Indoor Air 1996; 6: 181–187

INDOOR AIR
ISSN 0905-6947

Thermal Comfort and Air Quality in Three Mechanically Ventilated Residential Buildings

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Abstract Thermal comfort and air quality were studied in three multi-family buildings located in urban environments. Measurements of air velocities close to the supply devices are presented along with measurements of CO, TVOC, NO and NO_2. In addition, particle measurements were carried out to check the filter efficiency in one of the buildings (S1) which is specially designed for people with allergy problems. The total air change rate for this building is higher than for normal residential buildings and three different types of air filter are installed in the ventilation system. The results of the thermal comfort measurements in the buildings vary considerably. For two of the buildings thermal comfort can be regarded as acceptable, but can be further improved. The selection and location of the air inlet devices in the third building are not acceptable. The monitoring of the contaminants outdoors and indoors was carried out for diurnal periods. The measured contaminants outside building S1 show good correlation between each other, and the concentrations of gases and particles were considerably lower in the supply air than in the outdoor air outside the apartment where the measurements were made. The importance of not taking samples over too short a period of time is also shown.

Key words Thermal comfort, Air quality, Measurements, Residential, Ventilation

Received 5 April 1995. Accepted for publication 11 October 1995.

Introduction

Two of the most important indoor environment parameters are thermal comfort and indoor air quality. The aim of this study has been to study both these parameters in multi-family buildings situated in urban environments.

The thermal comfort parameters investigated are air temperature, air velocity and radiant temperature. As the buildings are well insulated, no problem was found with low surface temperatures or radiant temperature asymmetries according to the ISO 7730 Standard (ISO, 1990). Therefore, the critical part of the room with regard to thermal comfort is a zone close to the air inlet/supply devices. The air was supplied to bedrooms and living rooms. The results of air velocity measurements in the near-zone of the air devices are shown for all three buildings studied. In one of the buildings, especially, there is a risk that cold supply air can enter into the occupied space. In this building, the inlet air temperatures were also measured.

In buildings situated in urban areas, the indoor air quality is often influenced by outdoor contaminants. Therefore, the study focuses on the impact of outdoor contaminants on indoor air quality. Moreover, some modelling has been made of the indoor-outdoor relationship of contaminants in one of the buildings.

The air quality was generally measured outdoors (outside the actual apartments, for buildings G1 and G2, more specifically at air intakes), in supply and exhaust air. As indicators of the air quality, CO, CO_2, PAH, TVOC, NO_x (carbon monoxide, carbon dioxide, particulate polycyclic aromatic hydrocarbons, total volatile organic compounds, nitrogen oxides) and particulates were used, and monitoring was carried out as continuous measurements for diurnal periods. A previous study in residential buildings (Krüger, 1994) has shown the importance of not limiting the sampling period to just a few hours and this conclusion is again confirmed here. By studying the different contaminants, conclusions can be drawn as to the sources from which they originate. For example CO_2 usually originates from human activity, whereas TVOC usually originates from building materials or outdoor sources.

Buildings Included in the Study

All the buildings in the study are situated on the outskirts of Göteborg and Stockholm, the population of these cities being approximately 600,000 and 1,000,000, respectively. Two of the selected buildings (G1 and G2) have a mechanical exhaust ventilation system. The inlet air devices include slot devices placed above windows

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and radiator devices placed behind radiators. Both these buildings, and the thermal comfort achieved for the devices in question, have been described in previous papers (Krüger, 1992, 1995 a, b). The main street near building G1 has a traffic density of 5800 vehicles/day and 570 vehicles/peak hour, and the main street near building G2 has 4900 vehicles/day and 540 vehicles/peak hour. Both these main streets are located at a distance of about 150 m away from the buildings in question. In buildings G1 and G2 the design air change rate is 0.5 ACH, which is a normal design air change rate in residential buildings in Sweden.

