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THE PENETRATION FACTOR AND REMOVAL RATE BY THE BUILDING ENVELOPE FOR SO₂ AND NO₂ GAS

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ABSTRACT

The study presented here gives an indication of the removal rate of contaminants by the building envelope. To determine this removal rate and the corresponding penetration factor, a model of a residential building was built inside a controlled exposure chamber. SO₂ and NO₂ gases were injected into the supply air of the chamber, and concentrations in both chamber and model were monitored. The experiments indicated that the building envelope removed part of both gases, resulting in lower indoor concentrations. Exposure of the model to NO₂ gas resulted in elevated levels of NO inside.

INTRODUCTION

Ventilation and infiltration air can bring outdoor contaminants into the indoor environment. Using mechanical ventilation systems, the outside air can be cleaned as part of the conditioning before introduction into the occupied space. For building constructions with natural ventilation, contaminated outside air enters through windows, doors, cracks, and other openings in the structure. The fraction of the contaminants that will be absorbed by the materials that make up the building envelope is the removal rate. The fraction of outdoor pollutant concentration that is not removed by the building envelope, but enters the building, is the penetration factor. The entry and subsequent fate of outdoor contaminants in the building envelope are not well known. The study presented here gives an indication of the removal rate of SO₂ and NO₂ gas by the building envelope. These gases were used because they are major outdoor pollutants and relatively easy to generate and analyze.

METHOD

A mass-balance model has been developed (1), which relates outdoor pollutant concentration, building penetration factor, air exchange rate, indoor sources, and sink rate, with indoor pollutant concentration. This model assumes uniform mixing, and that air exchange rate, penetration factor, emission, and sink rate are constant. The building penetration factor, P, represents the fraction of outdoor pollutant concentration that penetrates indoors, i.e., is not removed by the materials that make up building envelope. If, for a compartment, the air exchange rate, the sink rate for a given pollutant, and the

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emission of sources present are known, the penetration factor for that compartment in a steady state situation can be derived from the mass balance equation:

$$P = \frac{C_i (n + k_s) - E}{n C_o} \quad (1)$$

where: C_i = indoor pollutant concentration (ppm); C_o = outdoor pollutant concentration (ppm); n = air exchange rate (h^{-1}); P = penetration factor (-); k_s = sink rate (h^{-1}); E = emission ($ppmh^{-1}$). If windows and doors are closed, air penetrates through cracks in the building envelope and a fraction of the pollutants will be removed by the sides of these small openings. The removal rate of the building envelope for the outdoor pollutants, k_s , is the rate of removal of the pollutants due to reaction of the pollutants with other pollutants, water vapor and/or surfaces inside the building envelope. For a steady state situation K_s can be calculated from:

$$K_s = n (1 - P) \quad (h^{-1}) \quad (2)$$

The experimental set up to investigate the penetration factor consists of a model of a residential building, built inside an exposure chamber. An all aluminum environmental chamber, 34 m³ with a total surface area of 185.2 m², was used for these experiments. The chamber possesses excellent temperature control, using modulated chilled water for cooling and modulated steam coils and electric heating elements for heating. Air enters the chamber via a plenum beneath the floor, streams upward through 13,900 perforations, and leaves the chamber via four return grilles in the ceiling. The design allows a volume flow upwards of up to 1,000 ls⁻¹ with low velocity and rapid mixing. The test house is modeled after an American residential building. These houses typically have a concrete basement, and one or two stories and an attic of wood construction. The basement and the attic have high air exchange rates with outside air and very low air exchange rates with the rest of the house. It can therefore be assumed that the air in the basement and attic is the same as outdoor air. The model therefore consists only of the living area of the house. The model was built using materials and techniques commonly used in the construction of this type of housing. Outside measures are 1283 x 1867 x 1607 mm³. Walls, floor and ceiling are insulated with 102 mm rockwool between studs (600 mm). Walls and ceiling are covered on the inside with gypsum board, painted with latex-based paint, the floor is plywood. The outside walls are covered with hardwood shingles, nailed on plywood, covered with wind barrier paper. The floor and ceiling are covered with plywood. The outside shingles and roof are painted with a penetrating clear wood finish and preservative. A window, with double glass and weather stripping is placed in one wall. The ratio between glass surface and total wall surface is approximately 14%, which is similar as for real residences. Surface to volume ratio (inside) is 4.92 (m⁻¹). For a real residence the surface to volume ratio would be about 0.4 (m⁻¹). The test house is placed about 25 cm above the floor of the chamber to allow air to flow underneath. The temperature in the test house is regulated with an electric heater, placed in the middle on the floor.

Before each experiment is started, the windows of the house are opened, and the chamber is flushed with outside air for several hours. Subsequently the windows are closed tightly, and the temperature of the chamber (15-25°C, 50-70% RH) and the test house (23-31°C, 40-55% RH) are set and given sufficient time to stabilize. SO₂ or NO₂ is injected at a high flow rate into the chamber until a concentration between 0.3 - 0.5 ppm is reached.

