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Journal

Indoor Air, 31(2)

ISSN

0905-6947

Author

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Publication Date

2021-03-01

DOI

10.1111/ina.12785

Residential Air-Change Rates: A Critical Review

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Abstract

Air-change rate is an important parameter influencing residential air quality. This article critically assesses the state of knowledge regarding residential air-change rates, emphasizing periods of normal occupancy. Cumulatively, about 40 prior studies have measured air-change rates in approximately 10,000 homes using tracer gases, including metabolic CO_2. The central tendency of the air-change rates determined in these studies is reasonably described as lognormal with a geometric mean of 0.5 h^{-1} and a geometric standard deviation of 2.0. However, the geometric means of individual studies vary, mainly within the range 0.2-1 h^{-1}. Air-change rates also vary with time in residences. Factors influencing the air-change rate include weather (indoor-outdoor temperature difference, wind speed), the leakiness of the building envelope, and, when present, operation of mechanical ventilation systems. Occupancy-associated factors are also important, including window opening, induced exhaust from flued combustion, and use of heating and cooling systems. Empirical and methodological challenges remain to be effectively addressed. These include clarifying the time-variation of air-change rates in residences during occupancy and understanding the influence of time-varying air-change rates on tracer-gas measurement techniques. Important opportunities are available to improve understanding of air-change rates and interzonal flows as factors affecting the source-to-exposure relationships for indoor air pollutants.

Practical Implications

- Residential air-change rates are reasonably described as lognormal and, absent other information, a good estimate for the distribution is a geometric mean of 0.5 per hour and a geometric standard deviation of 2.0. The corresponding 10th, 25th, 50th, 75th, and 90th percentiles in such a distribution would be 0.21, 0.31, 0.5, 0.80, and 1.2 per h, respectively.
- Important factors that influence the air-change rate include weather (temperature difference and windspeed), building-related factors (tightness of the building envelope), and occupancy-associated factors (window opening, use of flued combustion, operation of heating and cooling systems). Some residences are equipped with mechanical ventilation systems and, when present, their design and operation would also affect air-change rates.
- Some factors that influence residential air-change rates vary with time. That feature can have important influence on properly interpreting experimental measurements of air-change rates and also for understanding the effects of air change on indoor pollutant concentrations.
- Even though there are measurements of air-change rates in many thousands of homes, there remain important challenges to fully understand this key property in relation to indoor air quality. Among the challenges are these: to better differentiate between variation in individual homes over time versus across housing stocks; to better understand how different

measurement methods respond to time-varying air-change rates; and to advance understanding of the multizone character of residential air-change rates and interzonal flows.
- Future attention should include expanding the geographic scope of residential air-change studies.

Running Title: Residential Air-Change Rates
Keywords: Air quality, Exposure, Housing, Infiltration, Tracer gas, Ventilation

1. INTRODUCTION

Ventilation influences indoor environmental quality. Air exchange introduces pollutants into buildings from outdoor air while simultaneously removing pollutants from indoors. Ventilation also affects energy use in buildings, in part because of the need to alter the temperature and moisture content of outdoor air to provide thermal comfort for occupants. These multiple influences create tension. High ventilation rates that would be favored to limit the accumulation of pollutants from indoor sources must be tempered by concern about the energy cost of thermally conditioning the ventilation air. The extent of protection realized by being indoors against some pollutants of outdoor origin is attenuated when ventilation rates are high. Yet ventilation rates that are too low lead to unacceptable accumulation of pollutants emitted from indoor sources.

Residences are an especially important class of buildings in which to consider ventilation rates in the context of indoor environmental quality. Time-activity surveys document that the majority of peoples' time is spent inside their own residence.[1] Residences also commonly include certain types of high emitting pollution sources, such as cooking and smoking.

Ventilation is commonly categorized in three modes. Infiltration, driven largely by temperature differences and wind, refers to the uncontrolled leakage of air through unintentional openings in the building envelope. Natural ventilation, driven by temperature differences and wind, flows through designed openings, such as windows and vents. Mechanical ventilation is induced by fans. Historically, most residential ventilation has been provided by a combination of infiltration and natural ventilation. Over time, in part because of energy efficiency concerns, building envelopes have become more airtight, reducing the influence of infiltration. Mechanical ventilation is becoming more common in residential construction. However, the turnover time in the residential building stock is long, and so the transition from historical practice is proceeding slowly.

Residential ventilation is most commonly quantified in terms of air-change rates. In the idealized case, the household space is represented as a single, well-mixed volume, V. Ventilation air flows across the envelope of the interior space at a volumetric rate, Q. The air-change rate is the ratio, $a = Q/V$.

More accurately, to properly account for the dependence of air density on temperature, the quantity of indoor air and the ventilation flow rates would be expressed in mass or molar terms rather than in volume terms. For this paper, to be consistent with common practice, air volume and volume flow rates will be used. The air-change rate is based on the volume flow rate out of the building.

Important complexities must be addressed when representing real residences using the idealized conceptualization. One major issue is whether the indoor space can be appropriately regarded as a single well-mixed volume. A second issue that emerges in practice is how to effectively experimentally address and interpret the time-dependence of the ventilation flow rate, Q. The influence of these complexities on measurement results and on the air-change rate concept for residences will be substantially explored in this review.

Important terminology regarding residential ventilation is not consistent throughout the literature. A simple but important example is that what is referred to as the “air-change rate” in this review is often termed the “air-exchange rate” in published studies. More fundamental complexity arises in defining the volume of a residence. In a single-family dwelling, should the volume of a basement be considered as a part of the house when assessing the air-change rate? The proper answer to this question should depend on the use of such a space (i.e., whether it is a part of the actively used space of the home or not), but there is clear potential for ambiguity and the relevant literature is not especially clear. Another term to highlight in this regard is “natural ventilation.” In studies in the United States,[2] Korea,[3] and Singapore,[4] natural ventilation emphasizes airflow through occupant-controlled openings, such as windows. In Europe, purpose-designed venting systems have become a common means to provide for natural ventilation of residences, separate from occupant control.[5] Many studies report results for naturally ventilated residences without providing more detailed information about the actual means by which natural ventilation is achieved.

Two broad classes of techniques are used to evaluate air-change rates of residences. One group of methods is based on tracer gases, using, for example, the deliberate release of perfluorocarbons, or, alternatively, utilizing a tracer of opportunity, such as metabolically emitted carbon dioxide. The second class of methods applies a fan pressurization experiment to measure the leakiness of the building envelope. That information is combined with a model of driving forces and might also incorporate occupant behavior such as window opening to estimate either the infiltration rate or the total air-change rate.

Early research on residential ventilation was published in the first half of the 20th century.[6] Historical overviews with extensive references to early research have been reported by Axley[7] and by Persily.[8] An effective conceptual overview of the relationship between building ventilation and indoor air quality in the context of energy efficiency goals is presented in Seppänen.[9] Dimitroulopoulou[10] summarized studies in European dwellings; Ye et al.[11] have reviewed residential ventilation in China. Breen et al.[2] reviewed modeling methods for evaluating air change rates “in support of air pollution exposure assessments.” Hodas et al.[12] provide a detailed summary of residential ventilation measurements. Seppänen and Fisk[13] have summarized the manifold ways that building ventilation influences the human experience of indoor spaces. Although some studies have focused specifically on the relationships between ventilation and health, much remains to be learned.[14-18] Future studies that aim to elucidate the relationship between ventilation and health may benefit from deeper understanding of measurement and interpretation of residential air-change rates.

The preparation of this review was motivated by an observation that much of the prior work that has critically assessed residential air-change rate measurements is older, more theoretical than empirical, and – to the extent that indoor air quality concerns are motivating – has tended toward a simplistic treatment of pollutant-ventilation relationships. The more recent reviews of air-change rate measurements have compiled empirical data without an accompanying critical assessment. This review aims to address key limitations of the existing literature. It is guided by the goals of thoroughly assessing the substantial empirical studies of residential air-change rates, stressing quantitative results, emphasizing influencing factors, and critically assessing the methods employed. While being cognizant of energy use concerns, this review is motivated primarily by an interest in how residential air-change rates influence human exposures to indoor air pollutants.

With its heavy emphasis on empirical evidence, the scope of this review is limited to air-change rates in parts of the residential housing stock that have been well studied. Most of the published evidence has focused on North America, northern Europe, and, more recently, China. Conditions that affect residential air-change rates in other parts of the world could be materially different. That those circumstances are not addressed here reflects a lack of available evidence, not a lack of importance. Furthermore, in aiming to provide a critical synthesis, this study is constrained by the scope of the author's knowledge, which leads to a heavier emphasis on conditions in North America than in Europe or east Asia. It is hoped that the appropriate incorporation of first principles into the treatment combined with the care taken in assembly and analysis of the empirical evidence can provide some compensation for the limitations and make this a useful review.

2. LOGNORMAL DISTRIBUTIONS

In any given dwelling, the air-change rate can vary with time because, for example, of differences in the extent of windows being open or because of changes in the meteorological driving forces. Across a population of residences, air-change rates also vary because of differences among buildings in the leakage characteristics of the envelope or owing to the presence and use of mechanical ventilation. Quantitative representation is important both for the central tendencies and for variability of air-change rates. For example, to the extent that they influence indoor pollutant concentrations, the air-change rate specific to a particular residence at a particular time is meaningful. A relatively short duration of a low air-change rate can exacerbate acute exposures to pollutants of indoor origin, especially if emitted episodically. Across the building stock, pollutant exposures encountered by people will be influenced by the air-change rate in their own residence, which can differ from the central tendency value of a population of residences. Variability of air-change rates, in both time and space, merits attention.

This review relies heavily on the lognormal distribution to represent populations of air-change rate values. In this section, key properties of the lognormal are summarized.

The lognormal distribution can be fully described using two parameters, the geometric mean (GM) and geometric standard deviation (GSD). Whenever a population is lognormally distributed, then the logarithm of its values are normally distributed, with mean μ = ln(GM) and standard deviation σ = ln(GSD).

Given a lognormal distribution with specific GM and GSD values, the following properties apply. The median is equal to the GM. The GSD is a multiplicative factor that quantifies variance. Specifically, the central 68% of the values in a lognormal distribution lie between GM ÷ GSD and GM × GSD. Likewise, the central 95% of the values in a lognormal distribution are bounded by the range GM ÷ GSD^2 to GM × GSD^2. When applied to air-change rate, GM has the same dimensions as the primary measurement, i.e. h^{-1}; the GSD is dimensionless. Consider a specific illustrative example: a lognormal distribution of air-change rates with GM = 0.5 h^{-1} and GSD = 2.0. For this distribution, 68% of the values would be in the range 0.25-1 h^{-1} and 95% of the values would be in the range 0.125-2.0 h^{-1}. Given the parameters of a lognormal distribution, any specific air-change rate can be represented by its "standard score" or "z-score," representing the number of standard deviations from the mean. The "standard score" is a useful measure to fit lognormal distributions to data when percentile values of the cumulative distribution are reported, rather than the GM and GSD.

Although a lognormal distribution is fully specified by the values of GM (= e$^{\mu}$) and GSD (= e$^{\sigma}$), it can be useful for some purposes also to know the arithmetic mean (AM) and standard deviation (SD). For a lognormally distributed parameter, these equations apply:

$$\mathrm{AM} = \exp\left(\mu + \tfrac{1}{2}\sigma^2\right) \tag{1}$$

$$\mathrm{SD} = \exp\left(\mu + \tfrac{1}{2}\sigma^2\right) \times \sqrt{\exp(\sigma^2) - 1} \tag{2}$$

In contrast to a normal distribution, the lognormal has the intrinsic virtue of being positive-definite, a property it shares with the air-change rate. To illustrate, consider a lognormal distribution with GM = 0.5 h^{-1} and GSD = 2.0. Applying equations (1) and (2), the values for arithmetic mean and standard deviation would be AM = 0.64 h^{-1} and SD = 0.50 h^{-1}. Such a distribution of air-change rates cannot be accurately described as normal. That is evident when one considers that an air-change rate of 0 would correspond to a standard score for the normal distribution of -0.64/0.5 = -1.27. The cumulative distribution at this standard score is 0.10, indicating that a normal distribution with AM = 0.64 h^{-1} and SD = 0.50 h^{-1} would have 10% of its values being negative, an impossibility for air-change rates.

Although there is no formal theoretical justification to support the choice of a lognormal distribution, Ott[19] provides an interesting physical argument as to why environmental concentration data may follow (approximately) a lognormal distribution. His argument is also at least suggestive for the distribution of air-change rates. Empirically, air-change rate results have been reported to conform well to lognormal distributions in several studies.[20-23] Rather than striving for strict statistical validity, it is appropriate to consider the lognormal distribution as a useful approximation that conforms with reasonable fidelity to the empirical evidence.

An important and useful feature of the lognormal distribution is that the cumulative distribution function is represented by a straight line when plotted in log-probability coordinates. This point is illustrated in Figure 1, which displays lognormal distributions that are inspired by results of cross-sectional studies of residential air-changes rates. The medians, which can be read directly from the plot, correspond to the respective geometric means. The slopes of the lines correspond to the GSD values; these can be obtained numerically as the 84th percentile value divided by the median.

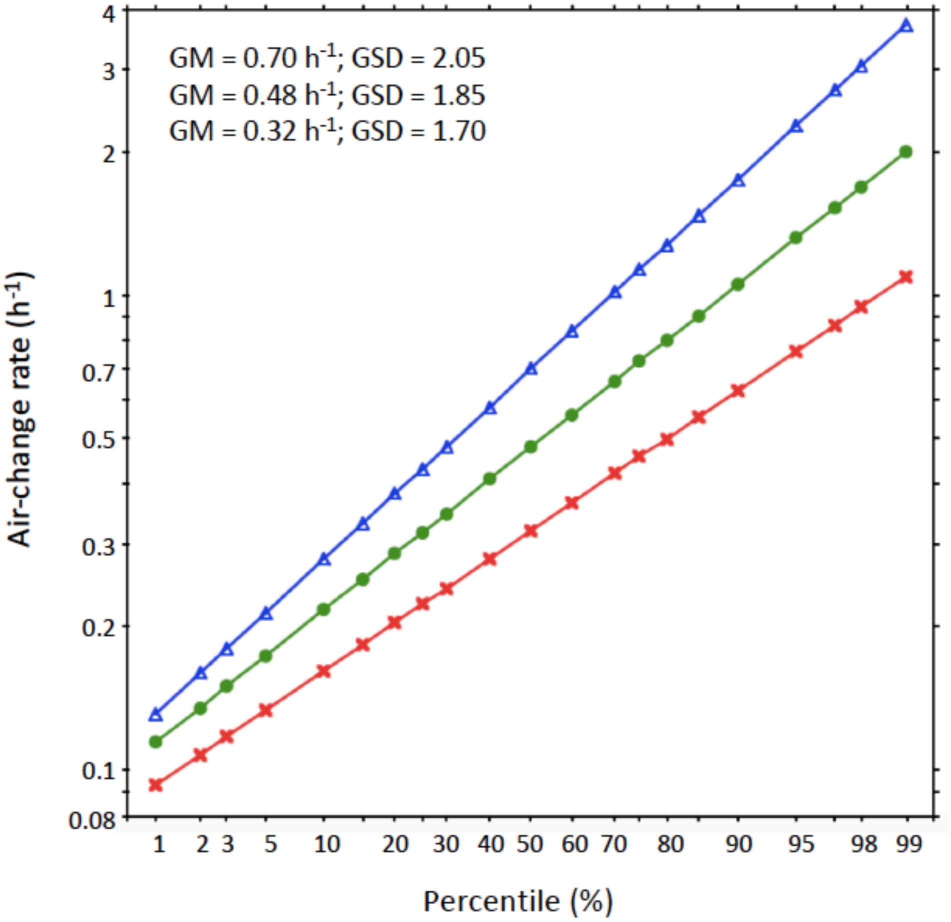

Figure 1. Cumulative probability plots for lognormal distributions of air-change rates. The values used to construct these distributions are guided by measurement results, but do not represent any specific study outcome. For the middle trace, the GM and GSD correspond approximately to the medians of cross-sectional study values reviewed for this paper. For the lower and upper traces, the GM and GSD values applied correspond approximately to the interquartile range of individual study results.

