revised March 19, 1990

Dispersion pattern of carbon dioxide from human sources - a factor to consider in demand controlled ventilation systems.

H Stymne, A Mellin and M Sandberg

The National Swedish Institute for Building Research
Box 785
S-801 29 GÄVLE
Sweden

Paper presented at the 5th International Conference on Indoor Air Quality and Climate - INDOOR AIR '90, Toronto Canada 29 July - 3 August 1990.

/

Dispersion pattern of carbon dioxide from human sources – a factor to consider in demand controlled ventilation systems

Hans Stymne, Anders Mellin and Mats Sandberg

The National Swedish Institute for Building Research
P.O. Box 785
S-801 29 GÄVLE
Sweden

Carbon dioxide from (simulated) people distributes fairly evenly in a closed office room, but can show an irregular height distribution when the door to a connecting space is open. The distribution and room to room transfer of carbon dioxide is evaluated in a 4-room test building and is discussed in terms of its implication for CO_2-controlled ventilation.

Background

In the present work the dispersion pattern of carbon dioxide (CO_2) (from simulated people) is investigated in an indoor test building. The goal is to achieve useful general information regarding the distribution of carbon dioxide from human sources which is necessary in order to be able to design an optimal CO_2 controlled ventilation system. Carbon dioxide concentration has been widely accepted as a useful control variable in buildings with a fluctuating personal load.

Generally the aim of a demand controlled ventilation system is to keep the total ventilation flow rate to a building at the minimum required in order to meet with some air quality requirement for the people who are using it. In a well designed system an unnecessarily high ventilation rate is avoided, thus saving energy.

Some of the factors which must be considered when designing a CO_2-controlled regulation system in a multi-room environment, and the ventilation concepts that describe these, factors are

1. The transfer of carbon dioxide from the sources to different locations - **the transfer probabilities** (P_{ij})
2. The expected equilibrium concentration at a location - **the purging flow rate** U_i
3. The rate constant for approaching equilibrium from a non-equilibrium state - **the local mean ages of air** τ_i
4. Concentration fluctuations- **amplitude and frequency** of variations.

   A short interpretation of the first two concepts is given below. A more detailed treatment is given in references (1, 2).

1. The **transfer probability** of a contaminant is the ratio between the rate at which a contaminant is transferred to a location **i** and that with which it is produced at a location **j**. Thus the total rate of transfer of a contaminant to a space **i** can be expressed as $\dot{r} = \sum_j P_{ij} \cdot \dot{m}_j$ where $\dot{m}_j$ is the rate of contaminant production in space **j**

2. The **purging flow** rate of a space **i** is the equivalent fresh air flow rate which transports the transferred contaminant away from that space. Thus the equilibrium concentration in space **i** will be $c_i^{eq} = \frac{\dot{r}}{U}$. The purging flow rate of a space **i** can be calculated from the transfer probabilities of air from several fresh air inlets **j**, each with a fresh air flow rate of q_j: $U_i = \sum_j P_{ij} q_j$

Test building and experimental layout

This investigation is carried out in an indoor test building of 175 m^3 (see Fig. 1). The building contains four rooms connected to a common corridor via doorways. There is a balanced ventilation system with air inlets in the ceiling of each room. The air stream from an inlet port is directed along the ceiling towards the middle of the room and away from the doorway. Exhaust air is extracted from the corridor. Overflow of air from the rooms is made possible by means of openings (grills) above the doors. This type of ventilation system is not uncommon in offices in Sweden.

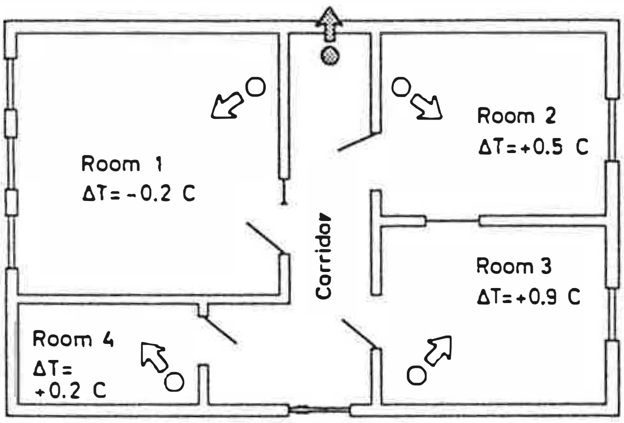

Figure 1
Plan of the test building. The south wall is an external wall of the laboratory hall, while all other walls are inside the laboratory hall. The ΔT-figures denote the difference between the mean room temperature and the temperature in the corridor when the room is a source room

The fractions of the total ventilation flow rate into the different rooms are kept fixed at 37.5%, 25%, 25% and 12.5% to room 1, 2, 3 and 4 respectively throughout the whole experiment. The total flow rate to the building is changed between two values (120 m^3/h and 240 m^3/h).

