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Indoor Air Quality in Renovated Dutch Homes

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Abstract

The indoor air quality in several types of dwellings that were renovated to save energy for spatial heating has been investigated. Concentrations of pollutants were monitored in three rooms of inhabited houses. Data of the outside air and ventilation and infiltration were also collected. Relationships were established between observed concentrations and ventilation. In some cases concentrations show a good relationship with the calculated air change rate, in other cases this relationship was poor or absent.

Elevated levels of pollutants could be related to sources in most cases. The ventilation behavior of the inhabitants has a major influence on the concentrations.

From this and other studies it can be concluded that, in general, making dwellings more airtight leads to higher concentrations of pollutants. Deviations from health-related guidelines then become more likely.

KEY WORDS:
Indoor air quality, Pollutants, Homes, Renovation, Concentration, Ventilation, Air permeability

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Introduction

Because of the high cost of energy for spatial heating (in the Netherlands usually with natural gas) new dwellings are built more airtight than in the past and are often heavily insulated against heat loss.

Older dwellings in the Netherlands are renovated; this means made more airtight, insulated, and in some cases provided with a mechanically balanced ventilation system with a heat exchanger to recover energy. This could possibly lead to increased levels of air pollutants, on the one hand, by introducing new sources such as insulation materials and, on the other hand by increasing the concentrations of pollutants generated from existing indoor sources such as building materials, gas appliances, tobacco smoke, consumer products and products of human metabolism, caused by reduced ventilation. The behavior of the inhabitants is expected to have a major influence on the concentrations. Especially in the winter season, when inhabitants do not use the ventilation supplies adequately, poor indoor air quality cannot be excluded.

In one renovation project, identical houses with only natural ventilation were investigated. The measurements were performed in *inhabited* houses.

The aim of this research is to evaluate indoor air quality in renovated, heavily insulated houses with mechanically balanced ventilation systems during the winter season.

The evaluation covers the following aspects:

- comparing concentrations of pollutants and ventilation in renovated homes that have mechanically balanced ventilation with those having only natural ventilation;
- comparing air permeabilities and concentrations of pollutants in renovated homes with those in other Dutch homes;
- relating concentrations of pollutants with outdoor and indoor sources;
- comparing measured concentrations of pollutants with standards in use in the Netherlands;
- correlating measured concentrations with calculated air change rates.

Set-up

Concentrations of CO, CO_2, NO, NO_2, dust particles, formaldehyde and hydrocarbons were measured in several types of dwelling in two Dutch cities (Rotterdam and 's Hertogenbosch). Measurements were performed in the living room, the kitchen and the parents' bedroom in the winter season. The air permeability of the dwellings and the airflow quantities of mechanical air supplies and exhausts were also measured, as well as the temperature and the relative humidity. With the help of the TNO ventilation computer program (Liddament, 1986), the ventilation conditions were calculated for the actual weather conditions. The input data are the measured air permeability and airflow quantities; the wind speed and direction and outdoor temperature measured by the nearest weather station; and measured indoor temperature. Correlations were made between measured concentrations of pollutants and calculated air change rates by non-linear regression analysis.

Methods

The methods of measurement of pollutants (real time (RT) and time-weighted average (TWA)) and of the temperature and relative humidity (RH) are summarized in Table 1. The analog signals of the monitors were digitalized with a Hewlett Packard 3497 A DTA acquisition/control unit and collected on a diskette with a Hewlett Packard 9816 microcomputer. All signals were screened (zero corrections, calibration factors, selecting of relevant periods, etc.) and calculated as concentrations. These were printed with an HP plotter.

The air permeability of the homes was measured by fan pressurization. The fan was

Table 1 Methods of measurement of pollutants, temperature and relative humidity.

Component	RT or TWA	Principle	Instrument
CO	RT	IR absorption	Unor 6N (Maihak) Model 8310 (Monitor Labs)
CO_2	RT	IR absorption	Sifor 2 (Maihak) APBA (Horiba)
NO and NO_2	RT	chemiluminescense	Type PW 9762/00 (Philips) Model 8101-C (Bendix) Model 2200 (CSI)
Respirable dust	RT	light scattering	TM Digital (Leitz) Hund TM Data
Total and resp. dust	TWA	gravimetry (filter sampling)	
VOC	TWA	charcoal adsorption gas chromatography	
Formaldehyde	TWA	impigner, colorimetry	
Temperature	RT	thermocouple	
RH	RT	thin film	6061 HM (Vaisala)

