20% dissatisfied persons is accepted (ASHRAE definition for accepted air quality [7]) then, based on the research of Fanger [2], an outside air volumetric flow rate of 8.24 l/s and olf, i.e. approximately 30 m^3/h and olf is required. If the restaurant is fully occupied, and if the occupants were the only source of pollution (= 550 olfs) the installed air volume flow of 17 600 m^3/h would be suffcient during the peak midday period (Fig. 2). Observations while measurement was in progress show that with the ventilation running, the air quality during this period was always satisfactory, despite the additional load caused by food smells. Outside the main meal period, the average level of occupancy is fewer than 100 people. Over the daily 12-hour period during which the ventilation system is in operation, the average occupancy level is less than 25% of the maximum capacity of the restaurant. Owing to smoking the olf load outside the main meal period is significantly higher, as shown in Figure 3, (steeper curve). If the setpoint for the control system were set to 6.5 AQU for example, (average of peak values during the midday peak with ventilation fully on) the system operating hours could readily be reduced by 30% using demand-controlled ventilation with a mixed-gas sensor for the reference variable.

An estimate of the energy used for distribution and to condition the air to the supply temperature shows that in the case of on/off operation with a conventional system using a plate exchanger for heat recovery, approximately 25 500 kWh per year (approx. 1/3 electricity, 2/3 heating) can be saved (for the climate of Zurich). For a system of this size, the cost of installing demand-based ventilation using a mixed-gas sensor for a reference variable can be recouped within a few months [8].

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VENTILATION RATE AND AIRFLOW MEASUREMENTS USING A MODIFIED PFT TECHNIQUE

Henk J.TH. Bloemen[1], Arnoud P. Verhoeff[2], Thécla T.M. Balvers[1],
Pieter van der Torn[3] and Joop H. van Wijnen[2]

[1] National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands
[2] Public Health Service, Amsterdam, The Netherlands
[3] Public Health Service, Rotterdam, The Netherlands

ABSTRACT

The ventilation rate and the airflows in buildings are important both for the management of (health) complaints related to indoor air quality, and for the assessment of the penetration of outdoor air pollutants into indoor air. A relatively simple method that provides reliable information on the ventilation rate and airflows over longer periods is needed. The BNL/AIMS PFT technique, initially developed by Dietz et al. [1], was modified using commercially available components. Three different perfluorcarbons; perfluordimethylcyclobutane, -methylcyclopentane and methylcyclohexane, were used as tracers. Source strengths were constant within 3% for periods of six weeks at temperatures ranging from 20 to 27 °C. Passive sampling was feasible using Carbotrap as adsorbent. The adsorption and desorption efficiencies were approximately 98%. Samples were analyzed using capillary gas chromatography, a porous-layer open tubular column (Al_2O_3) and electron capture detection. The accuracy of the tracer analysis at concentrations usually obtained for ventilation measurements was within 5 to 10%. In a pilot study the mean coefficient of variation was approximately 5%. The location of the sampling tube and of the source in the room had no significant influence. The mean ventilation rate in the living rooms and bedrooms was 1 and 1.7, respectively. The variation in time was small. The ventilation rate of the living room was higher in older dwellings and/or if occupants were smokers. The ventilation rate of the bedroom was higher in flats than in single-family dwellings and in older dwellings; the rate was also higher if the occupants were smokers and rose with an increasing number of occupants.

INTRODUCTION

The ventilation rate of and the air exchange rates in dwellings and buildings are relevant parameters to making extrapolation of indoor air pollution measurements possible. The ventilation rate is an important parameter for the evaluation of indoor air quality measurements initiated by (health) complaints. When hazardous chemicals are accidentally emitted into outdoor air, the assessment of potential penetration of these pollutants into buildings and the potential exposure is, for example, defined by the air infiltration rate. To identify the location and strength of sources in the indoor environment ventilation rates, as well as air exchange rates, may be of use.