The third building (S1), which is a specially designed building for people with allergy problems, has a balanced ventilation system. The ventilation system of building S1 includes both an F85 filter and an electrostatic filter, which are placed in the air-handling unit for the building, and activated carbon filters which are situated upstream of the supply devices in the apartments. The outdoor air intake is located on the roof. The balanced ventilation system is of the displacement type and the heat recovery system is an indirect liquid-coupled system, to avoid transportation of contaminants from the exhaust air to the supply air. In addition to the careful choice of materials and ventilation system for the building, apartment tenants are not allowed to smoke or keep pets in the apartments. Furthermore, the door to the apartments has no mail-drop. The total air change rate is 0.7 ACH in the apartments in building S1. The supply airflow to the different rooms can be individually controlled by a switch, and a "day" or "night" case can be set to distribute the supply air to the rooms where it is most needed. The night case means that proportionally more air is supplied to the bedrooms than to the living room. The building is located adjacent to a local main street with a traffic density of approximately 4000 vehicles/day and 250 vehicles/peak hour.

All of the apartments where the measurements were made were unoccupied at the time of the measurements.

Measurement System

A portable climate analyser (Brüel & Kjær Climate Analyser type 1213) connected to a PC was used to measure air temperature, air velocity, relative humidity, surface temperature and plane radiant temperature. Instantaneous values were measured and average values (3 minutes) were calculated.

Continuous measurements of CO, CO_2 and TVOC were carried out using a PAS instrument (photoacoustic spectroscopy), Brüel & Kjær type 1302, with a multipoint sampler unit. This gas-analyser measures the absorption of infrared light (IR). The wavelength of the IR-light is 4.7 µm for CO, 4.4 µm for CO_2 and 3.4 µm for TVOC detection, and the detection limits are 0.2 ppm, 3.0 ppm and 0.11 ppm, respectively. The PAS instrument is calibrated with methane, and the TVOC concentrations are given as methane equivalents. It is important to remember that the TVOC group consists of thousands of different substances, each having a different detection limit, and this instrument responds to the total TVOC concentration as a weighted average (cited in this paper as methane equivalents).

The concentrations of nitrogen oxides were measured with an instrument based on chemiluminescense (Echo Physics ALD 700) which measures the total concentration of nitrogen oxides (NO_x) and the NO concentration. The NO_2 concentration is obtained by calculating the NO_x-NO concentration difference and the detection limit is 1 ppb.

The total concentrations of particulate PAH were measured with an instrument that is based on selective photoionization (Matter LQ 1). The lowest detectable concentration is 1 ng/m^3.

Particulates of different sizes were measured by an optical particle counter (Met One 200L) which measures particles in six intervals in the range 0.3 µm to 10 µm. The sampling was carried out non-isokinetic. However, due to this sampling technique, the error in the particle concentrations measured can be regarded as negligible for particle sizes up to about 1.0 µm. In addition, only relative values were of interest in this case.

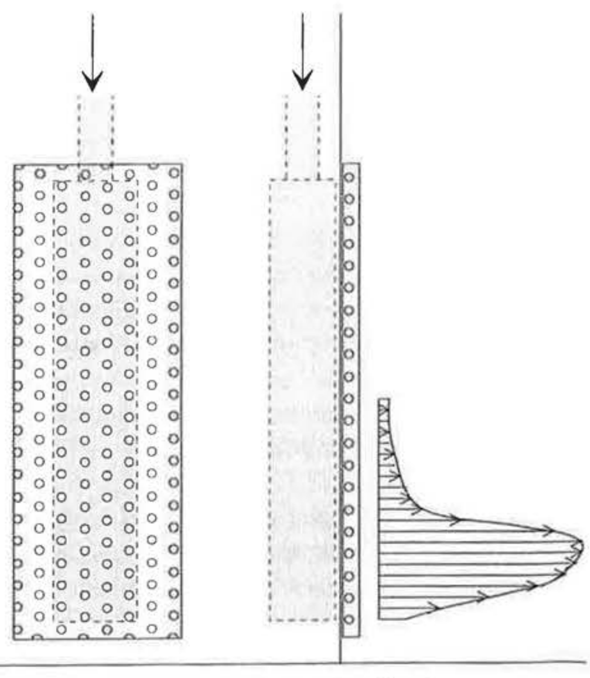

Fig. 1 Displacement air supply device in building S1.

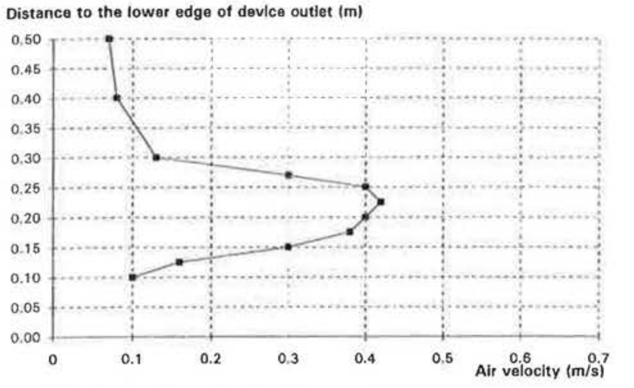

Fig. 2 Velocity profile in front of the air supply device in a bedroom in building S1.

