

Air Change Rate Measurement Methods and Database

Kiyoung Lee and Yukio Yanagisawa

Harvard School of Public Health

Department of Environmental Health

Environmental Science and Engineering Program

1. INTRODUCTION

In recent years the demand for energy conservation has resulted in "tight" buildings with decreased air change rates. Although a reduction in air change rates can save energy utilized for heating or cooling of dwellings, there is an increased concern for the air quality of the indoor environment where individuals spend most of their lifetime (Schwab *et al.*, 1990).

Indoor air quality depends upon indoor contaminant sources, outdoor contaminant concentrations, and the ventilation rate of a building. When the indoor concentration of a contaminant is mainly affected by its outdoor concentration, as in the case of ozone, the indoor concentration decreases as the air change rate is reduced. However, reduction of the air change rate may have adverse effects on indoor air quality when there are indoor sources.

Residential air change rate is primarily affected by several physical parameters: wind velocity and direction, opening of the house envelope, and the indoor/outdoor temperature difference across the house envelope. Human activities also affect air change rate. Therefore, air change rates vary among houses as well as over time. Considering the impact of indoor air quality on human health, the long-term average air change rate needs to be measured over several days to weeks.

Air change rate is difficult to predict or model but can be measured experimentally. Air change rate measurements usually involve a

pressurization method or the tracer gas method. The responses of a building to positive or negative pressure differences provide a measure of the air leakage rate. When the building tightness is of primary concern, the pressurization method is used.

The tracer gas method is the only way to directly measure air infiltration in residences under normal occupancy conditions. Using a tracer gas, the air change rate can be measured by either the constant injection or the decay method. This paper mainly describes the constant injection method and discusses the potential sources of error in the constant injection method and the tracer gas decay method. In addition, air change rates of residential houses are reviewed.

2. PRINCIPLES

Air change rate measurements using a tracer gas are based on the conservation of mass of tracer gas. N different tracers are injected once into a building with N zones. A zone can be defined as a combination of spaces having the same ventilation rate. For example, when several rooms in the same floor are mechanically ventilated at the same rate, they can be considered as a single zone. The definition of a zone in ventilation is quite different from a zone defined in thermal modeling or occupant behavior.

The rate of change of air mass m , equals the sum of incoming flows minus the sum of outgo-

ing flows:

$$\frac{dm_i}{dt} = \sum_{j=0}^N Q_{ij}(1-\delta_{ij}) - \sum_{j=0}^N Q_{ji}(1-\delta_{ij}) \quad (1)$$

where, Q_{ij} =mass air flow rate from zone j to zone i

$$\delta_{ij} = \text{Kronecker delta: } \delta_{ij}=1 \text{ if } i=j, \\ \delta_{ij}=0 \text{ if } i \neq j$$

This equation is based on the following three assumptions: 1) the tracer concentration is always homogeneous in each zone, 2) the atmospheric pressure is constant, and 3) injection of the tracer gas does not change the density of air. In practice, homogeneity of air is difficult to achieve. Nevertheless, the perfect mixing assumption is valid when the nominal time constant is significantly longer than the mixing time (Sherman, 1990).

When a tracer gas is continuously injected, the equation for the mass of tracer gas k in zone i is the sum of the masses of injected tracer gas and incoming tracer gas entering the zone minus the masses of outgoing tracer gas leaving the zone.

$$\frac{dm_{ik}}{dt} = S_{ik} + \sum_{j=0}^N C_{kj}Q_{ij}(1-\delta_{ij}) - C_{ik} \sum_{j=0}^N Q_{ji}(1-\delta_{ij}) \quad (2)$$

where, S_{ik} =mass injection rate of tracer gas k in zone i

C_{ik} =mass concentration of tracer gas k in zone i

In this equation, the homogeneity of tracer concentration in zone i is not modified by the incoming air flow. In other words, immediate and perfect mixing is assumed.

In a single zone, $i=1, j=0$, only one tracer is needed. Assuming a constant and homogeneous temperature, the equation (2) becomes

$$\frac{dm_i}{dt} = S_i + (C_o - C_i)Q_{10} \quad (3)$$

Therefore, the rate of concentration change may be expressed by the mass balance equation.

$$V \frac{dC(t)}{dt} = S + C_o Q - C(t) Q \quad (4)$$

where, V =volume of the zone (m^3)

$C(t)$ =indoor concentration of tracer gas at time t

S =generation rate of tracer gas

C_o =indoor concentration of tracer gas

Q =air flow rate crossing the zone (m^3/hour)

If the outdoor concentration of the tracer gas is negligible ($C_o=0$) and no tracer is generated indoors ($S=0$) or absorbed within the zone, the equation (4) becomes

$$\frac{dC(t)}{dt} = -\frac{Q}{V} \cdot C(t) \quad (5)$$

Equation (5) can be solved to the following equation

$$\ln \frac{C}{C_i} = -\frac{Q}{V} \cdot t = -Ft \quad (6)$$

Air change rate (F) can be determined by the division of air flow rate by space volume. When concentrations are measured more than twice, there are two ways to calculate the air change rate: 1) by plotting concentrations and 2) by calculating relative concentrations for a certain time interval.