To measure these parameters under normal occupancy conditions a simple method that provides reliable information over relatively long periods and does not affect the behaviour of the occupants is required. The BNL/AIMS (Brookhaven National Laboratory Air Infiltration Measurement System) technique developed by Dietz et al. [1] using perfluortracers (PFT) combines most of the required characteristics but lacks the possibility of applying the method using readily available equipment. Since the development of the BNL/AIMS technique substantial progress has been made in the production of capillary gas chromatography columns and instrumentation. Considering the necessity for measuring ventilation rates and air exchange rates as part of limited and extensive indoor-air quality studies, the BNL/AIMS method was modified using commercially available equipment, allowing the method to be adopted by more

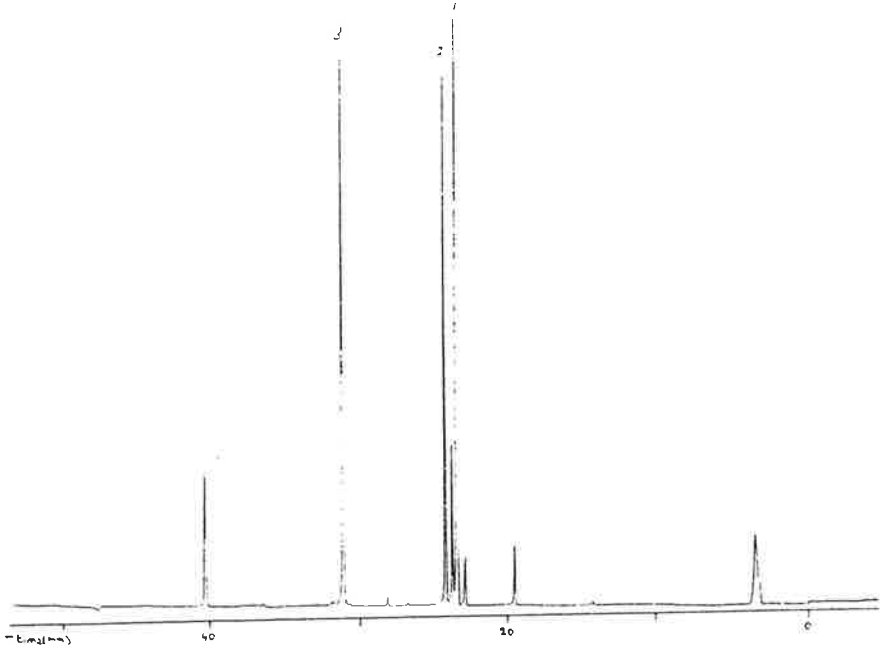
research groups in the field of indoor-air quality.
The modifications involved the replacement of tracer sources by autosampler vials containing one of three perfluorcarbons and using septa as the permeation medium. Thermal-desorption tubes were used for trapping and thermal desorption. The analysis was performed with capillary porous-layer open tubular columns and electron capture detection. The modified method was applied to a pilot study in the city of Rotterdam. In this study airflows were measured in the living rooms and bedrooms of 19 houses of various types. This paper will present the characteristics of the modified method and the results of the study.