A challenge to overcome in preparing this review was to estimate parameters of lognormal distributions from diverse styles of reporting results. To summarize briefly, when lognormal parameters were reported in a referenced study, then those values are reported here. Analogously, when a log-probability plot such as in Figure 1 was displayed, then the GM and GSD were determined by extracting the median value and the slope from the figure. When individual measurements were available, the GM and GSD were directly computed by evaluating μ and σ of the logarithmically transformed data. In many studies, parameters of the cumulative distribution were reported, such as the interquartile range or the 90th percentile value along with the median. In such cases, linear regression analysis was applied to the logarithm of the air-change rates against the standard scores for the respective percentile values and the GM and GSD were evaluated from the intercept and slope. In some studies, only the mean and standard deviation were available, and in such cases the GM and GSD were assessed through application of equations (1) and (2).

Individual studies varied considerably in important factors that could influence the outcome, such as the nature of the residences studied, the mode of ventilation, the season of measurement, and the duration of the measurement period. The goal in this review is to transparently report key factors that could materially influence the measurement results. No attempt was made to adjust results so as to make them more directly intercomparable.

3. AIR-CHANGE RATE MEASUREMENT METHODS

To provide background and context for the subsequent presentation and discussion of empirical information, this section summarizes the approaches used to determine air-change rates in residences. The emphasis is on techniques that have been broadly applied in real dwellings with a preference for those that incorporate the influence of occupants.

3.1. Tracer-gas methods

Tracer gases are used to chemically label air so that its net movement can be measured. In a common application, a tracer gas is released and mixed throughout the interior volume. Measurement of its concentration allows for inferences to be made regarding the air-change rate. Major differences among methods concern the time dependence both of tracer release and of its measurement. An ideal tracer is chemically nonreactive (including that it not sorb to indoor surfaces). It should be readily measurable at concentrations that are practical to realize. To be used in occupied residential environments, it must be safe and nontoxic. The background or baseline concentration in the absence of known releases should be either low enough to neglect or stable enough to be assessed. Among the commonly employed tracer gases is sulfur hexafluoride. A suite of perfluorocarbon compounds has been widely used, especially in connection with passive release and sampling methods. Carbon dioxide generated metabolically by building occupants is also commonly used as a tracer of opportunity for characterizing residential air-change rates, most commonly during nighttime periods.

For cases in which the indoor environment is well represented as a single zone, a useful reference is ASTM Method E741.[24] This document specifically describes the three most commonly used tracer techniques: decay, constant injection, and constant concentration.

Sherman[25] also has reviewed the strengths and limitations of tracer methods for measuring air-change rates in buildings that can be represented as a single zone. In the subsections that follow, the three major single-zone methods are described. The final two subsections are concerned with more advanced problems: characterizing time-dependent air-change rates and assessing air-change rates when a multizone representation of a residence is required.

3.1.1. Tracer-gas decay

Being perhaps the simplest experimental technique for measuring residential air-change rates, the tracer-gas decay technique requires short-term release of a suitable species, its mixing throughout the indoor air volume, and subsequent monitoring of its concentration over time. Typically, the release and mixing occur over a time scale of minutes and the time-dependent concentration is assessed over a period of a few hours. For ideal conditions, with the tracer being nonreactive and naturally absent from the environment, with thorough mixing maintained throughout the decay period, and with the air-change rate being constant during this interval, the tracer-gas concentration satisfies an exponential decay equation, derived by solving a differential material balance for the tracer species in the residence air with removal only by means of ventilation.

$$C(t) = C_o \times \exp(-at) \tag{3}$$

Here, C_o is the nominal well-mixed indoor tracer concentration at the time of release, designated as $t = 0$. The air-change rate can be evaluated by regressing the natural logarithm of the concentration against time, t, and determining the slope, which is the negative of the air-change rate. See ASTM[24] and Sherman[25] for extensive discussions of this method. A practical limitation is that this approach commonly requires the presence of trained technical staff during the measurement period. Typically, that limits measurements in individual residences to short intervals with disturbed occupancy as compared to normal living conditions. In some studies that have used tracer gas decay, the household was requested to keep doors and windows closed prior to and during the measurement so as to measure air-change rates in a "worst-case condition" with regard to the accumulation of pollutants from indoor sources. In a few studies,[26,27] time-resolved air-change rates have been determined over extended periods using automated systems that apply this tracer-gas decay technique.

3.1.2. Perfluorocarbon tracer: Constant injection, passive sampling

The technique that has been most widely used for measuring residential air-change rates is based on constant, passive release of a perfluorocarbon tracer (PFT) combined with passive sampling by diffusive sorption. Dietz et al.[28,29] describe the passive PFT method in detail. This method has been used to measure air-change rates for periods ranging from a day to several weeks. It has been applied in tens of studies, aggregately measuring thousands of residences.

For a single well-mixed interior volume with a constant air-change rate, the release of a tracer at a constant emission rate produces a steady-state concentration that balances the rate of emission, E, with the rate of removal by ventilation:

$$C = {}^{E}/_{Q} \tag{4}$$

The air-change rate is then evaluated as $a = Q/V = (E/C)/V$. The air-change rate determination requires knowledge of the emission rate, E, measurement of the indoor air concentration, C, and an assessment of the indoor volume, V.

A major advantage of this method over other approaches is its ease of use. It is also relatively inexpensive. The sources and samplers are small, so they can be transported by mail. Their use in the field needs no specific expertise. The chemical analysis of the samplers, e.g. using thermal desorption followed by gas chromatography and electron-capture detection, is conducted in a central laboratory.

Nevertheless, there are several important challenges and limitations to recognize in using the passive PFT method in occupied residences and in interpreting the results. Four issues are highlighted here. First, to use the passive PFT method to report an air-change rate, it is necessary to determine the interior volume. To be clear, the measured concentration depends on the ventilation flow rate (Q, with units of m^3/h), whereas the air-change rate is volume normalized ($a = Q/V$). Among the specific challenges that must be addressed in assessing volumes is whether coupled spaces such as basements are included or excluded. Many reports of air-change rates measured by the passive PFT method do not specify how house volumes are determined.

A second consideration involves the PFT emission rate, E. The passive sources described in Dietz et al.[29] rely on the permeation of PFT vapor through a polymeric material. The tracer emission rate would be temperature dependent. Although it is possible to apply temperature control so that the emission rate is constant,[30] that is not commonly done. The next best approach is to monitor the time-averaged temperature in the space in which the source is deployed. Doing so allows for a first-order correction for temperature differences but does not address the possibility of diurnal variation because, for example, the interior air temperature is commonly lower overnight than during the day.

A third factor is whether the well-mixed assumption is appropriately satisfied. A common approach to address this concern is to use multiple sources and/or multiple samplers widely dispersed throughout the indoor space. A few studies have taken a multizone approach, e.g. with the release of separate specific tracer chemicals on different floors of a residence.[31-33] The use of PFT technology to study air-change rates in a multizone environment is substantially explored in §6.2.

The fourth factor concerns the fact that the ventilation rate, Q, may vary with time during the measurement period. In that case, assuming that the emission rate is constant, the air-change rate as determined from the time-averaged tracer-gas concentration would be (approximately) the harmonic mean, rather than the arithmetic mean. To illustrate the point numerically, assume that a house is operated with windows closed for 12 h/d with an air-change rate of 0.5

h^{-1}. For the other 12 h/d, the windows are open, and the air-change rate is 1.5 h^{-1}. The (arithmetic) average air-change rate for a multiday period would be 1 h^{-1}. The value obtained from application of the passive PFT method under idealized conditions would be $\{½ [(1/0.5) + (1/1.5)]\}^{-1} = 0.75$ h^{-1}. In the presence of time-varying ventilation, the harmonic mean and the passive PFT method favor lower air-change rates. In this example, the harmonic mean value differs from the arithmetic mean by 25%. Often, the measurement result in studies that use the passive PFT method is reported as the "average" air-change rate, without elaboration. A few studies have highlighted this limitation.[34-36] Importantly, for application to estimate the concentration of an indoor air pollutant emitted at a constant rate from an indoor source, the harmonic mean is the relevant time-averaged air-change rate. How time-varying ventilation rates influence indoor pollutant concentrations varies among species, as is explored §7.

Lunden et al.[30] undertook multiday measurements of air-change rates in three households probing deeply the measurement accuracy of the perfluorocarbon tracer technique. Among their noteworthy findings was that continuous use of a central air-handling system fan promoted effective mixing of the tracer gas throughout the home.

3.1.3. Metabolic CO_2

The use of metabolically generated CO_2 as a "tracer of convenience" for measuring residential air-change rates has the attractive feature of not requiring the deliberate release of an unnatural substance into occupied spaces. The advent of technologies for relatively inexpensive, real-time monitoring of CO_2 in indoor air has enabled the widespread use of this method during the past decade. Nevertheless, there are important conditions for the method to be useful, and these are not always satisfied.

Bekö et al.[21] reported the first large study to apply metabolic CO_2 for measuring air-change rates in residences. In early, investigators applied CO_2 monitoring to assess ventilation rates in public buildings such as a library[37] and a school.[38] Persily[39] provided a critical assessment of the use of metabolic CO_2 for ventilation measurements, emphasizing mechanically ventilated buildings.

Among the major factors that can influence indoor CO_2 levels are supply from outdoor air, metabolic emission by occupants, emissions from unvented indoor combustion (such as natural-gas cooking) and removal by ventilation. Taking account of these factors, the indoor CO_2 concentration for a single, well-mixed space is described by this differential equation:

$$\frac{d(CV)}{dt} = E_m + E_c + C_o Q - CQ \tag{5}$$

Here, C and C_o respectively represent the CO_2 concentration in indoor and outdoor air. The respective direct indoor emission rates are E_m for metabolic generation and E_c for unvented combustion. As before, the air-change rate a would be the volume normalized flow rate, Q/V. It is convenient to use mass units to specify CO_2 emission rate and concentration; the conversion from mass concentration to mole fraction at $T = 293$ K and $P = 1$ atm is 1 ppm = 1.83

mg/m^3. If Q is expressed in units of volume/time, then the form of equation (5) strictly requires that indoor and outdoor temperature are the same. Accommodating the change of volume associated with a temperature shift requires a slightly more complex equation that obscures clarity and so this recounting is based on the simpler form.

Consider some analysis time-interval of interest, such as an overnight period with constant occupancy and limited indoor activity. How might equation (5) be applied to evaluate the air-change rate? Let's make some further assumptions: (a) that the only indoor emissions occur from occupant metabolism ($E_c = 0$); (b) that the occupancy and metabolic emission rate are constant (E_m = constant); and (c) that the ventilation rate is constant (Q = constant). The only further requirement for solving the differential equation is to specify an initial condition; let's call that $C(0)$, the indoor CO_2 concentration at the start of the analysis period, for which we set the time variable to be $t = 0$. The solution to equation (5) under these conditions can be represented as the sum of two terms, exponential decay from the initial concentration plus exponential ingrowth toward the final steady-state concentration. Both exponential terms have the same time-dependence, which includes the air-change rate as a rate constant.

$$C(t) = C(0)\,e^{-at} + \left(\frac{E_m}{Q} + C_o\right)(1 - e^{-at}) \tag{6}$$

Subject to the assumptions previously stated being at least approximately satisfied, numerically fitting equation (5) to the measured time-dependent indoor CO_2 concentration can yield a sound estimate of the air-change rate, a. The dynamic response is illustrated in the left frame of Figure 2, which depicts the CO_2 concentration in indoor air for the case of a small house, internally well mixed, with three occupants. The assumed starting condition is that the indoor air matches the outdoor air at 400 ppm CO_2 and then, starting from time $t = 0$, the occupants metabolically emit 64 g/h of CO_2, which corresponds to expectations for the three occupants during sleep. Over the course of an assumed 8-h sleeping period, the CO_2 level rises to an extent that varies with air-change rate. Note that for the higher two air-change rates in this figure, a steady-state condition is achieved, at a level $C_{ss} = (C_o + E_m/Q)$. From the measured steady-state value, the ventilation rate, Q, can be determined and the air-change rate can be assessed as $a = Q/V$. However, for a lower air-change rate, such as 0.25 h^{-1}, the indoor concentration does not attain its steady-state value within 8 hours, and so a fit to the time-varying concentration is required to extract an estimate of a. Note, too, that the three traces in this figure follow the same initial trajectory. The initial response of the system depends on the emission rate and the interior volume, but not on the air-change rate. If steady-state conditions are not achieved, then monitoring and analysis must continue for a sufficiently long period for the slope of the time-dependent concentration to change for CO_2 data to provide any information about ventilation rates.

Because of the stability of occupancy and level of activity, metabolic CO_2 has mainly been used to study air-change rates overnight. A challenge in such applications that has not been fully addressed is whether the single, well-mixed volume adequately represents indoor air spaces of residences. To the extent that bedroom doors are closed, e.g. for privacy, and absent the presence or regular operation of a central-air heating (or cooling) system, which would promote mixing, the bedroom air may be weakly coupled to air throughout the remainder of the residence. Such weak coupling would mean that outdoor air change rates cannot be uniquely determined from measurement of bedroom air CO_2 levels.

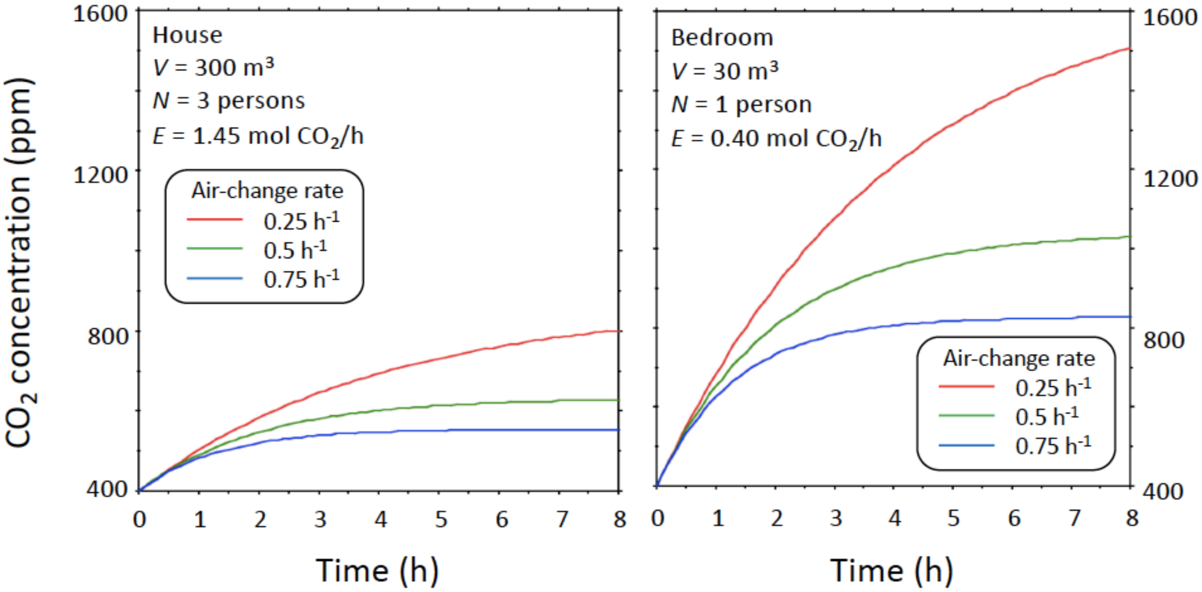

Figure 2. Time-resolved indoor air concentration of carbon dioxide in a residence. Left: House is well-mixed with three occupants emitting at a rate corresponding to sleep (two adults plus one child). Right: Case of a bedroom that is isolated from the rest of the house, with a single occupant (emissions rate corresponds to sleeping conditions for a child). In both cases, the initial indoor concentration matches the outdoor concentration of 400 ppm. The three traces in each frame represent different outdoor air-change rates.

