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THE DISTRIBUTION OF THE PERCEIVED AIR QUALITY IN AN OFFICE SPACE
Computer simulations and sensory evaluations

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SUMMARY

A Computational Fluid Dynamics Model (WISH3D) was used to predict the distribution of the perceived air quality in an office space with a mechanical air supply system, where several pollution sources were present. The results were compared with sensory evaluations of a trained panel.

The air flow pattern predicted by the computer programme WISH3D seemed to agree with the general air flow observed. The computer simulations of several cases indicated that boundary conditions such as temperature variations, standing persons and adsorption effects influence the predicted perceived air quality distribution. Sensory evaluations of a trained panel resulted in non-uniform distributions of the perceived air quality, which indicates that the location of a panel member can be of importance when the air quality of a space is evaluated. Computer simulations of the perceived air quality did not confirm these results completely, which might have been caused by the assumed boundary conditions and the assumption that air as it is perceived by a person is transported in the same way as a neutral gas. Furthermore the results showed that local adsorption can result in larger perceived air quality differences all over the space. In future studies adsorption and desorption effects should be taken into account.

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INTRODUCTION

Complaints about indoor air quality in non-industrial buildings have increased over the years. Parameters such as ventilation and pollution sources are documented to be of major importance. Most ventilation standards are based on the number of occupants present. All other pollution sources, such as building materials, ventilation systems and furnishings, are hereby ignored. Studies based on human perception have however indicated that these sources have to be taken into account when ventilation requirements are determined [1].

In many cases the human senses are superior to chemical analyses for assessing how air is perceived. The traditional way to determine the air quality in existing buildings is to ask people at their working place how they perceive the air. The use of independent people who visit the investigated buildings is another approach. Untrained panels of 50 to 100 subjects have been used to evaluate the air quality in office buildings [1]. A method to train a panel to evaluate perceived air quality in decipol has been developed [2,3] as well as a method to determine the total pollution source strength of a building [4]. Does this last method take possible perceived air quality distributions into account?

The required ventilation in a space depends on the total pollution source strength, the perceived air quality of the outdoor air, the desired perceived air quality and the ventilation efficiency in that space. Knowledge of the distribution of the perceived air quality (in decipol) in a space is still incomplete.

The Computational Fluid Dynamics Model WISH3D makes it possible to simulate air flow patterns and concentration distributions of pollutants in a space [5]. But can it also simulate the perceived air quality distribution in that space? In this study WISH3D was used to simulate the distribution of the perceived air quality in an office room and the results were compared with sensory evaluations of a trained panel in that same office room. Until now some perceived air quality simulations have been made [6], but a verification with a trained panel was still lacking.

METHOD

Office space

An office space with a mechanical air supply system was selected and furnished with an office table, an office chair, a two-seat, a small table and two comfortable chairs (Figure 1). The selected furniture had an average age of 10 years and was therefore considered only to emit possible adsorbed pollution. The office space had a surface area of 4.43 m x 5.05 m, and was 3.58 m high. The mechanical air supply system comprised three air induction units.

Computational Fluid Dynamics model

The computer programme WISH3D was developed at TNO to predict flow patterns, temperatures and pollutant concentrations in a space with a certain ventilation system [5]. The programme is based on the finite volume method [7] and uses non-linearly spaced grids to take high gradients near room walls into consideration.
The time-averaged equations of momentum, heat and mass transfer are solved with air as an incompressible fluid. The Boussinesq approximation is applied to include density variations as a result of temperature differences. Turbulence is modelled with the well-known k-ε model, resulting in extra transport equations for k (the kinetic energy of turbulent fluctuations) and ε (the dissipation rate of turbulent kinetic energy). A turbulent viscosity, determined by k and ε is added to the dynamic viscosity of air. The flow near walls is modelled with standard logarithmic wall functions [8].

The transportation of pollutants is based on convection and diffusion only. To account for turbulent mixing a turbulent diffusion coefficient is added to the molecular diffusion coefficient, assuming a turbulent Schmidt number of 1.

Trained panel

For a long time panels have been used in the food industry, cosmetics, perfumery and the wine industry. When a panel has to be trained to evaluate perceived air quality directly in decipol a reference is required. The units for perceived air quality (decipol) and pollution source strength (olf), introduced by Fanger [9], are based on the reference human bioeffluents. Human bioeffluents comprise a large number of chemical compounds and vary considerably from person to person. A reference that is easy to measure and to produce was therefore selected: 2-propanone [10]. The production of this reference source is based on passive evaporation and is introduced to the human nose by a constant air flow coming out of the so called decipolmeter [10]. The relation between the perceived air quality in decipol and the 2-propanone concentration in air was determined by 265 persons [10]. This relation is used to train people in evaluating air quality directly in decipol.