METHODS

Measuring method

Three perfluorcarbons were selected as tracers applicable to this method: perfluordimethylcyclobutane (PDCB), perfluormethylcyclopentane (PMCP) and perfluormethylcyclohexane (PMCH). These tracers were commercially available in a sufficiently pure form. PDCB appeared to be present as 1,2- and 1,3-isomers with, for this application, similar physical properties. The limited available toxicological information indicates that these compounds are not harmful at concentrations used for ventilation measurements. Background concentrations of the three PFTs ranged from 4 to 50 ng/m^3 [1].
Initially, a fourth perfluorcarbon, 1,3-dimethylcyclohexane (PDCH), was selected as well. Purity testing showed that it was contaminated with PMCH. Moreover, thermal desorption of PDCH was not complete at the maximum desorption temperature (250 °C) and so this PFT was excluded.
The source consisted of an autosampler vial (Alltech, volume 1.5 ml), filled with 0.3 ml tracer and closed with an open-hole cap containing the permeation medium (Chromsep Red, Chrompack), adjusted in size to fit the dimensions of the cap. The vial was weighed using a microbalance, with an accuracy of 0.01 mg, and stored in a well-ventilated room at a constant temperature of 23 °C. The strength of the source was determined by repeatedly weighing the vial at weekly intervals. Just before and immediately after the application, the vial was weighed again to determine the average source strength. The source strength, approximately 2 - 3 µg/min, was comparable to the strength of the sources reported by Dietz et al. [1]. The inhomogeneity of the permeation medium made it necessary to weigh each source individually. The relatively thin permeation medium allows the establishment of a constant emission rate after only 48 hours but makes this rate more sensitive to temperature variation. However, in a room, in which the temperature ranged from 16 - 22 °C, the source strength was constant within 3% over six weeks and was considered acceptable for this application.
The PFT sampling tubes consisted of slightly modified thermal desorption tubes of the ATD-50 (Perkin Elmer). The original gauzes were replaced with nickel gauzes (120 micron, Stork Veco) and fitted at both ends of the adsorption material (420 mg Carbopack 20/40 mesh, Supelco). Two other adsorption materials were tested: Tenax TA (Chrompack) was found to be too weak and Carboxen 564 (Supelchem) was found to be too strong for the selected tracers. Tracers of adsorbed compounds were removed by repeated desorption (at least five times) at 250 °C. The tubes were sealed with analytical end-caps. During passive sampling one analytical end-cap was replaced by a diffusion cap. The adsorption- and desorption efficiency was more than 98% for amounts ranging up to 1600 ng PFT per sampling tube, collected using active sampling. The passive collection rate was determined to be 15 ± 1 ml/h for the three PFTs.
The compounds were desorbed by thermal desorption at 250 °C, with an additional flow (7 ml/min) of carrier gas, by opening the post-trap split, and focused on a cold trap at -30 °C. Injection on an analytical column (Al_2O_3/KCl, 50 m, 0.32 mm) was achieved by flash heating the cold trap to 250 °C. The column oven was temperature programmed (50 °C for 1 min; 50 --> 180 °C for 3.5 °C/min; 180 °C for 7 min). The detector temperature was maintained at 300 °C. A typical chromatogram is given in Figure 1.
Calibration mixtures were generated by placing sources in a chamber through which a constant flow of 300 ml/min was maintained. This flow was diluted further with an additional flow. From this secondary flow a constant volume (56 ml) was drawn over a PFT sampling tube. The tubes were analyzed and the response factors were determined: PDCB 26.7 mVs/µg, PMCP 49.6 mVs/µg and PMCH 39.0 mVs/µg. The relative standard deviation was 5%.

The ventilation and air exchange rates were calculated using the formulas elaborated by Dietz et al. [1]. Based on the considerations of Ottavio et. al [2] the results of the analysis could be used to calculate the ventilation and air exchange rates if the overall error was less than 25%. The combined error was estimated to be approximately 10% at most if the temperature varied between 17 and 23 °C.
The reproducibility of the method was determined by placing a source in the centre of three different rooms of the Air Research Laboratory (volumes 50-80 m^3). After three days two clusters of PFT sampling tubes were placed at two different locations in that room. For each room a different PFT was used. On consecutive working days two PFT sampling tubes were taken and analyzed for PFT.



Peak identification: 1 - PMCP, 2 - PDCB, 3 - PMCH.

Fig. 1. Typical gas chromatogram of the analysis of a PFT sampling tube.

Field experiment

Nineteen houses of various types (6 flats built in the 1960s and 4 flats built in the 1980s, 5 single-family dwellings built in the 1960s, 4 singlefamily dwellings built in the 1980s) were selected from the Rotterdam Building Establishment Agency's database. The flats were situated on the second to the fifth floor, naturally ventilated and provided with central heating. No houses used forced ventilation in the kitchen. All occupants had taken precautions against draught. The single-family dwellings were also naturally ventilated. Some of the houses had ventilation hoods in the kitchen. All occupants had taken precautions against draught, mainly by reducing spaces in window and door frames. In figure 2 a plan of a typical flat and single-family house and the location of sources and sampling tubes is given.
For two periods consisting of a week, each in spring 1991, the ventilation and air exchange rates were measured in all the houses simultaneously. At the first visit the PFT sources were placed in the living room (PMCH) and in one of the bedrooms (PMCP) according to guidelines of Dietz et al. [1]. The occupants were instructed to ventilate as usual. A short questionnaire was completed and the house was characterized using a checklist. Three days later PFT sampling tubes equipped with a diffusion cap and a minimum-maximum thermometer were placed in the living room and

