Air change rate and indoor air quality in bedrooms of well tightened residential buildings

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Measurements of air change rates, carbon dioxide concentrations, room air temperatures and relative room air humidities in bedrooms of five well tightened dwellings were carried out in October 1989. With the results of the measurements and also based on simulation calculations, recommendations for an optimal window opening behaviour in bedrooms with the intention of saving energy and of providing sufficient indoor air quality were made. The measured air change rates varied between 0.01 and 12.3 h^{-1}, corresponding to an air supply of 0.16 to 320 $m^3h^{-1}pers^{-1}$ depending on inhabitant behaviour. The measured carbon dioxide concentrations at the end of the night varied between 515 and 4286 ppm. The average room air temperatures ranged from 20.1°C to 22.3°C and the relative humidities from 42.4 % to 64.7 %.

INTRODUCTION

Several studies have been carried out in recent years regarding air change rates, indoor air quality and window opening habits also in bedrooms of well tightened residential buildings (1,2,3). These studies revealed that in well tightened residential buildings with natural ventilation the air change rate depends above all on user ventilation behaviour. Again the window opening habits depend on several external (outdoor climate, noise level etc.) and internal (type of room, habits etc.) factors. Depending on these factors, 60 - 80 % of the inhabitants sleep with their bedroom window closed. In these cases, the air change rate can be very low. The aim of this study was to get informations about the influence of user ventilation habits in bedrooms of well tightened dwellings on indoor climate generally and on indoor air quality specifically. Moreover, based on the results of the measurements and on simulation calculations, recommendations for optimal bedroom ventilation behaviour with the intention of saving energy and of providing sufficient indoor air quality should be made.

MATERIAL AND METHODS

The measurements were carried out in five dwellings of two specially energy saving designed apartment buildings in Préverenges near Lausanne in Switzerland. These buildings were constructed in the years 1986 - 1988. Since then, they have been the object of intensive studies by the Laboratory of Solar Energy and Building Physics (LESO) of the Swiss Federal Institute of Technology in Lausanne (4). The following investigations were carried out in October 1989:

- Continuous measurements of air change rate and relative humidity over 12 hours at night. Both were measured with CESAR (Compact Equipment for Survey of Air Renewal) of LESO (5) using the constant concentration method with N_2O as tracer gas. The measured air change rate corresponds to the air exchange between the outdoor air and the bedroom air plus the air exchange between the bedroom air and the air of the rest of the dwelling.
- Continuous measurements of the concentration of carbon dioxide over 12 - 20 hours each night or day respectively. The measurements were carried out with a Leybold Binos 100 two chanel infrared gas analyzer.
- Continuous measurements of room air temperature and outdoor air temperature over 24 hours a day with radiation protected PT-100 resistance thermal detectors.

- Registration of the degree of bedroom window and bedroom door opening during the measurements with a questionnaire. Further the inhabitants were asked to leave the bedroom window and door closed for one night during the measurements, independent of their usual behaviour.
- In each of the five dwellings the measurements were carried out over two or three nights in two bedrooms (main and childrens bedroom). Totally 17 measurements could be carried out.
- Simulation calculations were made with a dilution equation (6), taking account of several different user behaviours.

RESULTS AND DISCUSSION

Air change rate and air supply in the bedrooms:
Table 1 shows the ranges of the measured and time weighted mean values. Also the corresponding room volume and occupancy dependent air supplies for the measured bedrooms are shown. Only 14 measurement could be used because of an equipment defect.

window	door	Numb. of measurements	Air change rate h^{-1}	Mean ± Standard dev. h^{-1}	Air-supply $m^3h^{-1}pers^{-1}$	Mean ± Standard dev. $m^3h^{-1}pers^{-1}$
closed	closed	9	0.01 - 0.31	0.12 ± 0.1	0.16 - 9.3	3.1 ± 2.6
closed	open	1	0.5	-	10.5	-
open	closed	4	3.2 - 12.3*	9.4 ± 3.6	100 - 320*	193 ± 79

Table 1: Measured air change rates and air supplies (from external and internal air) dependent on different inhabitant behaviour (Measurement error: ± 15 %, * measurement error ± 30 %). Measuring time: 12 hours.