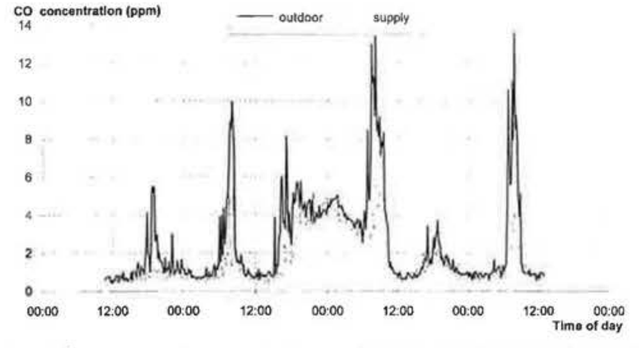

Fig. 3 The measured concentrations of CO in supply air and outside building S1.

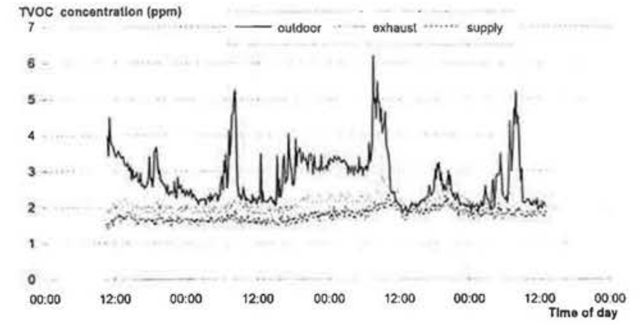

Fig. 4 TVOC concentration in outdoor, supply and exhaust air in building S1.

Results

The results of the measurements of thermal comfort and air quality are presented below for each building. It should be noted that the outdoor concentrations are presented for one side of each building only. The outdoor concentration can often be different for different sides of a building, especially during peak traffic hours and under certain weather conditions, for example, different wind directions (Krüger, 1994). However, the buildings are located on the outskirts and no street with heavy traffic is located close to the buildings; a relatively uniform concentration profile is thus to be expected outside the buildings.

The thermal comfort aspects will be presented at the beginning of each section describing the measurements at the different buildings, followed by air quality aspects.

Building S1

Since building S1 is intended for people with allergy problems, the airflow rate through the devices is higher than normal for residential buildings. The projected air change rate for the apartments is 0.7 ACH compared to 0.5 ACH normally. An activated carbon filter is placed in the supply device to clean the air from gaseous contaminants. The supply device dimensions are 0.25× 1.0 m and it is located 0.1 m above floor level. The supply air from the device is spread horizontally (Figure 1).

The air velocity was measured at a distance of 0.2 m from the supply device in a bedroom under "night" conditions when the airflow can be expected to be somewhat higher than during the day. This distance may be considered as very short, but the occupied space in residential buildings should include almost the whole floor area (Krüger, 1995a). In addition, very high demands were set on the indoor environment of this building, including also thermal comfort in the rooms. It is apparent that most of the air enters the room from the bottom of the device, due to the construction of the device and the supply duct. The maximum velocity was, in this case, 0.42 m/s (Figure 2).

The ventilation system in building S1 includes, as mentioned, two different types of particulate filters located in the air-handling unit. Measurements were carried out upstream and downstream of each filter for different particle sizes. For particle sizes in the range 0.5 µm - 1.0 µm the filter efficiency was 85% for the F85 filter and 90% for the electrostatic filter. The total efficiency measured was 97%. The corresponding values for particle sizes in the range 0.3 µm - 0.5 µm were somewhat lower.

The outdoor concentration of the contaminants studied, PAH, TVOC, CO, NO_2 and NO, varied considerably during the day and from day to day outside building S1. All the contaminants have a similar variation over time (Figures 3, 4). The highest concentrations were recorded in the mornings. During the monitoring period, the outdoor concentrations of NO_2, CO and TVOC were unusually high in the Stockholm area due to atmospheric inversion.