the selected bedroom. The sampling was carried out in duplicate. After one week the diffusion cap of the PFT sampling tubes were replaced by an analytical end-cap and the PFT sampling tubes were transported to the laboratory for analysis. Sources and sampling tubes were always transported separately. To investigate the variation within a season these measurements were repeated after two weeks.

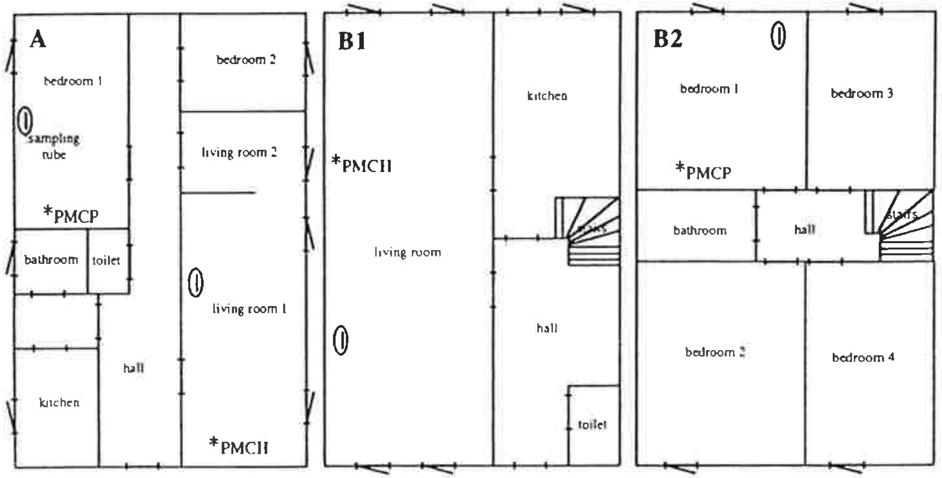


Fig. 2. Plan of a typical flat (A) and singel-family house groundfloor (B1) and first floor (B2)

RESULTS AND DISCUSSION

Measuring method

The results of the reproducibility test show that the amount of tracer collected on the PFT sampling tube increases with time, as was expected given the test design. A low value for PDCB measured after 72 hours was omitted as an outlier. The deviation between the duplicate samples is caused by variations in airflows at the different locations and the analytical error. The systematic and small differences between the duplicate samples for PDCB in one of the rooms of in the Air Research Laboratory (average ventilation rate after 336 hours: 2.3 per hour) indicate that the former is the most important source of the variation. This is because low concentrations occur at high ventilation rates, resulting in a better mixing of the air mass in that room. These results indicate that the overall accuracy depends on the ventilation rate and therefore on the mixing rate of the air mass in that room. The reproducibility after 168 hours (one week) with ventilation rates ranging from 0.4 to 2.5 appears to be more than 10%.

Perfect mixing of a compartment of a building is recalled as being one of the basic assumptions of the methods founded on tracer measurement. These results indicate that this condition is not always met. However, the effect of incomplete mixing was very unimportant; the variation in PFT concentration in a room explained by a sampling location in one room was less than 2%.