Subsequently, gas injection is reduced and the concentration in the chamber is kept constant. Concentrations, temperature, and relative humidity are recorded continuously in both the chamber and the house. The air exchange rate for both is calculated with the decay method using CO₂. Steady state is reached when the indoor concentration does not increase more than 5% per two hours. After several hours of steady state, the window is opened partially (open space of 20 cm²). When steady state is reached again, the window is closed, and the gas injection stopped. The penetration factor is calculated from equation 1, using the concentrations measured in the chamber and in the test house, the air exchange rate, and the sink rate determined in previous experiments. Subsequently, the removal rate of contaminants by the building envelope is calculated from equation 2.

CO₂ concentration was measured with the non-dispersive infrared (NDIR) analysis technique. The SO₂ analyzer used the principle of UV excitation of SO₂ molecules. The NO-NO_x analyzer was a gas phase chemiluminescence detection device which performs a continuous dry analysis of NO, NO_x, and NO₂.

RESULTS AND DISCUSSION

In order to determine the penetration factor using the mass-balance equation, several conditions have to be met: uniform mixing, constant air exchange rate, no emission, and constant sink rate. Several tests were carried out, measuring CO₂ at different locations in the house showing the air in the house to be well mixed. In all subsequent experiments, CO₂ concentration was measured in one location and the decay curve used to verify a well mixed condition. All showed only small fluctuations of concentrations on the decay curve, implying well mixed conditions. The air exchange rate of the test house was primarily dependent on the temperature difference between the house and the chamber and was not significantly influenced by the air change rate of the chamber. During each experiment, temperatures were constant and the air exchange rate of the test house was measured with the CO₂ decay method several times, and the average value used to calculate the penetration factor. There are no direct sources that emanate pollutants in the test house or the chamber. Spicer, 1986 (2), studied several materials for re-emission of NO₂ with increasing temperature, relative humidity, and extended times. NO₂ was never re-emitted, although some materials, including plywood and plasterboard, evolved NO. No data is available for SO₂, but since the sink rate for SO₂, found in the literature (3,4), is very high, it may be assumed that re-emission can be neglected.

The sink rate inside of the test house was determined for the same temperatures and relative humidity as used in the experiments to determine the penetration factor. The sink rate for the test house for SO₂ was determined for two different situations. In the first situation, the sink rate was 3.02 (h^{-1}). In the second situation, thermo-couples were placed inside, and temperature and relative humidity, were increased (30%). In the latter situation, the removal was more efficient: the sink rate increased to 4.02 (h^{-1}). The sink rate for NO₂ was 1.38 (h^{-1}). During the experiments to determine the sink rate for NO₂, the NO concentration inside the test house increased slightly. The sink rate for NO₂ can be compared to rates found in the literature, if adjusted for the surface to volume ratio, e.g., using the effective decay constant (2). The effective decay constant is defined as the sink rate found in the field, multiplied by the surface to volume ratio of the present study, and divided by the surface to volume ratio used in the field. The sink rate observed for NO₂

fits in the range found in the literature (adjusted rates: 0.92-2.46; 2,5,6). Data for SO₂ were not available from the literature.

To assess the penetration factor experiments were carried out in which concentration in the chamber, air exchange rate, and sink rate inside were varied. Table 1 gives the average concentrations in the chamber and the test house, the applicable sink rate, the average air exchange rate of the test house, and the calculated penetration factors and building envelope removal rates. Higher air exchange rates lead to higher removal rates for the building envelope. Consequently, the penetration factor is smaller. When the window of the test house was opened partially, the concentration inside the test house increased until the concentration penetrating equals the concentration removed by the interior. Since the air can enter freely through the open window, the removal by the building envelope had no effect on the indoor concentration. The concentration measured was slightly higher than expected probably due to the open window causing the air in the test house not to be well mixed. Note: a fan was not used to mix the air since this would influence the sink rate inside the test house.

Table 1. Results of SO₂ and NO₂ experiments, where: C_o: average concentration in chamber (SD≤ 0.03); C_i: average concentration in test house (SD≤ 0.03); k_s: sink rate of the inside of the test house; P:penetration factor; n: air exchange rate of the test house; K_b: removal rate of contaminants by the building envelope; SD: standard deviation (in brackets); SE: standard error (in brackets). Concentrations with an * were measured with the windows open.

