A COMPARISON OF THE PERFLUOROCARBON AND TRACER GAS DECAY METHODS FOR ASSESSING INFILTRATION RATES IN RESIDENTS

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Introduction

The only direct measure of air infiltration in residences under normal occupancy conditions is by the tracer gas technique, applied to assessing infiltration rates in two ways. The first method is generally referred to as the tracer gas decay method and the second is referred to as the steady-state tracer gas method.

One steady-state tracer gas method for assessing air-exchange rates, called the Brookhaven National Laboratory Air Infiltration Measurement System (BNL/AIMS) (1) is being extensively employed in large field studies of indoor air quality and impact of weatherization. The BNL/AIMS method consists of miniature perfluorocarbon tracer (PFT) sources and miniature passive capillary adsorption tube samplers (CATS). The sources and samplers are about the size of a cigarette. The PFT sources use one of our perfluorocarbon compounds: perfluorodimethyl cyclohexane (PDCH); perfluoromethylcyclohexane (PMCH); perfluoromethylcyclopentane (PMCP); or perfluorodimethylcyclobutane (PDCB). Vapors from the perfluorocarbon liquid in the PFT sources permeate through an elastomeric plug crimped into one end. The PFT sources emit the tracer gas at a constant rate for 2 to 7 years. The emission rate, however, does vary with temperature (2). The emission rates are determined gravimetrically. The CATS device is a passive sampler utilizing about 50 mg of type XE-347 Ambersorb as the collection media. After sampling, the collected tracer gas is thermally desorbed into a gas chromatograph for determination of the PFT.

This paper summarizes the results of experiments to evaluate the BNL/AIMS method. The accuracy of the BNL/AIMS system by comparison with CO_2 tracer decay and the impact of orientation of CAT samplers with respect to flow direction as well as the impact of variations in infiltration rate and temperature are evaluated under conditions of near ideal air mixing in an environmental chamber. Detailed description of the experiments and their results are presented elsewhere (3).

Methods

The all aluminum chamber in which these experiments were conducted was 34 m^3. The floor, 11 m^2, consisted of uniformly perforated aluminum sheets and served as an air diffuser. Air entered the chamber via a plenum beneath the floor and flowed upward through the perforations to the ceiling. The design allowed a volume flow (recirculation rate) up to 2000 cfm (1 m^3/s) with low linear velocity and very rapid mixing. A variable percentage of the recirculated air could comprise fresh ventilation air. The chamber possessed excellent temperature and humidity control.

The PFT sources and CAT samplers were supplied by the Department of Applied Science, Brookhaven National Laboratory (BNL). Analysis of the CAT samplers and emission rate determinations of the PFT sources was done by BNL. BNL was blind as to the placement of the CAT samplers and chamber conditions. In this set of experiments two perfluorodimethylcyclobutane (PDCB) PFT sources were used. The emission rates of the PFT sources were determined gravimetrically at a stabilized temperature of 25°C. The PFT sources were shipped via mail to the chamber facility laboratory where they were stored at 23°C for over two weeks prior to their use. The average PFT source strengths were adjusted to the 23°C base-temperature at which the experiments took place according to the following formula (2).

$$S'_t = S'_{25}\, e^{-4000\,(1/T - 1/298)} \qquad (1)$$

where: S'_t = PFT source strength at base-temperature (t,°C) in nL/h

S'_{25} = PFT source strength at 25°C (determined gravimetrically as 5688 ± 120 nL/h)

T = base-temperature (t, °C) in Kelvin at which the PFT source is used.

For short-term (less than 48 h) temperature changes, the exponential constant was found to be half that for long-term (greater than 10 days) changes (2).

The number of air changes per hour (ach) is calculated, using the BNL/AIMS method, under steady-state conditions by

$$Q = S/C = S'/(VC) \qquad (2)$$

where: Q is the ach; S' is the tracer source rate (nL/h); C is the measured steady-state average tracer concentration (nL/m^3); and, V is the volume of the chamber (m^3).

Ventilation rates (Q) throughout these experiments were determined by the tracer gas decay method using CO_2 as the tracer gas. At regular intervals during each experiment CO_2 was injected into the chamber until the concentration in the chamber reached 1%. The gas was then shut off and the decay of CO_2 recorded continuously using a Beckman LB-2 Infrared CO_2 Analyzer. The natural logarithms of eleven concentrations per decay (5 minute intervals) were plotted against time (background levels subtracted), and a least squares linear regression was used to obtain the slope and hence ventilation rate.