When the tracer gas is constantly injected, equation (4) becomes the following equation with the assumption of negligible outdoor concentration.

$$\frac{dC(t)}{dt} = \frac{S}{V} - \frac{Q}{V} \cdot C(t) \quad (7)$$

After deployment of a constant emission source, the indoor tracer concentration becomes constant and slowly changes as a function of the exfiltration. Equation (7) is solved to the following with the assumption of steady state ($dC(t)/dt=0$).

$$Q \approx S/C \quad (8)$$

By measuring the average concentration and knowing the emission source strength, the air flow rate can be determined.

A house or a building can be considered as a single zone or multiple zones. Generally, rooms on the same floor are considered as a single zone as if interior partitions did not exist. Different floors are considered as separate multiple zones. Assuming that a house has two zones, as shown in Fig. 1, the air change rate in each zone can be determined using the following four equations.

Zone 1

$$Q_{21}C_{12} - Q_{12}C_{11} - Q_{E1}C_{11} = -Q_{S1} \quad (9)$$

$$Q_{21}C_{22} - Q_{12}C_{21} - Q_{E1}C_{21} = 0 \quad (10)$$

Zone 2

$$Q_{12}C_{11} - Q_{21}C_{12} - Q_{E2}C_{12} = 0 \quad (11)$$

$$Q_{12}C_{21} - Q_{21}C_{22} - Q_{E2}C_{22} = -Q_{S2} \quad (12)$$

Since tracer concentrations and sources are

known, Q_{21} , Q_{12} , Q_{E1} , and Q_{E2} can be solved with the four equations. The rate of infiltration for each zone is

$$Q_{I1} = Q_{E1} + Q_{12} - Q_{21} \quad (13)$$

$$Q_{I2} = Q_{E2} + Q_{21} - Q_{12} \quad (14)$$

When the number of zones is N , a set of N^2 tracer material balance equations can be written for N^2 flow rates.

3. TRACER GASES

A number of gases have been used to measure air flow rate and air change rate in buildings. An ideal tracer gas requires the following characteristics (Hunt *et al.*, 1980 and Sherman, 1990):

- 1) The tracer gas should be non-toxic, non-flammable and non-explosive.
- 2) The gas must be chemically stable and should not react chemically or physically with any part of the system.
- 3) The gas should have a density comparable to air, so that it does not affect the air flow or air density
- 4) The gas must be detected accurately in the lowest possible concentration. The analytical method has negligible cross-sensitivity for other constituents of air.
- 5) The gas should not be a normal constitu-

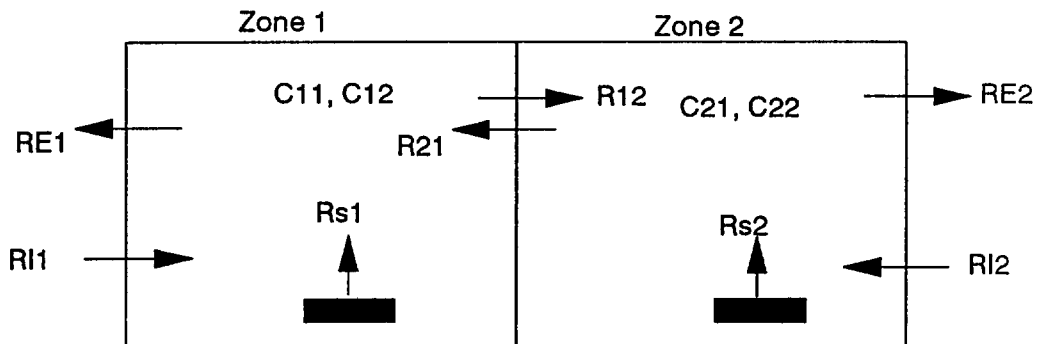


Fig. 1. Model for a two-zone.

ent of air. Thus, a gas with a zero background concentration is preferred. Injection of a tracer gas must make a significantly larger concentration than the steady or zero background.