Ventilation and climate conditions

The air supplies (primary and secondary) were determined and the air flow pattern was verified with smoke- and soap-bubble tests. During the experiments several air and surface temperatures were measured (see Figure 1 and Table 1) and the primary air supply was set at 100% outdoor air (no recirculation).

Computer calculations

The WISH3D programme was converted to be applied for perceived air quality simulations. Hereby it was assumed that air as it is perceived by a person is transported as if it was a neutral gas. The flow pattern of the selected office space was determined for several steady-state configurations with the same ventilation conditions as given in Table 1:

- configuration 1: isothermal boundary conditions (20°C), no persons;
- configuration 2: temperature conditions as given in Table 1, no persons;
- configuration 3: temperature conditions as given in Table 1, one person standing at location a (50 watt convective heat) (Figure 1);
- configuration 4: temperature conditions as given in Table 1, burning cigarette (20 watt) at location B (Figure 2).

The WISH3D programme calculated the perceived air quality distribution, using the calculated air flow patterns and the source strengths of the linoleum, the burning cigarette and the outdoor air, based on evaluations made by the trained panel (see Table 2), for the following cases:

- case 1: configuration 1 + linoleum at location A (12,2 olf)
- case 2: configuration 2 + linoleum at location A (12,2 olf)
- case 3: configuration 3 + linoleum at location A (12,2 olf)
- case 4: configuration 4 + burning cigarette at location B (25 olf)
- case 5: configuration 3 + linoleum at location A (26.4 olf) + negative source in air induction system (50 % of emitted pollution from linoleum).

Case 5 was calculated because it was suspected that the air induction system could be a negative source, i.e. adsorption of the emitted pollution from the linoleum. The source strength of the linoleum was increased to achieve the same average decipol level as in case 1, 2 and 3 (7.0 decipol). In this way the influence of a negative source on the perceived air quality distribution in the space could be checked. In case 3 the added standing person covered 5% of the total surface area of the linoleum (1.9 m^2). The source strength of a cigarette was estimated by taking the source strength of a smoking person.

The computational grid consisted of 35x33x36 = 41580 cells. Circa 6000 iterations were required to solve each case, lasting about 60 CPU-hours on the Silicon Graphics Personal Iris 4D/35 workstation used.

Four different 2-propanone concentrations (2, 5, 10 and 20 decipol) generated by four decipolmeters, called the "milestones", serve as the reference for the panel members. Several unknown decipol levels (2-propanone concentrations) are evaluated several times using the four milestones as a reference. After each evaluation the correct answer is given. During the training the panel members are also exposed to other pollution sources than 2-propanone, comprising several common materials from buildings. (further information concerning training of panels is given in [2]).

For this study a panel of ten subjects was selected and trained to evaluate perceived air quality in decipol.

Procedure

Added pollution sources

For two different situations the perceived air quality distribution in the office space was calculated with WISH3D and evaluated by the trained panel:

1. linoleum on the floor at location A (total surface area: 1.9 m^2) (Figure 1);
2. continuous burning cigarette on the table at location B (Figure 1).

Sensory evaluations

The panel evaluated the air in the selected office space at two different days (from 10.00 to 11.30 hours) at six different locations in the room (a, b, c, d, e, and f in Figure 2). At day 1 the linoleum was present and at day 2 the continuous burning cigarette.

The procedure of evaluation was as follows. The panel of 10 subjects was divided in two groups of 5. One group drove to the building with the selected office and was asked as soon as they stepped out of the car (at 10.00 hours) to evaluate the outdoor air. The group was brought to a waiting room, next to the selected office room, were the milestones were placed. The waiting room had the same outdoor air supply system as the selected room, but no extra pollution sources were present. After the panel had freshened up their memory with the milestones, they were asked one by one to go to the selected office space and make an evaluation of the air at location a. The panel members stayed no longer then 10 seconds in the selected room and then went back to the waiting room to compare their evaluation with the milestones and write their answer on a form. After each panel member had judged the air quality at location a, location b, c, d, e and f were evaluated in the same way. The whole procedure took no longer then half an hour. The next group came at 11.00 hours and followed the same procedure.

To achieve an adsorption/desorption equilibrium the linoleum was added to the room two weeks before the evaluation of the panel. To simulate a smoking person a cigarette was lighted half an hour before the evaluation of the panel started. Every 15 minutes a new cigarette was lighted, but not smoked.