A total of three experiments was conducted as outlined in Figure 1. The two PFT sources used throughout all experiments were placed in the center of the chamber 1.9 meters above the floor. This ensured that the PDCB tracer gas was well mixed in the recirculation loop before exposure to the samplers. The PFT sources were equilibrated at a temperature of 23°C. Twelve hours were allowed before each experiment to ensure steady-state concentrations of the PDCB tracer gas were reached in the chamber under the conditions of an air recirculation rate of 60 ach and fresh air ventilation rate of about 0.6 ach.

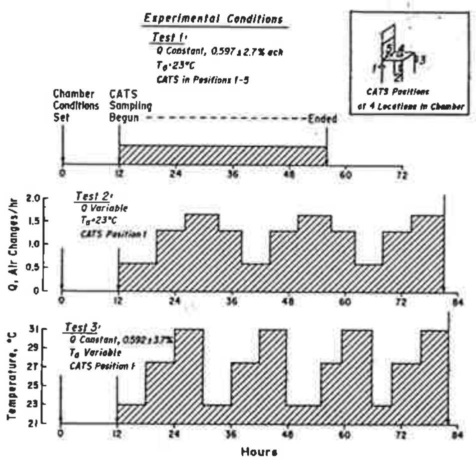

Figure 1. Experimental conditions in chamber for evaluating the BNL/AIMS method. CO_2 decays performed throughout each of the three experiments served as a base for comparison.

Experiment 1 evaluated the orientation of the CATS and accuracy of the BNL/AIMS method at a known and constant ventilation rate and temperature. All samples during this experiment were taken in duplicate at four locations in the chamber (four chairs, A-D). One chair (D) had samplers only in position 1. There was a total of 32 samplers (16 pairs).

Experiment 2 evaluated the BNL/AIMS method under conditions of variable ventilation and constant temperature while experiment 3 evaluated the impact of varying temperature on the PFT source emission rate under a constant ventilation rate.

Results and Discussion

The average of the 16 paired standard deviations from the CAT samples in experiment 1 was 4.6 ± 2.4 nL/m^3 [which, for an overall average measured PDCB concentration of 240.4 ± 5.7 nL/m^3, corresponded to an average relative standard deviation of 1.9 ± 1.0% with a range of 0.6 to 4.2% and a median of 2.2%.] Thus, the expected precision of duplicate samplers, ± 2%, demonstrates that there is no need to perform duplicate sampling during actual field use, since the sampling rates, handling, and analytical procedures for the CATS are consistent and reproducible. The average of the 10 samplers in each of the three chamber locations (A-C) in experiment 1 were statistically identical, indicating no concentration gradiant in the chamber.

Sampler orientation in experiment 1 did affect the average sampling rate. Positions 1 and 5 both exposed the sampler tubes at right angles to the chamber flow; their averages were identical within 0.7% and about 1.3% above the overall mean. Position 3, with tubes facing into the direction of flow, had an average that was 0.5% above the overall average. The lowest mean concentrations were for positions 2 (facing away from the direction of flow) and 4 (shielded by the chair seat). Those means were 2.0 and 1.4% below the overall mean. Only position 2 was statistically different (more than 1 standard deviation) from the overall average. The differences in concentration by sampler orientation observed here is due to the effect of wind speed. The maximum bias in the sampling rate of velocities expected in homes and buildings should be less than 2 to 3% based upon our results. In fact, by placing the sampler on a flat surface within a room, any local wind effects can be blocked.

The average chamber ventilation rate, Q, based on CO_2 decay measurements, was 0.601 ± 0.011 h^{-1}. The tracer source strength, S', at 23°C = 5195 ± 145 nL/h (Eq. 1) and dividing by the chamber volume (V = 34 m^3) gave S = 152.8 ± 4.3 nL/h m^3. The PDCB concentration can then be calculated from Eq. 2 to be 254.2 ± 12.8 nL/m^3 which, as shown in Table 1, is identical within the standard deviation of the average of the measured concentrations for the experiment.

