contamination of the outdoor air, the building envelope will remove part of the pollutants. Provided that doors and windows are tightly closed, the indoor concentrations will be lower than might be expected based on air exchange rate and sink rate alone.

CONCLUSION

The study presented here indicates that SO_2 and NO_2 gases are partly removed by the building envelope. As the air exchange increases the trend is towards increasing removal rates, resulting in a decreasing penetration factor. Since the velocity of the air penetrating the building envelope of real residences is larger, the removal of pollutants will be more efficient, and penetration factors may be lower. Exposure of the test house to NO_2 gas resulted in elevated levels of NO inside the test house, appearently because the NO_2 gas penetrating the test house was partly reduced by the building materials to NO. The removal rate for NO_2, as well as the emission of NO, tends to increase with increasing air exchange rate. Future investigations should include wind effects, different relative humidities, other pollutants, and other building materials. Furthermore, the reduction of NO_2 by building materials should be studied in more detail.

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MEASURING VENTILATION RATES ON A LARGE SCALE

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ABSTRACT

The paper presents the application of a passive tracer gas technique for ventilation measurements within a large nation-wide indoor climate study in Swedish dwellings (the ELIB-study). The method and experimental design are described, together with experiences gained from the project. The evaluation and error analysis techniques are discussed from an example. Special attention is paid to the accuracy of the results and probable causes and size of errors. It is shown that the ventilation flow rates could be estimated within an acceptable degree of uncertainty.

INTRODUCTION

As part of a nation-wide energy and indoor climate survey in Sweden during the winter season 1991/92 (the ELIB-project) the ventilation rates in a statistical sample of the stock of Swedish dwellings have been measured using a passive tracer gas method. For an overview of the ELIB-study, see a paper by Norlen & Andersson presented at this conference.

The present paper shortly describes the passive tracer gas technique, which has been used and serves to report the routines involved, the evaluation process and some experiences gained from the project. Special attention is paid to the possible magnitude and causes of errors in the computed values of ventilation flow rates.

The overall result and a statistical treatment of the study is presented in a paper by Boman Kronwall at this conference.

METHOD

Passive tracer gas techniques for ventilation measurements

The general principles of the passive tracer gas technique (PFT-technique) for ventilation measurements have been described in several papers the last few years. In the present work the SIB passive tracer gas technique has been used. This method which is a variant of the general concept, has been developed at the National Swedish Institute for Building Research. It has been described in detail elsewhere (1), and therefore only a short summary is given here.

The technique involves the following steps:

1. Diffusion sources, with a constant tracer gas emission rate are distributed in the dwellings. Two different tracer gases were used, both of the perfluoro-carbon type: perfluorobenzene (A) and perfluoromethylbenzene (B).

2. Diffusion air samplers are distributed in the dwellings. For this type of sampler the trapped amount of tracer is directly proportional to the sampling time and the average tracer concentration at the sampling point. The samplers are standard charcoal sampling tubes, open at one end. During non sampling periods, the opening is covered with a plastic cap.

3. After a suitable sampling time, the samplers are analysed at the laboratory for the amount of trapped tracer, using liquid extraction, gas chromatographic separation and electron capture detection.

4. The average ventilation rate is computed from the analysed amount of tracer and other known parameters.

In the one-zone approach only one type of tracer gas is used. In this approach it is assumed that it is possible, by air sampling, to obtain a single representative value of the concentration of the tracer gas in the air leaving the measured object. The average total ventilation rate Q can be calculated from this concentration (C) and the tracer gas emission rate ($\dot{m}$) using the simple mass balance for tracer gas:

$$Q = \frac{\dot{m}}{C} \qquad (1)$$

In the two-zone approach two different types of tracer gases are used - one in each zone. In this case it is assumed that it is possible, by air sampling to get representative values for the concentration of the tracer gases in the air leaving each zone. There are four different concentrations involved in the mass balance.