The nature of the challenge can be gleaned by comparing the left and right frames of Figure 2. The left frame assumes that the whole of the residence is well mixed. The right frame illustrates the case of a single-occupant bedroom that is assumed to be perfectly isolated from the rest of the house. At a whole-house air-change rate of 0.25 h^{-1}, the indoor CO_2 level rises to about 800 ppm overnight. With its much smaller volume, and correspondingly higher per-volume CO_2 emission rate, the isolated bedroom CO_2 level rises to 1500 ppm with a 0.25 h^{-1} air-change rate. Any exchange of air between this bedroom and the remainder of the house would tend to reduce the bedroom CO_2 concentration, but would not represent a higher air-change rate with outside air. The fundamental problem, which cannot easily be overcome, is that a multizone environment cannot be well-represented using a single-zone model. Also, the use of a single tracer gas for characterizing flows in a multizone environment is generally not suitable except under the restrictive assumption that flows are time invariant.[40] That condition will not generally be met in occupied residences.

3.1.4. Time-resolved tracer methods

Factors that influence residential air-change rates can vary with time. These factors include the driving forces (wind, indoor-outdoor temperature difference), window and door opening, and operation of exhaust or supply fans. Indoor pollutant emissions and outdoor concentrations vary with time. Residential occupancy is time dependent. Consequently, it is of interest to measure the time-dependence of residential air-change rates.

Several specific methods can be applied to measure time-dependent residential air-change rates using tracer gases. One possibility, which has been employed in a few studies is to apply tracer gas decay sequentially.[26,27] In this method, a pulse of tracer gas is released automatically every few hours and mixed throughout the interior space. The concentration is continuously monitored; the exponential function (equation 3) is fit to the concentration decay data to infer the air-change rate, *a*. The result is a time series of values with a resolution of a few hours.

Continuous tracer release can also be applied. For example, Liu et al.[41] used constant release of deuterated alkenes coupled with their continuous measurement to assess air-change rates with two-hour time resolution in an occupied residence. In that case, the air-change rate was evaluated by applying an integral form of the material-balance equation, accounting for the change in the amount of the tracer in the house during the analysis period in addition to its removal by ventilation. Equation (6) was applied:

$$a(t) = \frac{E\,\Delta t - \left(C(t+\Delta t) - C(t)\right) \times V}{C_{avg}\,V\,\Delta t} \tag{7}$$

Here, E is the controlled tracer release rate, $C(t)$ is the time-dependent tracer concentration, Δt is the analysis interval during which the time-averaged indoor tracer concentration is C_{avg}.

Another technique adjusts the rate of emission of tracer gas with the aim of maintaining a constant indoor concentration. The approach is described by Sherman.[25] It has rarely been applied in ordinarily occupied residences. The most extensive example is its application for multiday periods in five homes in Denmark, sampled in each of four seasons.[42]

3.1.5. Multizone methods

A fundamental challenge in characterizing air-change rates of residences is whether the indoor air space is reasonably represented as a single zone or, conversely, whether a multizone representation is needed. Theoretically, for the single-zone representation to be suitable, the transport time scales between rooms and the mixing time scales within rooms need to be fast relative to the air-change time scale, which is $1/a$.

Techniques have been developed and substantially explored in theory and in laboratory studies for using tracer gases to quantitatively assess air flow rates for multizone building systems. Sinden[40] and Sandberg[43] have described mathematical aspects for using tracer gases to assess flows in multizonal systems. Afonso et al.[44] presented a laboratory evaluation of interzonal transport using a single-tracer technique.

Consider a multizone indoor environment that can be appropriately represented as N independently well-mixed zones, coupled by airflows between the zones. If air can be transported from each zone to each other zone, including the outdoors, and vice versa, then the total number of flow paths to quantify is $N \times (N + 1)$. That each zone has a fixed volume introduces N constraints, so that the number of independent flow rates is N^2. Mathematically, the use of tracer gases to assess air flow rates is an *inverse problem* in which the governing equations predict concentrations from flows, but the experimenter seeks to infer flows from measured concentrations. Inverse problems rapidly grow in complexity and in susceptibility to experimental limitations as the dimensionality of the problem increases. Because of these considerations, practical applications of multizone representations of real buildings with normal occupancy have been limited to the use of two or three zones.

Prospects for effectively solving the inverse problem are also improved when chemically distinct species are released in each zone of the system, with measurements of each tracer in each zone. In this way, with each species in each zone being one independent measure, the number of measures is equal to the number of unknowns in the inverse problem.

Miller et al.[45] have demonstrated how to determine multizone flows in a two-chamber laboratory environment using pulsed release of independent tracers in each chamber followed by time-resolved measurement of each species in each zone.

In field studies of residential air-change rates, most measurements have been made based on the single-zone representation. When multizone approaches have been used, they have most commonly applied the passive PFT technology with separate tracers released in each zone and with time-averaged concentrations determined for each species in each zone. D'Ottavio et al.[46] explore errors in the use of such methods to assess multichamber flows. As is common with the literature exploring the theory multichamber flow, D'Ottavio et al. restrict their analysis to steady-flow conditions. They acknowledge the limitations of this assumption. However, given that flows cannot be expected to be constant in residences even on a diurnal time scale, it is important that the resulting errors be effectively addressed. The relative silence of multichamber theory about the consequences of time-varying flows is a gap in the literature that has consequences of uncertain scale for applying multizone tracer gas methods in real residences.

Another key limitation arises in practical application. How many zones are needed to represent a residence? By what criteria should they be selected? These topics have not been substantially addressed in the literature. In some studies, individual rooms on a single floor have been selected. In other studies, different floor levels have been chosen. As one example, Dodson et al.[47] used a multizone approach to investigate the air-change rates and airflow patterns in 45 residences in the Boston area. In that case, the main living space was treated as one zone. Basements, when present, were a separate zone. For apartments, common hallways were treated as a separate zone. Attached garages were included as a separate zone when present. Either two or three tracers were used at each site. Du et al.,[48] using passive PFT technology, assessed air-change rates and interzonal flows in 126 houses in Detroit. In that case, a child's bedroom was treated as one zone and the remainder of the living space was a second zone. The analysis necessarily interpreted the time-averaged concentration data as resulting from constant air-flow rates. The validity of that assumption has not been demonstrated.

The work of Bekö et al. illustrates the challenge of applying multizone methods in real-life situations.[42] They applied multiple techniques to measure air-change rates in several residences in Denmark. Included were passive PFT technology, continuous injection designed to maintain constant concentrations in multiple zones, and metabolic CO_2 to determine bedroom air-change rates at night. For the passive PFT technology, collected tracer samples reflected monthly average concentrations, which were repeatedly sampled throughout the year. By contrast, the continuous injection system determined air change rates with high temporal resolution. The study reported substantial differences in results using the different methods, in particular the active versus passive tracer methods and also comparing bedroom air-change rates inferred from controlled tracer releases with those determined from metabolic CO_2. The researchers noted that air-change rates "changed frequently during the day," and that "window opening behavior had a strong influence."

3.2. Leakage area measurements and infiltration modeling

In addition to tracer-gas methods, a second major approach has been applied to determine residential air-change rates. Fundamentally, this method is based on measuring the leakiness of the building envelope. The leakage area measurement is integrated into a mathematical equation to estimate the infiltration rate. Contributions to the total air-change rate from natural ventilation can be added, e.g. based on either direct empirical or statistical evidence about window opening behavior. Many measurements have been made of residential envelope leakage as part of weatherization programs to improve energy efficiency in the building stock. An advantage of this approach relative to the tracer-gas techniques is that a single short-term measurement of the constant physical property of envelope leakage can serve as the basis for estimating air-change rates across an entire season. To the extent that infiltration is the dominant mode (as is often the case during winter), then the estimates can be reasonably accurate, especially in their statistical properties. A limitation is that window opening behavior can materially alter residential air-change rates, especially during periods with mild weather when window use is common. Evidence for incorporating occupant-influenced contributions into total air-change rate determinations is much sparser than for determining infiltration rates.

To measure the leakiness of a residential building, a "blower door" is temporarily installed into an exterior door frame.[49,50] The blower door consists of a powerful axial fan mounted in a plywood panel. The fan speed can be adjusted. Calibration provides a known relationship between measured rotational speed and resulting volumetric flow rate. A manometer with pascal-scale sensitivity measures the pressure difference between indoors and outdoors. In a common blower-door test, the pressure difference (ΔP) is measured in relation to the volumetric flow rate (Q_f) across a range of pressure differences up to ~ 50 Pa. Commonly, both pressurization and depressurization of the residence is applied. The flow rate is related to the pressure difference using a power law of this form:

$$Q_f = \kappa(\Delta P)^n \tag{8}$$

The parameters in this equation, which are determined from experimental data, are κ, the air leakage coefficient, and n, the pressure exponent. Theoretically, the value of n should lie in the range 0.5 (for airflow resistance that is purely inertial) to 1.0 (for resistance that is purely viscous). Empirically, n is commonly found to be in the range 0.6-0.7.

As summarized in Chan et al.,[51] the measured leakage parameters κ and n are used to determine the effective leakage area of the building, which can then be combined with meteorological data (wind speed and indoor-outdoor temperature difference) to estimate the infiltration rate.

A rule of thumb is that the seasonal average air-change rate can be estimated from the air-change rate measured by a blower-door at a pressure difference of 50 Pa. Specifically, ACH ~ ACH_{50} / 20, where ACH is the seasonal average air-change rate and ACH_{50} is the air-change rate measured during a blower-door test at 50 Pa pressure difference.[2,50] Breen et al.[2] describe this rule of thumb along with other infiltration models, exploring their accuracy in relation to empirical air-change rate measurements.

4. RESIDENTIAL AIR-CHANGE RATES

This section presents compilations of air-change rates determined in substantial cross-sectional studies and in longitudinal studies. The aim is to be thorough without aspiring to be comprehensive. To be included in the tabulated cross-sectional studies, a minimum sample size of 20 dwellings was required and sufficient evidence must have been reported to allow for estimates of the geometric mean and geometric standard deviation. To be included in the longitudinal studies, time-resolved air-change rate measurements needed to be reported for a minimum of one week, with individual measurements resolving air-change rates on a time scale of a few hours. Beyond these conditions, no additional exclusion criteria were applied. In addition to reporting parameters of the lognormal distributions, key additional information that may influence the results or their interpretation is included when available, such as these factors: number of residences studied, duration of the sampling period, season of sampling, geographic location, whether the residences were single-family homes or apartments, and type or mode of ventilation. Details regarding how the parameters of the lognormal distribution were determined from the original report are presented in the Supporting Information.

The method used in studies for determining air-change rate is pivotal. Results are organized and presented according to measurement method, as follows: cross-sectional studies using passive perfluorocarbon technology (Table 1), time-resolved studies in individual houses based on successive decay or constant tracer injection (Table 2), metabolic CO_2-based determinations (Table 3), cross-sectional studies using tracer-gas decay (Table 4), and determinations from leakage-area measurements (Table 5).

The entries in Table 1 are rank ordered according to the GM of the residential air-change rate in each study. The range of these values spans almost an order of magnitude, from 0.16 h^{-1} to 1.49 h^{-1}. The variability, as indicated by the GSD, is more consistent across all studies, with a minimum value of 1.4 and a maximum of 2.85. Treating each of the 40 rows in the table as an independent and equally informative indicator, across almost 9000 households measured (a minority subset of which are repeat measurement sites), the median value (and approximate interquartile range) for the GM and GSD are 0.5 (0.3-0.7) h^{-1} and 1.86 (1.7-2.1), respectively. The USEPA Exposure Factors Handbook[52] recommends (Table 19-1), for US housing, a median air-change rate of 0.45 h^{-1} with a 10th percentile value of 0.18 h^{-1}. For a lognormal distribution, these values correspond to GM = 0.45 h^{-1} with GSD = 2.0, a result that is consistent with the central tendency of the full body of data reported in Table 1. Factors that influence air-change rates, both within and across studies such as these, are explored in §5.

Among the noteworthy features to highlight for the information summarized in Table 1 are that all of these studies took place in North America (Canada and USA) and in northern Europe (Sweden, Denmark, Norway, Finland). There is a tendency for the air-change rates to be lower in areas with colder climates. Housing types and modes of ventilation do not emerge from this evidence as particularly strong predictors of air-change rates.

Table 1. Residential air-change rate distributions from cross-sectional studies using perfluorocarbon tracers with constant injection and time-averaged sampling.

Location	***N***	**Duration**	**GM (h^{-1})**	**GSD**	**Season**	**Reference**	**Note**
Windsor, ON	93	5 × 1 day	0.16	2.12	Summer	53	a
Toronto, ON	35	5 days	0.18	1.85	Su, F	54	b
Canada	26	3 weeks	0.18	1.84	W, Sp, Su	55	c
Quebec	96	1 week	0.2	1.5	W, Sp	56	d
Edmonton, AB	50	7 × 1 day	0.23	1.70	Winter	57	e
Sweden	29	1 week	0.23	1.74	Winter	58	f
Sweden	~ 750	1 month	0.29	1.71	W, Sp	31	g
California	108	1 day	0.30	2.09	Su, F, W	59	h
Windsor, ON	93	5 × 1 day	0.32	1.94	Winter	53	a
Edmonton, AB	50	7 × 1 day	0.32	2.42	Summer	57	e
Sweden	320	1 week	0.32	1.54	F, W, Sp	60	i
Sweden	582	2 weeks	0.32	1.6	F, W, Sp	61	j
Sweden	150	2 weeks	0.33	1.64	F, W, Sp	22	k
Denmark	117	7-25 days	0.34	1.4	F, W	5	l
Detroit, MI	61	7 days	0.39	2.03	All	32	m
Sweden	129	2 weeks	0.42	1.76	F, W, Sp	22	k
Finland	242	2 weeks	0.43	1.72	F, W, Sp	62	n
Sweden	~ 750	1 month	0.43	1.79	W, Sp	31	g
Boston, MA	50	2 weeks	0.47	2.06	F, W, Sp	63	o
Houston, TX	100	2 days	0.48	2.13	All	64	p
Norway	77	2 weeks	0.52	1.66	F, W, Sp	65	q
N Carolina	37	4 × 7 × 1 d	0.53	1.98	All	66	r
USA	2844	unspecified	0.53	2.19	All	20	s

Detroit, MI	126	1 week	0.55	2.15	All	48	t
Norway	92	2 weeks	0.58	1.71	F, W, Sp	65	q
Nunavut	46	unspecified	0.6	1.7	Winter	67	u
Detroit, MI	24	10 × 1 day	0.60	2.03	F, Sp	68	v
Sweden	540	4 weeks	0.63	1.63	F, W, Sp	69	w
Norway	175	2 weeks	0.67	1.68	F, W, Sp	65	q
New York, NY	46	2 days	0.72	2.04	W, Sp	70	x
Boston, MA	55	2 days	0.72	1.60	Su, W	71	y
Boston, MA	40	2 weeks	0.81	1.87	Su	63	o
Los Angeles, CA	105	2 days	0.88	1.95	All	64	p
Elizabeth, NJ	96	2 days	0.93	2.03	All	64	p
Detroit, MI	90	5 × 1 day	0.94	1.78	W	72	z
Riverside, CA	175	1 day	0.97	2.18	Fall	73	aa
Los Angeles, CA	41	2 days	0.98	2.11	W	70	x
Detroit, MI	105	5 × 1 day	1.20	2.85	Su	72	z
New York, NY	46	2 days	1.36	2.13	Su	70	x
Los Angeles, CA	41	2 days	1.49	1.87	Su, F	70	x

[a] Windsor, Ontario: 93% detached, single-family homes; no information about modes of ventilation. About half were sampled during 2005 and the others in 2006. The goal was to sample each home for 5 consecutive 24-h periods during winter and again in summer.

[b] Toronto: Fifty homes studied during August-November 2006. Results reported for 35 (no explanation for missing data) as mean (standard deviation) = 0.22 (0.15) per h. Probable that all were single-family dwellings; no information about modes of ventilation.

[c] Canada: Twenty-six homes in greater Toronto and Ottawa areas; 25 were single-family homes (19 with basements). No information about modes of ventilation. Utilized 2- or 3-zone models with multiple tracer gases. Sampled 3-week averages during February – July 2015.

[d] Quebec City: Single-family dwellings (with one duplex), sampled during January-April 2005; 30% equipped with an "air exchanger."

[e] Edmonton: Fifty homes were sampled during winter and summer seasons of 2010. (Among these, 26 participated in both sampling seasons, whereas 24 were different between winter and summer.) In each home, a 7-day campaign was undertaken, with 24-h measurements made using passive PFT sampling. A total of 338 (winter) and 340 (summer) daily air-change rate measurements were made. Type of home and modes of ventilation not clearly reported.