	C _o ppm	C _i ppm	k _s h ⁻¹ (SD)	n h ⁻¹ (SD)	P (SE)	K _b h ⁻¹ (SE)	C _o ,NO ppm	C _i ,NO ppm	E _{NO} ppmh ⁻¹
SO ₂	0.38	0.04	3.02(0.02)	0.53(0.05)	0.74(0.15)	0.14(0.08)			
	0.18	0.02	4.02(0.06)	0.69(0.02)	0.75(0.14)	0.17(0.10)			
	0.40	0.04	4.02(0.06)	0.82(0.05)	0.59(0.07)	0.34(0.06)			
	0.16	0.02	4.02(0.06)	1.04(0.05)	0.49(0.10)	0.53(0.11)			
	0.41*	0.16*	4.02(0.06)	-	-	-			
NO ₂	0.38	0.02	1.38(0.00)	0.68(0.04)	0.18(0.01)	0.56(0.01)	0.03	0.21	0.12
	0.36	0.03	1.38(0.00)	0.92(0.01)	0.23(0.03)	0.71(0.03)	0.05	0.19	0.13
	0.41	0.04	1.38(0.00)	1.06(0.04)	0.23(0.02)	0.82(0.02)	0.03	0.18	0.16
	0.41*	0.24*	1.38(0.00)	-	-	-	0.03*	0.08*	

Similar experiments were carried out to assess the penetration factor for NO₂, using the same calculations and assumptions as for the SO₂ experiments. During the experiments, the concentration of NO₂ in the test house increased slightly as expected, but the NO concentration increased considerably, see Table 1 for results. The emission of NO was calculated assuming that no NO is removed by the building. The emission of NO, as well as the removal rate for NO₂ seem to increase with increasing air exchange rate, but not statistically significant. The penetration factor increases slightly, but from these data it is not clear whether the penetration factor will further increase for higher air exchange rates.

After several hours of steady state, the window of the test house was opened partially. The NO₂ concentration in the test house increased, while the NO concentration decreased. Apparently, the NO₂ gas penetrating through the building envelope was partially reduced to NO. An annular denuder (7,8,9) was used to filter the air sample for HONO before analyzing. These measurements showed that the NO evolved from the building materials is primarily NO, not HONO, as might be expected. The coatings of the denuders were not further analyzed, so it could not be determined whether HONO was generated at all.

Although the chamber concentration is higher than concentrations found outdoors, we assume that this does not influence the penetration factor. The indoor/outdoor concentration ratio in this study is in the range of the ratios found in field studies (10,11). Brauer, 1991, measured indoor and outdoor concentrations of SO₂ during summer and winter periods in Boston, Massachusetts. For the winter period they found a ratio of 0.05, with outdoor concentrations ranging from 2.05 to 10.46 ppb, and indoor concentrations ranging from below detection to 1.57 ppb. For the summer period they found a ratio of 0.39, with outdoor concentrations ranging from 0.62 to 13.86 ppb, and indoor concentrations ranging from below detection to 8.34 ppb. Assuming that in the winter period windows and doors are closed most of the time, this situation is comparable with the test house with closed windows. In the summer windows and doors are opened more frequently and during extended periods of time, this situation is comparable with the test house with opened windows. Both ratios found in the field study are lower than the ones found in our study. These differences are possibly caused by the fact that measurements were taken inside occupied homes, which are likely to have a higher sink rate due to differences in internal surfaces and furnishings. Wanner, 1990, measured indoor and outdoor NO₂ concentrations in 1225 apartments, in four different cities in Switzerland. For homes with no sources of NO₂, they found an indoor/outdoor ratio of 0.36 during the winter period. During the summer period, a ratio of 0.55 was found, which is only slightly lower than the one found in our study for the situation with partially opened windows. Comparing the ratio for the winter period with the one found in the situation with the window closed show different results. This might be due to different building materials and/or change of temperature and humidity. More research is needed to investigate the reduction of NO₂ to NO by materials.

In order to translate the penetration factor found for the test house to a factor for real residences, the scale factor should be taken into account. The model is built with the same materials and construction techniques as a real residence and a similar percentage of openings. Therefore, we assume that the amount of cracks through which the air penetrates per square meter is equal for model and real residence. The air exchange per hour for the test house is the same as one may expect for a real residence, but the air volume penetrating per square meter for a real residence is higher. Comparing the model to a two-story residence, the air volume is approximately 12.5 times higher than the volume penetrating through the walls of the model. Therefore the air velocity in the cracks for the real residence must be 12.5 times higher. In addition, the velocity of the air penetrating the building envelope may also be larger due to wind effects. The results from these experiments indicate that increasing air exchange, i.e., increasing air velocity, increases the amount of pollutants removed by materials. For real residences, the penetration factor could be even smaller than the one found for the test house. Temperature, relative humidity, and concentration levels are different in ambient air and change during the diurnal cycle and may also affect the penetration factor. During a case of a sudden

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 SO₂ and NO₂ 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 NO₂ gas resulted in elevated levels of NO inside the test house, apparently because the NO₂ gas penetrating the test house was partly reduced by the building materials to NO. The removal rate for NO₂, 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 NO₂ 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).