THE INDOOR AIR QUALITY IN RENOVATED DUTCH HOMES

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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 the ventilation and infiltration were also collected. Relations were made between the observed concentrations and the ventilation. In some cases concentrations show a good relationship with the calculated air exchange rate, in other cases this relationship was poor or absent. Increased levels of pollutants can be ascribed to obvious sources in most cases. The ventilation behaviour of the inhabitants has a major influence on the concentrations.

INTRODUCTION

Because of the high cost of energy for spatial heating - in the Netherlands usually with natural gas- new built dwellings are built more airtight than in the past and 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 mechanical ventilation system with a heat exchanger to recover energy. This could possibly lead to increased levels of air pollutants, on the one side by introducing new sources such as insulation materials, on the other side 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 behaviour 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, a poor indoor air quality can not be excluded.
Concentrations of CO, CO_2, NO, NO_2, dust particles, formaldehyde and hydrocarbons were measured in several types of dwellings in two Dutch cities (Rotterdam and 's Hertogenbosch). Measurements were performed in the living room, the kitchen and the parents' bedroom. The air tightness of the dwelling and the air flow quantities of mechanical air supplies and exhausts were also measured, as well as the temperature and the relative humidity. With the help of the MT-TNO ventilation computer programme (1) the ventilation conditions were calculated for the actual weather conditions.
The relevant characteristics of the homes are summarised in Table 1. The mechanical balanced ventilated homes have also a heat recover unit, consisting of a heat exchanger and two fans.

METHODS

The methods of measurements of pollutants (real time (RT) and time weighted average (TWA)) and of the temperature and relative humidity (RH) are summarised in Table 2. The analog signals of the monitors were digitalised 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 a HP plotter.

Table 1 Characteristics of the homes.

Type	Apartments built in 5 layers	Apartments built in 5 layers	Single in a row 2 layers	Single in a row 2 layers
City	Rotterdam	Rotterdam	Rotterdam	's Hertogenbosch
Ventilation	natural	mechanical balanced	natural	mechanical balanced
Heating	central gas	central gas	vented gas stove	central gas
nr. of bedrooms	2-4	2-5	4	3
nr. of inhabitants	2-5	2-7	4	2-4
Insulation:				
facade	min. wool	min. wool	PS	min. wool, PU, UF
roof	PS	PS	PS	roofmate
floor	PU	PU	-	PU
Warm water supply	geyser vented	geyser vented	geyser vented	geyser 1 unvented 3 vented
Exhaust hood above gas furnace	yes	yes	no	yes, home with unvented geyser excepted
nr. of homes investigated	4	4	2	4
nr. of homes with smokers	4	2	2	4 (2 also invest. without smoking)

PU = polyurethane foam, PS = polystyrene foam, UF = ureaformaldehyde foam

Table 2 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	filter weighing	
VOC	TWA	charcoal adsorption gas chromatography	
Formaldehyde	TWA	impigner, colorimetry	
Temperature	RT	thermocouple	
RH	RT	thin film	6061 HM (Vaisala)

The air tightness of the home was measured using the blow-up method. The air volume flow rates of inlets and exhausts were measured with a compensating flow-meter (ACIN flowfinder). The meteorological data were used from the nearest meteorological station.

RESULTS

Rotterdam

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

The calculated air change rates of the complete homes varied for the natural ventilated apartments between 0.30 and 0.95 h^{-1}, for the mechanical ventilated apartments between 1.05 and 1.35 h^{-1} and was for both natural ventilated single homes 0.60 h^{-1}. For the calculations it was assumed that all doors, windows and additional ventilation openings were closed.

Regression analysis was carried out to find relations between concentrations and air change rates. Most likely is a power curve according to

$$c = a + b/n$$

where c = concentration and n = air change rate.

Table 3 Summarized results of the measurements in Rotterdam average concentrations over 48 hours. The ranges per type of home are mentioned.

Type home	Location	Average concentration (48 h)					
		CO ppm	CO_2 ppm	NO ppb	NO_2 ppb	RSP $\mu g.m^{-3}$	RH %
Apartment natural ventilation (n=4)	kitchen	0.9-2.0	560-950	34-54	19-22	55-240	31-48
	living	1.0-2.0	820-1360	34-79	12-15	120-370	32-44
	bedroom	0.6-1.4	820-1000	11-21	4-14	20-150	51-67
	outdoor	<0.5-1.2	340-460	17-30	16-29	-1)	90-100
Apartment mech. balanced ventilation (n=4)	kitchen	<0.5-1.4	480-840	<2-42	8-16	65-130	18-29
	living	0.5-1.1	460-600	23-41	4-12	40-210	16-28
	bedroom	0.5-1.4	280-870	4-46	4-9	<20-70	15-65
	outdoor	0.6-2.0	290-370	12-37	19-27	-1)	54-65
Single natural ventilation (n=2)	kitchen	0.8-1.3	470-700	15-29	18-31	90-170	23-31
	living	1.1-1.2	550-610	18-32	15-20	90-130	21-26
	bedroom	1.0-1.2	860-950	5-6	<2-6	70-130	29-43
	outdoor	0.7-1.4	300-320	5-12	12-19	-1)	46-59