Table 1 Ventilation and temperature conditions of the selected office space

Ventilation conditions

Parameter	value
total primary air supply (Q)	55.5 l/s
. air induction unit 1	20 l/s
. air induction unit 2	20 l/s
. air induction unit 3	15.5 l/s
total secondary air supply:	220.6 l/s
. air induction unit 1	84.2 l/s
. air induction unit 2	84.2 l/s
. air induction unit 3	52.2 l/s
air supply velocity (primary + secondary)	
. air induction unit 1	1.08 m/s
. air induction unit 2	1.08 m/s
. air induction unit 3	0.71 m/s
turbulence intensity	
. air induction unit 1	12 %
. air induction unit 2	12 %
. air induction unit 3	15 %
exhaust . exhaust 1	27.75 l/s
. exhaust 2	27.75 l/s

Temperature conditions

Parameter	value	Parameter	value
total air supply	20°C	wall- corridor	20°C
window	16°C	wall left	19°C
floor	22°C	wall right	20°C
ceiling	19°C	facade	20°C

RESULTS

The sensory evaluations of the trained panel are presented in Table 2 and Figure 4. Velocities and perceived air quality simulations as calculated with the WISH3D programme are presented in Figures 3 and 4.

For comparison of the flow pattern in the isothermal situation (case 1) and the buoyant situation (case 2), Figures 3a and b respectively present the vertical cross section at 0.80 m from the right wall (z=0.80 m) and the vertical cross section at 2.18 m from the window (x=2.18 m). To show the influence on the flow pattern of a person standing on the linoleum in case 3, a vertical cross section is given at 0.80 m from the right (z=0.80 m) wall and at 4.25 m from the window (x=4.25 m) in Figure 3c. The flow pattern as a result of the burning cigarette is given in Figure 3d by the vertical cross sections at 0.80 m from the right wall (z=0.80 m) and at 2.18 m from the window (x=2.18 m) plus the horizontal cross sections at 0.53 m (y=0.53 m, height of burning cigarette) and at 1.00 m from the floor (y=1.00 m, average height of nose of a sitting person).

For comparison of the computed simulations with the sensory evaluations of the panel Figure 4 presents for case 1 to 5 a horizontal cross section at the average height of the nose of a standing panel member (y=1.65 m), for case 4 an extra horizontal cross section at the height of the nose of a sitting panel member (y=1.00 m), for case 1 to 5 a vertical cross section at 0.80 from the right wall (z=0.80 m) and for case 4 an extra vertical cross section at 2.18 m from the window (x=2.18 m).

Table 2 Sensory evaluations of the air quality in the selected office space

location	day 1	day 2
	linoleum at location A	cigarette at location B
	mean vote (stand.dev.)(3)	mean vote (stand.dev.)
	(decipol)	(decipol)
a	7.1 (2.4)	7.7 (5.7)(5)
b	5.6 (2.1)	9.3 (3.9)
c	7.5 (2.5)	10.6 (3.9)
d	8.3 (1.8)	9.6 (4.3)
e	6.1 (3.3)	8.9 (3.7)
f	7.3 (3.2)	9.5 (4.5)
average (C_i)	7.0 (1)	9.3 (2)
standard error(4)	0.81 (n=10)	1.28 (n=10)
outdoors (C_o)	.	2.9 (1.9)

(1): total pollution load (incl.room, furniture) = Q x (C_i - C_o)/10 = 55.5 x(7.0-2.9)/10 = 22.7 olf
(2): total pollution load (incl.room, furniture) = Q x (C_i - C_o)/10 = 55.5 x(9.3-2.9)/10 = 35.5 olf
(1 burning cigarette = circa 25 olf, so empty room incl. furniture had a pollution load of 10.5 olf and the linoleum a source strength of 12.2 olf)
(3): standard deviation = $s = \sqrt{\sum(\bar{x}-x_p)^2/n}$ with: $\bar{x} = x_p/n$ and n=number of panel members = 10
(4): standard error = $\bar{s}/\sqrt{n}$ with: $\bar{s}$ = mean standard deviation
(5): stand.dev. is high; this evaluation will not be considered in the further analysis; the reason for this high standard deviation could be that location a is rather close near the door opening.

DISCUSSION

Air flow simulations

The computations under isothermal (case 1) and buoyant (case 2) conditions result in different flow patterns near the right wall, the table and the floor. (Figures 3a and 3b). The supply jet (20°C) along the window is decreased by the cold window (16°C), which results in reduced velocities nearby the ceiling. Due to the higher temperature of the right wall (21°C) the downward flow along 3/4 of this wall is changed into an upward direction. As a result the flow direction above the table is turned from left to right. Due to the warm floor (22°C) the flow along the floor is brought upward between the table and the two-seat. The general flow pattern, as well as the above mentioned flow characteristics, were also observed during the soap-bubble and smoke tests.