[f] Sweden: Sample of single-family homes near Stockholm selected to contrast houses with high (n = 13) versus low (n = 17) dust-mite allergen in mattress dust. Measurements made during December 1989. Mode of ventilation not specified.

[g] Sweden: Total of 1500 homes with unspecified apportionment between single-family houses (GM = 0.29 h^{-1}, GSD = 1.71) and multifamily homes (GM = 0.43 h^{-1}, GSD = 1.79). Sampled between November 1991 and April 1992, specifically excluding warmer weather period. Apportionment of ventilation mode in overall Swedish housing stock (Table 4 of cited reference) indicates 60% of households use natural ventilation and 40% mechanical ventilation.

[h] California: Newer single-family homes in California, built between 2002-2004; sampled between summer 2007 and winter 2007-2008. Among 108 houses studied, there were "26 homes with mechanical outdoor-air ventilation systems."

[i] Sweden: 390 dwellings sampled between October 2001 and April 2002. Distribution of house type was 83% single-family, 6% row house, and 11% multifamily house. Among houses studied, 66% were naturally ventilated, 24% had mechanical exhaust, and 10% had mechanical exhaust and supply. Reported data in this table are for single-family houses only. Mean air-change rate was 0.36 h^{-1} for single-family houses, 0.35 h^{-1} for row houses and 0.48 h^{-1} for multifamily houses.

[j] Sweden: BETSI study assessed respiratory health of 1160 adults occupying 605 single-family homes. Including data from 582 of the 605 houses, the reported distribution parameters were AM = 0.36 h^{-1} and SD = 0.18 h^{-1}. Among studied households, 46% relied on natural ventilation whereas 54% were equipped with mechanical ventilation systems.

[k] Sweden: Measurements made between October 2007 and May 2008 in 150 single-family homes (GM = 0.33 h^{-1}, GSD = 1.64) and 129 apartments (GM = 0.42 h^{-1}, GSD = 1.76). Combining household types but disaggregating by ventilation system, GM (*n* samples) were natural ventilation = 0.32 h^{-1} (101, 36%), exhaust only = 0.39 h^{-1} (97, 35%), and balanced mechanical = 0.43 h^{-1} (81, 29%).

[l] Denmark: All single-family dwellings (constructed 1984-1989) measured during Jan-Mar and Oct-Nov 1992. "In newer Danish single-family houses, it is standard that natural ventilation is driven by two vertical exhaust vents … through the ceiling: one in the bathroom and one in the kitchen, and that outdoor-air inlets … are placed in other rooms." In this study, 97/117 homes had outdoor-air inlets; in 66 they were normally open.

[m] Detroit: Studied 61 residences (79% single-family houses) with 170 total week-long visits analyzed. Used distinct tracers between basement and main occupied space. Air-change rate for living space tabulated; basements had GM = 1.1 h^{-1}, GSD = 2.27. No information reported about mode of ventilation.

[n] Finland: Among 242 dwellings studied, 155 (64%) were houses and 87 (36%) were apartments. In all, 31% had natural ventilation, 42% had mechanical exhaust, and 26% had balanced mechanical systems. Measurements made between November 1988 and April 1989.

[o] Boston: Public housing (apartment) units sampled during the heating season (50 homes, GM = 0.47 h^{-1}, GSD = 2.06), Sep 2002 – May 2003 and during the nonheating season (40 homes, GM = 0.81 h^{-1}, GSD = 1.87), June – Sep 2002. No information reported about modes of ventilation.

[p] Houston, Los Angeles, Elizabeth: Measurements made between June 1999 and February 2001. Total of 524 air-change rate measurements in 301 homes, with repeated measurements in separate seasons.[72,74] Proportion single-family dwellings (others mainly apartments) by city: Elizabeth = 23%, Houston = 52%, Los Angeles = 46% single-family dwellings. No clear information about modes of ventilation.

[q] Norway: Total of 344 households sampled: 77 single-family (GM = 0.52 h^{-1}, GSD = 1.66), 92 detached and semi-detached (GM = 0.58 h^{-1}, GSD = 1.71), 175 apartments (GM = 0.67 h^{-1}, GSD = 1.68). Measurements conducted during 1992-1995, excluding June, July and August. Ventilation mode per household was about 67% "natural" and 33% "mechanical exhaust," not disaggregated by type of home.

[r] North Carolina: Each measurement represents 24-h sample. In all, 37 residences were studied (86% single-family dwellings) and for each the goal was to conduct 7 consecutive days of sampling across each of four seasons between summer 2000 and spring 2001. Mode of ventilation not fully specified; 70% of homes had central air conditioning and window use was reported in aggregate for 23% of monitored time.

[s] USA: Composite database from many studies conducted during 1982-1987. Koontz and Rector[75] reported an analysis of essentially the same database. They corrected for repeat sampling and adjusted for uneven geographic coverage. Their analysis yielded GM = 0.46 h^{-1} and GSD = 2.25. No information reported on type of housing other than "single and multi-family dwelling units in the continental United States." Mode of ventilation not reported.

[t] Detroit: 263 week-long measurements in 126 houses sampled between March 2009 and September 2010. Residences were occupied by "predominantly low income African American and Latino [families] and each had a child with asthma." Apportionment by type was 79% single-family houses, 14% duplex or flat, and 3% apartment. No reported information on modes of ventilation.

[u] Nunavut, Canada: Investigation of indoor air quality and infection risk in Inuit houses, sampled during Jan-Mar 2005, "under extreme Arctic weather conditions." Homes were "single-storey dwellings, raised above ground … small relative to houses in southern Canada." Sampling details not provided. Reported air-change rate for 46 houses with children were 0.7 ± 0.4 h^{-1}. An additional 46 houses from the same community not occupied by young children had "a lower calculated air change rate (0.53 v. 0.70 h^{-1})." Modes of ventilation not reported.

[v] Detroit: 24 dwellings sampled during fall 2010 (*n* = 24) and spring 2011 (*n* = 17). For each home monitored in each season, five daily average AER determinations were made. Likely all were single-family houses; mode of ventilation not specified.

[w] Sweden: 540 homes sampled for 4-week intervals. Sampling occurred during October-March (heating season). Among the homes, about 25% were single-family dwellings and the rest were apartments. Ventilation mode apportionment: 34% natural ventilation; 44% mechanical exhaust; 22% balanced mechanical systems.

[x] New York, Los Angeles: Inner city housing sampled during two seasons in two cities. For New York, 46 households (78% apartments) each sampled during heating season (Feb-Apr 1999, GM = 0.72 h^{-1}, GSD = 2.04) and summer (Jun-Aug 1999, GM = 1.36 h^{-1}, GSD = 2.13). For Los Angeles, 41 households (68% single family homes) each sampled during cooler months (Feb-Mar 2000, GM = 0.98 h^{-1}, GSD = 2.11) and late summer, early autumn (Sep-Oct 2000, GM = 1.49 h^{-1}, GSD = 1.87). Ventilation mode note reported.

[y] Boston: Reinterpretation as single-zone air-change rates for data originally reported in Dodson et al.,[47] using a multizone model. Convenience sample of homes, with measurements occurring during summer 2004 and winter 2005. "Majority of the residences were single-family dwellings." Mode of ventilation not reported.

[z] Detroit: Distributions based on arithmetic averages of five consecutive 24-h samples at each of the homes. Separate reporting for winter (90 households sampled during January-March 2004-2007, GM = 0.94 h^{-1}, GSD = 1.78) and summer (105 households sampled during July-August 2004-2007, GM = 1.20 h^{-1}, GSD = 2.85). Houses in the DEARS study were 87% single-family dwellings and 8% duplex units.[76] Mode of ventilation not specified.

[aa] Riverside, CA: Sampled during September-November 1990. Probable that studied houses were mainly single-family dwellings with ventilation provided by combination of infiltration and window use.

One otherwise qualified study is not included in Table 1 because insufficient information is available to estimate GM and GSD of the air-change rate distribution. MacNeill et al.[77] conducted weeklong sampling in Halifax, Nova Scotia, Canada. They sampled 50 homes each during winter (Jan-Apr) and summer (Jun-Sep), with 42 of the homes sampled during both seasons. They reported values for the median (range) of daily air-change rate measurements: for summer 0.44 (0.09-4.07) h^{-1} and for winter 0.30 (0.08-1.14) h^{-1}.

Table 2. Residential air-change rate distributions from detailed studies of individual houses.

Location	Duration	Interval	GM (h^{-1})	GSD	Season	Reference	Note
Illinois	15 weeks	3 h	0.18	1.74	W, Sp	26	a
California	5 weeks	2 h	0.33	1.31	Winter	41	b
California	8 weeks	2 h	0.47	1.57	Summer	41	b
Virginia	1 year	2-4 h	0.56	2.00	All	27	c

[a] Illinois: Measurements made Feb-May 1982 in an ordinarily occupied single-family home with a full basement (volume = 470 m^3). Measurements based on tracer-gas decays utilizing SF_6 with distribution via fan in central air-handling system. Ventilation provided by a combination of infiltration and natural ventilation (windows).

[b] California: Measurements made during two sampling campaigns, 5 weeks in winter (Jan-Mar 2017) and 8 weeks in summer (Aug-Oct 2016) in an ordinarily occupied single-family home (volume = 350 m^3). Measurements based on constant injection and continuous monitoring of deuterated alkenes interpreted using an integral material balance. Ventilation provided by a combination of infiltration and natural ventilation (open windows and doors). Window use reported in the cited reference.

[c] Virginia: Measurements were made during a year-long campaign in an ordinarily occupied townhouse (volume = 400 m^3). Measurements based on tracer-gas decays utilizing SF_6 with distribution via fan in central air-handling system. Fan was operated for most of the duration of the study. Most of the time, ventilation provided by combination of infiltration and natural ventilation through window opening; some augmentation by thermostatically controlled attic exhaust fan.

In only a few instances have extensive series of hourly-scaled, time-resolved measurements of residential air-change rates been reported for normally occupied residences. The results of studies in three houses are summarized in Table 2. In the Illinois and Virginia houses, air-change rates were measured by the tracer-gas decay technique, using repeated pulsed injections of SF_6 combined with continuous monitoring. In the California house (studied in winter and summer), investigators used continuous injection of deuterated alkenes combined with continuous sampling as a basis to determine 2-h average air-change rates over multiweek periods. In each of these studies, investigators made special efforts toward ensuring well-mixed conditions within the house. In the Illinois study, the tracer gas was injected into the central air handling system with the fan deliberately operated to distribute SF_6 throughout the house. Air was continuously sampled from several distributed locations in the house and blended before being introduced to the instrument. In the Virginia study, the central air fan was continuously operated throughout most (90%) of the monitoring period. In the California study, the occupants maintained interior doors open throughout the study. Two separate tracers were released in that house and monitoring was conducted in two separate locations, allowing for confirmation that the well-mixed assumption had reasonable validity.

Comparing the individual house results in Table 2 to the cross-sectional results in Table 1 reveals some interesting features. First, a direct GM to GM comparison suggests that the ventilation rates of the three individual houses were within the range but toward the lower values of the population studies. However, an important caution should be stated. The individual values that factored into the statistical reporting in Table 1 would not be the geometric mean values. Rather, as noted previously, the harmonic mean is the more appropriate representation of the result of a PFT measurement. For the four entries in Table 2, assuming the distribution of time-resolved measurements are indeed lognormal, the corresponding harmonic means would be 0.15 h^{-1} (Illinois), 0.32 h^{-1} (California, winter), 0.43 h^{-1} (California, summer), and 0.44 h^{-1} (Virginia). The lognormal statistics for these for averages are GM = 0.31 h^{-1} and GSD = 1.65, which is similar to the lower edge of the interquartile range of study results summarized in Table 1.

The second significant feature is that the air-change rate measurements are broadly distributed in these individual houses, with GSDs in the range 1.3-2.0. These values indicate only moderately less variability in the time dependent air-change rates of individual houses (as measured under normal living conditions) as compared with cross-sectional studies in populations of houses. It is noteworthy that the individual PFT measurements reflected in Table 1 have a minimum sampling duration of one day, as compared to the measurement durations of a few hours for the longitudinal studies in individual houses. As argued by Spear et al.,[78] time-varying environmental parameters will tend to have smaller variances when measured over longer durations. Specifically, any contribution of diel variation in the air-change rate could influence the GSD values reported in Table 2 but would have no influence on the values in Table 1. Still, it is intriguing to consider and important to understand the extent to which the variance of measured air-change rates from cross-sectional studies is a consequence of differences among houses versus variations over time in individual houses.

Beginning in year 2010, many studies have been published that used CO_2 (most commonly metabolic CO_2) as a tracer to measure residential air-change rates. Results of cross-sectional studies are summarized in Table 3. As in Table 1, the results are ordered by GM. All of these studies were conducted either in Europe or in China. Many were undertaken in apartments. Some of the reported results are for bedrooms only; others are for entire dwellings.

Monitoring was typically conducted for periods ranging from a few nights to a week. Approaches to data analysis vary among the studies. Illustrative examples include fitting a concentration growth curve,[21] as displayed in Figure 2, and applying a steady-state material balance using a subset of the monitoring data with the highest concentrations.[83]

Table 3. Residential air-change rates utilizing CO_2 as a tracer.

Location	N sites	Housing type	GM (h^{-1})	GSD	Reference	Note
Guangzhou, China	202	Apartment bedroom	0.29	2.0	79	a
China (F, W, Sp)	273	Apartment	0.29	2.0	80	b
China	294	Bedrooms	0.33	2.2	81	c
France	450	Dwelling	0.43	2.3	82	d
Denmark	500	Child's bedroom	0.46	2.1	21	e
France	57	Bedroom, heating	0.51	2.6	83	f
France	58	Bedroom, nonheating	0.51	2.3	83	f
Sweden	21	New houses	0.62	1.4	23	g
Slovakia	45	Apartment	0.64	1.9	84	h
China (Winter)	223	University dorms	0.70	2.3	85	i
Sweden	20	Passive houses	0.71	1.3	23	g
China (Summer)	59	Apartment	0.86	3.6	80	b
China (Summer)	223	University dorms	4.4	3.0	85	i

[a] Guangzhou: Bedrooms sampled overnight during the cooling season of Aug-Sep 2016. Air-change rate based on material balance applied to metabolic CO_2 for bedroom. Researchers sampled 400 bedrooms, "however, only 202 samples could be used due to various reasons, such as: windows or interior door left open (causing very low CO_2 concentrations), logger with no data and windy night." These conditions should be recognized to generate potential bias in the results, with higher air-change rates less likely to be included. All studied dwellings appear to be apartments, ventilated by infiltration and natural ventilation (via open windows).

[b] China: Homes in Tianjin and Cangzhou, with air-change rates measured overnight using metabolic CO_2. Results combined for autumn, winter, and spring seasons (2013-2016) for 273 households and reported separately for 59 households during summer (2013-2016), when window opening was more common. Among 383 homes studied (with occupants present during sampling), 317 were apartments, 64 were bungalows and 2 were villas. Natural ventilation dominated, via infiltration and opening of windows.

[c] China: 847 overnight measurements in bedrooms of 294 residences distributed across 11 cities in China. Among 294 residences, 284 were apartments. Natural ventilation dominated, via infiltration and opening of windows.

[d] France: Monitored CO_2 for 7 days in each dwelling between October 2003 and December 2005. Aimed for selection of households that is representative of the main housing stock in France; apportionment was 60% single-family dwelling and 40% apartments. Among all dwellings tested, 37% had mechanical ventilation, 33% passive stack, and 30% "no ventilation." Computed "averaged air exchange rate" using steady-state material balance and averaged CO_2 level measured between 1 AM and 5:10 AM each night. GM was 0.38 h^{-1} for heating season ($N = 300$) and 0.56 h^{-1} for nonheating season ($N = 150$).

[e] Denmark: Sampled CO_2 continuously for 2 nights in each bedroom during 10 Mar – 18 May 2008. Data fit by time-dependent material balance model. On average, 18 h of CO_2 data was used to best determine AER in each bedroom. "Homes included apartments, single-family homes and row houses of different ages. … 41% of the inspected homes had some kind of exhaust ventilation."