Field experiment

For the field experiment in Rotterdam the mean coefficients of variation of the ventilation rate in the living room (VR1) and the bedroom (VR2) in the first sampling period were 8.6 and 3.7%, respectively. For the second period these figures were 1.6 and 4.0%. Outliers were indicated by very low amounts of PFT. The accuracy of the results was better in the second period. As some of the results for two of the houses appeared to be outliers, they were omitted from the evaluation. Therefore the results obtained in 17 dwellings are given (Table 1) and are used for the statistical analysis. The geometric mean ventilation rate of the living rooms (VR1) of all the houses in both sampling periods was approximately 1 (0.9 - 1). For the bedrooms (VR2) this was considerably higher (1.7 -1.8). The average air exchange rate from the living room to the bedroom (AER12) was higher than from the bedroom to the living room (AER21). This implies a net air transport from the living room to the bedroom. The geometric mean of the infiltration of outdoor air (AIR1) and exfiltration flows (AExR1) of the living room were higher than in the bedroom. Considering the recommendation in the Netherlands to have 25 m^3/h fresh air per person in a room, to avoid odour annoyance [3], the air infiltration rate of the living room (AIR1) is just enough for two persons. For the bedroom this is only sufficient for one person. The relative infiltration rate (AIR1/volume of the living room) can be dubbed as the refreshment rate (REFRESH1). This parameter is important for assessing the exposure of occupants to outdoor pollutants, as well as for eliminating the room of pollution from emissions from indoor sources. The difference between REFRESH and VR is the volume of air originating from other compartments of the building relative to the volume of that compartment. As the ventilation in only two of the rooms of the house were measured the overall ventilation rate could not be calculated.

An analysis of variance was performed to estimate the within-home and between-home components of variance. The estimated variance ratio of "error" to "true" variance was generally smaller than one, indicating that the differences in the ventilation rates and airflows between houses were high compared to the variation in time within houses over a period of several weeks. These results are in agreement with those presented by Dietz et al. [1]. Analyses of variance were performed using the different ventilation parameters as dependent variables and a number of house characteristics as explanatory variables. The results for ventilation rates in the living room and the bedroom are presented in Table 2. The ventilation rate in the living room was (marginally) significantly higher in older houses and in houses where smokers were present. Older homes are probably less airtight, and smokers tend to ventilate more. The ventilation rate of the bedroom was significantly higher in flats than in single-family dwellings, in older houses, in houses where smokers were present and with an increasing number of occupants. However, the ventilation rate of the bedroom was lower if a ventilation hood was used in the kitchen. The models for the ventilation rates in the living room and the bedroom explained 48 and 75% of the variance (multiple R^2), respectively.

The air exchange rate between the bedroom and the living room was significantly higher in flats compared to single-family dwellings, and when precautions were taken against draught. The models for the living room and the bedroom explained 47 and 55% of the variance, respectively. None of the explanatory variables included in the analysis of variances had a statistically significant influence on the ventilation rate of the living room. For the bedroom, the exfiltration was significantly higher with an increasing number of occupants, the presence of smokers, in older houses and when the ventilation hood in the kitchen was used. The model explained 80% of the variance. The infiltration rate of the living rooms in singlefamily dwellings was significantly higher than in flats, and where smokers were present. The infiltration rate in the bedroom was higher in older houses, with increasing number of occupants, with the presence of smokers and with the use of a ventilation hood in the kitchen. The models for the living room and bedroom explained 50 and 75% of the variance, respectively.

Table 1. Distribution of ventilation parameters for both sampling periods

Parameter	period I			period II		
	n	GM	GSD	n	GM	GSD
VR1 ($hour^{-1}$)	17	0.90	2.46	17	1.0	1.4
VR2 ($hour^{-1}$)	17	1.66	2.89	17	1.8	2.5
AER12 ($m^3/hour$)	17	17.1	4.7	17	12.9	3.8
AER21 ($m^3/hour$)	17	9.5	5.6	17	9.7	5.0
AExR1 ($m^3/hour$)	16	42.9	1.8	17	55.6	1.5
AExR2 ($m^3/hour$)	17	26.6	3.9	17	31.3	2.9
AIR1 ($m^3/hour$)	17	54.9	1.6	17	59.2	1.5
AIR2 ($m^3/hour$)	13	26.0	2.8	17	26.1	3.4
REFRESH1 ($hour^{-1}$)	17	0.83	1.51	17	0.89	1.48
REFRESH2 ($hour^{-1}$)	13	1.07	2.65	17	1.10	3.30

GM: geometric mean; GSD: geometric standard deviation)
For explanation of the abbreviations see text.