The influence of a standing person on the flow pattern is demonstrated in case 3 (Figure 3c). The body acts as a heat source and causes a rising convection layer around its surface. In order to simulate this layer more accurately, a finer computational grid near the body is required.

The influence of the heat generated by the cigarette (case 4) is shown in Figure 3d. The velocities near the table are slightly increased.

Sensory evaluations

In previous studies with trained panels it was found that a panel of 8 persons has a standard error of 1.1 decipol for evaluations of the perceived air quality in a space [2]. The trained panel of 10 panel members which was used in this study had a standard error of 0.8 decipol during the first evaluation day and a standard error of 1.3 decipol on the second evaluation day, which results in an average standard error of 1.1 decipol.

Comparison sensory evaluations and computer simulations

For each simulated case the calculated perceived air quality distribution is shown in respectively Figures 4a to 4e. The sensory evaluations of the trained panel are presented in these figures as well.

From the air flow pattern simulations in case 1 and 2 followed that the temperature distributions have a great influence on the air flow pattern. Therefore case 1 did not seem to be of importance to consider in the comparison.

From the air flow pattern simulations in case 2 and 3 followed that a person (a panel member) standing on a specific place has a great influence on the local air flow pattern of that place. Since not for each evaluated location in the space the influence of a standing panel member has been taken into consideration, the comparison between the calculated and evaluated decipol values is difficult.

For cases 2, 3, 4 and 5, the calculated decipol values and the sensory decipol values are presented in Table 3 for each evaluated location in the office space (a to f in Figure 2).

The computer simulations show in all cases, except case 5, a rather uniform perceived air quality distribution, while the sensory evaluations indicate a variation. This variation reaches 2.7 decipol (location b and d) on day 1 (linoleum) and 1.7 decipol (location c and e) on day 2 (cigarette).

Case 5 indicates that the introduction of a negative source can influence the decipol levels. The variation in calculated decipol levels increases (from 0.7 in case 3 to 2.2 decipol in case 5).

Both the computer simulation and the sensory evaluation at the evaluated situation of day 1 (linoleum) result in the highest decipol level at location d, which can partly be explained by the computational pollutant transportation from the linoleum along the right wall into the room. This indicates that when a major source of pollution is present in a space, the perceived air quality distribution can vary in that space. At the evaluated situation of the second day (cigarette) the perceived air quality distribution of the computer simulation was rather uniform, while the sensory evaluation showed some variation (1.7 decipol). Considering the standard error of the panel (1.3 decipol) on that day, this variation seems less important. It should be mentioned however that the cigarette pollutants are transported with the rising plume towards the right wall and the ceiling, and all sensory evaluations were made outside this plume. However, it seems that the sensory evaluations indicate on both days that there is a higher variation in decipol levels then the computer simulation predicts.

Cases 2, 3 and 5 respectively show that boundary conditions taking into account in the computer simulation such as temperature variations, standing persons and adsorption effects, influence the perceived air quality distribution, but do not completely explain the differences with the results of the sensory evaluations. Standing persons and opening of the door merely have a local effect, while temperature differences have an overall effect. A standing person in the room may cause convection of pollutants from the floor along the body, resulting in a higher perceived air quality. This effect however, did not appear in the computation, which could be due to the coarse computational grid near the body.

The computer simulation programme is based on convection and (turbulence) diffusion. Air adsorption and density differences between pollutants and air are not taken into account. In the computer simulation it is assumed that air as it is perceived by a person behaves as a neutral gas. Furthermore is assumed that the tested space without any added source (linoleum or cigarette) had a uniform emission profile. An evaluation of the tested space without any added source could result in a different profile.

In case 5 the adsorption of the induction system was assumed to be 50% of the emitted linoleum pollution. The results show that local adsorption can result in larger perceived air quality differences all over the space. In all other cases the adsorption and desorption effects of the floor, ceiling, walls and furniture were not taken into account. Case 5 indicates that in future studies adsorption and desorption effects should be considered.

The sensory evaluations of the trained panel resulted in non-uniform distributions of the perceived air quality. Taken the standard error of the panel into account, the variations are still significant. The computer simulations do not confirm these results completely, which might be caused by the assumed boundary conditions. It can be concluded however, that the location of a panel member in a space can influence the evaluation. When evaluations of spaces are made it is therefore important to consider the location of the panel member and the number of locations that the panel member has to evaluate. Computer simulations might be of help to determine these locations, when the boundary conditions are correctly formulated and the transportation of air as it is perceived by a person is similar to the transportation of a neutral gas.