People are simulated by metallic bodies which are heated from the inside by a 100 W bulb. Each simulated person continuously emits approximately 25 l of carbon dioxide per hour mixed with 0.6 m^3 pre-warmed air. The total flow rate of carbon dioxide and air is measured with a rotameter. The air is sampled at 19 different points inside the building and at one point outside of the building. Analysis of carbon dioxide and nitrous oxide concentration is performed by a non-diffractive infra-red photometer (Binos).

Carbon dioxide is spread in one room at a time via the simulated persons. The chosen loads are three persons in room 1, two in rooms 2 and 3, and one in room 4. Simultaneously with the emission of carbon dioxide, dynamically passive N_2O/He tracer gas mixture is spread at a height of 30 cm above the floor level and 1 m away from the "persons". The experiments are carried out both with open doors and closed doors. Conventional tracer decay experiments and constant concentration measurements are also carried out.

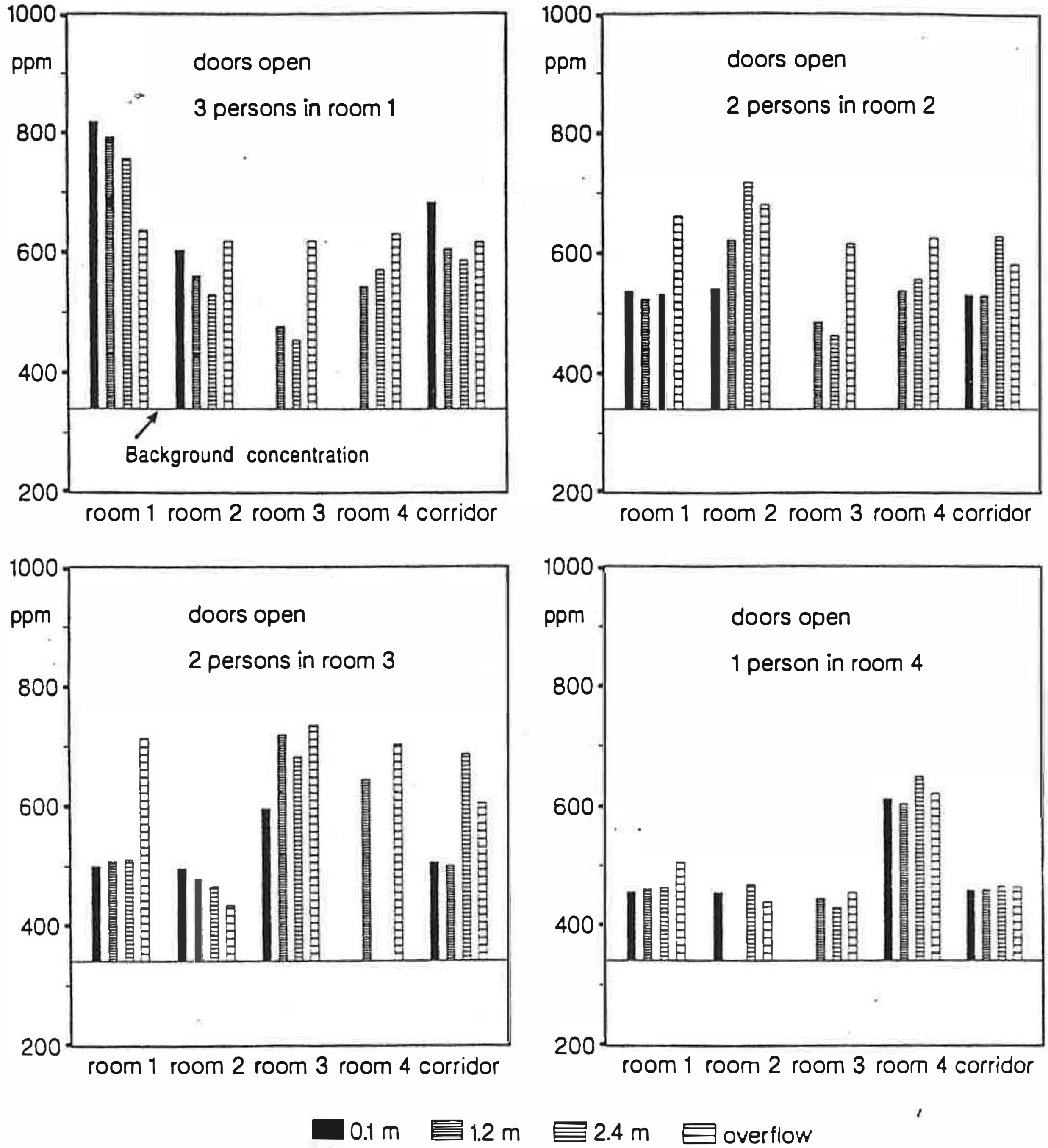

Figure 2 Bar graph showing the time averaged concentration of CO_2 (ppm) at different locations in the 4-room office shown in Fig. 1. From left to right, the bars in a group represent the concentrations at 0.1 m, 1.2 m, and 2.4 m above the floor in the middle of the room. The last bar in a group represents the concentration in the overflow grill above the door, except in the corridor group, where it represents the concentration in the common extract in the corridor. All doors are open and one room is occupied by the indicated number of simulated persons. The nominal total ventilation flow rate is 240 m^3/h. The bars are extended above the atmospheric background concentration (340 ppm).

Results and discussion

Closed doors

The measurements show that when the door to an occupied office room is closed then a relatively good mixing is achieved within the room, with only a slight tendency for higher concentration of carbon dioxide at the ceiling level (max difference 10% of the room average $\Delta(CO_2)$). The concentration fluctuations are small. This means that the question of where to place the sensor is not a critical one. A tendency for a higher CO_2 concentration at the ceiling level in occupied rooms is a common observation. See Homma (3) for a classroom investigation and a literature review.

Open doors

When the doors are open the differences in concentration of carbon dioxide at different heights are more pronounced, not only in a source room, but also in unoccupied rooms connected to the corridor by open doors. Concentration differences as large as 75% of the room average $\Delta(CO_2)$ have been observed (room 2 as a source room at high flow rate). Generally there is no preferred direction of concentration increase. Referring to Fig. 2, the highest concentration can appear at the floor level (room 1), the ceiling level (room 2), or the mid level (room 3).

A comparison between the distribution pattern of carbon dioxide and the simultaneously emitted nitrous oxide tracer gas shows great similarities. Accordingly, it is not the fact that the carbon dioxide is released in the air convection current around the heated bodies that determines the distribution pattern. The reason for the uneven distribution is the large air exchange through the open doorways and its interaction with other air movements set up by the convection currents around the heated bodies, the radiators, cold external walls, and the jet from the inlet duct.