- 6) The gas should be inexpensive and readily available.

Although no tracer gas meets all of these requirements, many gases have been successfully used as tracer gases.

SF₆ is commonly used as a tracer. Since the analytical method for this tracer, an electron capture detector, measures as low as a few parts per billion, this gas is feasible for ventilation measurements in a large building and over a long period of time. Since oxygen is also an electron capturing gas, it is a common practice to separate SF₆ from oxygen chromatographically. SF₆ is nonflammable, relatively non-toxic, and very stable. In addition, several gases such as hydrogen, methane, ethane, carbon monoxide, neon, butane, and fluorinated hydrocarbons have been used as tracer gas (Hunt *et al.*, 1980).

Carbon dioxide (CO₂) can also be used as a tracer. Although CO₂ is easy to monitor, background CO₂ concentration in a building is not zero and occupants generate significant amounts of CO₂. When the CO₂ generation rate and air infiltration rate are constant, indoor CO₂ concentration reaches an equilibrium. Using equilibrium CO₂ concentration (C_{eq}), the air infiltration rate is given by the following equation:

$$Q = \frac{\text{Number of occupant} \cdot G_p}{C_{eq} - C_{out}} \quad (15)$$

where G_p is the average CO₂ generation rate per person.

G_p depends on a person's age and activity level. A typical value of G_p is 5.3 × 10⁻⁶ m³/s. This method may not yield results as accurate as those achieved by the constant injection method

or the tracer gas decay method. Errors can occur from estimating the number of occupants and their respiration rates. Therefore, this method can be used if the limitations of the method are considered and controlled for (Persily and Dols, 1990).

4. AIR CHANGE RATE MEASUREMENTS

Air change rate measurements using a tracer gas can be divided into two categories based on the purpose of the measurement: transient method and steady-state method (Sherman, 1990). The air change rate, or nominal time constant, can be determined by the transient method, which provides large changes in concentration. Air flow rate can be determined by the steady-state method which maintains a quasi-constant concentration. Since the air flow rate (Q) and the air change rate (F) in a single zone are directly related by equation F=Q/V, Q and F can be estimated using either method.

The tracer gas decay method can directly measure air change rates in dwellings with the least measurement time and equipment. The determined air change rate depends upon the experimental duration, since the air change rate vary temporally due to the effect of temperature differential, outdoor wind velocity, and activities. An optimum measurement period is required for accurate measurement, although the measurement period is determined by time constants of the measured space. For example, when the concentration decay is measured in an enclosed space for a limited time, relative error in the air change rate is related to the ratio of measurement time constant to nominal time constant.

Among the assumptions of the decay method, perfect mixing of air at the beginning and throughout the measurement is not easily achievable. Usually fans are used to mix the air but they may also affect infiltration conditions.

ions. When the air is not well mixed, there is a sampling location problem as well as inherent error. When samplers are located in the area where air is not well mixed, air change rate can be underestimated. On the other hand, air change rate can be overestimated by placing samplers near a ventilation inlet. Hunt (1980) illustrated some examples comparing perfect mixing models with imperfect or non-mixing models.

The decay method is sensitive to measurement errors when the sampling interval is short. The error in air flow rate, e_i , may be calculated from the following equation (Hunt, 1980).

$$e_i = \frac{1}{t_m} \left[\ln \frac{C_n}{C_{n-1}} (1+a) \ln \frac{C_n}{C_{n-1}} \right] \quad (16)$$

where, a = fractional error in C_n/C_{n-1} .

When there is a 5% error in C_n/C_{n-1} , the error in the air change rate is 0.3 hr^{-1} for a 10-min interval or 0.05 hr^{-1} for a 1-hour interval. Although the use of a short interval may indicate a short-term fluctuation in the ventilation rate, this fluctuation may mainly result from the sampling error.

When tracer concentrations are measured twice, the uncertainty from the measurement period is calculated by the following equation with a negligible timing error (Sherman, 1990).

$$\frac{\delta F}{F} = \frac{\delta(\underline{C})}{\underline{C}(T)} \cdot \frac{1}{\underline{F}T} \sqrt{1 + \exp(2\underline{F}T)} \quad (17)$$

where, δF is the uncertainty of the air change rate

$\delta(\underline{C})$ is the uncertainty of the tracer gas concentration.

When measurement time is equal to the nominal time constant, relative error is at minimum of 3. However, the accuracy can be improved by repeated measurements.