Table 3a Comparison sensory evaluations on day 1 (added source: linoleum) and computer simulations case 2, 3 and 5

location	sensory evaluation	computer simulation		
	(decipol)	case 2	case 3	case 5
		(decipol)	(decipol)	(decipol)
a	7.1	7.5	7.3	7.6
b	5.6	7.5	7.4	7.6
c	7.5	7.2	7.1	6.8
d	8.3	7.7	7.9	9.0
e	6.1	7.4	7.3	7.5
f	7.3	7.3	7.1	6.9

Table 3b Comparison sensory evaluations on day 2 (added source: cigarette) and computer simulations of case 4

location	sensory evaluation	computer simulation case 4
	(decipol)	(decipol)
a	.	10.1
b	9.3	10.3
c	10.6	9.9
d	9.6	10.0
e	8.9	10.2
f	9.5	10.0

CONCLUSIONS

Sensory evaluations of a trained panel resulted in non-uniform distributions of the perceived air quality. Computer simulations of the perceived air quality did not confirm these results completely, which might have been caused by the assumed boundary conditions and the assumption that air as it is perceived by a person is transported in the same way as a neutral gas.

The air flow pattern predicted by the computer programme WISH3D seemed to agree with the general air flow observed, verified by smoke- and soap-bubble tests.

The computer simulations of several cases indicate that boundary conditions such as temperature variations, standing persons and adsorption effects influence the predicted perceived air quality distribution.

Local adsorption can result in larger perceived air quality differences all over the space. In future studies adsorption and desorption effects should be considered.

The location of a panel member can be of importance when the air quality of a space is evaluated.

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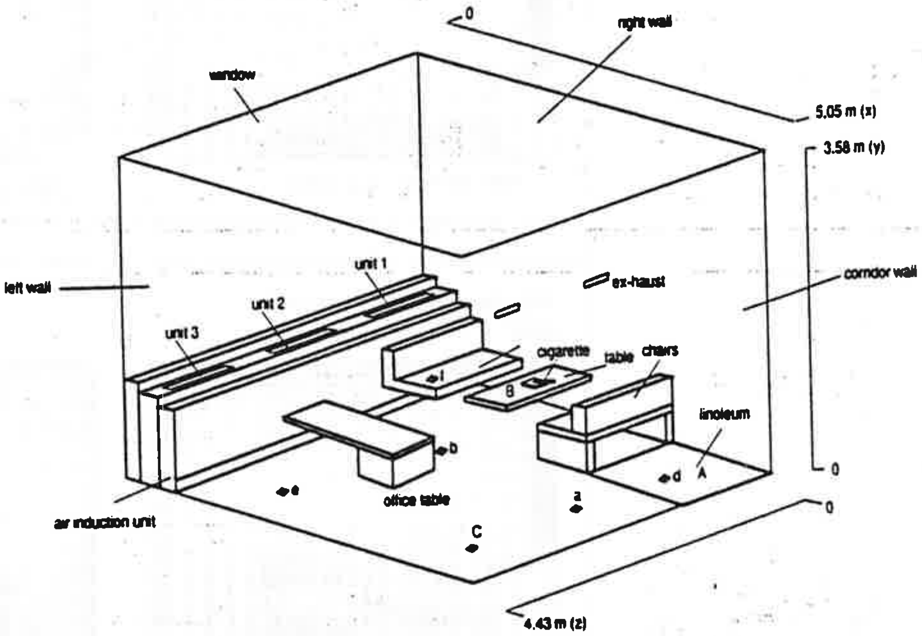


Figure 1 Tested office space

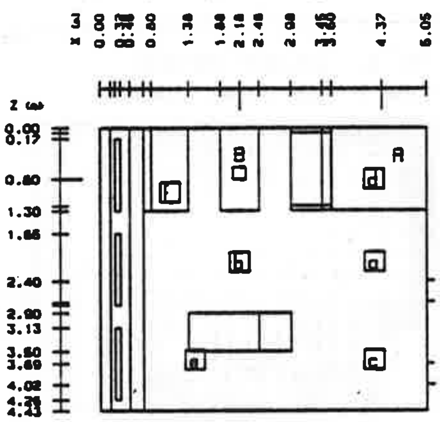


Figure 2 Sensory evaluation locations (a, b, c, d, e and f) and locations of added sources (A and B) in the tested room.