IR = infrared, VOC = volatile organic compounds

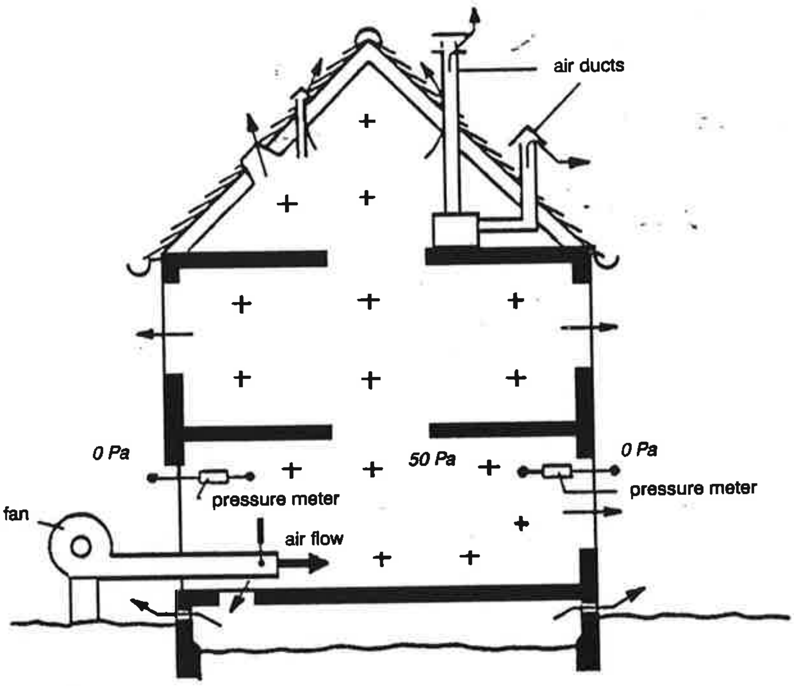

Fig. 1 Measurement of the air permeability of a dwelling by pressurization.

Table 2 Characteristics of the homes in Rotterdam.

Type	Apartments built in 5 stories	Apartments built in 5 stories	Single homes, 2 stories, in row
Built in year	1891	1929	1925
Renovated in year	1984	1983	1984
Measurements in year	1986	1986	1986
Ventilation	natural	mechanically balanced	natural
Heating	central	central	vented stove
Heating fuel	natural gas	natural gas	natural gas
No. of bedrooms	2-4	2-5	4
No. of inhabitants	2-5	2-7	4
Structural materials	brick	brick	brick
Interior walls	gypsum board	gypsum board	gypsum board
Insulation:			
window	double glass	double glass	double glass
facade	10 cm min. wool	10 cm min. wool	6 cm PS
roof	8 cm PS	8 cm PS	5 cm PS
floor	3 cm PU	3 cm PU	–
Warm water supply	local in kitchen (geyser)	vented	vented
Fuel for cooking and warm water	natural gas	natural gas	natural gas
Exhaust hood above gas furnace	yes	yes	no
No. of homes investigated	4	4	2
No. of homes with smokers	4	2	2

PU = polyurethane foam, PS = polystyrene foam

Table 3 Summarized results of the measurements in Rotterdam: average concentrations over 48 hours giving ranges and averages (in brackets) per type of home.

Type of home	Location	Average concentration (48 h)					
		CO ppm	CO_2 ppm	NO $\mu g.m^{-3}$	NO_2 $\mu g.m^{-3}$	RSP $\mu g.m^{-3}$	RH %
Apartment natural ventilation (n = 4)	kitchen	0.9-2.0(1.4)	560- 950(720)	43-68(60)	36-42(38)	55-240(140)	31-48(37)
	living room	1.0-2.0(1.6)	820-1360(980)	43-99(74)	23-29(25)	120-370(250)	32-44(38)
	bedroom	0.6-1.4(0.8)	820-1000(930)	14-26(19)	8-27(13)	20-150 (90)	51-67(56)
	outdoor	<0.5-1.2(0.8)	340- 460(390)	21-38(31)	31-56(44)	-1)	90-100(97)
Apartment mech. balanced ventilation (n = 4)	kitchen	<0.5-1.4(0.9)	480- 840(600)	<2-53(31)	15-31(23)	65-130(110)	18-29(23)
	living room	0.5-1.1(0.9)	460- 600(570)	29-51(39)	8-23(15)	40-210(110)	16-28(21)
	bedroom	0.5-1.4(0.8)	280- 870(600)	5-58(20)	8-17(13)	<20-70(45)	15-65(30)
	outdoor	0.6-2.0(1.2)	290- 370(330)	15-46(46)	36-52(46)	-1)	54-65(60)
Single natural ventilation (n = 2)	kitchen	0.8-1.3(1.1)	470- 700(590)	19-36(28)	35-59(47)	90-170(130)	23-31(27)
	living room	1.1-1.2(1.2)	550- 610(580)	23-40(31)	29-38(34)	90-130(110)	21-26(24)
	bedroom	1.0-1.2(1.1)	860- 950(910)	6- 8(6)	<4-12(6)	70-130(100)	29-43(36)
	outdoor	0.7-1.4(1.1)	300- 320(310)	6-15(11)	23-36(30)	-1)	46-59(53)