The CO concentration in the building originated from outdoor sources since smoking is not allowed in the building. The peak values of the CO concentration in supply air are much lower than the corresponding out-

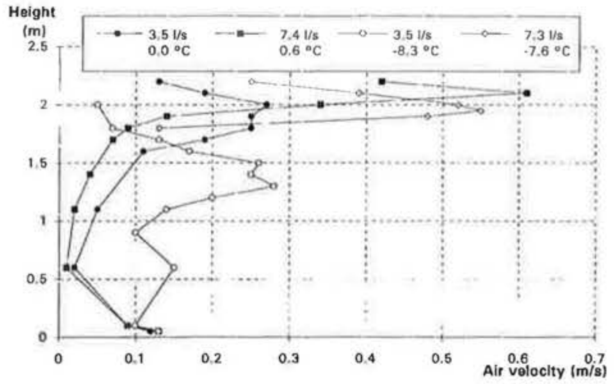

Fig. 5 Air velocity profiles 0.6 m from the outer wall in building G1.

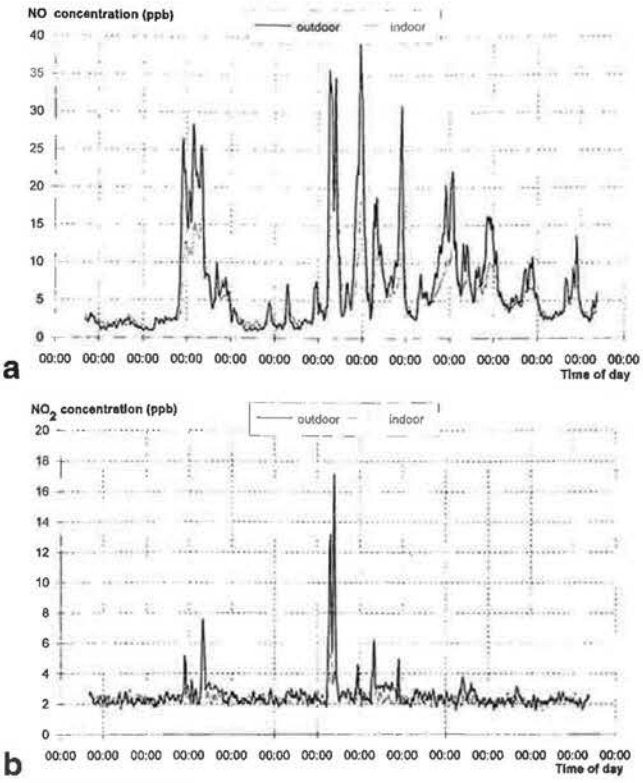

Fig. 6 Outdoor and indoor concentrations of NO and NO_2 in and outside building G1.

door concentrations measured outside the apartment (Figure 3). This is mainly due to the fact that the outdoor air intake is located on the roof of the building.

TVOC is an example of a contaminant that is generated both in the indoor and outdoor environment. Figure 4 shows a comparison of the concentrations of TVOC in the outdoor air outside the apartment, in supply air and in exhaust air. The supply air is affected very little by the traffic peaks in the morning, as it is cleaned in an activated carbon filter. Furthermore, the supply air is taken in at the top of the five-storey building and dilution of the contaminants may have taken place. The concentration of TVOC in the exhaust air is approximately 0.3 ppm higher than in the supply air. However, during the outdoor peaks the difference increases between exhaust and supply air. This can be a result of unwanted infiltration to the building.

When comparing Figures 3 and 4, it can be seen that there is a good correlation between the CO and TVOC concentrations in the outdoor air. In the section "Discussion", the correlation with NO, NO_2, NO_x and PAH is also shown.

Building G1

In building G1, the inlet slot devices are placed 2 m above floor level in the window frame. The inlet area is 300×11 mm. In the bedroom investigated, the airflow rate was approximately 3.5 L/s through the device. According to Swedish recommendations for airflow rate to a two-person bedroom, i.e. 8 L/s, the flow was too low. By tracer gas measurement it was found that 2/3 of the airflow rate could be related to the flow through the inlet device. By increasing the airflow rate in the kitchen exhaust hood, the recommendations could almost be fulfilled in the bedroom. The actual airflow rate then became around 7 L/s. This airflow rate corresponds to ASHRAE Standard 62-1989 for minimum ventilation for residential buildings.