5. CONSTANT INJECTION METHODS

Unlike the tracer gas decay method, the constant injection method provides an air flow rate which can be divided by space volume to produce the air change rate. This method also gives a biased estimate of the average air flow rate. This bias may not be negligible due to the extended measurement time of the constant injection method. However, the constant injection method is appropriate for indoor air quality studies since it provides an unbiased estimate of the average tracer concentration.

In a constant injection method developed by Brookhaven National Laboratory (BNL) (Dietz *et al.*, 1986), a small amount of the perfluoro-carbon tracer gas (PFT), which is colorless, odorless and harmless, is emitted into a space at a constant rate from a liquid permeation source. The tracer gas is mixed using fans until the space reaches a steady-state and then collected using adsorption passive samplers. The air change of the zone dilutes the tracer gas and reduces the amount of gas adsorbed by samplers. The total amount of tracer gas adsorbed during the measurement period is the indication of the average air filtration rate between the inside and outside of a house.

5.1 Equipment for the PFT constant injection method

PFT source: PFT is released from a permeation tube at a constant rate and at a known temperature. The PFT source is an aluminum shell (32 mm long by 6.6 mm inside diameter) which contains exactly 0.4 mL of the appropriate PFT liquid. The shell is closed by an oversized silicone rubber plug. There are four types of PFT available: PDCH, PMCH, PMCP, and PDCB. They can be used to characterize a building with as many as four zones.

Capillary Adsorption Tube Sampler (CATS): The passive sampler collects tracer by diffusion and releases it by thermal desorption. The

CATS are passive sampling tubes made of glass (6.4 cm long, 6.4 mm OD, 4 mm ID) which contain 64 mg of adsorbent, named Amber-sorb. The adsorbent is put through a conditioning process before being used. It is boiled in distilled water three times and those shapes that are not nearly perfect spheres are separated out. After being boiled again until the decanted fluid is clear, the adsorbent is dried and sieved through a 30~50 mesh. The passive sampler is filled with the conditioned adsorbent and both ends of the sampler are capped with polyurethane rubber caps, one of which is removed during the test period.

Gas chromatographic analyzer: The CATS sampler is thermally desorbed and analyzed by gas chromatography using an electron capture detector (GC/ECD). Since the analysis system is complex, it is only briefly described here. The passive sampler is purged with carrier gas (5% H₂ in N₂) to remove oxygen. The adsorbed tracer gas is recovered by thermal desorption at 400°C. Chlorofluorocarbon compounds and oxygen are reduced in a catalyst bed prior to the analysis by ECD. An integrator determines the total quantity of PFT collected. The analysis can be repeated with 10-minute cycle.

5.2 Perfluorocarbon tracer (PFT) emission rates

The emission rate of the PFT source can be determined by periodically weighing one PFT source out of every 50 which are kept in a constant temperature chamber. The volumetric rate can be determined by the gravimetric rate using the gas law constant and the molecular weight. The emission rate can be determined chromatographically when a source is placed at a known temperature and the PFT concentration is measured.

5.3 Placement protocols

Since the PFT concentrations during measurements are very low, contamination can cause

a significant error. Contamination of passive samplers underestimates the air change rate. Therefore, the PFT sources must be shipped separately from the passive samplers.

The emission rate is sensitive to temperature (about 4% change per degree C), thus the PFT sources should not be placed near heating or cooling devices. Direct sunlight or a drafty location should be avoided as well. During the measurement, the average temperature must be recorded. As long as the true average source temperature is used to calculate the emission rate, no bias in the results are shown (Dietz *et al.*, 1986). To maintain a constant emission rate, temperature controlled source holders can be used.

It is desirable to deploy the PFT sources in a manner which provides uniform emission into a zone. The sources should be located several feet from the external envelope (outside walls and windows of the room).

Desirable PFT source strength can be estimated in the bases of mixed volume, sampling period and detection level. The source strength depends on the number of sources and/or changes in source temperature. The number of sources is determined by the sampling period, estimated air change rate and house volume.

$$N = \frac{F \cdot M \cdot V}{S \cdot t \cdot r} \quad (18)$$

where, N = the number of sources

M = gas volume of PFT collected on CATS (pL)

S = emission rate of PFT source at a given temperature (pL/hr)

t = period of sampling (hr)

r = sampling rate of CATS (L/hr)

The number of CATS per building depends on the number of zones and the area of these zones. The constant injection method assumes that concentration is uniform in a zone. In pra-

ctice, at least two passive samplers are placed in each zone. The number of samplers needed increases proportionally with the size of the test area. The CATS should not be located within six feet of the PFT source in order to avoid the possibility of a directional flow effect. It is also desirable to place the samplers at least 0.5 m away from walls, floor or ceiling.