1) not measured, RSP = respirable suspended particulates

Table 4 Summarized mechanical airflows in $m^3.h^{-1}$ in the four houses in Rotterdam with mechanically balanced ventilation.

Location	Dutch standard	Design	Measured
Supply:			
Living rooms	75	100	40-100
Parents' bedrooms	50	95	35-58
Other bedrooms	25	60	20-50
Exhaust:			
Kitchen ≤ 10 m²	75	150	55-72(n=3)
> 10 m²	100	150	135(n=1)
Bathroom	50	50	43-54
Toilet	25	25	7-35

placed in a dummy-door. The inner doors were opened. The test-setup is shown in Figure 1. The home is maintained at a constant pressure in all rooms. The required airflow is measured at different pressure differences between indoors and outdoors. The pressure difference is measured with differential pressure meters.

The airflow can be described as:

$$Q = C\,(\Delta P)^{1/n}$$

where

Q = airflow ($m^3.h^{-1}$)
P = pressure difference (Pa)
C = air permeability, $m^3.h^{-1}\,(Pa)^{1/n}$
n = power exponent, related to the type of airflow, lying between 1 and 2

Characteristics of the Homes in Rotterdam

The relevant characteristics of the homes are summarized in Table 2. The homes with mechanically balanced ventilation have also a heat recovery unit, consisting of a heat exchanger and two fans. Each unit is connected to 3-5 homes. The air is supplied in the living room and the bedroom and exhausted in the kitchen, the shower and the toilet.

Results of the Measurements and Calculations in Rotterdam

The results of the real-time measurements in Rotterdam as average concentrations over 48-hour periods are summarized in Table 3.

The results of the measurements of the

Table 5 Air permeabilities (C) and air change rates (ACR). Range (average).

Type of home		C, $m^3.h^{-1}(Pa)^{1/n}$	ACR, h^{-1}
Apartment,	natural ventilation	108-162(134)	0.3-0.95(0.6)
Apartment,	mech. balanced ventilation	36-234(129)	1.05-1.35(1.2)
Single home,	natural ventilation	176-227(202)	0.6(0.6)

mechanical airflows are summarized in Table 4. The required airflows according to Dutch standards (1975) and the designed flows are mentioned as well.

The measured air permeabilities and the calculated air change rates of the homes are summarized in Table 5.

For the calculations it was assumed that all doors, windows and additional ventilation openings were closed.

Regression analysis was carried out to establish the relationship between concentrations and air change rates. The most likely relationship is a quotient curve according to

$$c = a + b/ACR$$

where c = concentration, ACR = air change rate and a is a constant that represents the contribution of the infiltrating outdoor air (concentration in outdoor air minus loss by sinks).

ACR was calculated only for the complete home. For the average concentration of the home the concentrations of the three rooms where the measurements were taken were averaged. The average periods were, as mentioned, 48 hours.

Results:

c = 0.6 + 0.3/	ppm CO	R = 0.76
c = 550 + 115/AC	ppm CO_2	R = 0.56
c = 14 + 5.9/ACR	$\mu g.m^{-3}$ NO_2	R = 0.61
c = 21.8 + 9.8/ACR	$\mu g.m^{-3}$ NO	R = 0.46
c = 42 + 54/ACR	$\mu g.m^{-3}$ RSP	R = 0.73

The correlations are significant with the exception of NO. The local concentrations, however, are often totally different from the average concentrations for the total home; they are higher in the rooms where the source(s) are located.

The following can be derived from the real-time measurements.

- *CO*. The base level is 0.5-2 ppm both indoors and outdoors. Peaks reach several ppm above base level. Their sources are smoking and gas appliances and they are found in the living room and the kitchen (Figure 2).