Table 1. Comparison of BNL/AIMS measured versus calculated PDCB concentrations

Experiment No.	Conditions	No. of changes	Average PDCB concentration, nL/m^3 Measured[a]	Calculated[b]	Meas. conc.
1	Constant temp. Constant ach	0	240.4 ± 5.7	254.2 ± 12.8	0.946 ± 0.074
2	Constant temp. Variable ach	11	139.3 ± 2.5	149.2 ± 7.7	0.934 ± 0.068
3	Variable temp. Constant ach	12	290.5 ± 8.0	280.9 ± 19.3	1.034 ± 0.107

[a] Measured concentrations were determined with CAT samplers

[b] Calculated concentrations were obtained from either Eq. 2 (experiment 1) or from the time-weighted average concentration over each measurement period.

There was a total of 11 periods with constant but different ventilation rates in experiment 2. The time-weighted overall calculated average concentration, 149.2 ± 7.7 nL/m^3 (Table 1), for this experiment was obtained by summing the product of the average concentration and duration for each period (from the CO_2 decay rates) and dividing by the total experimental time, 69h. The overall average PDCB concentration measured in experiment 2 (8 samplers) was 139.3 ± 2.5 nL/m^3. The calculated and measured concentration agrees within the standard deviation of each determination. Thus we estimate from this experiment that for measurement periods of several days or longer where fluctuation in ventilation rates occur the BNL/AIMS approach may underestimate the true ventilation rate by about 3 to 6%, a tolerable bias for this convenient technique.

The time weighted overall calculated average concentration of PDCB over the 12 temperature periods during experiment 3 (a 8° range) was 280.9 ± 19.3 nL/m^3. The measured concentrations of 290.5 ± 8.0 nL/m^3 agreed well with the calculated concentration and within the standard deviation of each determination.

The time-weighted averages of a PDCB source strength and CAT samplers concentration were 167.5 ± 5.9 nL/hm^3 and 280.9 ± 19.3 nL/m^3, respectively. Substituting in equation 2 gives a ventilation rate of 0.596 ± 0.067 h^{-1}, which is essentially identical to the measured average ventilation rate (CO_2 decay) of 0.595 ± 0.022 h^{-1}. Thus, the BNL/AIMS technique is not biased to any significant extent if the appropriate temperature for the sources is known.

If these measurements had been conducted over a 2-week or longer period, then the average source strength could have been estimated from the time-weighted average source temperature and used in Eq. 1 (long term variations); this would be the procedure for a ventilation rate determination in a home, where the time-weight average thermostat setting would be used as the average base-temperature. Assuming long-term equilibration at the chamber base-temperature of 27°C, the calculated source strength from equation 1 becomes 182.9 nL/hm^3 which, divided by the calculated coverage concentration of 280.9 nL/m^3 (Eq. 2), gives a ventilation rate of 0.651 h^{-1}. This is about 9.4% higher than the true ventilation rate of 0.595 h^{-1} (CO_2 decays) because the sources had not equilibrated at the experiment 3 base-temperature of 27°C in just the 3-day period.

Conclusions

The relative standard deviation of multiple paired passive samplers is ± 1.9 ± 1.0%, indicating that the reproducibility in the manufacture, handling, and analysis of the CATS is sufficiently good to preclude the necessity of duplicate sampling in field experiments.

For the low air movement velocities in homes (< 0.2 m/s, away from any forced air vents), the effect of sampler orientation is not consequential on the sampling rate, having less than a 2 to 3% positive bias in the worst case.

Under conditions of widely varying tracer concentrations, the passive sampler accurately measures the correct time-weighted average tracer concentration. However, because the determination of ventilation ratios requires the determination of the average reciprocal tracer concentration rather than the reciprocal of the average tracer concentration, which is the item measured by the passive sampler, there is an estimated negative bias in the ventilation rate determination of about 3 to 6%, a tolerable bias for this convenient technique.

By using a time-weighted average temperature for determining the estimated source strength, room temperature fluctuations or intentional cycling differences of as much as 8°C (14°F) can be accounted for to produce essentially no bias in the determination of ventilation rates.