[f] France: Study covered 72 energy-efficient dwellings with sampling conducted between Jan 2013 and July 2014. Among 57 homes sampled in heating season (58 in non-heating season), 14 (15) were single-family dwellings. Mostly, homes were mechanically ventilated (with ~ 10% using passive stack/hybrid system). Each home was sampled for 1 week during heating and non-heating seasons. Air-change rate determined from steady-state material balance on CO_2, measured in the master bedroom, using the 60 highest 1-min readings from overnight periods during sampling. Only about 80% of the homes have reported results.

[g] Sweden: Sampled during 2012/2013 and 2013/2014 heating seasons. Apportionment of home type was 5 single family, 13 attached houses, and 23 multi-family houses. All homes equipped with mechanical ventilation including heat recovery units.

[h] Slovakia: Study of naturally ventilated apartments using metabolic CO_2 to determine bedroom ACR in overnight periods. The result tabulated here applies for "non-renovated" units.

[i] China: Dormitory rooms at Tianjin University studied during 2006-2007. Metabolic CO_2 used to evaluate overnight ventilation rates during winter (GM = 0.7 h^{-1}; GSD = 2.3) and summer (GM = 4.4 h^{-1}; GSD = 3.0). "All the inspected rooms had natural ventilation by opening windows/doors." The explanation for the very high summer values is that "doors/windows of dorm rooms are fully opened because of the hot weather."

Despite the major differences among studies, the overall results reported in Table 3 are remarkably similar to those in Table 1. Considering each row of Table 3 as an independent study, more than 2400 sites have been measured across the thirteen investigations. The median (interquartile range) of the geometric means is 0.51 (0.4-0.7) per hour and for the GSD, the median (interquartile range) is 2.2 (2.0-2.5).

Recently Zhu et al.[86] reported an extensive investigation of ventilation conditions in relation to acute respiratory infection (ARI) in university dormitories. That study combined extensive monitoring of metabolic carbon dioxide levels with multizone modeling for a low ventilation building (LVB) and a high ventilation building (HVB). Air-change rates were not reported. Instead, the researchers reported average per-person outdoor air ventilation rates: 2.3 L/s per person in the LVB and 6.6 L/s per person in the HVB. The researchers observed many more occurrences of ARI in the LVB than in the HVB during the 4-mo investigation.

Table 4. Residential air-change rates based on short-term tracer-gas decay measurements.

Location	**N houses**	**Tracer**	**GM (h^{-1})**	**GSD**	**Reference**	**Note**
Denmark	114	CFC-113	0.26	2.6	87	a
USA	98	SF_6	0.29	2.2	88	b
USA	266	SF_6	0.86	2.2	89	c

[a] Denmark: Tracer-gas decay in bedrooms of 114 houses with windows and doors closed. "Dwellings were single-family houses as well as apartments, mainly located in the suburbs of Aarhus." "All dwellings were without mechanical ventilation systems."

[b] USA: Combined results from three clusters of houses: 17 energy efficient, 29 from SF Bay Area, and 52 in Maryland. Probable that all were single-family dwellings. Windows and doors were closed so air-change rates reflect infiltration only.

[c] USA: Short-term tracer decay experiments (1048 measurements in 266 dwellings) with "low income" occupants. Houses were distributed among 14 US cities. Mainly single-family houses with six "row" houses and 13 "other" (unspecified type). Measurement results reported as reflecting "natural air infiltration" rate, suggesting no mechanical ventilation or open windows.

A few older studies used measurements from single tracer-gas decay experiments to assess air-change rates in cross-sectional samples of residential units. Table 4 summarizes the findings from three such investigations. Overall, these results are consistent with other available evidence. The two investigations in the USA indicate that housing occupied by those in lower income groups tend to have higher air-change rates than other residences, an aspect that is associated with their higher level of envelope leakage.[51] The variance in the measurement results, reflected in the GSD values, would be among the higher values reported from studies using passive PFT technology, an outcome that might be anticipated given the shorter sampling duration of the decay-based measurements. In analogy with metabolic CO_2 based measurements, which are concentrated in overnight periods, the measurements from the tracer-decay studies are generally restricted to daytime hours because of the needed involvement of field research staff combined with the convenience and cooperation of the occupants.

Table 5. Residential infiltration or air-change rates based on leakage-area measurements.

Location	N houses	Interval	GM (h^{-1})	GSD	Reference	Note
Massachusetts	Note a	Summer	0.36	2.0	90	a
USA	Note b	Annual	0.40	2.1	91	b
USA	70,000	Annual	0.51	2.0	51	c
Colorado	216	Annual	0.55	1.6	92	d
Massachusetts	Note a	Winter	0.72	1.9	90	a
USA, 4 cities	58	4-5 mos	0.76	1.8	93	e

[a] Massachusetts: Infiltration modeled for winter and summer seasons for all housing in the state based on leakage area measurement data. Excludes natural ventilation and mechanical ventilation.

[b] USA: Infiltration rates for a nationally representative set of single-family dwellings. Only accounts for infiltration, so does not include effects of natural ventilation or mechanical ventilation.

[c] USA: Distribution of annual averaged air-change rate in US single-family homes based on analysis of 70,000 fan-pressurization measurements of leakage collected prior to 2001. A calibration procedure in the cited reference provides for an estimate of total residential air-change by comparing leakage distribution to database of passive PFT measurements of air-change rate.

[d] Colorado: Low-income single-family homes (85%), duplexes and town homes in Colorado's Northern Front Range. For each home, annual average infiltration rate modeled by combining climate information with leakage area determination. Includes increment to account for contribution from mechanical ventilation for 11 homes so equipped.

[e] USA: Four US cities (Charleston, SC; Colorado Springs, CO; Portland, ME; Fargo, ND) with 11-20 houses in each. Leakage area measured. Homes studied had lower-income inhabitants that qualified for fuel subsidy or weatherization. Infiltration rate modeled for periods of 4-5 months during winter-spring of 1981-82.

Study results assessing residential infiltration rates based on measurements of leakage area are summarized in Table 5. The overall findings are similar to those determined by the passive PFT methods. Median values of the lognormal distribution parameters are approximately GM = 0.5 h^{-1} and GSD = 2.0. Note that Chan et al.[51] used a cross-comparison to PFT tracer results to effectively calibrate their air-change rate determination. The more independent comparison would be with the study of Persily et al.,[91] which aimed to provide infiltration rate distributions for a nationally representative set of dwellings in the US. This study did not aim to include the effects of occupancy, such as window-opening behavior. The parameter values of GM = 0.40 h^{-1} and GSD = 2.1 for infiltration in US dwellings might be best compared with the national (but not statistically representative) sample of passive PFT measurement results for air-change rates with GM = 0.53 h^{-1} and GSD = 2.19.[20] That the GM values are similar (with a difference that is less than 30% of the mean) suggests that the effects of occupancy do not dominate residential air-change rates, at least in central tendency.

In a few additional efforts, available evidence has been combined to assess air-change rate distributions for residences across a national scale. For example, Asikainen et al.[94] estimated the mean and standard deviation of air-change rates for European households. Their procedure generated estimates of variation by country. The overall description for EU-26 would be lognormal with GM = 0.57 h^{-1} and GSD = 1.9. By country, the lowest air-change rates are estimated for Ireland and the UK at GM = 0.52 h^{-1}, GSD = 1.7; the highest values are reported for Cyprus with GM = 0.97 h^{-1}, GSD = 1.9.

Azimi et al.[95] generated hourly air-change rate estimates for 22 US cities intended to represent the breadth of US climate and housing stock conditions. For each city, they reported mean ± standard deviation results for these four categories: "old homes, infiltration only," "existing homes, infiltration only," "new homes infiltration only," and "new homes with mechanical ventilation." Their analysis specifically excluded any contribution from window opening or other occupancy-associated effects. Computing the average ± standard deviation of the 22 city means for the four categories yields the results summarized in Table 6. Note that the variance reflected in this table is based on differences among citywide averages and does not reflect the distribution of values among houses within a city.

Table 6. Residential air-change rates for 22 US cities, excluding natural ventilation.

Category	**Air-change rate** [a]
Old homes, infiltration	$0.53 \pm 0.21\ h^{-1}$
Existing homes, infiltration	$0.28 \pm 0.09\ h^{-1}$
New homes, infiltration	$0.11 \pm 0.02\ h^{-1}$
New homes, mechanical	$0.25 \pm 0.05\ h^{-1}$

Source: Azimi et al.[95]

[a] Average ± standard deviation based on based on reported city-wide averages. Excludes any effect of natural ventilation (i.e. from window opening).

5. FACTORS INFLUENCING AIR-CHANGE RATES

Across the full empirical range, residential air-change rates can vary across about two orders of magnitude, from ~ 0.05 h^{-1} at the low end to ~ 4 h^{-1} at the high end. This span can be identified, for example, by considering that – excluding outliers – the approximate lower and upper bounds of lognormal distributions are GM ÷ GSD^2 and GM × GSD^2, respectively. So, for GM = 0.2 h^{-1} and GSD = 2.0, a reasonable estimate for the lower bound of individual measurement results would be 0.05 h^{-1}. Conversely, with GM = 1 h^{-1} and GSD = 2.0, a reasonable estimate of the upper bound would be 4 h^{-1}. The entries near the beginning and end of Tables 1 and 3-5 substantiate this overall finding. Over short periods and under special circumstances, air-change rates can take on values beyond this range.

Conceptually and qualitatively, the factors influencing residential air-change rates are well understood. The process combines the effects of a permeable building envelope with driving forces — primarily wind and buoyancy that is induced by temperature differences — to deliver exchange flows between outdoors and inside. Mechanical ventilation, when present, contributes. However, beyond these basic ideas, the reality is sufficiently complex and nuanced to defy our ability to reliably translate a sound conceptual understanding into robust quantitative predictive power. The work by Logue et al.[96] to construct a mechanistic model of the indoor-outdoor relationship of fine particulate matter illustrates the challenges to be overcome in connecting a physics-based modeling approach with empirical data from tracer gas investigations when attempting to assess residential air-change rates.

In light of such challenges and limitations, this section explores evidence about how residential air-change rates vary in relation to underlying factors. The approach is strongly empirical, but also informed by process-level expectations.

5.1. Housing stock features

Considering the example of data from the United States, three important features of dwellings are associated with higher infiltration rates. Older dwellings tend to be leakier than newer construction. Dwellings with low-income occupants tend to have higher infiltration rates than the overall average of the building stock. And single-family homes tend to have higher infiltration rates than apartments. Table 7 illustrates the scale of effects for two of these factors. In central tendency, homes constructed before 1940 are 2-2.5× as leaky as those constructed after 1990. Single-family homes have infiltration rates that are in the range 1.5-2× those of apartments.

Fazli and Stephens[97] used the leakage information reported by Persily et al.[91] to support an overall assessment of residential ventilation in the US housing stock. They incorporated into their analysis estimates of natural ventilation associated with window opening. Figure 3 shows their estimate of central tendency as a function of construction year. The estimated mean contribution of natural ventilation is less than half of the total, but the fractional contribution is growing over time as building envelopes have become less permeable.

Table 7. Geometric mean (GSD) infiltration rate for US housing stock, sorted by year of construction and comparing apartments to single-family houses.

Construction year	Apartments	Single-family houses
Before 1940	0.30 h^{-1} (1.74)	0.57 h^{-1} (1.94)
1940-1969	0.27 h^{-1} (1.81)	0.48 h^{-1} (1.94)
1970-1989	0.22 h^{-1} (1.93)	0.32 h^{-1} (1.98)
1990 or newer	0.14 h^{-1} (1.84)	0.23 h^{-1} (2.18)

Source: Persily et al. [91]

Chen et al.[98] utilized the results of Persily et al.[91] to investigate how the indoor-outdoor ozone relationship might vary across the housing stock in the US. They estimated annual average air-change rates for residences in each of 18 cities, including an estimate for the effect of window opening. Mean values by city ranged from a low of 0.44 h^{-1} in Los Angeles to a maximum of 0.76 h^{-1} for New York and Boston.

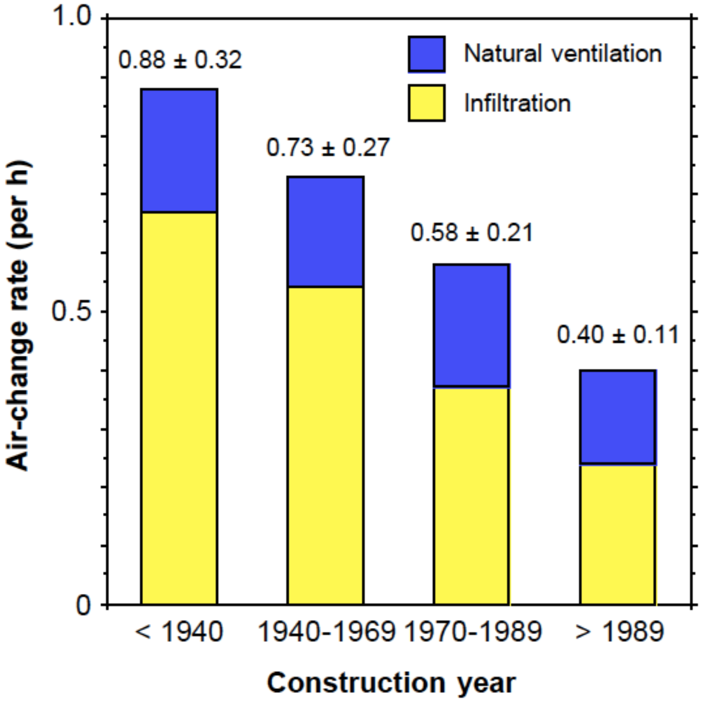

Figure 3. Estimated mean of the annual average air-change rate for the US housing stock, by year of construction, separately indicating contributions from infiltration and natural ventilation. (Data source: Fazli and Stephens.[97])

5.2. Climate and weather

5.2.1. Temperature difference and wind

Models of air infiltration incorporate meteorological driving forces along with building leakage characteristics as key input parameters. The centrally important meteorological parameters are the windspeed and indoor-outdoor temperature difference.[99]

In an early investigation, Malik[100] used SF_6 decay to make repeated measurements of the air infiltration rate of two townhouses in New Jersey over extended periods during winter and spring months. Temperature difference and wind speed were quantified as factors influencing the air-change rate. Specifically, "an increase of 0.1 exchange per hour is associated with each of the following: (1) an increase in DT [temperature difference] by 7 °C at low wind speeds [and] (2) an increase in normally incident wind by 3 km/h at low DT…."

Liu et al.[41] reported a similar influence of temperature difference on the air-infiltration rate measured in a northern California house during normal occupancy. Specifically, when the windows were closed and the windspeed was low (< 2 m/s), a regression of air-change rate against indoor-outdoor temperature difference had a slope of 0.013 per h per °C. Hence, an increase of 0.1 h^{-1} in air-change rate would be associated with a 7 °C change in temperature difference for those conditions.

5.2.2. Seasonal effects

Given the important influence of temperature difference on infiltration rates, one might expect that regions with cold winters would have higher air-change rates during winter than during summer. However, empirical evidence suggests otherwise. The almost-certain explanation is the much higher use of windows during periods of warm weather.

For example, Shinohara et al.[101] used passive tracer sampling technology to evaluate multizonal flow rates for 26 Japanese residences across five seasons, starting with summer 2005 and ending with summer 2006. In their sampling system, they used three distinct tracers with each being placed in one of three rooms of the residence. They defined an effective residence air-change rate as the sum of the flow rates of outdoor air into the three rooms sampled, divided by the sum of the three room-volumes. (Worth noting is that, by isolating a fraction of the interior space, this approach could systematically overestimate the true air-change rate of the house as a whole by understating the interior volume. That would be particularly so if interzonal mixing indoors is strong.) The authors reported seasonal air change rates that were highest in the summer and lower in the autumn and winter. Specifically, the reported means ± standard deviations of the weekly averaged residence air-change rates were 1.6 ± 1.7 h^{-1} and 1.7 ± 1.8 h^{-1} for summer 2005 and summer 2006, respectively. The corresponding values for autumn 2005 and winter 2006 were much lower: 0.58 ± 0.94 h^{-1} and 0.61 ± 0.93 h^{-1}, respectively.