With closed bedroom windows and doors the measured air change rates were the lowest. In five cases the air change rate was below 0.1 h^{-1}. With opened bedroom windows and closed doors the measured air change rates were very high. These results coincide well with the results of measurements made in the same dwellings during the heating period 1988/89 (4).

Carbon dioxide concentration in the bedrooms:
Table 2 shows the measured carbon dioxide concentrations dependent on user behaviour and time of room occupation. The highest concentrations of carbon dioxide at the end of the night were measured when the bedroom doors and windows where closed all night long. Opening the bedroom door with closed window resulted in a lower concentration at the end of the night. The lowest values were measured with opened windows.

window	door	Numb. of measu- rements	Numb. of persons	CO_2 Median ppm	CO_2 Maximum ppm	CO_2 Increase ppm	Time of- room occ. h:min	CO_2 Increase ppm/min
closed	closed	4	2	999-2934	1182-4286	789-3364	7:20-11:40	1.47-7.64
closed	closed	5	1	740-1352	828-2084	196-1399	9:45-13:00	0.25-2.39
closed	open	1	2	986	1318	413	9:00	0.76
ajar	closed	1	2	760	1210	835	9:30	1.46
ajar	closed	1	1	820	909	543	11:10	0.80
open	closed	2	2	519	615- 718	219- 331	8:00	0.45-0.69
open	closed	3	1	419- 542	515- 644	128-272	7:30- 9:30	0.24-0.47

Table 2: Measured carbon dioxide concentrations (Median, maximum, increase during the time of room occupation and increase per time unit) dependent on user behaviour and time of room occupation (Measurement error: ± 5 %).

Figure 1 shows the distribution of the measured average increase of the carbon dioxide concentrations per minute during the night dependent on different inhabitant behaviour.

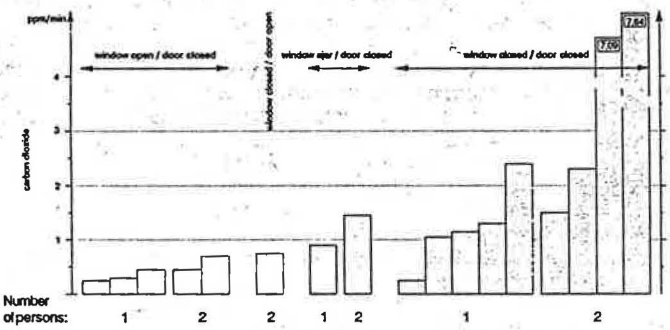


Figure 1: Distribution of the average increase of the carbon dioxide concentrations per minute during the night dependent on different inhabitant behaviour and occupancy.

The following statements can be made regarding the average increase of carbon dioxide concentration per time unit (Table 2, Figure 1): The increase per time unit is the highest with closed windows and doors. Leaving the windows ajar is better than leaving the windows closed. Opening the bedroom door with closed windows is better than leaving the windows ajar. The best for indoor air quality is to open the windows widely.

Figure 2 shows the difference between the carbon dioxide concentrations during the night, dependent on whether the window was closed or opened.

With closed window the concentration rose continuosly until at eight o'clock in the morning the bedroom door or window was opened. With opened window during the night the concentration rested at 500 - 600 ppm.