Acknowledgments

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SUMMARY

L. Schaap, B.P. Leaderer, S. Renes, H. Verstraelen, T. Tosun and R.N. Dietz. A Comparison of the Perfluorocarbon and Tracer Gas Decay Methods for Assessing Infiltration Rates in Residences. The passive perfluorocarbon tracer (PFT) technique for determining air infiltration rates into homes and buildings was evaluated in a environmental chamber. The impact of sampler orientation at a constant ventilation rate and a constant temperature, of variable ventilation rate at a constant temperature, and of variable temperature at a constant ventilation rate were evaluated in three experiments. The average relative standard deviation of 16 paired samplers deployed in experiment 1 was ± 1.9% ± 1.0% indicating good reproducibility of the passive sampling rate and sample analysis. No impact of sampler orientation with respect to low air velocities (< 0.2 m/s) present in houses is expected. The passive samplers accurately measured the average tracer concentration as compared with calculations based on the known source strength (CO_2 decays) and the measured ventilation rate under conditions of a 3-fold variation in ventilation rates (experiment 2). Temperature cycling differences of 8°C (experiment 3) did not produce a bias in the PFT determined ventilation rate. The PFT technique is applicable to the expected range of condition in homes and buildings.

RESUME

L. Schaap, B.P. Leaderer, S. Renes, H. Verstraelen, T. Tosun, et R.N. Dietz. Comparaison entre la méthode des traceurs au perfluorocarbure et celle au gaz radioactif appliquées à la détermination des taux d'infiltration de l'air dans les habitations. L'application de la méthode passive de traceur au perfluorocarbure (TPF) pour déterminer les taux d'infiltration de l'air dans les habitations et bâtiments a été évaluée dans les conditions micro-climatiques d'une enceinte. Dans trois experiences, nous avons étudié les effets de l'orientation de l'échantillonneur à un taux de ventilation et température constantes, les effets du taux de ventilation à température constante, et les effets de la température à un taux de ventilation constante. L'écart standard relatif moyen de 16 échantillonneurs utilisés dans l'expérience 1 et analysés en paires, était de ± 1.9% ± 1.0%, ce qui indique une bonne reproducibilité du taux d'échantillonnage passif et de l'analyse des échantillons. Les faibles vélocités des courants d'air existant dans les habitations (< 0.2 m/s) ne font pas prévoir d'effet causé par l'orientation de l'échantillonneur. Les échantillonneurs passifs ont mesuré avec précision la concentration moyenne du traceur, ce qui peut etre comparé avec les résultats des calculs obtenus à partir de l'intensité de la source (désintégrations du CO_2) et du taux de ventilation mesuré (expérience 2); dans cette expérience, le taux a varié d'un facteur de trois. Le cyclage de la température sur une plage de 8°C (expérience 3) n'a pas eu d'effet sur le taux de ventilation dérivé par la méthode TPF. On peut donc conclure que cette méthode peut être appliquée dans les conditions qui prédominent dans les habitations et les bâtiments.

KURZFASSUNG

L. Schaap, B.P. Leaderer, S. Renes, H. Verstraelen, T. Tosun, und R.N. Dietz. Vergleich der Perfluorocarbon und Tracergaszerfall-Methode zur Abschätzung von Infiltrationsraten in Wohnhäusern. Die Anwendung der passiven Perfluorocarbon Tracer Technik (PFT) zur Bestimmung von Lufinfiltrationsraten in Wohnhäusern und Gebäuden wurde in einer Klimakammer untersucht. In drei Experimenten wurde der Einfluss von Messproben-Orientierung bei konstanter Belüftungsrate und Temperatur, von variabler Belüftungsrate bei konstanter Temperatur, sowie von variabler Temperatur bei konstanter Belüftungsrate abgeschätzt. Die durchschnittliche relative Standardabweichung der in Experiment 1 eingesetzten 16 gepaarten Messproben betrug ± 1.9% ± 1.0%, was auf eine gute Reproduzierfähigkeit der passiven Messrate sowie der Probenanalyse hindeutet. Bei der für Ihnenräume typischen geringen Luftgeschwindigkeit (< 0.2 m/s) wird kein Einfluss der Messproben-Orientierung erwartet. Die passiven Messproben bestimmen präzise die durchschnittliche Tracerkonzentration, im Vergleich mit der nach gegebener Quellenstärke (CO_2 Zerfälle) berechneten, für Belüftungsraten, die um einen Faktor 3 varierten. Zyklische Variationen der Temperatur in einem Bereich von 8°C führte zu keiner mit der PFT Technik messbaren Veränderung der Belüftungsrate. Im Rahmen der in Wohnhäusern und Gebäuden zu erwartenden Gegebenheiten kann die PFT Technik angewendet werden.