Several of the studies summarized in Table 1 include separate entries for different measurement seasons. Several, but not all of these studies tend to exhibit higher air-change rates during the summer. For example, for Boston homes, Zota et al.[63] reported medians of 0.49 h^{-1} for the heating season (15 September — 15 June) and 0.85 h^{-1} for the nonheating season, respectively. Sax et al.[70] reported average air-change rates in a housing sample in New York city to be 1.8 h^{-1} in the summer compared with 1 h^{-1} in the winter. In Los Angeles, the same study reported an analogous outcome for the averages: 2.5 h^{-1} in the summer compared with 1.4 h^{-1} in winter. On the other hand, the study by Wheeler et al.[53] reported medians of 0.18 h^{-1} for summer and 0.35 h^{-1} for winter in Windsor, Ontario.

In areas with mild winters and uncomfortably warm summers, lower air-change rates might be expected in the summer, when residential air conditioning use is likely to be high. This point is illustrated in Figure 4, which shows the median air-change rates measured in residences in four US cities as a function of the outdoor air temperature. Note that the two cities with cold winter climates, Detroit and Elizabeth, have higher median air-change rates when the weather is warm and lower air-change rates when the weather is cold. Conversely, Houston, Texas, which has very warm and humid summers, exhibits a much lower median air-change rate during warm weather than under cold-weather conditions. A probable explanation is climate-related differences in the seasonal pattern of window use.

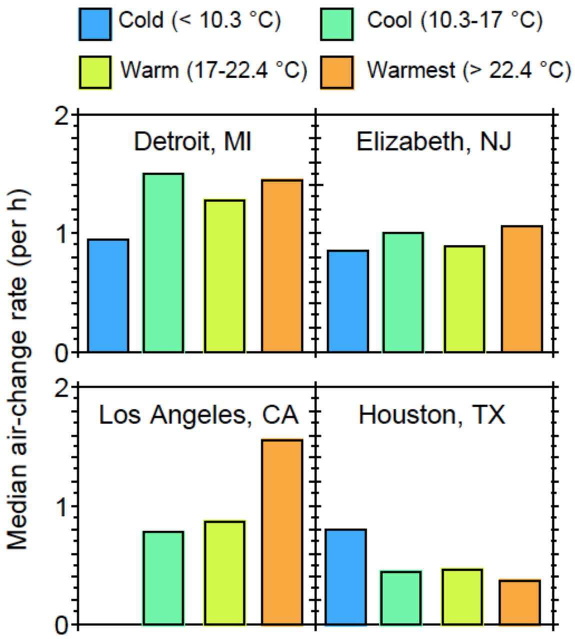

Figure 4. Median air-change rate in residences sorted according to thermal environmental condition. Air-change rates were determined using perfluorocarbon tracers with time-integrated samples collected over 24-h periods in Detroit and over 48-h periods for other cities. Temperatures represent daily average outdoor values. (Source: Baxter et al.[102])

Evidence concerning the interplay among climate, season, and residential air-change rates is available in studies of night-time air-change rates in Chinese apartments.[80,81] In particular, Hou et al.[81] reported median overnight bedroom air-change rates in Chinese residences (predominantly apartments), sorted according to season and climatic zone. In the "severe cold," "cold," and "mild" zones, median air-change rates were highest in the summer (1.9, 1.4, and 2.3 h^{-1}, respectively), much higher than in the winter (0.34, 0.41, and 1.6 h^{-1}, respectively). On the other hand, in the "hot summer and cold winter" and "hot summer and warm winter" zones, summertime median air-change rates (0.91 and 0.57 h^{-1}) were similar to those measured in other seasons. The extent to which climate and technology (e.g. compressor-based air conditioning) affect occupants' choice regarding window use are key to understanding these findings.

5.2.3. Diurnal variation

Systematic diurnal variation might be anticipated in residential air-change rates because of a combination of weather conditions and occupant behavior. Factors that might vary with a strong diurnal pattern include indoor-outdoor temperature difference, indoor heating and air-conditioning use, and use of windows.

Although limited in scope, the empirical evidence from detailed studies of individual houses supports this expectation. In the investigation of a northern California house by Liu et al.,[41] in the wintertime the air-change rate did not vary much diurnally. However, in the summer, there was a pronounced increase in air-change rate during the afternoon and evening hours, with values approximately twice those prevailing during the overnight period (i.e. approximately 0.6 h^{-1} versus 0.3 h^{-1}). Similar effects are seen in the monitoring results from the detailed study of a Virginia townhouse.[27,103] These data show effects of both season and diurnal variation. Systematically higher air-change rates are observed during summer and spring months than during winter or fall. The summer data in particular exhibit a pronounced diurnal variation, with an enhancement from about 0.8 h^{-1} to 1.2 h^{-1} persisting for about 6 h during the afternoon and evening hours.

5.3. Influence of occupancy

Warner[104] conducted early investigations of the influence of occupant behavior on residential air-change rates. He used H_2 as a tracer gas and assessed air-change rates by the decay method, conducting 312 experiments distributed across 32 rooms in six buildings, mostly residential. Among the specific features observed were increased air-change rates associated with either open windows or a heated flue.

Kvisgaard and Collet[105] used a constant-concentration tracer gas system to make time-resolved measurements of air-change rate in 28 dwellings in Denmark during cold-weather conditions. The distribution of week-long average air-change rates is characterized by GM = 0.63 h^{-1} and GSD = 1.68. In that study, the air-change rate was measured for 16 naturally ventilated households when unoccupied and contrasted with the value when inhabited. The authors reported that “63% of the total air change is caused by the behavior of the occupants.” The air-change rate distributions in the unoccupied and occupied dwellings had GM = 0.20 h^{-1} (GSD = 1.52) and GM = 0.49 h^{-1} (GSD = 1.67), respectively.

Iwashita and Akasaka[106] used a constant-concentration tracer-gas injection and monitoring system to investigate the ventilation rate of eight apartment units in Kagoshima City, Japan. Measurements were made during the hot and humid summer, spanning a few days in each dwelling. The results are remarkable for the very high air-change rates determined, much higher than reported in any other study: GM = 12.3 h^{-1}, GSD = 2.0 for “total air change rate,” as reported in Table 6 of the cited work. The authors found that “87% of the total air change rate is caused by the behavior of the occupants,” such as through opening doors and windows.

In an intensive study of a single-family house in California, Liu et al.[41] reported that the GM and GSD for the distribution of air-change rates both increased with occupancy, indicating an increase in the central tendency and also in the variability. For winter conditions, the change was from GM = 0.22 h^{-1} (GSD = 1.19) for unoccupied conditions to GM = 0.33 h^{-1} (GSD = 1.31) when occupied. In summer, the occupancy effect was more pronounced, with GM = 0.25 h^{-1} (GSD = 1.24) for unoccupied conditions increasing to GM = 0.47 h^{-1} (GSD = 1.57) when occupied. Key factors influencing these outcomes were window and heating system use.

5.3.1. Windows

Howard-Reed et al.[107] reported on a systematic investigation of the effects of window opening for two homes, one (a townhouse) in Virginia and the other (a single-family dwelling) in California. Experiments were conducted by first measuring the air-change rate with the home closed, then repeating the measurement after opening one or more windows to a predetermined extent. For the California house, 30 experiments were conducted in which the second state had one window open. The resulting increase in air-change rate had a GM of 0.32 h^{-1} with a GSD of 2.0. The analogous results from 34 experiments in the Virginia house were a GM of 0.42 h^{-1} with a GSD of 2.3. In the California house, 18 experiments were conducted with 2-3 windows open, and in this case the resulting increase in air-change rate above the baseline was characterized by GM = 0.73 h^{-1} with GSD = 2.4. Note that the volume of the CA house was 510 m^3, so that 0.32 h^{-1} (for one window open) would correspond to a volume flow rate through the window of 160 m^3 h^{-1}. The VA house had a volume of 400 m^3, so that 0.42 h^{-1} would correspond to about 170 m^3 h^{-1}.

In the study of a northern California house with normal occupancy during summer conditions, Liu et al.[41] found that the air-change rate increased with the number of open windows (mainly) and doors. In this study, time-resolved data were collected on window and door open/closed status, but no information was available on the extent of opening. Window opening was at the discretion of the occupants who were instructed to behave as they normally would. A regression analysis yielded the following central estimates for air-change rates in relation to the number of open windows: zero — 0.29 h^{-1}; one — 0.37 h^{-1}; two — 0.48 h^{-1}; three — 0.61 h^{-1}. The inferred average air-change rate increment of 0.11 h^{-1} per open window would correspond to about 40 m^3 h^{-1} for this 350 m^3 home. The 4× smaller volumetric flow per open window in this study as compared to that of Howard-Reed et al.[107] is striking. The difference might originate in the thermal environmental conditions. In the Liu et al. study, window opening was most commonly used to regulate thermal comfort when the weather was warm, and the indoor-outdoor temperature difference was consequently small. Window opening tended to be sustained for many hours. In the Howard-Reed et al. investigation, the experiments were conducted on a short-term basis without regard for weather conditions, which may have selected for a higher indoor-outdoor temperature difference and, consequently, an increased overall driving force for natural ventilation.

Marr et al.[108] measured air-change rates by tracer decay in an unoccupied research house. They found that the air-change rate increased from a baseline average of 0.2 h^{-1} with all windows closed (n = 23 measurements) to an average of about 0.35 h^{-1} with one window open (n = 48). The house volume was about 300 m^3, so the increase of 0.15 h^{-1} corresponds to 45 m^3 h^{-1} volumetric flow rate. Experiments were conducted during warm weather months of June-July 2000, in North Carolina.

Johnson et al.[109] measured air-change rates in an unoccupied house with scripted manipulations that were changed at hourly intervals. Data were acquired for 67 h in all. When the windows and doors were closed, the air-change rate distribution had a GM of 0.77 h^{-1} (GSD = 1.44). With one or more windows or doors open, the air-change rate increased to a GM of 1.98 h^{-1} (GSD = 1.90). This study was conducted in Columbus, OH, during winter. The mean indoor-outdoor temperature difference for the three-day experimental period was 12 °C. The main floor volume was approximately 160 m^3 (70 m^2 × 2.3 m, with the height assumed). The difference in geometric mean ventilation flow rate between closed (0.77 h^{-1}) and window/door open (1.98 h^{-1}) conditions would correspond to about 190 $m^3 h^{-1}$ for these experimental conditions.

Sun et al.[110] measured overnight air-change rates in apartments in Tianjin, China, using metabolic CO_2 as the tracer. Comparing cases with an open/ajar window (n = 22) to a closed window (n = 101), the median air-change rate for the window open case was 1.45 h^{-1}, much higher than the closed window median of 0.37 h^{-1}.

Zhao et al.[111] monitored 20 residences each in Leipzig (Dec 2016 – Dec 2017) and in Berlin (Jan 2018 – Mar 2019), with each home being monitored during two seasons for durations ranging from 2 to 14 days. It appears that the decay of metabolic CO_2 after people departed was used to infer the air-change rates of the residences. The authors reported that the mean ventilation rate with closed windows was 0.2 ± 0.2 h^{-1} as compared with 3.7 ± 2.8 h^{-1} with one or more windows open. The increment associated with open windows in this study is much higher than in the other investigations reviewed here. Insufficient information is provided by Zhao et al.[111] to fully account for these differences, although the finding of a relatively large effect of window opening during winter in the investigation of Johnson et al.[109] does indicate that the combination of windows being open and a large indoor-outdoor temperature difference can produce high air-change rate increments.

Levie et al.[112] reported on household use of windows and vents during the heating season in the Netherlands. Based on questionnaire responses, window opening had the following responses, with units of hours per week (h/wk). For living rooms (n = 4181 responses), 40% never opened windows, and the median (75th percentile) value was 1 (6) h/wk. For bedrooms (n = 3141), 10% never opened windows, and the median (interquartile range) value was 15 (4-56) h/wk. El Orch et al.[113] have suggested that the median percentage time with windows open for the US housing stock is 13%.

A synthesis of the volumetric flow rate data suggests an increment of ~ 50 $m^3 h^{-1}$ associated with opening one window when weather conditions are mild (small indoor-outdoor temperature difference and low wind speed). With a larger indoor temperature difference or higher wind speeds, a flow rate of 150-200 $m^3 h^{-1}$ through an open window might be anticipated. Occupant behavior is key, however, and not well understood. Fabi et al.,[114] based on a substantial literature review, concluded, “what seems to be a simple task, to open or close windows, is in reality a task that is influenced by many factors, which interact in complex ways.”

5.3.2. Fireplace use and other flued combustion

When fuel is burned indoors and the byproduct gases are exhausted through a flue, the net outflow caused by combustion will tend to depressurize the interior space causing increased infiltration of outdoor air and a higher air-change rate.

Dietz and Cote[28] reported on the effect of fireplace operation increasing residential air-change rate. They found that an air-change rate averaging 0.28 h^{-1} for 16 h prior to fireplace use increased to an average of 0.71 h^{-1} during fireplace operation. Nazaroff et al.[26] also reported fireplace use to be a factor influencing air-change rate. In a single-family home monitored in Illinois during winter and spring 1982, fireplace use was recorded on five occasions. For the 12 h before and after each fireplace use, the average ± standard deviation air-change rates were $0.24 \pm 0.06\ h^{-1}$ and $0.38 \pm 0.11\ h^{-1}$, respectively. During fireplace use, the air-change rate rose to $0.73 \pm 0.12\ h^{-1}$.

Malik[100] noted that a similar feature would be expected for combustion-based heating systems if the combustion air is provided from within the house, rather than separately supplied from outdoors. "One should expect air infiltration to be enhanced when the furnace is running, because the furnace combustion reduces the pressure in the basement, and combustion air must enter the basement either directly or by way of the living area."

5.3.3. Operation of fans

Even in residences without mechanical ventilation, it is common for there to be fans whose operation, generally under the control of or influenced by occupants, can alter the air-change rate.

In the United States, most residences are heated (and often also air conditioned) by central, forced-air systems. During the heating season, air is recirculated by a fan that is operated under thermostatic control. In a common design, air from the house travels through a centrally located return-air grill and then to the heating system via a return air duct. After warming, the air is redistributed through a network of supply ducts and discharged into rooms throughout the residence. The operation of the fan affects the extent of mixing throughout the residence and therefore can play a role in the extent to which a single, well-mixed zone appropriately represents the occupied space.

In addition, operation of the central air system can affect the net air exchange between indoors and outdoors. Commonly, system air ducts pass through unconditioned space (e.g. an attic or crawl space). To the extent that the ducts leak, then the reduced pressure inside the return air duct and the increased pressure inside the supply ducts can promote increased air-change rates. Similarly, if there is significant airflow resistance inside the house between the supply registers and the return register, then the fan operation can alter the pressure across the building envelope in a way that would be expected to increase the net infiltration rate.

Hawthorne et al.[115] used tracer decay to measure air-change rates in homes in Tennessee. On two or three occasions in each of 10 homes, they made separate air-change rate determinations with the central air fan off and on. With the fan off, the lognormal distribution parameters of the house-average air-change rate values were GM = $0.51\ h^{-1}$ and GSD = 1.54. With the fan on, the GM increased to $0.82\ h^{-1}$; the GSD also increased, to 1.71. In these houses, the net effect of fan operation on the mean air-change rate was substantial.

Stephens and Siegel[116] observed a similar effect in a manufactured research house at the University of Texas. With the central air system fan off, they measured an air-change rate of $0.26\ h^{-1}$. With the system on, and fitted with filters of various efficiency, the results of seven experiments exhibited a substantially higher air-change rate, with mean ± standard deviation = 0.44 ± 0.06 h^{-1}. The authors reported that, "the operation of the HVAC fan increased [air-change rates] relative to the HVAC off case, presumably due to … supply duct leakage and envelope depressurization."