The inverse flow matrix Q^{-1} can be calculated from the measured concentrations and the known tracer emission rates $\dot{m}$.

$$Q^{-1} = \begin{bmatrix} \frac{c_{11}}{\dot{m}_a} & \frac{c_{12}}{\dot{m}_b} \\ \frac{c_{21}}{\dot{m}_a} & \frac{c_{22}}{\dot{m}_b} \end{bmatrix} = \begin{bmatrix} \frac{1}{\bar{q}_{11}} & \frac{1}{\bar{q}_{12}} \\ \frac{1}{\bar{q}_{21}} & \frac{1}{\bar{q}_{22}} \end{bmatrix} \qquad (2)$$

where it is assumed that tracer gas A has been emitted in zone 1 and tracer B in zone 2. As an example c_{12} stands for the concentration in zone 1 of the tracer gas emitted in zone 2.

Field investigation

The ELIB indoor air quality study, in total involved 1500 dwellings and included measuring averages of ventilation rates during approximately one month. Due to the large size of the study, it was necessary to use a simple and well-defined method for measurement and evaluation.

The measurement protocols were prepared in advance at the laboratory, with all available information filled in, including the proposed locations of all the equipment, on available plans of the dwellings. A trained staff of consultants visited the homes and started the measurement. Any deviations from the proposed locations were notified by them. After a month the occupants returned the measuring devices to the laboratory by mail.

The general proposed positions of samplers is to sample at identifiable air exhaust points (e.g. kitchen, outside bathroom and at other exhaust points) . An extra sampler (not intended for evaluation of the total ventilation flow rate) is also positioned in source rooms. A minimum of two samplers in apartments and three in houses, besides those in the source rooms were used.

In single storey apartments one source (type A or B) was placed in the living room. In one-family houses two sources (A and B) were used - one in the living room and the other one preferably in a bedroom. If there were two storeys, the sources were positioned on different floor levels.

Motivation for deployment of samplers and sources

In the mass balance equation for evaluation of the total ventilation flow rate, the pertinent concentration is that of the air leaving the system. Therefore, if the mixing of tracer gas is not uniform, the air should be sampled, where most of the air is expected to leave the zone, i.e. at the exhaust points. In the one-zone approximation, it is assumed that the concentrations are equal at all exhaust points. However, this will seldom be the case, and the air should therefore be sampled at more than one exhaust point, in order to evaluate the extent to which the one-zone approximation is valid.

The choice of the living room for the position of the tracer gas source, is due to the fact that it is usually the room, which has the greatest supply of air. Therefore, it is assumed that tracer gas injection in that room, will give the most uniform spreading of the tracer gas towards the exhaust points. This was verified by a series of experiments in both laboratory and field.

The ELIB study was preceded by an extended field test in approx. 20 apartments and houses, where the routines and evaluation techniques were tested.

Error estimation

There are several sources of uncertainty involved in the measurement. Firstly, there are uncertainties connected to the tracer gas technique itself. Those uncertainties have been studied in the laboratory. Below, these sources of error have been listed together with their relative standard deviations s [%]. The total uncertainty in the technique is obtained from the square root of the sum of squares of the individual standard deviations.

-emission rate from tracer gas sources	8%
-sampling rate in sampling tubes	5%
-sampling rate calibration	5%
-analysis	3%
-total (technique)	11.1%

The second, often more important source of uncertainty is due to the fact that the assumptions made in the calculation model are not exactly valid during measurements. The two most important error sources due to the measuring object are that the sampling points are not representative of air leaving the zone and that the ventilation rate might have varied during the measurement period. The former of these error sources is estimated by using more than one sampler located at different possible air exhaust points in the zone. The standard deviation (s_r) between the ventilation flows calculated from each of these samplers is used as an estimate of the uncertainty of the zone flow, due to this source of error. Integrating sampling of tracer gas, yields an underestimate of the calculated ventilation flow, if the flow rate varies during the sampling time. This underestimate may be as large as 15% for naturally ventilated houses, but has not been taken account of in the error calculation.

The third important source of error is contamination and other mistreatment of samplers. Contamination causes calculated ventilation flows to be too low, and thus gives a varying systematic error towards low ventilation rates. Approximately a hundred of the investigated 1500 dwellings showed samplers with exceedingly high concentrations of the tracer gases, and were sorted out. However, analysis of delivered, but unused samplers, showed that contamination of capped samplers was uncommon. Certain contamination occurring at the post office, can not be completely ruled out, as an influence on some of the data.