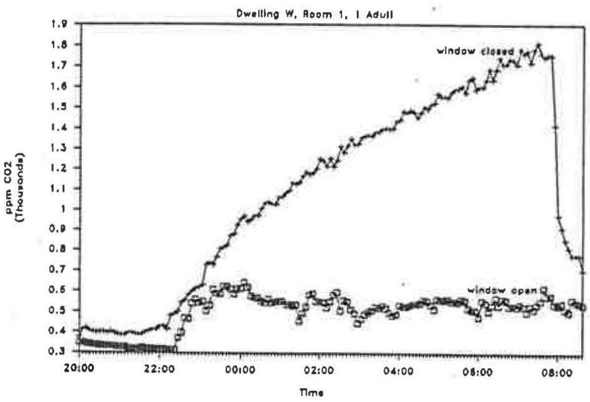
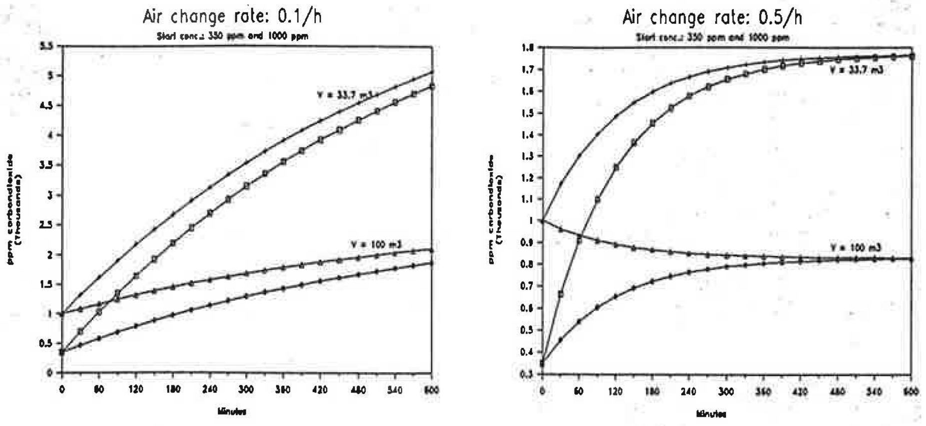


Figure 2: Concentration of carbon dioxide during the night in a bedroom occupied by one adult.

Simulation calculations:
With the dilution equation for gases (6) several simulation calculations have been carried out. In a first phase the results of the measurements made in Préverenges were calculated over again to check the equation and the other input data. In a second phase simulation calculations were carried out. Together with the measurements these form the basis for making recommendations about optimal ventilation behaviour. The following input data and assumptions were used to do the simulation calculations of the second phase: Occupation of the bedroom with two adult persons producing together 24 liters of carbon dioxide per hour. For the bedroom volume the average volume of the bedrooms in Préverenges (33.7 m^3) was taken. To simulate the opened bedroom door a dwelling volume of 100 m^3 was assumed (bedroom plus living room volume). The calculations have been made for an assumed time of room occupation of 10 hours. The carbon dioxide concentration of the incoming air was assumed to be 350 ppm. Perfect mixing of the room air was implied. The simulation calculations were made for air change rates of 0.01 h^{-1}, 0.1 h^{-1}, 0.5 h^{-1} and 1 h^{-1}. For each air change rate a calculation was made for four times changing the room volumes, and changing the concentration levels at the beginning of the calculation to simulate whether the room had been aired before or not. Figures 3 and 4 show the results of the simulation calculations for an air change rate of 0.1 h^{-1} and 0.5 h^{-1}.

The following statements can be made from the results of the simulation calculations:
1) Bedroom door closed (V = 33.7 m^3):
a) Start concentration 350 ppm: With an air change rate of less than 0.5 h^{-1}, the carbon dioxide concentration passes rapidly over 1500 ppm. With an air change rate at about 0.5 h^{-1}, the carbon dioxide concentration reaches a concentration of about 1700 ppm after 10 hours sleeping.
b) Start concentration 1000 ppm: With an air change rate of less than 0.5 h^{-1}, the carbon dioxide concentration passes rapidly over 1500 ppm and is at all times about 600 ppm higher than if the start concentration would have been 350 ppm. With an air change rate at about 0.5 h^{-1}, the difference between the lapses of the two curves starting from 350 ppm and 1000 ppm gets relatively rapid less with time. After four hours the difference is less than 100 ppm.
2) Bedroom door opened (V = 100 m^3):
a) Start concentration 350 ppm: With an air change rate of about 0.1 h^{-1}, the carbon dioxide concentration reaches a level of slightly more than 1500 ppm. This is the effect of the larger room volume for dilution which is available. With an air change rate of about 0.5 h^{-1}, the concentration remains clearly below 1500 ppm.

b) Start concentration 1000 ppm: With an air change rate of about 0.1 h^{-1}, the carbon dioxide concentration will reach a level of about 1500 - 2000 ppm. With an air change rate of equal or more than 0.5 h^{-1}, the concentration of carbon dioxide is rarefied with time. The reason for this rarefaction is that through the higher room volume the air supply (in $m^3h^{-1}pers^{-1}$) becomes higher although the air change rate (in h^{-1}) remains at the same level.