On the other hand, in their year-long study of air-change rates in a townhouse, Wallace et al.[27] reported that "the central furnace fan had no apparent effect on air change rates. The ductwork for the fan was found to have leaks; however, no part of the ductwork was external to the house…"

El Orch et al.[113] constructed estimates of central air system operation parameters for the US housing stock. They used lognormal distributions to represent operation flow rate and "run time." Results for the estimated distribution of recirculating flow rates were GM = 5.7 h^{-1} and GSD = 1.26. It is important to stress that these flow rates represent internal recirculation of air within houses; they do not represent air-change rates. For system runtime, the lognormal distribution had GM = 25% and GSD = 1.85. To put these results in perspective, note that an increment of 0.2-0.3 h^{-1} caused by central fan operation, combined with runtime of 25%, would increase the overall average air-change rate of a residence by about 10-15% of the central tendency value of 0.5 h^{-1}.

Other common modes of heating and cooling residences are likely to influence air-change rates indirectly, through altering indoor-outdoor temperature differences, rather than because of directly inducing air movement across the building envelope. For example, residential heating is commonly provided through radiators that are connected to water heating units and circulation systems. Internal buoyancy from the warmed radiator surfaces would help to promote internal transport and mixing but would not directly enhance air-change rates. Similarly, ductless mini split air conditioning units circulate a refrigerant between indoor evaporation units and an outdoor compressor unit. A fan is used to blow air over the indoor coils to promote cooling. As with a radiator, the resulting air motion would promote indoor transport and mixing but would not be expected to directly affect air-change rates.

In some cases, when environmental conditions are favorable, large-scale exhaust fans can be used to provide for cooling through enhancement of the air-change rate. A noteworthy example is from a year-long study of residential ventilation.[27] The studied home was equipped with a thermostatically controlled attic exhaust fan. When operating, 20% of the summer period and 11% of the full year, it added 0.8 h^{-1} to the whole-house air-change rate.

Other fans commonly present in residences include those that provide for exhaust from bathrooms, remove cooking fumes via range hoods, and vent clothes dryers to outdoors. In the United States, such units would each typically be rated to remove 50-250 cubic feet per minute of operation, corresponding to 85-425 m^3/h. These flows would represent substantial contributions to air-change rates. However, expected use patterns would suggest low fractional time operating and therefore relatively small contributions to overall household air-change rates. For example, summed use of such fans for 1 h per day would correspond to an average exhaust flow rate in the range 3.5-18 m^3/h, which would add an increment in the range 0.01-0.05 h^{-1} to the air-change rate of a 350 m^3 house.

6. METHODOLOGICAL CRITIQUE

In this review, some issues of concern about the measurement and reporting of residential air-change rates have been identified. In this section, general areas of concern are highlighted. The reader is reminded that the scope of interest for this critique is ordinarily occupied residences with an emphasis on how air-change rates influence indoor air quality.

6.1. Time-varying air-change rates

A fundamental and important fact is that the air-change rate of a residence is a time-dependent parameter. In part, this feature means that any measurement of air-change rate is contingent on the factors causing that parameter to vary with time. Two explicit aspects of time dependence merit emphasis. First, one should understand how time variability might influence the measurement of air-change rate. That point is especially important for the passive PFT methods, which rely on extended sampling durations, from a day to a week or more, and need to infer an overall air-change rate using only the time-averaged concentration that results from a controlled (nominally constant) tracer release. Second, in the context of the total body of knowledge regarding residential air-change rates, there is a relative dearth of information about its time-dependence.

Although airflow across a building envelope can vary at short time scales, it is probably not meaningful to consider air-change rates on time scales that are very much smaller than the reciprocal of the air-change rate itself. The shortest measurement periods routinely used are for tracer-gas decay experiments and these typically analyze data over periods of at least one hour and typically a few hours. Using that time scale as a lower bound for resolving air-change rates seems appropriate.

When the passive PFT method is used, the sampled tracer concentration will, to a good approximation, vary in proportion to the harmonic mean air-change rate during the period of sampling. It is common in the literature to see passive PFT measurements being referred to as determinations of “average” air-change rates. The common understanding of “average” would be the arithmetic mean. The harmonic mean and the arithmetic mean of a time series are equal only when the parameter is time invariant. In all other cases, the arithmetic mean is larger than the harmonic mean. The difference between the arithmetic mean and the harmonic mean scales with the variance. Consequently, the difference between arithmetic and harmonic means might be of particular concern during times when the air-change rate could vary markedly during sampling. Such might be the case, for example, when windows are opened to provide increased natural ventilation during warm periods of a day but closed during other times.

The few houses in which the air-change rate has been monitored in great detail provide some indications about temporal variability and temporal patterns of residential air-change rates as summarized in Table 2 and discussed in §5. An opportunity to investigate temporal variability in broader samples of residences appears to have been overlooked. In Table 1, eight entries have the duration indicated as some multiplier of one day. In these studies, repeated 24-h samples were collected of the perfluorocarbon tracer, allowing for repeated determinations of the daily harmonic mean air-change rate in hundreds of houses, in aggregate.[53,57,66,68,72] However, in reporting the results of these studies, the investigators have not included the temporal patterns of air-change rates in individual houses.

A related opportunity is available in the RIOPA data.[64] In that study, a goal of the research team was to measure air-change rates in two separate seasons for each of the residences studied. The original data are available.[117] Table 8 presents a synopsis of results contrasting the case of each measurement being analyzed separately ("raw") versus using the harmonic mean of a residence's results when two measurements were made ("HM"). Table 8 also presents the correlation coefficient (R^2) values for cases with repeated measurements. The most striking feature of this analysis is that the repeated measurements in individual residences (but in different seasons) are poorly correlated. Consequently, the differences in the distributional statistics are relatively small whether each measurement is analyzed separately, or the repeated measurements are (harmonically) averaged before determining the lognormal distribution parameters. Note that the central tendency values, as indicated by the respective GMs, change very little. Using harmonic means for repeated measurements in individual residences decreases the variance, as reflected in the finding that GSD results are about 10% lower for the HM case.

Table 8. Reanalysis results for RIOPA air-change rate measurements, either giving equal weight to each measurement ("raw") or equal weight to the harmonic mean for each residence ("HM") when a second measurement is available. [a]

Location	***N* (*N* repeat)**	**GM (GSD) raw**	**GM (GSD) HM**	***R*²**
Los Angeles, CA	105 (79)	0.89 h^{-1} (2.15)	0.88 h^{-1} (1.95)	0.08
Houston, TX	100 (70)	0.52 h^{-1} (2.38)	0.48 h^{-1} (2.13)	0.12
Elizabeth, NJ	96 (74)	0.98 h^{-1} (2.23)	0.93 h^{-1} (2.03)	0.13

Sources: Weisel et al.;[64] RIOPA Team[117]

[a] For the GM and GSD determinations, air-change is capped at 5.0 h^{-1} with higher values replaced by this cap. For R^2 determination, which reflects paired sampling in individual residences from different seasons, residences are removed from the analysis if one or both air-change rate determinations are reported as > 5 h^{-1}. As such, the correlations are based on 77 residences for Los Angeles, 66 residences for Houston, and 69 residences for Elizabeth. See also Yamamoto et al.[74]

6.2. Zonal characteristics of residences

A central challenge in characterizing residential air-change rates is that, in some circumstances, a multizone representation is needed to effectively describe the occupied indoor space. What makes the challenge especially large is that interzonal flows may vary markedly with time, yet the passive PFT method, the most common technique used to study multizone flows, assumes that flow rates are time invariant. This problem is recognized in theoretical studies but seems to have been forgotten in practice. For example, D'Ottavio et al.[46] wrote, "in cases where there are large, short term variations in the ventilation flows … this technique will not provide an accurate assessment of the average ventilation flows and should be avoided." Sherman[35] wrote, "Interzonal flows are unreliable. Multiple tracer gases ostensibly allow the estimation of average interzonal airflows. The uncertainties on all but the largest flows are sufficient to make these estimates quantitatively useless.”

Several situations can be described to illustrate the potential for residential environments to have a multizone character that is time varying. The following paragraphs summarize some key elements of the current state of knowledge, introducing quantitative aspects where possible, but recognizing that the domain is intrinsically complex and relatively data poor.

In the US, it is common (but not universal) for residential heating and air conditioning to be provided by a central system that uses air as the heat-transfer medium. The system would not provide for ventilation with outside air by design, although as noted in §5.3.3 operating the fan could lead to increased air-change rates. A common operation mode is for the fan to be powered only when needed for temperature control. Reviewing the available evidence, El Orch et al.[113] estimated a geometric mean value of 5.7 residence volumes per hour of airflow processed when the central fan is on. The high internal airflow would tend to promote a well-mixed condition throughout the house, so that a single, well-mixed zone could be an effective description if the fan operated with sufficient frequency.

However, there are many circumstances in which the central system fan would not operate for extended periods, and during these times mixing between rooms would need to rely on other driving mechanisms. The fraction of time that the central system fan operates has been investigated most recently in a study by Touchie and Siegel,[118] which acquired data from web-connected thermostats installed in North American homes. They reported an overall median runtime of 18%, with an interquartile range of 8-33%. The 10th and 90th percentile values in their study were 2.3% and 52%, respectively.

Buoyancy-driven airflow across open doorways can effectively mix the air between rooms located on the same floor level. Even a slight temperature difference between rooms is sufficient to promote a bidirectional flow in which air flows from the warmer room across the upper part of the doorway and is replaced by air from the cooler room across the lower portion of the doorway. Door position is critical, however. Across closed doorways, air flow can be sufficiently small to effectively decouple the air between the two rooms.

Ferro et al.[119] measured airflow rates between rooms on a single level of two homes as a function of door position. Results from their study are displayed in Figure 5. Note the contrast in central tendency between the “closed” and “fully open” cases. A reasonable criterion for two rooms to behave as one zone would be to have the interzonal flow rate much larger than the outdoor air flow rate. If we consider a room of 40 m^3 volume with an outdoor air-change rate of 0.5 h^{-1}, then the outdoor air ventilation rate would be 20 m^3 h^{-1}. Data in Figure 5 indicate that — with a door fully open between two rooms — the interzonal flow would be 10× this outdoor air flow scale and so representing two rooms connected by an open doorway as a single zone would be appropriate. Conversely, with a door between the rooms closed, an exchange flow of order 2 m^3 h^{-1} would be very much smaller than the outdoor air ventilation rate; consequently, rooms might need to be represented in a multizone manner in this case.

This point is reinforced by laboratory investigation of flow between two rooms (volumes of 31 and 36 m^3) connected by a doorway.[120] With the door open between the two rooms, the airflow rate was approximately balanced at about 60 m^3 h^{-1}, which was much greater than the low outdoor air ventilation rate of about 2.4 m^3 h^{-1}. However, with the door closed, the average flow rate between the rooms declined to approximately 1 m^3 h^{-1}.

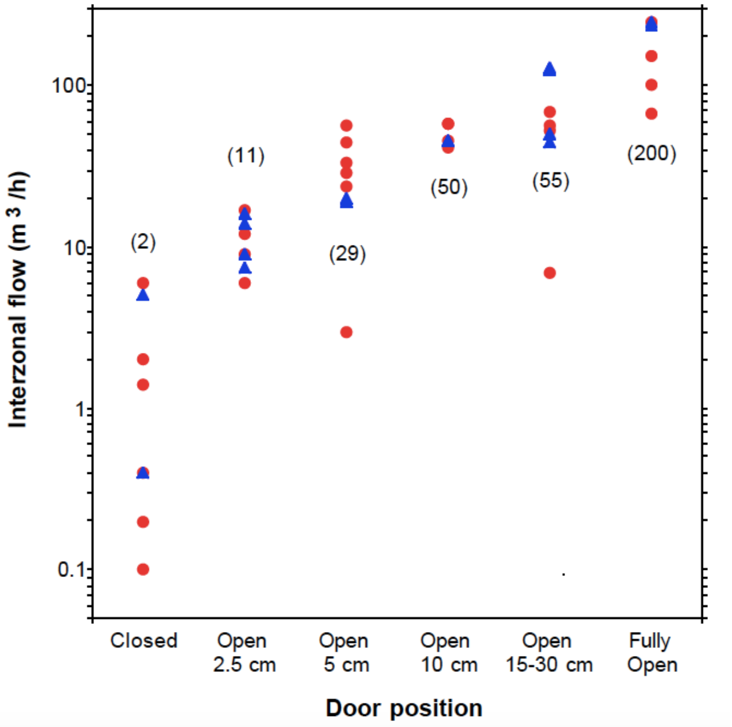

Figure 5. Interzonal airflow measured experimentally in two residences as a function of door position. Each data point represents the result of one experiment, reporting either the flow from Room A to Room B or the reverse. Red circles indicate experiments in "House #2," a split-level detached home in California (510 m^3 volume). Blue triangles are from experiments in "House #3," a two-story townhouse in New York (200 m^3 volume). The number in parenthesis is the median of the replicate interzonal flow rates for that experimental condition, with the A to B and B to A results averaged prior to determining the median. (Data source: Ferro et al.[119])

This quantitative evidence regarding flow rates between rooms in relation to door position is important when trying to characterize air-change rates using measurements in bedrooms. As was illustrated in Figure 2, the accumulation of CO_2 (and other bioeffluents) during sleeping hours depends critically on whether the sleeping room air is well coupled to the air in the remainder of the house. If the door is closed, and there is no central air system operating to promote mixing, then a multizone representation would be necessary. For airflows in even a two-zone system to be completely characterized, four independent flow rates must be determined. It is not possible to do so reliably using a single tracer, such as metabolic CO_2, under field conditions. The most common alternative, of using the passive PFT system, is highly vulnerable to the constant-flow condition assumption. An operational change as simple as having bedroom doors closed at night but open during the day could alter interzonal flow rates so completely as to risk making the quantitative interpretation of time-averaged tracer concentrations meaningless.

Although common in the US, a central, forced air heating and air conditioning system is not universal and it is not even the most common means of residential temperature control in other countries. Systems that use liquids instead of air for heat transfer are common, such as radiators for heating and ductless mini-split air conditioners for cooling. Residences that use these or other local heating and cooling units would tend more toward a decoupled, multizone behavior than would residences using central air systems for thermal control.

The vertical arrangement of a residence is another potentially important aspect of the multizone nature of indoor environments. Single-family houses often have two floors of living space. Basements beneath the main living floor also are common in areas with cold winter climates. When considering interior spaces on two (or more) separate levels, buoyancy can promote transport between the levels when the cooler zone is above the warmer zone. Conversely, buoyancy can impede air transport between the levels when the higher level is warmer than the lower level.

Few studies have quantified transport between floor levels of a house. Riffat[121] used SF_6 as a tracer gas to explore exchange flows between the upper and lower floors of a house when the lower level was heated, and the upper level was unheated. He found only a weak dependence on temperature difference. Volumetric flows were in the approximate range 200-360 $m^3 h^{-1}$ for temperature differences in the range 0.5-13 °C.

Several studies have used passive PFT technology to investigate multizone airflows in residential environments. These are limited in their quantitative utility because they use a time-invariant model to interpret microenvironmental systems that almost certainly have time-dependent flows. Nevertheless, a brief review of findings is warranted.

Dodson et al.[47] used multiple tracer monitoring to investigate interzonal flows in 45 residences, 35 of which had a basement. Ten of the residences were apartments with a common interior hallway. The results reflect the interpretation of time-averaged concentration data collected over 48-h sampling periods. They reported mean ± standard deviations of volumetric flow rates and percentage contributions from the basement and common hallway to the occupied zone of the residences. Basement flows were also determined seasonally. For winter, the flow rate of air from the basement to the occupied zone was 174 ± 164 $m^3 h^{-1}$ (47 ± 26%; $N = 31$); corresponding results for summer were 67 ± 54 $m^3 h^{-1}$ (26 ± 34%; $N = 23$). For the hallway (not seasonally differentiated), the mean flow was 36 ± 30 $m^3 h^{-1}$ (22 ± 33%; $N = 10$).

Du et al.[48] used week-long sampling of two perfluorocarbon tracers to separately characterize the bedroom and whole-house air-change rates in 126 homes in the Detroit area. They found a tendency for higher air-change rate values for the bedrooms. They reported average ± standard deviation air-change rates for the general living area to be 0.73 ± 0.76 h^{-1} and for the bedrooms to be 1.66 ± 1.50 h^{-1}. The authors also reported that the bedrooms "received an average of 55 ± 18% of air from elsewhere in the house; the living area received only 26 ± 20% from the bedroom." In analyzing their data, the authors assumed that a steady-state model would apply. Because only time-averaged tracer concentration data are available, it is not possible to interpret the data in a way that accurately accounts for time-varying flows.