1) not measured

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

Results:
$c = 0.6 + 0.3/n$ ppm CO $R = 0.76$
$c = 550 + 115/n$ ppm CO_2 $R = 0.56$
$c = 7.5 + 3.1/n$ ppb NO_2 $R = 0.61$
$c = 17.4 + 7.8/n$ ppb NO $R = 0.46$
$c = 42 + 54/n$ $\mu g.m^{-3}$ 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.

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 ppms above base level, their sources are smoking and gas appliances; they are found in the living and the kitchen (Fig. 1).

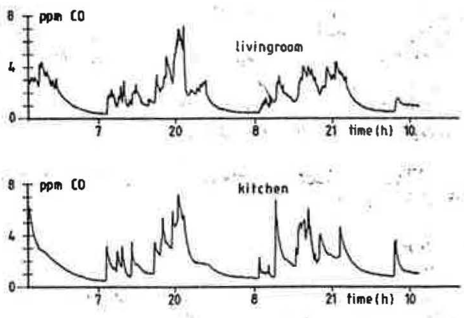

Fig. 1 CO-concentration in the living and the kitchen in a natural ventilated apartment house. Peaks are caused by smoking and the use of gas appliances in the (open) kitchen.

- *CO_2*. In the outdoor air 340-450 ppm CO_2 was found. The main indoor sources are inhabitants (exhaled air) and gas appliances in the kitchen (geyser, furnace). In the bedrooms the average concentration during the night (23.00-08.00 h) in the natural 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 (Fig. 2).

- *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 also raised in the adjacent livingroom. The same patterns as in the kitchen are found in the livingroom, but at a lower level.
  NO is less reactive than NO_2 and concentrations are higher compared with outdoor air.

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

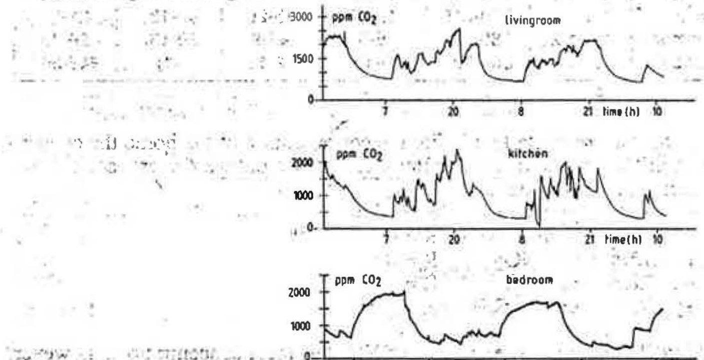

Fig. 2 CO_2-concentrations in the living, the kitchen and the parents' bedroom in a natural ventilated apartment house. CO_2 sources are in the living and the kitchen during the day and in the bedroom at night.

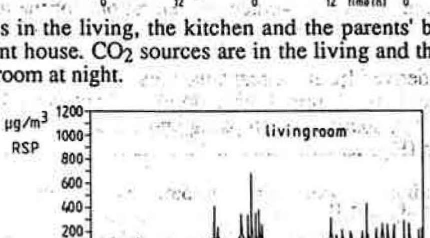

Fig. 3 Respirable dust concentration in the livingroom of a mechanical balanced ventilated single family house. Each peak is caused by smoking of a cigarette.

Time weighted average (TWA) concentrations of volatile organic chemicals (VOC). The results are summarized in Table 4.

Concentrations of CO, NO_2, respirable dust and VOC in other Dutch homes were measured by Lebret e.a. (2). 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 Lebret investigated homes with unvented geysers. The respirable dust concentrations are often higher. In almost all homes lived smokers and in all homes was smoked during the measurements (inhabitants and visitors). The VOC concentrations fall within the range of Lebret's results.
The formaldehyde concentrations are comparible with those found in other Dutch houses where no UF based building materials were used (3).
The sources are tobacco smoke and consumer products.
Styrene not mentioned by Lebret could be generated by the polystyrene foam insulation.

The ventilation was higher in the mechanical ventilated homes than in the natural ventilated homes. The concentrations were lower of most components as is also shown with the presented correlations.