Table 2. Analysis of variance of the ventilation rate in the livingroom and the bedroom.

source	ventilation rate livingroom DF	SS	MS	F	p	ventilation rate bedroom DF	SS	MS	F	p
model	9	2.22	0.24	2.47	0.037	9	24.00	2.67	7.98	<0.001
error	24	2.23	0.10			24	8.02	0.33		
period	1	0.14	0.14	1.43	0.242	1	0.06	0.06	0.18	0.678
type house	1	0.16	0.16	1.66	0.210	1	1.75	1.75	5.24	0.031
age of house	1	0.39	0.39	4.05	0.056	1	8.81	8.81	26.37	<0.001
number of occupants	3	0.22	0.08	0.77	0.520	3	6.42	2.14	6.41	0.002
smoking	1	0.42	0.42	4.42	0.046	1	5.52	5.52	16.52	<0.001
ventilation hood	1	0.18	0.18	1.92	0.179	1	1.66	1.66	4.96	0.036
draught precautions	1	0.07	0.07	0.72	0.404	1	0.83	0.83	2.49	0.128
Multiple R^2	0.481					0.750				

DF: degree of freedom; SS: sum of squares; MS: mean square; F: variance ratio; p: significance.
$N = 17$

These results are in agreement with the results presented by Van Dongen and Phaff [4]. They investigated the behaviour of the occupants of about 280 dwellings in the Netherlands in ventilating using a questionnaire. Non-smokers reported ventilating more in comparison to smokers, whereas with increasing moisture production (related to the number of occupants), people reported ventilating more.
In conclusion, the modified BNL/AIMS technique has been found feasible for measuring ventilation rates and airflows in dwellings and buildings. The field experiment, although performed in a limited number of houses, shows that relevant information can be obtained. This information describes the ventilation habits of occupants in combination with the ventilation due to the construction, and can be used to assess the exposure of occupants during normal occupancy conditions.

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LIMITS OF NATURAL AND MECHANICAL VENTILATION FOR RESIDENTIAL REQUIREMENTS

C. Giaconia [1], G. Cannistraro [1], A. Mazzon [1], G. Rizzo [2]

[1] Dipartimento di Energetica ed Applicazioni di Fisica, Università di Palermo, Viale delle Scienze, Palermo, Italia.
[2] Istituto di Ingegneria Civile ed Energetica, Facoltà di Ingegneria, Università di Reggio Calabria, Italia.

ABSTRACT

This paper reports on an investigation to determine the proper amount of air exchanges available through natural or mechanical ventilation. The "olf" and "decipol" methodology is used to check the quality level of the air. A computer code, developed by some of the authors, makes it possible to compute the ventilation rates for a building utilizing natural ventilation. Thus it is possible to verify the conditions suitable for satisfactory amount of air exchanges available through window and door openings to satisfy an acceptable indoor air quality (IAQ) to the occupants before the need to resort to mechanical ventilation. Two examples, of different geometrical situations, are depicted using a graphic simulation that synthesizes building conditions related to the level of comfort provided by the ventilation.

INTRODUCTION

A recent methodology, proposed by P.O. Fangers and coauthors (1), allows the determination of both the quantity (ventilation rates) and quality of the air to be provided inside a building, in order to bring comfortable conditions to the occupants.
This represents a remarkable enhancement in the analysis of the indoor air quality. The current standards, in fact, only take into account the ventilation rate (l/s, m^3/hour or A.C./hour), with no regards to the quality of the air introduced in the confined environment, implicitly assuming that a high frequency of the exchanges guarantees the needed air cleanliness.

With this new approach, the quality of the air and the pollution produced by a given source, are checked by means of computing the "olf" and "decipol" quantities.
The method, is particularly recommended for commercial buildings and for dwellings operated by mechanical ventilation, when the value of the ventilation rate is known.
But a large amount of residential dwellings (as well many commercial), are currently served by natural ventilation. In these buildings, the comfort conditions are achieved by the occupants properly operating the windows or door openings. For these buildings, there is an urgent need for methods to determine if the natural ventilation rates are satisfactory.