Evaluation

The calculation of the total ventilation flow rates was performed by use of the computer program EXCEL, in which all the pertinent data, including the result of the analysis was included. The calculation can be illustrated by the example given below.

For each sampling point a $\bar{q}$-value (corresponding to the ventilation flow rate in a perfectly mixed ventilation) is calculated from:

$$\bar{q}_i = \frac{\kappa \cdot (\dot{m} \cdot T)}{M_i} \tag{3}$$

where κ is the equivalent air sampling rate for the tracer gas on the samplers, $\dot{m}$ the emission rate of tracer gas, T the sampling time and M_i the analysed amount of tracer at the measuring point *i*. For the tracer A the sampling rate has experimentally been determined to be $18 \cdot 10^{-6}$ [m^3/h] and for the tracer B $16 \cdot 10^{-6}$ [m^3/h].

In the one-zone approach the total ventilation rate Q is computed from the harmonic average of the $\bar{q}$-values at the sampling points.

The relative standard deviation of the computed total ventilation flow rate, due to different analysed amount of tracer at the different sampling points (s_r) is calculated from the standard deviations of the $\bar{q}$-values, divided by the calculated total ventilation flow rate (Q).

For the two zone calculation, the calculation scheme is indicated in the table 1.

Table 1. Calculation parameters for one- and two-zone approaches

	-------- zone 1 ---------				zone 2				one zone approx.		total error
tracer type	M_1 [ng]	$\bar{q}_1$ [m^3/h]	M_2 [ng]	$\bar{q}_2$ [m^3/h]	M_3 [ng]	$\bar{q}_3$ [m^3/h]	$\dot{m}$ [ng/h]	T [h]	Q [m^3/h]	s_r%	%
A	3.37	142	3.23	148	2.67	179	27420	970	155	12.8	16.9
B	0.82	183	1.04	144	1.71	88	9660	970	126	37.9	39.5
Two zone calculation					Q = 149 [m^3/h], total relative error = 15.6 %						

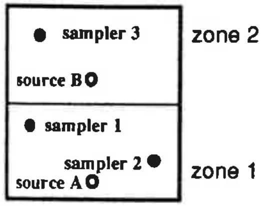

Fig. 1. Positions of sources and samplers in a two-storey house

From this example, it is evident that the tracer gas, which is emitted in zone 1 is spread fairly evenly between the two zones, as indicated by the low value of the relative standard deviation s_r (12.8%). However, the tracer gas emitted in zone 2, has a very uneven distribution between the two zones (s_r= 37.9%).

This behaviour is very common in two-storey houses. Most two storey-houses have an open stairway. The stack effect means that most air at the top level emanates from the ground level. Thus, both levels will have approximately the same concentration of the tracer emitted at the ground level.

In a case like this, the one zone approximation, using only the tracer gas emitted at the ground level, would give a satisfactory result. However, calculation according to the two zone approximation is always tried when possible. The elements in the Q^{-1}-matrix (see equation 2) for the illustrated case are shown in the table 2 .

Table 2. Elements in the in the inverse flow matrix Q^{-1}

1/145	1/161
1/179	1/88

The elements of the flow matrix Q are obtained by inversion of the Q^{-1}-matrix and are displayed in table 3 in bold numbers.

Table 3. Elements in the flow matrix Q and the computed inter-zone flows.

	from zone		
to zone	1	2	outdoor
1	**259**	**-141**	118
2	**-131**	**161**	31
outdoor	128	20	149

Table 3 shows that there is a total ventilation flow rate of 149 m^3/h to the house, very close to the value computed with the one zone approximation, using the tracer gas emitted in zone 1 only (155 m^3/h, see table 1, and that very little air is exchanged directly between zone 2 and the ambient. In this case, the 2-zone approximation gives reasonable results, and can be used to compute the total ventilation flow rate. However, in many cases, the two zone approximation fails. In these cases, the total ventilation flow rate has been computed from a weighted average of the two one-zone approximations. The weighing functions being the total variances in the computed one-zone flows. The total variances for the one-zone flows in the example given above are:

$$s_A^2 = (0.128^2 + 0.111^2) \cdot Q_A^2 = 0.169^2 \cdot Q_A^2 \quad \text{and} \quad s_B^2 = (0.379^2 + 0.111^2) \cdot Q_B^2 = 0.394^2 \cdot Q_B^2 \tag{4}$$

$$\bar{Q} = \frac{s_B^2 \cdot Q_A + s_A^2 \cdot Q_B}{s_A^2 + s_B^2} \quad \text{and} \quad \bar{s}^2 = \frac{s_B^2 \cdot s_A^2}{s_B^2 + s_A^2} \tag{5}$$

which yields a total ventilation flow $\bar{Q}$ = 148.6 m^3/h, with an estimated standard deviation $\bar{s}$ of 15.6%.

