and 3.2 without).

Movement of the worker acts like a fan, causing dilution of the contaminant concentration when the table is not used. Movement of the worker slightly increased the concentrations in the case when the table was present. With the table, the higher concentrations near the source were only diluted upwards and sideways, not downwards as in the case of a free source.

With the line source, a larger proportion of the contaminant followed the reverse flow, because of the lower initial velocity. In the case of the point source, the initial velocity was significantly higher than the reverse flow velocities.

CONCLUSIONS

Given a certain contaminant source with low impulse in the near field of a worker, his/her orientation relative to the main air flow direction is the most important factor for reducing occupational exposure, when the air velocity is around 0.3 m/s.

When carrying out experimental studies on this type of phenomenon, heating of the mannequin or the use of a person plays an important role.

The movements of a worker influence the spreading of the contaminant from the source, and should be included when models explaining exposure are to be developed.Spreading of the source in a direction perpendicular to the main air flow, and a simultaneous lowering of the initial velocity result in increased concentrations in the breathing zone. A work table placed close to the worker reduces the contaminant concentration in the breathing zone, when the worker is not moving.

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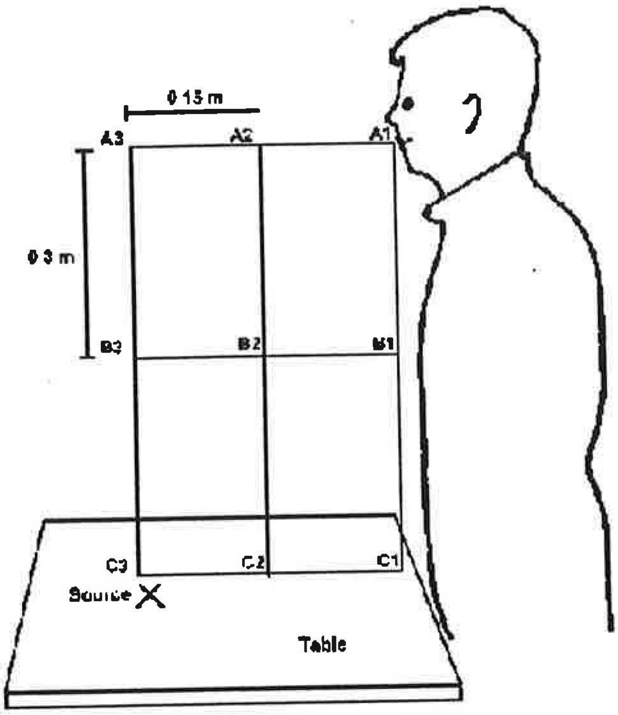
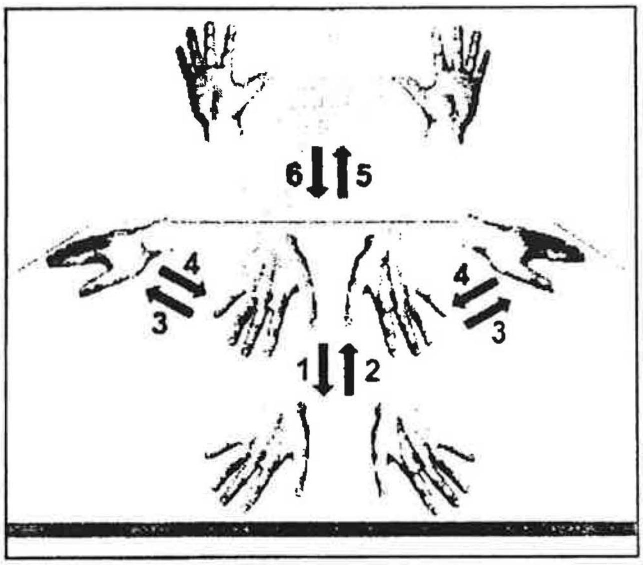
Appendix 1. The location of the source and the grid of measurement points.

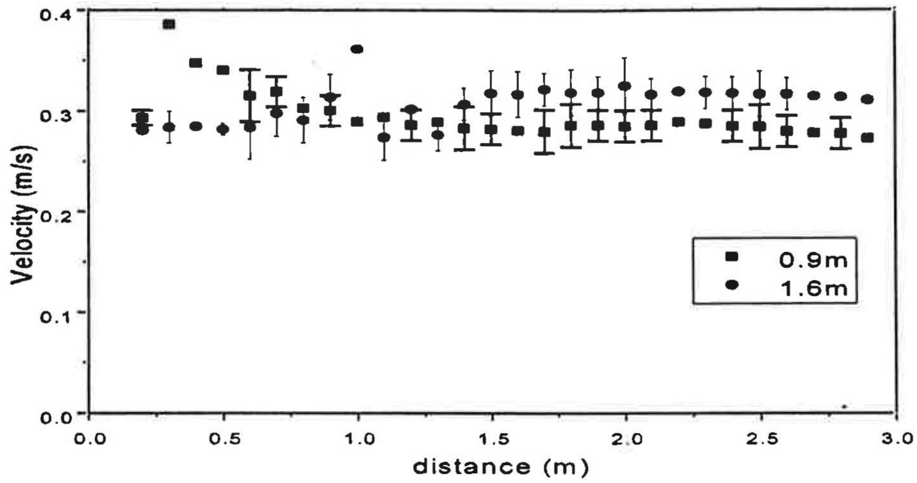


Appendix 2. The geometry used to move the arms of the worker.