Sampling is initiated by removing only one cap and the sampler is recapped at the end of the sampling period. The sampling date and time must be recorded. Samplers will accumulate tracer gas for a specified sampling duration at each sampling point. After the measurements are completed, the samplers are returned, along with information on the average temperature, the air volume of the space and the sampling time, to the laboratory for the analysis of the tracer concentration. GC/ECD is used to analyze the amount of the tracer gas accumulated in the sampler.

5.4 Calculating air filtration and air change rate

The PFT concentration is calculated as:

$$C = \frac{M}{t \cdot r} \quad (19)$$

If the assumption of complete mixing of indoor air is valid, the air filtration rate (F) between the indoors and outdoors (or air change rate) can be calculated as:

$$Q(\text{m}^3/\text{hr}) = \frac{N \cdot S}{C} \quad (20)$$

$$F(\text{hr}^{-1}) = \frac{Q}{V} \quad (21)$$

where, N, Q, F and V are as defined previously.

5.5 Associated error

The detection limit of the air change rate is inversely related to that of the PFT measurements. In addition, exposure time, house volume and source strength can affect the detection limit. The GC/ECD can measure as low as 0.35 fL/L of PDCB for a 25 L sample (Dietz *et al.*, 1986). The minimum concentration required for analysis corresponds to approximately a 20-minute exposure of a passive sampler under typical home conditions. For example, 0.35 fL/L of a 25 L sample is equal to 8.75 pL. With a typical concentration of 3 pL/L in the field, the CATS sampler can collect 5.2 pL in a week. Therefore, it takes about a 20-minute exposure to collect the minimum amount. Considering the minimum amount for analysis, the maximum detection limit of air change rate may be high enough to measure most residential air change rates.

The maximum detection limit was also estimated by the root mean square error of collocated samples whose concentrations were below that of the lowest standard (Suh *et al.*, 1994). The lowest amount of PFT that could be measured was calculated as three times the root mean square error of the collocated samples. The maximum measurable air change rate was determined to be 3 hr⁻¹ for a 12-hour sampling period, which corresponds to 42 hr⁻¹ for a week of sampling.

Uncertainties in emission rate of source, sampling rate of the passive sampler, and calibration and analysis of the GC system can cause inherent error in the measurement method. The uncertainty of each error source was expressed as relative standard deviation: 8% for emission rate of source, 8% for sampling rate of the passive sampler, 5% for sampling rate calibration, and 3% for analysis of the GC system (Stymne *et al.*, 1994). Stymne *et al.* calculated total uncertainty of 11.1% from the square root of the sum of squares of the individual standard deviation.

Contamination and mistreatment of the passive sampler can also cause error. In order to prevent contamination, sources must be shipped separately from passive samplers. Contamination of a passive sampler can cause various systematic errors resulting in underestimated ventilation rate.

Concentration is usually uniform in a conventional room and the variation between rooms on the same floor are within 10% (Maldonado, 1982). When a house has more than one zone in a multiple story building, several tracer gases can be used. Although a tracer is found to be well mixed in a single zone, a fan is required for mixing. Sandberg *et al.* (1985) found that perfect mixing in a multi-zone building is difficult to achieve. They proposed to use one fan in each room with an additional fan in the largest room.

The constant injection method is based on the assumption of perfect mixing and steady state. Inadequate mixing was found to be a major impediment to the interpretation of the air change rate results and could completely invalidate the measurement (Sherman, 1989). When flow rate varies during the measurement even in a well-mixed house, integrated concentration of the tracer gas can cause underestimation of the ventilation rate. The underestimation can be as large as 15~35% for leaky and naturally ventilated houses on annual basis (Stymne *et al.*, 1991). Sherman (1989) also showed that the average ventilation rates determined by passive sampling methods are consistently underestimated (20 to 30 percent). When the ventilation rate is measured during similar weather conditions, the underestimation may diminish, especially in a tight house.

With the assumption of well-mixed tracer, the measurement of constant injection provides an effective ventilation rate, that is, the product of temporal ventilation efficiency and average air change rate (Sherman, 1989). Usually, the goal is to measure the average ventilation

rate when the ventilation efficiency is unknown. Therefore, the difference between actual and effective ventilation rates represents a systematic error in the measurement method. However, the effective ventilation rate determined by the constant injection method is appropriate for indoor air quality studies.

When a single zone assumption does not work, the subject house should be considered as multiple zones. In multiple zones, uncertainty is related to spatial efficiency, which is the ratio of the concentration of a gas in a zone to the concentration that would have occurred had the entire building been a single well mixed zone. The uncertainty associated with interzonal airflow varies by house type (Sherman, 1989).