In the bedroom, which has floor dimensions 2.65 m ×4.0 m, the air velocity was measured at a distance of 0.6 m from the device. At an airflow rate of about 7 L/s, air velocities up to 0.6 m/s were measured (Figure 5). This high velocity was, however, measured at 2 m above floor level, and 0.6 m from the device, but further away from the device the air jet dropped into the occupied space.

At an airflow rate of 3.5 L/s, thermal comfort was considerably affected by the outdoor temperature. The height above floor level, where the maximum velocity occurred, ranged from 1.3 to 2.0 m for outdoor temperatures of −8.3° and 0°C, respectively.

The recorded concentrations of the contaminants outside building G1 show no clear diurnal variation. The concentrations of TVOC and CO outdoors show no clear correlation to the corresponding NO and NO_2 concentrations. NO is the most varying compound both indoors and outdoors. In Figure 6, the NO and NO_2 concentrations, as 1-hour running average values, are shown for a monitoring period of 12 days. The highest outdoor concentrations of NO are approximately twice as high as the indoor concentrations. The NO_2 concentration indoors is usually 2 - 3 ppb, with peak values up to 5.5 ppb.

Building G2

Building G2 has a mechanical exhaust ventilation system with preheated inlet air. Thermal comfort is, in this

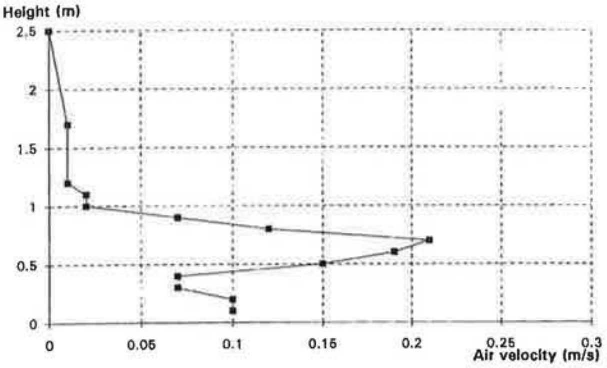

Fig. 7 Air velocity profile 0.6 m from the radiator air device in building G2.

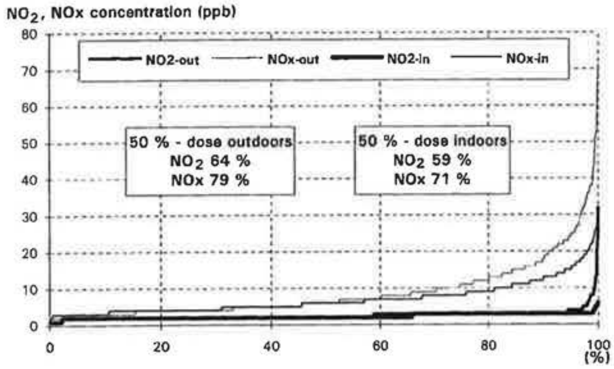

Fig. 8 Cumulative distribution of NO_2 and NO_x indoors and outdoors.

case, dependent on the surface temperature of the radiator, but of even more importance is the fact that a window-sill is located close to the device outlets. When the sill is located in a standard position, it obstructs the inlet air. However, if the sill is moved away from the wall by only three centimetres (so that the supply air can pass between the sill and the wall more easily), then high velocities can be avoided in the occupied area (Krüger, 1995b). The result of the air velocity measurements when the sill was in the standard position is shown in Figure 7 for an airflow rate of about 4.5 L/s.

In Figure 8 the recordings of the NO_x and NO_2 concentrations during a two-week monitoring period are presented as cumulative distributions for building G2. The figure also includes values of the calculated doses of NO_x and NO_2. The 50% dose value outdoors is reached after 79% and 64% of the time, respectively. The corresponding dose values indoors are reached in a shorter time as the concentrations vary less indoors than outdoors, possibly due to dilution in the indoor air.

Discussion

The concentration of NO_2 is generally lower indoors than outside the three buildings. The highest reductions of NO_2 and CO are reached in building S1 (See Table 1).