Table 4 Concentrations of volatile organic chemicals in $\mu g.m^{-3}$ as time weighted average over 48 hours.

Component	Apartment nat. vent	Apartment mech. vent.	Single home nat. vent.
benzene	9-31	4-14	6-14
toluene	55-79	18-290	27-51
xyelene isomers	19-40	13-50	8-10
other aromatics	20-35	19-105	10-16
n-alkanes	10-35	17-250	10-17
formaldehyde	5-60	-	-
limonene	10-97	87-130	26-100
α-pinene	4-10	2-40	2
styrene	5-10	1-12	1-2
trichloroethene	20-60	<2	<2

's HERTOGENBOSCH

In the mechanical balanced ventilated homes 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, 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 hours periods. The periods considered were 08.00-16.00 and 16.00-24.00 h, for the living and the kitchen and 00.00-08.00 h for the bedroom. The results of the measurements are summarized in Table 5.
In some homes with smoking inhabitants measurements were also performed during a 48 hour period when the inhabitants abstained from smoking.

The ventilation behaviour of the inhabitants is very important for the levels. A clear example is given for the bedrooms. A significant relation was found between the CO2 concentration and the calculated air change rate; the equation of the best fitting power curve is

$$c = 500 + 265/n \qquad \text{ppm CO2} \qquad R = 0.90$$

With closed windows: $n = 0.3\text{-}0.9\ h^{-1}$ and $c = 840\text{-}1540$ ppm CO_2
With open windows : $n = 1.5\text{-}4.0\ h^{-1}$ and $c = 470\text{-}740$ ppm CO_2

The high CO_2 concentrations and low air change rates were not expected in the mechanical ventilated homes. The reason was a poor design and the habits of the inhabitants.
According to Dutch standards (4) 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 and 5.6 $dm^3.s^{-1}$ (20 $m^3.h^{-1}$) in the low position of the fan. The actual measured airflows were 3.3-4.2 $dm^3.s^{-1}$ (12-15 $m^3.h^{-1}$) in the lower position that is usually established 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. In homes formaldehyde concentrations of up to 130 $\mu g.m^{-3}$ are found, likely due to the application of UFF insulation.
The concentrations of non respirable (total-respirable) dust varied between <10 and 60 $\mu g.m^{-3}$.
The concentrations measured are of the same order as 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 registrating the use of the geyser (Fig. 4).

Table 5 Summarized results of the measurements in single homes with mechanical balanced ventilation in 's Hertogenbosch. Ranges of average concentrations over 8 h periods are given; for the living and kitchen over the periods 08-16 and 16-24 h, for the bedroom over the period 00-08 h and for outdoor over 24 h.
U = unvented geyser, V = vented geyser S = smoking inhabitants; NS = no smoking inhabitants.

Location	Kitchen	Living	Bedroom	Outdoor
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, ppb	<5-120 V 30-235 U	15-70 V 35-195 U	10-25	5-95
NO_2, ppb	30-80 V 50-100 U	15-40 V 25-50 U	10-25	20-40
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
AC, h^{-1} (calc.)	1.7-8.3	0.6-3.1	0.3-4.0	

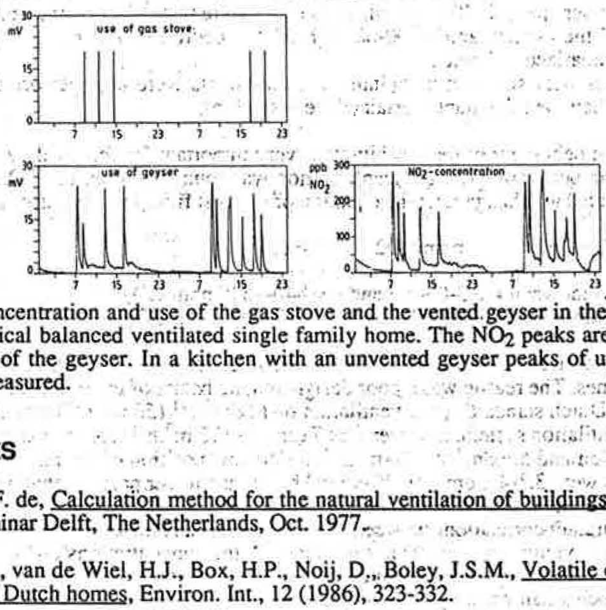

Fig. 4 NO_2 concentration and use of the gas stove and the vented geyser in the kitchen of a mechanical balanced ventilated single family home. The NO_2 peaks are related with the use of the geyser. In a kitchen with an unvented geyser peaks of up to 400 ppb were measured.

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