The air flow pattern is unstable, as can be seen from the relatively large standard deviation of the concentrations (10-20% of $\Delta(CO_2)$ in source rooms). This instability is dramatically illustrated in Fig. 3 which shows the observed carbon dioxide concentration in the different rooms when room 1 is the source room. The periodical oscillation was shown to be correlated with the on/off regulation of the radiators in room 1. Unlike the other rooms, room 1 had a large external wall with three windows.

The transport of air between a room and the corridor is primarily due to the air exchange through the door opening which is driven by air temperature differences.

The approximate air temperature differences between the rooms and the corridor are given (valid when the room acts as source rooms) in the plan of the building (Fig. 1). Much of the observations regarding concentration differences in a room can successfully be explained in terms of such temperature differences. For example, room 2 has a higher mean temperature than the corridor. Therefore air from the corridor enters at the floor level, giving a better dilution and a lower concentration at this level than at the ceiling level. In contrast to this, room 1 is cooler than the corridor and will show a reverse concentration gradient.

The room to room transfer of contaminants and ventilation air can best be quantified in terms of the concepts transfer probabilities and purging flow rates. Though the transfer probabilities and purging flow rates are dependent on air temperature differences and ventilation air flow rate and distribution, it is of interest to know the magnitude of these factors as determined from tracer gas experiments in the present case.

Table 1 shows the experimentally determined transfer probabilities, purging flow rates, and mean ages of air in the different rooms with their doors open at two different nominal total flow rates. Values at the low flow rate (120 m^3/h) are given within brackets, while those valid for 240 m^3/h are given without brackets.

Table 1 Transfer probability matrix (P_{ij}), purging flow rates (U) and air mean ages (τ). Figures within brackets refer to a nominal total flow rate of 120 m^3/h, while figures without brackets refer to 240 m^3/h

	Source room 1	2	3	4	Purging flow rate m^3/h	Mean age of air h
Room 1	1 (1)	0.5 (0.7)	0.3 (0.5)	0.5 (0.7)	145 (100)	0.69 (1.31)
Room 2	0.5 (0.7)	1 (1)	0.3 (0.4)	0.6 (0.8)	141 (93)	0.74 (1.43)
Room 3	0.3 (0.6)	0.3 (0.7)	1 (1)	0.4 (0.6)	152 (108)	0.75 (1.47)
Room 4	0.2 (0.3)	0.2 (0.4)	0.3 (0.4)	1 (1)	57 (53)	0.74 (1.38)

An example of how to use the table may be illustrative. A transfer probability of P_{12} = 0.5 from room 2 to room 1 means that 2 persons in room 2 contribute to the equivalent of carbon dioxide of 1 person (25 l/h) in room 1. However, the purging flow rate of room 1 is 145 m^3/h, so if the 2 persons in room 2 are the only ones in the office then the $\Delta(CO_2)$-concentration in room 1 will be $25 \cdot 10^{-3}/145 = 172$ ppm, that is a CO_2 concentration of 172 + 340 = 512 ppm. Note that because the room to room transfer is mainly due to air exchange through the door openings, the transfer probabilities will increase as the mean age of the contaminants increases, i.e. as the total ventilation flow rate decreases.