6. DATABASE

Air change rate can be affected by building construction method, climate and surrounding terrain, and occupant lifestyle. Air change rates in the same house may vary enormously from day to day (Lawrence Berkeley Laboratory, 1984). Typically, the air change rates for U.S. residences, as estimated in a report for the Bonneville Power Administration (1983), are within the following ranges: 0.5 to 1.5 hr⁻¹ for single-family detached house, 0.35 to 1.0 hr⁻¹ for single-family attached house, 0.3 to 1.5 hr⁻¹ for mobile homes, and 0.3 to 0.9 hr⁻¹ for apartments. The National Research Council (1981) estimated the typical US residential air infiltration rate to be 0.5 to 1.5 hr⁻¹.

The Brookhaven National Laboratory (BNL) has measured air change rates in more than 4,000 residences using PFT measurements since 1982. The results were summarized by Kennedy (1993). The data file including air exchange rate, measurement season, and location is provided with the report. The summarized air change rates are shown in Table 1. Arithmetic and geometric mean of the air exchange

rate data were 0.68 hr^{-1} and 0.42 hr^{-1} , respectively. Using the BNL database, Pandian *et al.* (1993) summarized air change rates of 1,846 residences. The residential air change rates are shown in Table 2. Arithmetic and geometric mean of the air exchange rate data were 1.99 hr^{-1} and 0.89 hr^{-1} , respectively. In addition, several studies measured residential air change rates using the constant injection method. In these studies, the average US residential air change rates ranged from 0.37 to 1.9 hr^{-1} , as shown in Table 3.

Unlike the constant injection method, the tracer gas decay method measures air change rate during a relatively short period of time in the order of hours. Since long-term measurement by the constant injection method may be affected by physical factors and behavior of occupants, air change rates measured by the tracer decay method and the PFT method are expected to be different. Kvisgaard *et al.* (1990) measured air change rates of 28 dwellings in Denmark by maintaining a constant concentration. Amount of tracer gas to maintain a constant concentration was used to calculate air change rate at a specific time. They concluded that occupants greatly influence the air change rate not only in naturally ventilated

Table 1. The U.S. residential air change rates (Kennedy, 1993).

	No. of house	Arithmetic mean	Geometric mean
All regions	3442	0.68 ± 1.43	0.42 ± 2.36
West	2253	1.36 ± 2.97	0.61 ± 3.00
Northcentral	63	0.27 ± 0.13	0.24 ± 1.71
Northeast	722	0.65 ± 0.47	0.52 ± 2.06
South	404	0.58 ± 0.42	0.46 ± 2.12
Winter	1370	0.59 ± 0.52	0.47 ± 1.97
Spring	1339	0.63 ± 1.05	0.39 ± 2.51
Summer	566	1.34 ± 3.52	0.43 ± 3.50
Fall	167	0.34 ± 0.29	0.27 ± 1.93

Table 2. The U.S. residential air change rates (Pandian *et al.*, 1993).

	No. of house	Arithmetic mean	Geometric mean
All regions	1846	1.99 ± 3.28	0.89 ± 3.44
Northwest	423	0.42 ± 0.33	0.34 ± 1.88
Northeast	423	0.60 ± 2.23	0.40 ± 2.07
Southwest	990	3.25 ± 3.79	1.86 ± 3.02
Winter	670	0.54 ± 0.54	0.42 ± 1.97
Spring	726	1.89 ± 2.71	1.01 ± 3.14
Summer	352	5.36 ± 4.96	3.53 ± 2.80
Fall	88	0.43 ± 0.28	0.35 ± 1.93

buildings but also in mechanically ventilated buildings. The behavior of the occupants caused 63% and 65% of the total air change rate in naturally ventilated buildings and mechanically

Table 3. Residential air change rates measured by constant injection method.

Location	No. of house	Season	Air change rate (mean \pm sd, hr^{-1})	Reference
Boston, MA	310	winter	1.47 ± 1.13	Yanagisawa <i>et al.</i> , 1990
Pacific Northwest of US	134	NA	0.37 ± 0.18	Parker <i>et al.</i> , 1990
Riverside, CA	178	fall	1.08 ± 0.79	Pellizzari <i>et al.</i> , 1991
State College, PA	47	summer	1.9 ± 2.08	Suh <i>et al.</i> , 1994
Southern California	287	winter	0.57 ± 0.43	Wilson <i>et al.</i> , 1986
Toronto, Canada	40	winter summer	0.69 ± 0.88 1.04 ± 1.28	Liu <i>et al.</i> , 1995
Netherland	17	NA	1.0 ± 1.4 (living room) 1.8 ± 2.5 (bedroom)	Bloemen <i>et al.</i> , 1993
Sweden	1500	winter	0.21 (median in single family house) 0.44 (median in multi family house)	Stymne <i>et al.</i> , 1994

NA: not available

Table 4. Residential air change rates measured by tracer gas decay method.