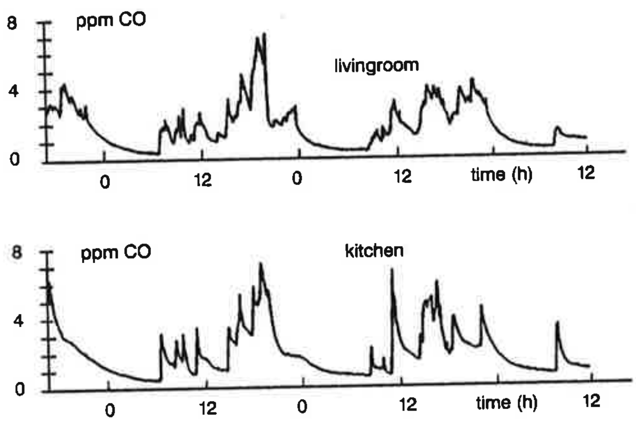

Fig. 2 CO concentration in the living room and the kitchen in a naturally ventilated apartment house. Peaks are caused by smoking and the use of gas appliances in the (open) kitchen.

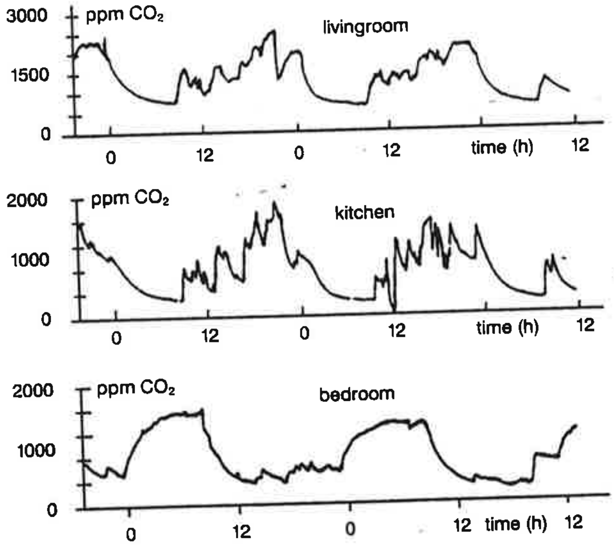

Fig. 3 CO_2 concentrations in the living room, the kitchen and the parents' bedroom in a naturally ventilated apartment house. CO_2 sources are in the living room and the kitchen during the day and in the bedroom at night.

- *CO_2*. In the outdoor air 290-450 ppm CO_2 was found. The main indoor sources are inhabitants (exhaled air) and gas appliances in the kitchen (geyser (gas-fired demand water heater) and furnace). In the bedrooms the average concentrations during the night (23.00-08.00 h) in the naturally ventilated homes are between 1000 and 1800 ppm and they rise at the end of the rest period to up to 2400 ppm. In the kitchen, peaks of 1200 to 4000 ppm are measured during cooking (Figure 3).
- *NO and NO_2*. Fluctuating concentrations are measured in the outdoor air; sources are combustion processes of fossil fuels: traffic, spatial heating of buildings, and industry. When indoor sources are absent, the indoor concentrations are lower, especially for NO_2 caused by adsorption and/or chemical reaction on building and furnishing materials. The concentrations of NO_2 in the bedrooms, where sources are absent, are 2-10 times lower than outdoors. The concentrations are highest in the kitchen – peaks of up to 200 ppb – and are raised in the adjacent living room. Similar patterns to those in the kitchen are found in the living room, but at a lower level.

  NO is less reactive than NO_2 and concentrations are higher compared with outdoor air.

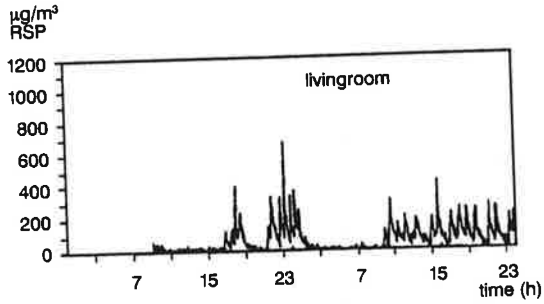

Fig. 4 Respirable dust concentration in the living room of a single family house with mechanically balanced ventilation. Each peak is caused by the smoking of a cigarette.

- *Respirable dust*. A dominant source is the smoking of tobacco products. The highest concentrations are found in the living room. Peaks of up to 2000 $\mu g.m^{-3}$ are found in rooms where people smoke. Figure 4 shows the RSP concentration in a living room with smokers; each peak is caused by the smoking of one cigarette.