FIG. 3a : VELOCITY PATTERN
CASE 1 : ISOT. LINO

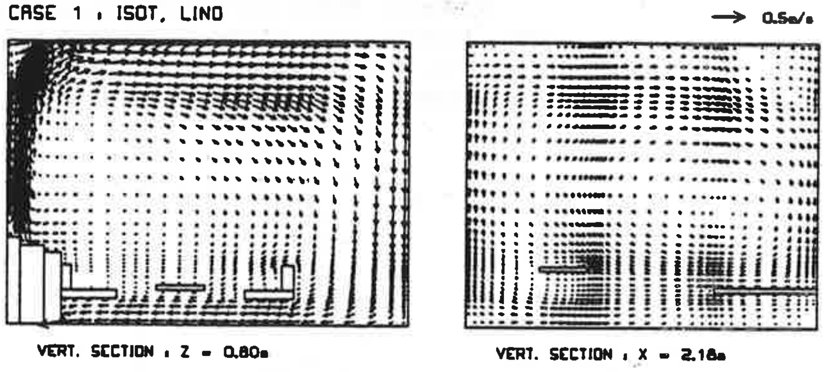


FIG. 3b : VELOCITY PATTERN
CASE 2 : BUOY. LINO

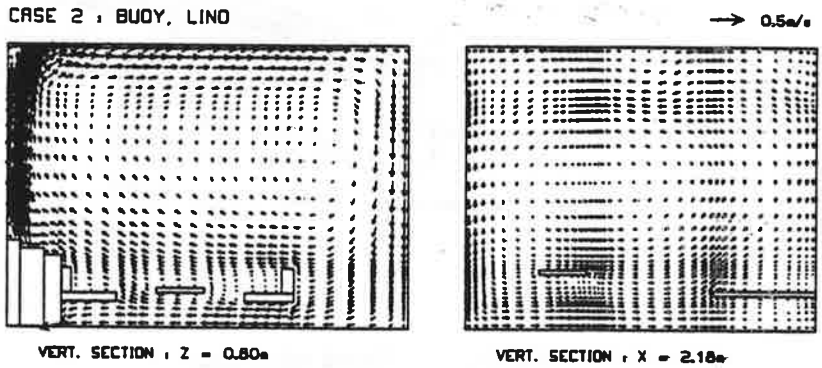
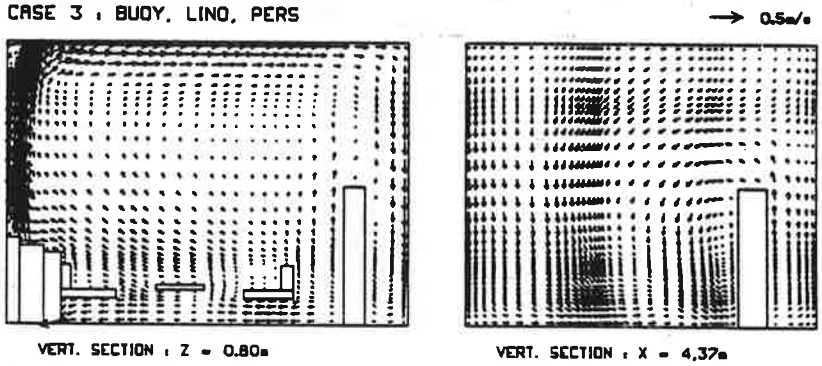