Location	No. of house	Season	Air change rate (mean \pm sd, hr ⁻¹)	Reference
US	54	SF ₆	0.42 \pm 0.3	Persily, 1986
Tennessee	31	Freon-12	0.49 \pm 0.29 (fan off) 0.87 \pm 0.39 (fan on)	Gammage <i>et al.</i> , 1986
Portland, ME	10	SF ₆	1.21 \pm 0.40 (first floor) 1.32 \pm 0.38 (second floor)	Grot, 1980
US and Canada	312	NA	0.63 \pm 0.50	Grimsrud, 1982
US	266	SF ₆	0.9	Grot, 1979
Norfolk, VI	24	SF ₆	0.77 \pm 0.26 (summer) 1.44 \pm 0.69 (winter)	Lagus, 1986
Japan	10	SF ₆	0.35 \pm 0.71	Yoshino <i>et al.</i> , 1990

NA: not available

ventilated buildings, respectively. The average air change rate was 0.67 hr⁻¹ while the data ranged from 0.2 to 1.56 hr⁻¹. Air change rates in naturally ventilated dwellings and mechanically ventilated dwellings were 0.51 and 0.93 hr⁻¹, respectively.

Several studies have measured residential air change rates by the tracer gas decay method. Average US residential air change rates ranged from 0.42 to 1.44 hr⁻¹, as shown in Table 4.

REFERENCES

- Bloemen, H.J.T., A.P. Verhoeff, T.T.M. Balvers, P. Van er Torn, J.H. Van Wijnen, "Ventilation rate and airflow measurements using a modified PFT technique", The 6th International Conference on Indoor Air Quality and Climate, proceeding Vol 5, pp.91-96, July 4-8, Helsinki, Finland, 1993.
- Bonneville, Power Administration, The Expanded Residential Weatherization Program, Draft Environmental Impact Statement, U.S. Department of Energy, 1983.
- Dietz, R.N., R.W. Goodrich, E.A. Cote, and R.F. Weiser, Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurements, Measured Air Leakage of Buildings, Trechsel and Lagus Eds., ASTM, STP 904, Philadelphia, 1986.
- Gammage, R.B., A.R. Hawthorne, and D.A. White "Parameters affecting air infiltration and airtightness in thirty-one east tennessee homes" Measured Air Leakage of Buildings, ASTM STP 904, H.R. Trechsel and P.L. Lagus, Eds., ASTM 1986, pp.61-69.
- Grimsrud, D.T., M.H. Sherman, and R.C. Sonderegger, "Calculating Infiltration : Implications for a Construction Quality Standard" ASHRAE/DOE Conference on Thermal Performance of the Exterior Envelopes of Buildings II, as Vegas, NV Dec 6-9, 1982.
- Grot, R.A., and R.E. Clark, "Air Leakage Characteristics and Weatherization Techniques for Low-Income Housing" DOE/ASHRAE Conference on Thermal Performance of Exterior Envelopes of Buildings, Orlando, Florida, December 1979, ASHRAE.
- Grot, R.A. "A Low-cost Method for Measuring Air Infiltration Rates in a Large Sample of Dwellings", Building Air Change Rate and Infiltration Measurement, Hunt King Trechsel eds. ASTM STP 719, 1980, pp.51-59.
- Hunt C.M. "Air Infiltration : A Review of Some Existing Measurement Techniques and Data" Building air change rate and Infil-