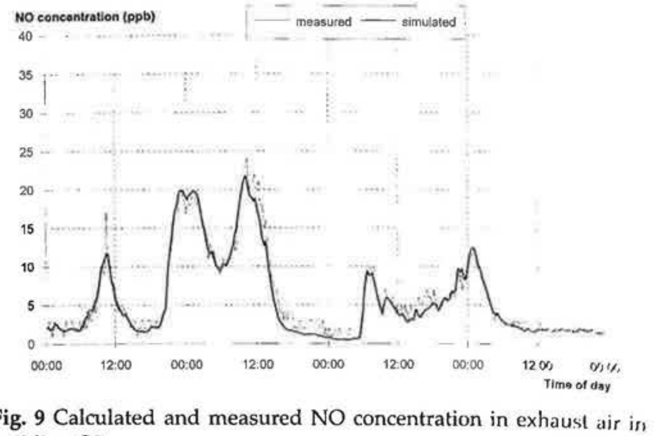

Fig. 9 Calculated and measured NO concentration in exhaust air in building G2.

This is reasonable due to the fact that the air intake is located on the roof of the building. Further, activated carbon filters impregnated for NO_2 reduction are installed in the air supply devices of the apartment where the measurements were made. The reduction of NO and NO_2 as a function of distance from a road can be seen in Baumbach (1993).

The outdoor concentrations of NO_2 and CO during the monitoring period are higher for building S1 than for the other buildings. The contribution of TVOC from indoor sources is low, especially for buildings S1 and G1. In building G2, about 0.9 ppm of the TVOC concentration can be traced to indoor sources. However, the measured total TVOC concentration is, to a large extent, due to methane which can be regarded as a background source. The background concentration of methane in outdoor air is as high as 1.6–1.9 ppm, even in non-urban areas (Dlugokencky et al., 1994). Since methane can be regarded as less harmful than many other VOCs, the methane concentration may be subtracted from the TVOC concentration. The ratio between indoor/outdoor concentrations of TVOC will vary considerably whether the methane compensation is made or not. A promising method of methane background compensation, for the PAS instrument in question, has recently been investigated (Krüger et al., 1995c).

From Figures 3 and 4 a good correlation between CO and TVOC concentrations outside building S1 can be seen. However, the correlations between all the measured contaminants outdoors are good as can be seen in Table 2.

The concentrations of contaminants outside buildings G1 and G2 do not have strong diurnal cycles. The peak and average values are also much lower compared to building S1. The cycles are most evident for NO and NO_2. However, the CO measurements, for example, do not have a cyclical diurnal variation and therefore the traffic does not seem to be the only pollutant source.

Table 1 Average and 98-percentile concentrations of measured contaminants (NO_2, CO, TVOC) at the three buildings. The monitoring periods were at least one week, except for the NO_2 measurements outside building S1

Building	Measuring location	Average conc.			98-percentile			References[1]	
		NO_2 (ppb)	CO (ppm)	TVOC (ppm)	NO_2 (ppb)	CO (ppm)	TVOC (ppm)	NO_2 (ppb)	CO (ppm)
S1	outside	40[2]	2.5	2.8	114[2]	9.2	4.8	18	0.5
	supply	11	1.7	1.8	52	5.0	2.1	–	–
	exhaust	–	1.9	2.1	–	5.1	2.7	–	–
G1	outside/supply	2.6	0.9	2.1	5.5	1.3	2.7	17	0.4
	exhaust	2.3	0.9	2.3	3	1.4	2.8	–	–
G2	outside/supply	3.6	0.9	2.1	26	1.7	2.5	23	0.8
	exhaust	3.1	1.0	3.0	19.0	1.7	3.9	–	–

[1] The concentrations at the reference sites were recorded on the roofs of buildings situated in the city centres (Miljöförvaltningen, 1994a, b).
[2] The monitoring period is the last 2 days of the monitoring period given in Figures 3 and 4.

In addition to the air quality measurements, the relationship between indoor and outdoor concentrations of various contaminants was calculated. A model was used for the calculation of indoor concentrations, where the outdoor concentrations and internal sources and sinks are considered under transient conditions. With a knowledge of the variation of the outdoor concentration of a contaminant, the indoor concentration over time was calculated and compared with the measured concentration. According to the model, which has previously been described (Ekberg, 1994), the indoor concentration can be calculated from:

$$C_I^{n+1} = \left(\frac{\dot{V}_{source} - \dot{V}_{sink} + \dot{V} \cdot \left(C_S - C_I^n \right)}{V} \right) \cdot \Delta t + C_I^n \quad (1)$$

where:
C_I^n=indoor concentration at current time step (volume by volume)
C_I^{n+1}=indoor concentration at the next time step (volume by volume)
C_S=supply air concentration (volume by volume)
Δt=time step (s)
V=volume of the room (L)
$\dot{V}$=airflow rate (L/s)
$\dot{V}_{source}$=internal source strength (L/s)
$\dot{V}_{sink}$=internal sink effect (L/s)