Time-weighted average (TWA) concentrations of volatile organic compounds (VOC). The results are summarized in Table 6.

Table 6 Concentrations of volatile organic chemicals in $\mu g.m^{-3}$ as time-weighted average over 48 hours (averages in brackets).

Component	Apartment natural ventilation		Apartment mechanical ventilation		Single home natural ventilation	
benzene	9-31	(18)	4-14	(9)	6-14	(10)
toluene	55-79	(60)	18-290	(107)	27-51	(39)
xylene isomers	19-40	(27)	13-50	(24)	8-10	(9)
other aromatic hydrocarbons	13-40	(27)	19-105	(53)	10-16	(13)
n-alkanes	10-110	(40)	17-250	(89)	10-17	(14)
formaldehyde	5-60	(30)	–		–	
linonene	10-97	(47)	87-130	(105)	26-100	(63)
α-pinene	4-10	(5)	2-40	(16)	2	(2)
styrene	5-10	(7)	1-12	(5)	1-2	(2)
trichloroethene	20-60	(30)	< 2	(< 2)	< 2	(< 2)

Discussion of the Results in Rotterdam

Comparison between Natural Ventilated Homes and Homes with Mechanically Balanced Ventilation

The calculated air change rates of the naturally ventilated homes varied between 0.30 and 0.95 h^{-1} and for the homes with mechanically balanced ventilation between 1.05 and 1.35; averages were 0.60 and 1.2 h^{-1} respectively. Thus, the air change rate is generally lower in the naturally ventilated homes. This means that concentrations are higher if source strengths are equal.

For CO, CO_2, NO_2 and RSP significant correlations were found between concentration and air change rate according to a quotient curve. This indicates that source strengths of these compounds in the different homes are of the same order of magnitude. Concentrations of the compounds mentioned are thus generally higher in the naturally ventilated homes (see Table 3).

No significant correlation was found for NO or any of the measured VOC. This indicates that source strengths of these compounds are variable. For NO, the outdoor air contributes significantly to the indoor air concentration.

Although mechanical airflows in the homes with mechanically balanced ventilation do not comply with Dutch standards in all cases (see Table 4), mechanical ventilation improves indoor air quality.

Comparison of Measured Concentrations with those in Other Dutch Homes

Concentrations of CO, NO_2, respirable dust and VOC in other Dutch homes were measured by Lebret (1985, 1986). Compared with these data, the CO and NO_2 concentrations were lower. This is due to the absence of unvented geysers in the kitchen, whereas the geysers in the homes investigated by Lebret were unvented. The respirable dust concentrations are often higher. Smokers lived in almost all homes and smoking took place during the measurements (inhabitants and visitors). The VOC concentrations fall within the range of Lebret's results.

The formaldehyde concentrations are comparable with those found in other Dutch houses where no UF-based building materials were used (Cornet, 1982). The sources are tobacco smoke and consumer products. Styrene, not mentioned by Lebret, could be generated by the polystyrene foam insulation.

No correlation was found between the air change rate and any of the measured VOC.

Table 7 shows the median concentrations of some VOC in:

- the outdoor air in the city of Vlaardingen, measured in 1980 (Guicherit, 1985);

Table 7 median concentrations of VOC in Dutch homes.

Compound	Oudoor Vlaardingen (n = ca 400)	Prewar homes Rotterdam (n = 102)	Prewar homes Ede (n = 174)	Renovated homes Rotterdam (n = 10)
Benzene	5	7	7	12
Toluene	19	23	40	46
Xylene isomers	12	9	12	18
Ehtyl benzene	3	2	3	7
n-propyl benzene	1	<1	1	3
methylethylbenzene isomers	5	5	7	15
trimethylbenzene isomers	9	5	9	14
n-heptane	<1	3	3	5
n-octane	<1	1	2	3
n-nonane	<1	3	4	4
n-decane	<1	8	9	9
n-dodecane	<1	1	2	3
n-tridecane	<1	1	1	2

- prewar (1940) homes in Rotterdam, measured in 1981-1983 (Lebret, 1985, 1986);
- postwar (1945) homes in the city of Ede, measured in 1981-1983 (Lebret, 1985, 1986);
- renovated homes in Rotterdam, measured in 1986 (the present study).

The general trend is outdoor < prewar homes < postwar homes < renovated homes.

This trend could be ascribed to the following:

- indoor sources of VOC increase the concentrations;
- postwar homes are generally made more airtight than prewar homes and are better ventilated. The renovated homes investigated were very airtight and had low air change rates (especially the homes with only natural ventilation).