- tration Measurement. Hunt King Trechsel eds. ASTM STP 719, 1980, pp.3-23.
- Kennedy, P. "Estimation of Distributions for Residential Air Exchange Rates" GEOMET Report Number IE-2603, 1993.
- Kvisgaard, B., and P.F. Collet, "The Users' Influence on Air Change" Air change rate and Airtightness in Buildings, ASTM ST 1067, M.H. Sherman, Ed., American Society for Testing and Materials, 1990, pp.67-76.
- Lagus, L. and J.C. King, "Air Leakage and Fan Pressurization Measurements in Selected Naval Housing" Measured Air Leakage of Buildings, ASTM STP 904, H.R. Trechsel and P.L. Lagus, Eds., ASTM 1986, pp.5-16.
- Lawrence Berkeley Laboratory, Manual on Indoor Air Quality, Electric Power Research Institute, Research Project 2034-3, EM-3469, 1984.
- Liu L-J S., P. Koutrakis, J. Leech and I. Broder, "Investigation of spatial and temporal patterns of ozone concentration within a metropolitan area using an ozone passive sampler", Manuscript in progress.
- Maldonado, E.A.B. "A Method to Characterize Air Exchange in Residences for Evaluation of Indoor Air Quality", Ph.D. dissertation, Iowa State University, Ames, Iowa, 1982.
- Pandian, M.D., W.R. Ott, and J.V. Behar (1993) Residential Air Exchange Rates for Use in Indoor and Exposure Modeling Studies, *J. of Exposure Analysis and Environmental Epidemiology*, 407-416, 1993
- Parker, G.B., M. McSorley, and J. Harris, "The Northwest Residential Infiltration Survey: A Field Study of Ventilation in New Homes in the Pacific Northwest", Air change rate and Airtightness in Buildings, ASTM ST 1067, M.H. Sherman, Ed., American Society for Testing and Materials, 1990, pp.93-103.
- Pellizzari, E.D., K.W. Thomas, C.A. Clayton, R.W. Whitmore, R.C. Shores, H.S. Zelon, and R.W. Perritt, Particle Total Exposure Assessment Methodology (PT-EAM) : Riverside California Pilot Study Research Triangle Institute, RTI/4948/108-02F, 1991.
- Persily, A.K. "Measurements of Air Infiltration and Airtightness in Passive Solar Homes" Measured Air Leakage of Buildings, ASTM STP 904, H.R. Trechsel and P. L. Lagus, Eds., ASTM 1986, pp.46-60.
- Persily, A.K. and W.S. Dols (1990) The Relation of CO₂ Concentration to Office Building Ventilation, Air Change Rate and Airtightness in Buildings, ASTM STP 1067, M.H. Sherman, Ed. American Society for Testing and Materials, Philadelphia.
- Sandberg, M. and C. Blomqvist (1985) A Quantitative Estimate of the Accuracy of Tracer Gas Methods for the Determination of the Ventilation Flow Rate in Buildings. *Building and Environ*, 20, No.3.
- Schwab, M., S.D. Colome, J.D. Spengler, P.B., Ryan, and I.H. Billick (1990) Activity Patterns Applied to Pollutant Exposure Assessment : Data from a Personal Monitoring Study in Los Angeles. *Toxicol. Ind. Health* 6(6):517-532.
- Sherman, M.H. (1989) Analysis of Errors Associated with Passive Ventilation Measurement Techniques. *Building and Environment*, 24, 131-139.
- Sherman, M.H. (1990) Tracer Gas Techniques for Measuring Ventilation in a Single Zone. *Building and Environment*, 25, pp. 365-374.
- Stymne H. and A. Eliasson (1991) A New Passive Tracer Gas Method for Ventilation Measurements, Proc. of the 12th AIVC Conference-Air Movement and Ventilation Control within Buildings, Vol 3. p1. Ottawa, Canada.
- Stymne, H., C.A. Boman, and J. Kronvall (1994) Measuring Ventilation Rates in the Swedish Housing Stock, *Building and Environment* 29, 3, 373-379.
- Suh, H.H., P. Koutrakis, J.D. Spengler (1994)

- The relationship between airborne acidity and ammonia in indoor environments, *Journal of Exposure Analysis and Environmental Epidemiology*, 4:1-22.
- Wilson, A.L., S.D. Colome, P.E. Baker, and E.W. Becker (1986) Residential Indoor Air Quality Characterization Study f-Nitrogen Dioxide Report to Southern California Gas Company.
- Yanagisawa, Y., J.D. Spengler, P.B. Ryan, and I.H. Billick, "Relationships among Indoor NO₂, Air Exchange Rate and House Characteristics of Residential Houses in Boston", The 5th International Conference on Indoor Air Quality and Climate, proceeding Vol 4. pp.485-490, Toronto, Canada, 1990.
- Yoshino, H., M. Nagatomo, Y. Yamamoto, H. Matsumoto, and Y. Utsumi, "Measurement of Airtightness, Air Infiltration, and Indoor Air Quality in Ten Detached Houses in Sendai, Japan", Air change rate and Airtightness in Buildings, ASTM ST 1067, M.H. Sherman, Ed., American Society for Testing and Materials, 1990, pp.249-266.