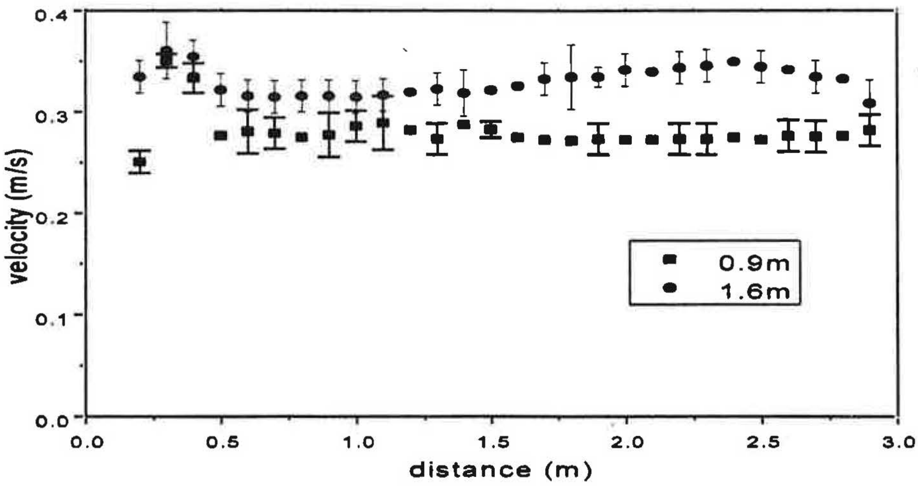


Appendix 3. Velocities and standard deviations along 3 longitudinal lines (centreline and two sidelines) at two heights 0.9 and 1.6 m.

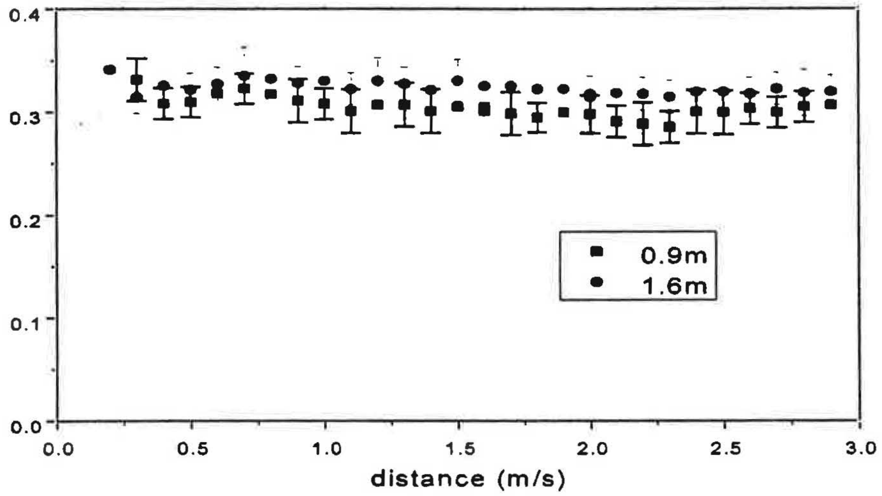
Centre line



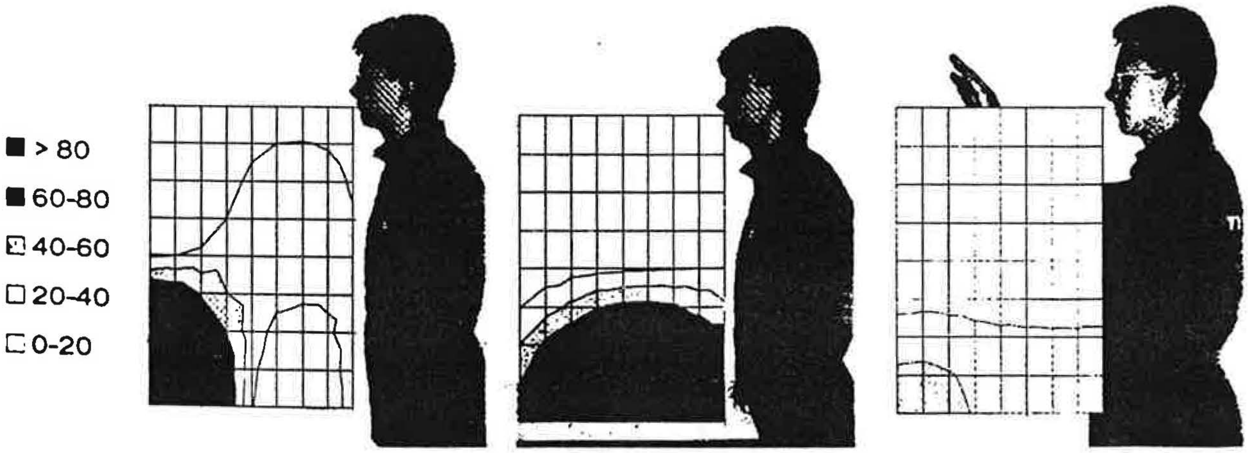
Left line



Right line



Appendix 4. The figures illustrate the concentration of acetone measured at nine points in front of the worker. The scale shows concentration of acetone relative to the source (per mill); the darkest colour represents the highest concentration. In figure a: the worker stands still without a table, b: the same situation with a table and c: the worker moves his arms his arms and no table is present.



a b c