Figures 3/4: Influence of room volume and starting concentration to the time sequence of the carbon dioxide concentration with a room occupation of two persons and an air change rate of 0.1 h^{-1} and 0.5 h^{-1}.

Room air temperature and relative humidity:
With closed windows the range of the measured bedroom air mean temperatures was between 20.1°C and 22.3°C. With opened windows the measured range was between 20.1°C and 20.7°C. At the same time the mean values of outdoor air temperature were from 6.0°C to 9.8°C. With closed windows the average values of room air temperatures were about 0.6°C higher than with opened windows, although the outdoor temperatures during the measurements with closed windows were about 0.6°C lower on average.
The mean values of the measurements of the relative humidity were between 46.6 % and 64.7 % with closed and between 42.4 % and 45.3 % with opened windows. In both cases the mean values of outdoor air humidity were 76.5 %. With closed windows the average of the mean values of relative humidity were about 10 % higher than with opened windows. In two cases the measured relative humidity was higher than 60 %. The measured increases of the relative humidity during the night were between 1.6 % and 9.3 %.

CONCLUSIONS AND RECOMMENDATIONS

Regarded from the viewpoint of hygiene the air change rates in the bedrooms of the appartement buildings in Préverenges were too low when the windows and doors were closed. Above all, in the parents' bedroom, but also in the bedrooms occupied by only one person, the carbon dioxide concentration mostly exceeded 1000 - 1500 ppm. A carbon dioxide concentration of 1000 - 1500 ppm is regarded in several standards as the upper limit for comfort. A minimum ventilation rate between 12 - 15 $m^3h^{-1}pers^{-1}$ (for 1500 ppm) and 20 - 30 $m^3h^{-1}pers^{-1}$ (for 1000 ppm) is required to stay below the comfort limit. Recent investigations showed that sleeping in well sealed rooms with closed windows can cause the typical sick building symptoms such as headache, sore throat, sleepiness, stuffiness etc. (3).
Regarded from the viewpoint of saving energy, the measured air change rates with opened window during the night would be much too high during the heating period. If people are sleeping with closed windows and doors the measured relative room air humidities are at the upper limit . But this is also dependant on the overall window opening habits of the in-

habitants. With relative humidities at about 65 %, condensation on cold surfaces followed by mould growth and allergy reactions to the spores can occur. Moreover building damage can also occur.
Based on todays knowledge, the results of the measurements in Préverenges and on the simulation calculations, the following recommendations for optimal bedroom ventilation behaviour with the intention of saving energy and of providing sufficient indoor air quality can be made: (a) To guarantee sufficient indoor air quality in bedrooms a sufficient outdoor air supply is necessary. (b) Outside of the heating period sufficient outdoor air supply can be obtained by opening the bedroom window during the night. (c) With an air change rate of 0.5 h^{-1}, an occupancy of two persons, a room volume at about 30 m^3 and closed windows and doors, the carbon dioxide concentration will not pass much over 1500 ppm after 10 hours. (d) From the energy point of view it is not very wise to leave the windows open during the night in the heating period. On the other hand, the outdoor air supply with closed windows is too small in well tightened buildings. Moreover the inhabitants may be forced to keep the bedroom windows closed during the night even outside of the heating period (outdoor noise, pollen allergy etc.). In these limited cases it can be recommended that the bedroom door be left open during the night in well tightened buildings. If the whole dwelling is well aired beforehand (opening all windows for 5 minutes) and the air change rate of the whole dwelling is at least 0.1 h^{-1}, the carbon dioxide concentration will not, or only slightly, pass over 1500 ppm.

ACKNOWLEDGEMENTS
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