Equation (1) was applied on measurements of NO over four days indoors and outside building G2 (Figure 9). The source and sink terms were disregarded in this case. However, some transformation of NO to NO_2 may occur in the presence of ozone. Further, the outdoor concentration of NO was assumed to be equal outside all of the air intakes. Measurements have shown that the difference in NO concentration outside the two outdoor walls of the apartment can be very small. The 98-percentiles for the two sides of the building were 20 and 21 ppb, respectively, and the average concentration was 6 ppb for both sides during the monitoring period.

The air change rate in the apartment in building G2 was measured to 0.5 ACH by a tracer gas method. Equation (1) is valid for complete mixing of the air in the apartment. However, in a real case, complete mixing does not exist but the good agreement between the measured and simulated concentrations indicates that the mixing can be assumed to be close to complete (Figure 9).

When designing ventilation systems, a knowledge of both thermal comfort and air quality is required. In buildings such as S1, for instance, where much effort is spent on examining air quality indoors, thermal comfort in the rooms should not be forgotten.

The air velocity distribution of the displacement device used in building S1 could be improved. In order to give a more uniform velocity profile, one of the following is needed: guidevanes, a deeper supply device, or a higher pressure drop over the filter. The skewed velocity distribution may also give a filter performance that is less than optimum.

The connection between outdoor and inlet temperature for air slot devices has previously been reported (Krüger, 1995a). According to the previous study, the in-

Table 2 Correlation between measured contaminants in the outdoor air outside building S1

	PAH	NO	NO_2	NO_x	CO	TVOC
PAH	–	0.89	0.85	0.88	0.91*	0.79*
NO	0.89	–	0.97	1.00	0.81*	0.69*
NO_2	0.85	0.97	–	0.98	0.77*	0.65*
NO_x	0.88	1.00	0.98	–	0.80*	0.70*
CO	0.91*	0.81*	0.77*	0.80*	–	0.86
TVOC	0.79*	0.69*	0.65*	0.70*	0.86	–

* To measure all the contaminants, two different measuring systems were used. Thus, samples have not been taken exactly at the same time, but during the same monitoring period.

let temperature is raised by approximately 2–3°C at outdoor temperatures of around 6°C, i.e. instead of supplying air with a temperature of 6°C to the room, air with a temperature of 8–9°C is supplied. The moderate preheating inside the device affects the thermal comfort in the room to some extent, especially when an airflow rate of 3.5 L/s is supplied to the room (Figure 5). In this figure it can also be seen that the height at which the maximum velocity occurs depends on the outdoor air temperature (inlet air temperature). Thus, without this preheating, a high draught risk exists for a greater part of the year.

Conclusions

One way to create good indoor air quality is to increase the airflow rate in the building, presuming that good air quality is available outdoors or that the outdoor air is well filtered. However, this means that the risk of draught increases if the air is not supplied through more, or larger, supply devices. The measurements in building S1 have indicated that good thermal comfort can be achieved if the actual air device is slightly modified.

Thermal comfort in buildings with slot devices is very poor. In building G2, with radiator air devices, thermal comfort is just acceptable with the window-sill placed in a standard position.

The filters in building S1 reduce the concentrations of particles in the size range 0.3 µm–1.0 µm considerably (around 95%). Furthermore, indoor concentrations of gaseous contaminants are much lower than outdoors, especially during peak hours outdoors. For some hours after a peak, the concentration indoors may be higher due to the time needed for the air to be exchanged in the rooms. The diurnal cycles for CO, TVOC, PAH and NO show that there is a good correlation between these contaminants. The results also show the importance of not taking samples over too short a period of time.

It is noted that during days with inversion, the outdoor concentration can be considerably higher than normal, even for buildings located on the outskirts. By locating the air intakes on the roof and using high-efficiency filters in supply air, it is possible to reduce the concentration of contaminants indoors to a low level. During days with high concentrations outdoors, the concentration indoors will be much lower if a ventilation system comparable to the one in building S1 is used, than if the building is ventilated by a mechanical exhaust ventilation system with air intakes on the facade.

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