In figure 2 the distribution of uncertainties in the total ventilation flows in apartments is illustrated . It can be seen that no ventilation flows are estimated better than within 11.1% (technique uncertainty) and that approximately 50% of the cases have an uncertainty in the estimate that is less than 16%.

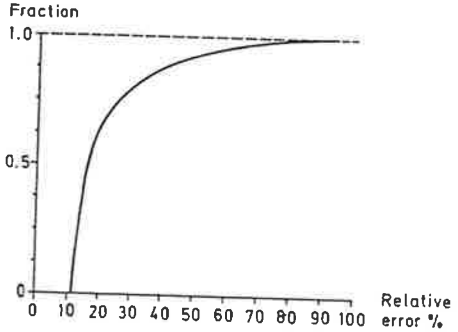

Fig. 2. Distribution function of relative uncertainties in the estimated ventilation flows in apartments. The diagram displays the fraction of cases, which has a relative standard deviation less than a given value.

CONCLUSIONS

This large-scale study of ventilation rate, required a simplified approach of experimental design, stringent laboratory routines and an uniform evaluation process. Experimental layout could not be optimised for every dwelling. In spite of this, the error analysis shows a satisfactory distribution of uncertainties. Only 10% of the cases show an uncertainty larger than 40% in the estimated ventilation flow rate, while 50% of the cases show an uncertainty less than 16%. Example of factors which helped to perform the study in a uniform way are: a pilot pre-study, a training course for the staff working in the field, and the fact that most dwelling plans were available in advance. There were a limited number of drop outs, due to contamination of samplers during use and transport. In a few cases (less than 10), the samplers were not returned to the laboratory.

The laboratory staff has followed accurate and disciplined laboratory and data filing routines. The importance of this can not be emphasised too much in such a large study.

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THE HELSINKI OFFICE ENVIRONMENT STUDY: AIR CHANGE IN MECHANICALLY VENTILATED BUILDINGS

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ABSTRACT

In this study the ventilation of office rooms of 1782 persons were measured in 33 randomly selected office buildings in Helsinki metropolitan area. Ventilation system characteristics in these buildings were also studied.

The average exhaust air flow rate was 1.2 l/s,m^2 or 17.2 l/s,occupant. The variance of air flows was found to be very high among the buildings, and among the rooms in a building. This indicates poorly balanced air flows in office buildings. Therefore, even though ventilation rates on the average comply with the Finnish building code (1), many people are exposed to either too low or too high ventilation rates.

Most office buildings in the Helsinki metropolitan have a ducted supply and exhaust system with hot water radiator heating. Air recirculation is used in about half of the buildings with mechanical supply and exhaust systems.

INTRODUCTION

This study is a part of the Helsinki Office Environment Study with a general objective to study the building related determinants of health and well-being of the office workers.

The magnitude of air change affects both the concentrations of chemical and biological indoor air pollutants and the components of thermal climate, such as air temperature and velocity, thus it is an important factor in the health and well being of the office workers (2).

The type and performance of a heating, ventilating and air conditioning (HVAC) system affect the indoor air quality of the building or ventilation zone. The symptoms and perceptions concerning health and comfort of an occupant have been attributed to the characteristics of the HVAC system (3). There is evidence that buildings with mechanical supply and exhaust, especially in connection with water-based humidification or air conditioning might present a greater risk of the symptoms connected to the sick building syndrome than naturally ventilated buildings (4)(5).

The aim of this study was to assess the magnitude and balance of mechanical air change in office buildings of Helsinki metropolitan. Also the use of air recirculation, humidification, air conditioning, the type of heating and filtering systems as well as the size and age of the buildings were studied.