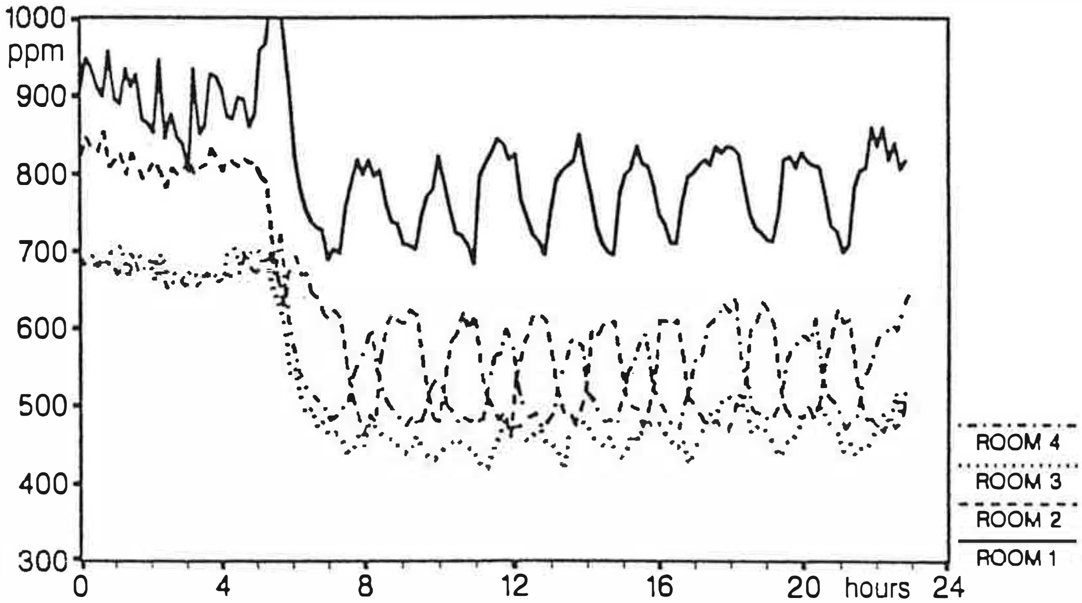

Figure 3 Concentration histories at 1.2 m height in the four rooms, when room 1 is the source room with three simulated persons. The total flow rate is 120 m^3/h during the first 5 hours, thereafter 240 m^3/h. The doors are open

6

Conclusion

The results and the conclusions below are valid only for the special type of ventilation system investigated here, but much of the reasoning is also useful for other systems, where short circuiting in the ventilation system is not a problem.

If a room is going to be ventilated by demand control then the position of the sensor is not critical if the doors to connecting spaces are normally closed.

However, if the room is connected to surrounding spaces by open doors then large differences and instabilities in the carbon dioxide concentration may occur, which implies problems both with regard to the positioning of the sensor and the possibility of achieving a stable ventilation control. It is not recommended to locate the sensor in an overflow duct. A sensor should preferably be placed at a mid-height in a room, and away from doorways, radiators, windows, people and air inlet devices. This requirement may not be possible to fulfill in practice. The regulation of ventilation air to a room must be made with a large time constant in order not to react to fluctuations.

A regulation system for an office building must function satisfactory regardless of whether the doors to individual rooms are open or closed. In every room there should therefore be a measuring point which controls the distribution of ventilation air to the room. However, the total flow rate to the system can be governed by a sensor in the combined air extract.

Aknowledgement

This work was initiated by the IEA annex 18 "Energy Conservations in Buildings and Community Systems - Demand Controlled Ventilating Systems", and is partly financed by the Swedish Council for Building Research through grant no BFR: 880614-8, which is here gratefully acknowledged.

References

1. Sandberg M (1984) The Multichamber Theory Reconsidered from the View Point of Air Quality studies. Bldg. Envir. 19, 221-233.

2. Sandberg M, Stymne H (1989) The Constant Tracer Flow Technique. Bldg. Envir. 24, 209.

3. Homma H (1979) The Effects of Free Convection around a Human Body on Indoor Environment. Proceedings from CIB symposium on energy conservation i the built environment, Copenhagen May 1979, vol 4, p 287