FIG. 3c : VELOCITY PATTERN
CASE 3 : BUOY. LINO. PERS



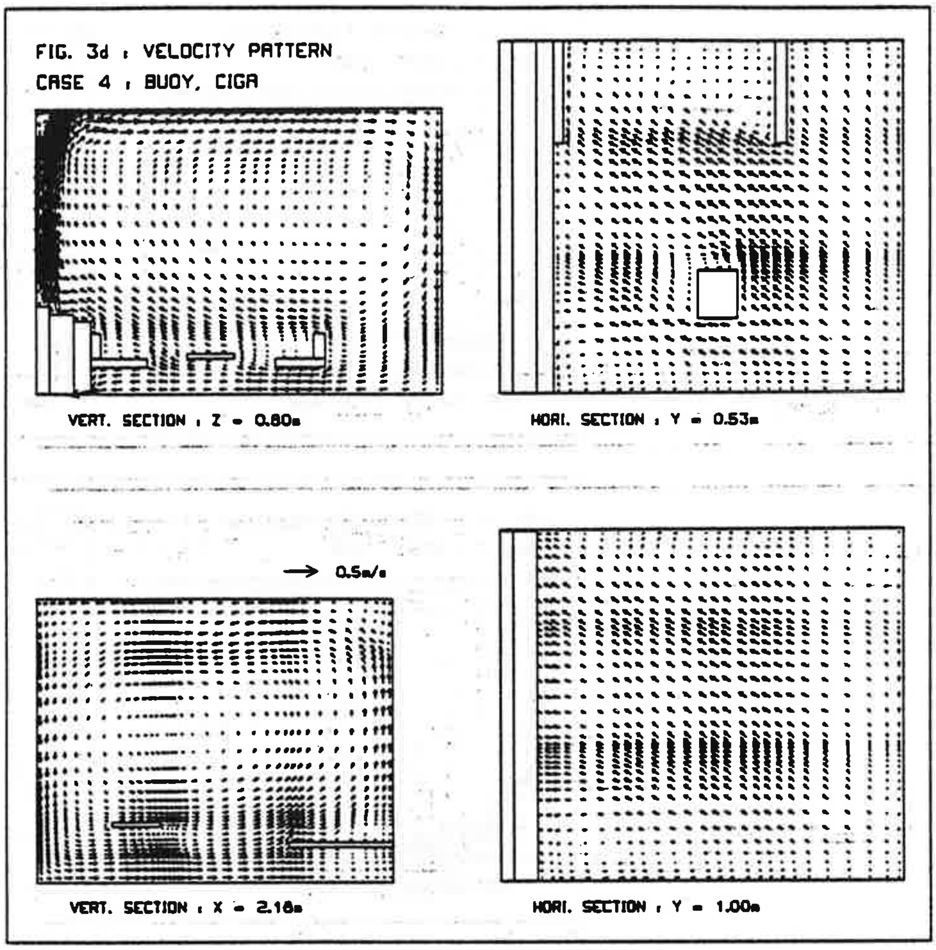


Figure 3 Simulated air flow patterns. The air velocities are presented by vectors projected on the selected sections.

Figure 4 Distribution of perceived air quality
The computed distributions are presented by contours of equal decipol values. The sensory evaluations are given in rectangular frames. The following contours are presented.
Case 1: 7.0, 7.1, 7.2, 7.5, 8.0, 9.0, 10.0;
Case 2, 3 and 5: 6.0, 6.5, 7.0, 7.2, 7.4, 7.6, 7.8, 8.0, 9.0, 10.0;
Case 4: 8.0, 8.5, 9.0, 9.2, 9.4, 9.6, 9.8, 10.0, 11.0, 20.0, 30.0.

Abbrev.: isot = isothermal, buoy = buoyant, lino = linoleum, pers = person, ciga = cigarette, neg = negative source