Unfortunately, no measurements could be performed in the investigated homes before the renovation. Direct evaluation of the effects of the renovation is therefore not possible.

The average air permeability of the 10 renovated homes is 146 $m^3.h^{-1}$ $(Pa)^{1/n}$ (coefficient of variation CV = 45%). The air permeability of the average Dutch home is 360 $m^3.h^{-1}$ $(Pa)^{1/n}$ (CV = 38%) (de Gids, 1984).

Guidelines for a "healthy indoor environment" in the Netherlands are given for some compounds (van de Wiel, 1990):

CO	9 ppm (10 $mg.m^{-3}$)	8 h
CO_2	1200 ppm	
NO_2	150 $\mu g.m^{-3}$	24 h
	300 $\mu g.m^{-3}$	8 h
RSP	140 $\mu g.m^{-3}$	24 h
Benzene	12 $\mu g.m^{-3}$	1 year
Formaldehyde	120 $\mu g.m^{-3}$	1 h

No deviations for CO, NO_2 and formaldehyde were found. Concentrations of CO_2, deviated from the guideline values in the naturally ventilated apartments, due to poor ventilation. The respirable dust concentration was often too high in the living room and the adjacent open kitchen, due to smoking. In all types of home, deviations from the guideline were found for benzene.

Characteristics of the Homes in s'Hertogenbosch

In the city s'Hertogenbosch, 4 mechanically balanced houses were investigated. The characteristics are summarized in Table 8.

Table 8 Characteristics of the homes in 's Hertogenbosch.

Type	Single homes, 2 stories, in row
Built in year	1970
Renovated in year	1987
Measurements in year	1988
Ventilation	mechanically balanced air supply in living room and 3 bedrooms (3 homes) air supply in hall and main bedroom (1 home) air exhaust in kitchen, shower and toilet
Heating	central gas
No. of bedrooms	3
No. of inhabitants	2-4
Structural materials	concrete
Inner walls	gypsum
Insulation:	
window	double glass
facade	UF-foam 4 cm plates (3 cm mineral wool, 1 cm gypsum) 7.5 cm plates (3 cm Trespa, 1.5 cm PU-foam, 3 cm Trespa)
roof	6 cm roofmake plates
floor	4 cm PU-foam
Warm water supply	geyser vented (3 homes), unvented (1 home)
Exhaust hood above gas furnace	yes, home with unvented geyser excepted
No. of homes investigated	4
No. of homes with smokers	4 (2 also investigated without smoking)

PU = polyurethane foam, UF = ureaformaldehyde foam.

Each home had its own ventilation system with a heat recovery unit and two fans. The fans could be switched in two positions (high and low), the choice being made by the inhabitants.

Results of the Measurements and Calculations in s'Hertogenbosch

In the homes with mechanically balanced ventilation in s'Hertogenbosch, real-time measurements were carried out of CO_2, respirable dust, temperature and RH. In some houses, CO, NO and NO_2 were also measured. Total and respirable dust, sampled with filters, were measured as TWA calculated for 8-hour periods and for three individual rooms (living room, kitchen and parents' bedroom). It was expected that a better correlation could be found between TWA concentrations and air change rates for individual rooms and 8-hour periods than for the whole home and 48-hour periods. The periods considered were 08.00-16.00 and 16.00-24.00 h for the living room and the kitchen, and 00.00-08.00 h for the bedroom. The results of the measurements are summarized in Table 9.

In some homes where the inhabitants smoked, measurements were also performed during a 48-hour period with the inhabitants abstaining from smoking. The perceived indoor air quality, comfort and health in 57 almost identical homes in this project are discussed in another paper (van Dongen, 1990). For the calculation of the air change rate, an estimation is made of the area of the ventilation openings, based on the questionnaire filled in by the inhabitants during the measurements.

The measurements of the mechanical airflows are summarized in Table 10. The flows required according to the Dutch standard and the design are also mentioned. The air

Table 9 Summarized results of the measurements in single homes with mechanically balanced ventilation in 's Hertogenbosch. Ranges of average concentrations over 8 h periods are given; for the living room and kitchen over the periods 08-16 and 16-24 h, for the bedroom over the period 00-08 h and for outdoors over 24 h.