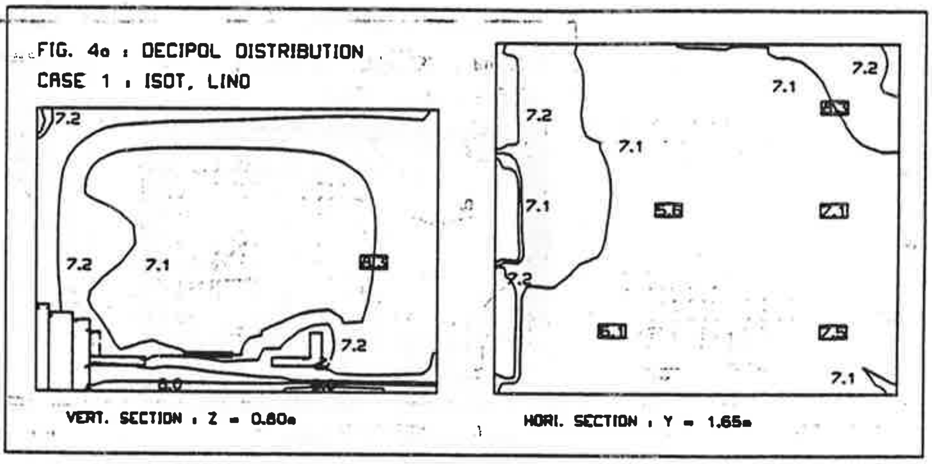


FIG. 4a : DECIPOL DISTRIBUTION
CASE 1 : ISOT, LINO

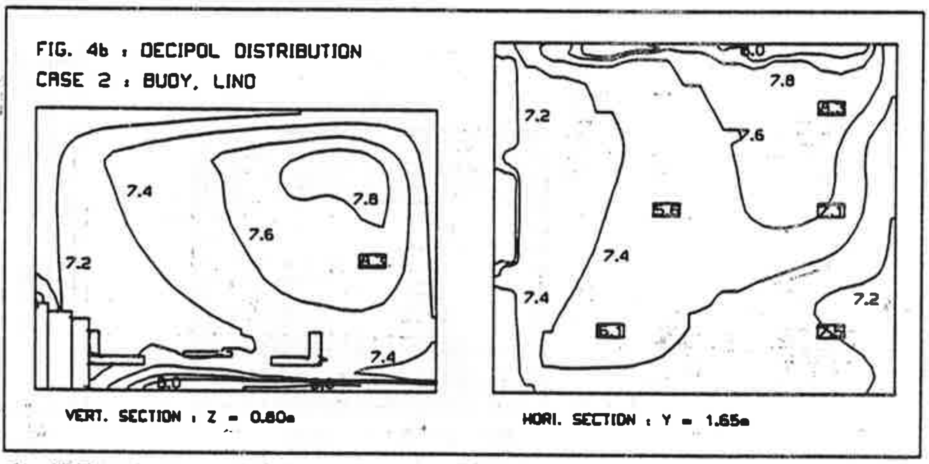


FIG. 4b : DECIPOL DISTRIBUTION
CASE 2 : BUOY, LINO

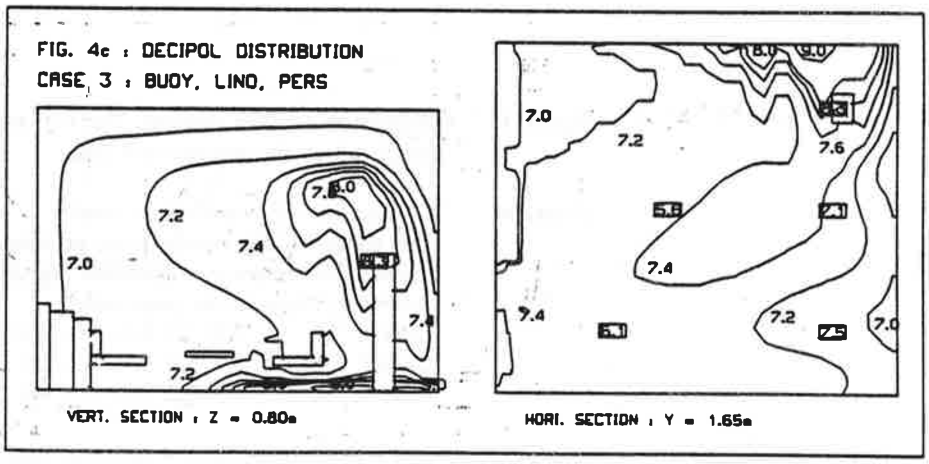


FIG. 4c : DECIPOL DISTRIBUTION
CASE 3 : BUOY, LINO, PERS

FIG. 4d : DECIPOL DISTRIBUTION
CASE 4 : BUOY, CIGA

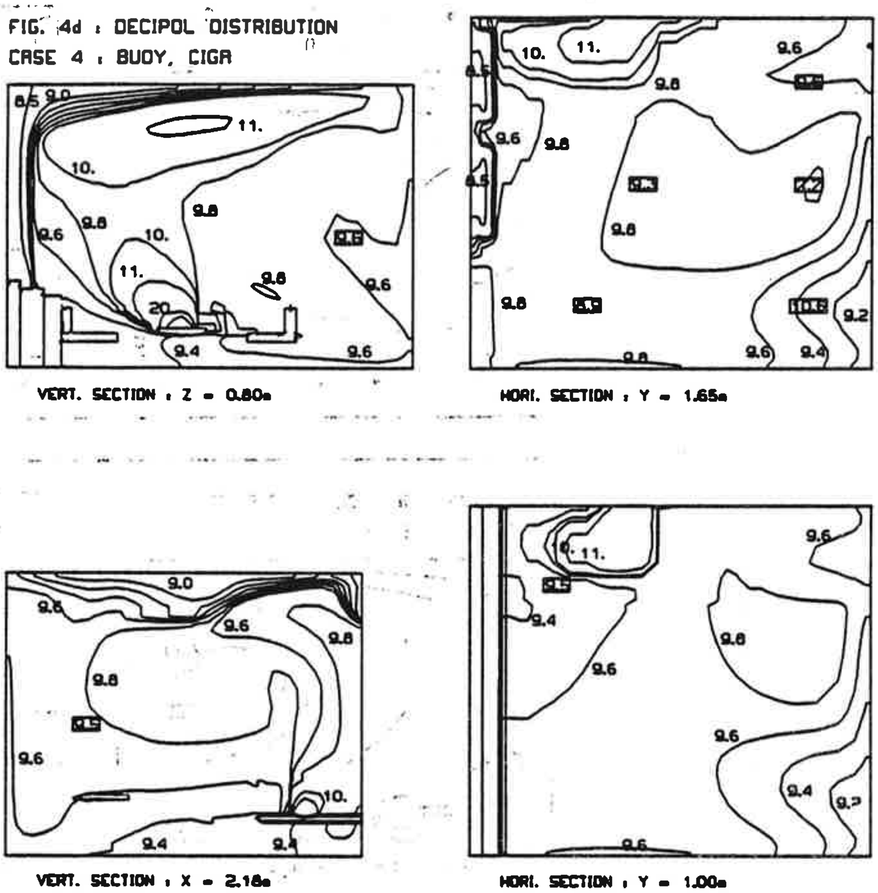


FIG. 4e : DECIPOL DISTRIBUTION
CASE 5 : BUOY, LINO, PERS, NEG