Location	Kitchen	Living room	Bedroom	Outdoors
CO, ppm	1.0-1.5 V 1.7-2.9 U	0.3-1.2 V 0.9-2.1 U	0.1-0.5	
CO_2, ppm	540-1210 V 760-1180 U	480-1040	470-1540	
NO, $\mu g.m^{-3}$	6-150 V 40-290 U	20-90 V 45-245 U	13-31	6-120
NO_2, $\mu g.m^{-3}$	60-155 V 95-190 U	30-75 V 50-95 U	20-50	38-75
TSP, $\mu g.m^{-3}$	30-85 NS 65-260 S	35-55 NS 75-235 S	10-65 NS 25-95 S	
RSP, $\mu g.m^{-3}$ (filter)	10-70 NS 50-195 S	10-40 NS 70-205 S	<5-30 NS 10-55 S	
Formaldehyde, $\mu g.m^{-3}$		20-130 NS 30-220 S		
RH, %	37-46	34-46	43-51	22-53
ACR, h^{-1} (calc.)	1.7-8.3	0.6-3.1	0.3-4.0	

U = unvented geyser, V = vented geyser S = smoking inhabitants; NS = no smoking inhabitants.

permeabilities of the 4 homes varied between 137 and 173 $m^3.h^{-1}.(Pa)^{1/n}$.

The ventilation behavior of the inhabitants is very important for the levels. A clear example is given for the bedrooms (see Figure 5). A significant relation was found between the CO_2 concentration and the calculated air change rate; the equation of the best fitting power curve is

$$c = 500 + 265/ACR \quad \text{ppm CO2} \quad R = 0.90$$

With closed windows:
ACR = 0.3-0.9 h^{-1} and c = 840-1540 ppm CO_2

With open windows:
ACR = 1.5-4.0 h^{-1} and c = 470-740 ppm CO_2

The high CO_2 concentrations and low air change rates were not expected in the mechanically ventilated homes. The reason was a poor design and the habits of the inhabitants (see also Table 10).

According to Dutch standards (1975) a ventilation of 14 $dm^3.s^{-1}$ (50 $m^3.h^{-1}$) is required. The design of the ventilation system, however, was 7 $dm^3.s^{-1}$ (25 $m^3.h^{-1}$) for the parents' bedroom in the high position of the fan and 5.6 $dm^3.s^{-1}$ (20 $m^3.h^{-1}$) in the low position. The actual measured airflows were 3.3-4.2 $dm^3.s^{-1}$ (12-15 $m^3.h^{-1}$) in the lower position that usually pertains during the night to reduce the noise nuisance.

No other significant correlations between air change rates and concentrations were found.

The influence of venting the geyser is significant on the concentrations of CO, NO and NO_2. The influence of smoking on the respirable dust concentration and the formaldehyde concentration is also clear. Formaldehyde concentrations of up to 130 $\mu g.m^{-3}$ are found in some homes, most likely due to the application of UFF insulation. The concentrations of nonrespirable (total – respirable) dust varied between <10 and 60 $\mu g.m^{-3}$. The

Table 10 Summarized mechanical airflows in $m^3.h^{-1}$ in the four homes in 's hertogenbosch.

Location	Dutch standard	Design high	Design low	Measured high	Measured low
3 homes with normal design					
Supply:					
Living room	75	75	40	60-80	38-43
Parents' bedrooms	50	25	20	24-27	12-15
Children's bedrooms	25	25	20	16-28	7-14
Exhaust:					
Kitchen	100	75	50	55-70	34-42
Toilet	25	25	25	36-53	30-34
Shower	50	50	25	45-52	26-31
1 home with special design (central supply in hall)					
Supply:					
Hall	(250)*	150	100	170	100
Exhaust:					
Living room/kitchen (open connection)	150	75	50	58	36
Toilet	25	25	25	36	36
Shower	50	50	25	54	36

* Total required

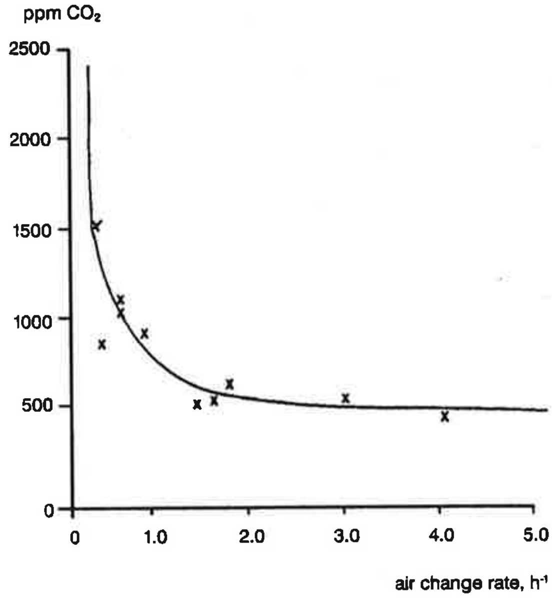

Fig. 5 Relationship between measured 8h averaged CO_2 concentrations and calculated air change rates in the bedrooms. Period: 0.00-08.00 h.
ACR < 0.5 $h^{-1} \rightarrow c >$ 1000 ppm.
ACR < 0.4 $h^{-1} \rightarrow c >$ 1200 ppm.

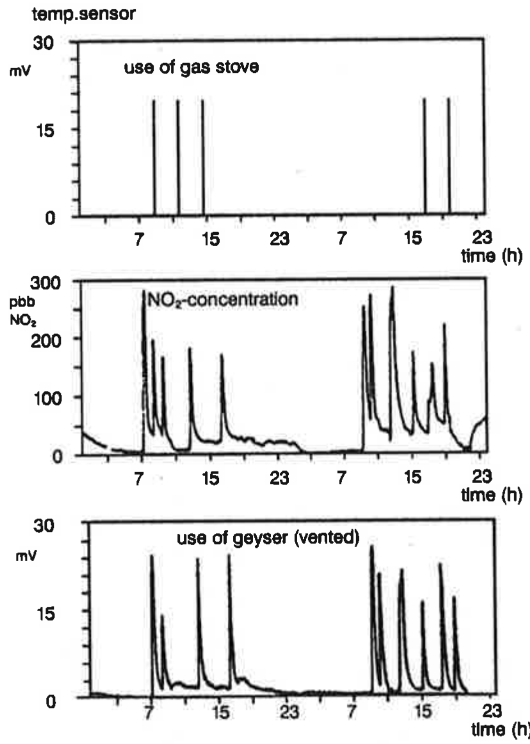

Fig. 6 NO_2 concentration and use of the gas stove and the vented geyser in the kitchen of a single family home with mechanically balanced ventilation. The NO_2peaks are related to the use of a geyser. In a kitchen with an unvented geyser, peaks of up to 400 ppb (770 $\mu g.m^{-3}$) were measured.

concentrations measured are similar to those in Rotterdam for CO and NO (vented geyser), CO_2 and respirable dust (smokers). The NO_2 concentrations were higher with vented geysers (and much higher with unvented geysers). The NO_x concentrations are dominated by the geysers (also vented) and hardly influenced by the gas stove. This is shown by comparing the peaks of NO_x and the use of the gas appliances: the NO_x peaks coincide with those registering the use of the geyser (Figure 6).

Deviations from the guidelines were found for:

- CO_2, especially in the bedrooms;
- NO_2 in the kitchen with unvented geyser;
- RSP in the living room and kitchen of homes where the inhabitants smoked;
- formaldehyde.

General Discussion

Renovation of homes to save energy means that they are made more airtight and air change rates decrease when the behavior of the inhabitants is not adjusted. Mechanical ventilation improves the ventilation if properly designed; energy can be recovered by application of a heat exchanger.

More airtight means less ventilation and higher concentration levels of pollutants from indoor sources. Moreover, the insulating materials could act as new sources of indoor air pollution (see also van der Wal, 1989).

Although direct comparison before and after renovation of the same homes was not possible, the general trend for concentrations of VOC could be determined from this study and other studies performed in the Netherlands: outdoor air < prewar homes < postwar homes < heavily insulated homes as investigated in this study. This trend is related to decreasing air permeabilities of the homes.

Usually, indoor concentrations are higher than outdoor concentrations due to indoor sources. Exceptions are possible for compounds that are strongly adsorbed when penetrating (sinks), such as NO_2 and particulates.

New developments may lead to increasing source strength, for example NO_x from warm water appliances (geysers). Unvented geysers, widely used in the past, are no longer installed in newly built homes.

Health-related guidelines are in use in the Netherlands for some compounds. The probability of deviations due to indoor sources increases as air permeability decreases.

Deviations from the recommended guidelines were found for:

- CO_2 in rooms with poor ventilation. This concerns homes with natural ventilation only, but also applies in some homes with poorly designed mechanical ventilation.
- NO_2 in a kitchen with an unvented local warm water supply (geyser).
- Respirable dust in homes with smokers.
- Formaldehyde, emitted by insulation materials and tobacco smoke.
- Benzene, from outdoor and indoor sources.

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