A subsequent report by Du et al.[32] applied a two-zone representation to a subset of the Detroit homes focusing on the 74 single-family dwellings with basements. Again, the investigators used passive PFT technology with week-long time-averaged sampling, releasing distinct tracers in the main living space and in the basement. Repeated measurements were made in many houses; the total number of sampling periods was 266 with air-change rates determined for 170 periods. The results were interpreted using a steady-state two-zone model. The authors reported overall average (± standard deviation) air-change rates for the main living spaces as 0.51 (± 0.48) h^{-1}, with seasonal variation showing the highest air-change rates in the summer and the lowest in the winter. Surprisingly, the outdoor-air change rate was considerably higher for the basements, with an overall average (± standard deviation) of 1.52 (± 1.42) h^{-1}. The outdoor air-change rate for the basement showed the opposite seasonal dependence of the main living space, with the highest value in winter and the lowest in the summer. Inferred volumetric flows from basement to living zone varied seasonally from a maximum of 141 ± 110 m^3/h in winter to a minimum of 37 ± 34 m^3/h in summer. Correspondingly, the proportion of air entering the living zone from the basement (instead of directly from outside) was highest in winter at 58 ± 14% and lowest in summer at 21 ± 18%.

Van Ryswyk et al.[33] explored the relationship between single-zone and two-zone determinations of residential air-change rates using daily PFT measurements in single-family houses. In the single-zone treatment, the emitters and samplers were placed on the main floor of the house. In the two-zone treatment, a second PFT tracer was emitted either in the basement or on the second floor of the house, with a second set of samplers also utilized. The single-zone and two-zone treatments were applied in 287 daily samples across a total of 35 homes in three Canadian cities. The authors reported that the single-zone determinations were lower than the two-zone determinations by an average of 16%.

The study by Bekö et al.[42] reveals the complexity associated with the multizone character of indoor residences during normal occupancy. That investigation assessed air-change rates and interzonal flows in five dwellings in greater Copenhagen, sampled across all four seasons. Three different methods were applied: a single-zone passive PFT technique, metabolic CO_2 monitoring in bedrooms, and an active tracer system designed to maintain a spatially and temporally invariant tracer gas concentration by separately controlling the release rate to several different zones. With the active system, by measuring the amount of tracer gas released so as to maintain a constant concentration in a zone of known volume, the outdoor air-change rate of that zone can be directly assessed.

A striking feature of the study by Bekö et al.[42] is that the variation in air-change rate across season in a single house was comparable to the variation across houses in a given season. Based on the active tracer gas measurements, the ratio of highest to lowest seasonal average air-change rate for each house varied across the range 7-59 with a median value of 10. For each season, the ratio of highest to lowest average air-change rate in the five houses varied across the range 4-22, with a median value of 13. Window opening behavior was centrally important; the air change rates were highest in the summer and spring and lowest in the winter and autumn.

Another striking feature of the Bekö et al.[42] study was the generally poor agreement between different methods that nominally measure the same parameter. Bedroom air-change rates, for example, were systematically higher when evaluated based on the metabolic CO_2 method as compared to the active tracer method. The differences were large, with the ratio of medians by season ranging from about 2-3 in the spring and summer to 4-5 in the autumn and winter. Similarly, the air-change rates determined over five-day periods during winter by the PFT method were larger by 2.5× (based on the ratio of averages) than the active tracer gas determinations for the same times. That finding is surprising, since the passive PFT method is biased low in the presence of time-varying air-change rates because the method determines the harmonic mean rather than the arithmetic mean. The authors openly describe the differences among these methods but do not account for the underlying causes. They do note that "occupant behavior, especially window and door opening," is a major factor influencing the temporal and spatial patterns of residential air-change rates.

6.3 Intrazonal mixing

The meaning of air-change rate is clear and unambiguous in the event that the residential environment is a single, well-mixed zone. That condition should be reasonably satisfied if the time scale for mixing is fast compared with the time scale for air-change, which is the reciprocal of the air-change rate. Hunt[122] provides a good discussion of the influence of stratification and imperfect mixing on tracer-gas methods.

The indoor air mixing time scale has been assessed only in a few experiments that are pertinent to the residential environment. Baughman et al.[123] introduced a specific definition of the mixing time scale as that interval, following a pulsed, point-source release of a nonreactive pollutant (such as a tracer gas), for the relative standard deviation of concentrations measured across a broad array of locations to diminish to 10% or less. This definition of mixing time scale is suitable for experiments in which the well-mixed condition is attained. But if the air-change rate is too rapid, then the well-mixed condition may never be practically attained. Baughman et al. measured mixing times driven by natural convection in an unoccupied, low air-change rate test-facility room of volume 31 m^3. For thermally quiescent conditions, the mixing time scale was long: 80-100 min. However, it diminished to values in the range 7-15 min when either a 500-W electric resistance heater was operated or when incoming solar radiation heated a spot on the floor. In a follow-up study in the same facility, Drescher et al.[124] assessed mixing time scales under forced convection flow conditions. "The resulting mixing times, from 2 to 42 minutes, are related to the mechanical power of the air jets produced by the blower."

Another approach to characterizing intrazonal mixing is to apply the theory of turbulent diffusion. Given an eddy diffusivity, ε, with dimensions L^2/T, the time scale for transport across a characteristic distance, L_c, by means of turbulent diffusion is L_c^2/ε. In magnitude, this time scale would correspond to the mixing time for a point-source pollutant to become fully dispersed throughout a room. Cheng et al.[125] conducted experiments in two residential rooms to characterize the turbulent diffusivity for a point-source release of CO in relation to the air-change rate. Across 11 experiments, the turbulent diffusivity spanned a factor of seven, from 0.0019 to 0.0129 $m^2 s^{-1}$ with a median value of 0.0045 $m^2 s^{-1}$. If one uses as the characteristic length scale one half of the cube root of the room volume, then the corresponding mixing time scales would be in the range 5-64 min (median = 24 min). However, this approach, in which transport is only by means of turbulent diffusion, overlooks the potential for structured airflow to accelerate movement over room-scale distances. For example, at a typical indoor air speed of 10 cm/s, less than a minute would be required to transit the dimension of a common residential room. Overall, room scale mixing might commonly result from the combined effects of advective transport over longer distances and turbulent diffusion across shorter dimensions to yield effective mixing times that are much faster in occupied residential rooms than suggested by the results of Cheng et al.[125]

Ventilation can be more or less efficient at removing pollutants emitted from indoor sources than is the case for well-mixed conditions. The core principles in achieving efficient ventilation are two: to remove pollutants at concentrations that are higher than the room average and to supply clean air to where it is most needed, such as to the breathing zone of occupants. In residences, the application of these principles is mainly found in the use of local exhaust, such as from bathrooms and above cooking appliances. Other concepts that have been developed for improved ventilation efficiency in commercial buildings, such as displacement ventilation, have not been applied in residences.

Overall, topics related to the transport and mixing of air within a zone in the context of residential ventilation are relatively understudied in comparison with their potential importance.

6.4. Using pollutant measurements to infer air-change rates

It should be possible to evaluate residential air-change rates given sufficient knowledge about indoor and outdoor pollutant concentrations combined with information about pollutant sources and indoor pollutant dynamic behavior. Hänninen et al.[126] used this idea to construct estimates of residential air-change rates for European cities based on measurements of indoor and outdoor $PM_{2.5}$ levels. In doing so, they applied the following model equation

$$C_i = \frac{Pa}{a+k} C_o + \frac{E}{V(a+k)} \tag{9}$$

In this equation, the parameters have the following definitions: C_o and C_i are, respectively, the time-averaged outdoor and indoor $PM_{2.5}$ concentrations; *P* is the penetration factor; *a* is the air-change rate; *k* is the first-order loss rate for $PM_{2.5}$ indoors; *E* is the time-averaged indoor emission source strength; and *V* is the indoor volume. This model equation is based on the solution to a material-balance model for a well-mixed indoor environment in which the air-change rate is assumed to be time-invariant.[127] In applying the model, Hänninen et al. used regression analysis from measurements of indoor and outdoor $PM_{2.5}$ concentrations to determine the slope, referred to as the $PM_{2.5}$ infiltration factor, $F_{inf} = Pa/(a + k)$. They combined this measurement result with literature-based values of the penetration factor ($P = 1.0$) and particle loss rate coefficient ($k = 0.39\ h^{-1}$). This approach has problems: the assumption of a constant air-change rate during the monitoring period is generally not valid; the relative contribution of indoor emission sources is likely to vary with time in a manner that may correlate with outdoor pollutant concentrations, interfering with the regression-based estimate of F_{inf}; and the particle loss-rate coefficient, *k*, is likely to vary across the building stock. Mismatches between the model and real-world conditions for any of these assumptions would contribute to uncertainties in the estimated air-change rates.

Notwithstanding their limitations, tracer gas methods appear superior to techniques that utilize indoor-outdoor air pollutant relationships as a means of measuring residential air-change rates.

6.5. Needed improvements in reporting

The reporting of residential air-change rates is heterogeneous. This section highlights some areas in which future reporting could be strengthened so as to improve the usefulness of findings.

It would be helpful in all cases to provide clear information about the type of housing studied and the mode(s) of ventilation. It is important, for example, to differentiate clearly between single-family dwellings and apartments. A common shortcoming encountered is inadequate specification of the means by which the residences are ventilated. A specific example is the use of the term “natural ventilation” to include both purpose-designed vent and stack systems as well as user-controlled window (and door) opening. Future research on residential ventilation and air-change rates should aim to be both complete in reporting important characteristics of the residences studied and clear in defining terms.

When reporting results, both central tendency and some indication of variability should be featured. Some studies have reported arithmetic mean and standard deviation. However, as argued in this review, air-change rates are more likely to be distributed lognormally than normally and so the geometric mean and geometric standard deviation are generally better indicators of the distribution. Researchers could also consider reporting nonparametric values of the distribution, such as the 10th, 25th, 50th, 75th, and 90th percentiles. This slightly more extensive reporting provides rich information content. Extrema are not so useful as they tend to be too dependent on sample size and are susceptible to experimental outliers.

In many cross-sectional studies, repeat measurements are made in individual houses. In such cases, it would be useful to assess both the variability with time in individual houses as well as variation across the housing stock. The common practice of treating each measurement as an independent sample to be equally weighted in constructing a distribution contributes to a loss of useful information about how stable the air-change rates are in homes over time.

Reporting has generally been good in describing most of the important parameters that influence air-change rates, at least to the extent that they can be easily determined. Season is regularly reported as is the sampling duration. Information about the stock of houses studied is usually provided. On the other hand, it is clear that window use is a key determinant of residential air-change rates and more effort could be dedicated to collecting information on window use and its influence. Likewise, the type of heating and/or cooling system along with the extent to which it was used during the measurement period would be valuable. Meteorological parameters such as indoor-outdoor temperature difference and wind speed are known to affect infiltration and natural ventilation rates. Incorporating stronger information about these parameters in future studies of residential air-change rates would be worthwhile.

A final important improvement would be consistently reporting indoor volumes and the method of their determination in cases in which that parameter is needed to evaluate air-change rate. In particular, in the use of passive PFT technology and in some uses of metabolic CO_2, the outdoor airflow rate (volume per time) is computed from the measured concentration. The air-change rate is obtained by dividing this flow rate by the interior volume through which the tracer is mixed. Important ambiguities can arise. For example, in a single-family dwelling with a basement, should the basement volume be included? The answer could vary depending on the use of that space (whether it is living space or unfinished storage space, for example) and with the nature of air flow coupling between the main floor and the basement. There is no simple approach that would apply in all conditions. It is incumbent on investigators to state their assumptions and to provide appropriate justification.

7. INFLUENCE OF VENTILATION ON INDOOR POLLUTANT CONCENTRATIONS

7.1. Air-change rate dependence

The influence of air-change rates on indoor pollutant concentrations is complex and nuanced. A basic notion is that increasing air-change rates makes the indoor air more like the outdoor air, and vice versa. For pollutants with strong indoor sources, increasing the air-change rate tends to decrease indoor pollutant concentrations. Conversely, when a pollutant has indoor losses and originates primarily from outdoors, then increasing the air-change rate tends to increase the indoor concentration.

Beyond this broad generalization, the specifics can vary markedly across pollutant classes. The nature of the relationship can interact with the air-change rate determination in ways that materially influence proper interpretation of experimental results. A thorough discussion of these issues lies beyond the scope of the present review. Some examples are warranted, though, to illustrate the nature of these issues and to substantiate the point that the topic merits careful study. The cases considered illustrate commonly used representations of the dependence of indoor concentrations on air-change rate for some important pollutants.

Leaderer et al.[128] explored the influence of ventilation on indoor air concentrations of particulate matter (total suspended particles or TSP) and carbon monoxide when these were generated by cigarette smoking. Under steady-state conditions (i.e., with continuous smoking), and with indoor emissions dominating, the indoor species concentration is well modeled by the following equation:

$$C = \frac{E/_V}{a+k} \tag{10}$$

In this equation, *E*/*V* represents the volume-normalized pollutant emission rate into indoor air, *a* is the air-change rate, and *k* is the first-order loss rate coefficient. For carbon monoxide, $k = 0$, whereas for particulate matter, *k* would reflect the sum of losses by deposition to room surfaces and by filtration, if any. Although developed for a chamber study of environmental tobacco smoke, equation (10) would apply to any indoor pollutant whose abundance is dominated by constant emissions from an indoor source and which is either chemically inert or removed by first-order processes from indoor air. However, even for pollutants whose behavior is sufficiently simple to be effectively represented by equation (10), the dependence of time-averaged concentrations on time-varying air-change rates can be complex. Interestingly, for an inert species, such as CO, the time-averaged indoor concentration varies with the harmonic mean air-change rate, the form of the time-average that is well characterized by the passive PFT technology. On the other hand, for a pollutant class like fine particulate matter, the time-averaged indoor concentration in the presence of a constant indoor emission source would vary with the time average of the reciprocal of $a + k$, a parameter that cannot be accurately assessed by passive PFT technology in the presence of time-varying air-change rates, even if *k* is well known.

Ozone is another pollutant of considerable interest indoors.[129] Commonly, ozone is primarily introduced from outdoors along with ventilation air. The indoor concentration is lower than the outdoor concentration, mainly because of reactions on surfaces that decompose ozone. A model equation for the indoor concentration of ozone can be written as follows:[129]

$$C = \frac{a}{a+k} C_o \tag{11}$$

Here, C_o is the outdoor concentration of ozone and *k* is the first-order loss-rate coefficient for ozone reaction indoors.

In the general case of fine particulate matter, Dockery and Spengler[127] proposed a model (equation 9) that emphasizes the time-average value of the indoor concentration and so interpreted C_o as the time-average outdoor pollutant concentration and *E* as the time-average indoor source strength.

An examination of equations (9) - (11) reveals the challenge that arises in attempting to understand how time-averaged indoor pollutant concentrations vary in relation to air-change rate when the air-change rate itself varies with time. Because air-change rate appears in the denominator of each equation, the harmonic mean is generally more relevant than the arithmetic average as an effective time-average measure of air-change rate. However, the situation is more complex, as revealed by the multiple appearances of the air-change rate in equations (9) and (11).

Another important feature of indoor pollutant dynamic behavior that can materially influence the relationship with air-change rate is sorptive partitioning to indoor surfaces, which commonly applies for organic contaminants (VOCs and SVOCs) and whose influence can be profound. A simple exploration of the influence from the perspective of time-varying air-change rates can be found in Sherman and Hult.[130] The influence of reversible partitioning on the short-term dynamic response to strongly changing ventilation conditions has been reported.[131] Longer-term response is illustrated in the experimental data of Willem et al.[132] and, in the case of formaldehyde and acetaldehyde, in the work of Hult et al.[133]

7.2. Per-person ventilation rate dependence

Air-change rate is the standard metric for characterizing residential ventilation. As indicated in the examples discussed in §7.1, this measure is appropriate for circumstances in which the important pollutant sources are independent of occupancy, such as particulate matter and ozone introduced from outdoor air or VOCs emitted from building materials and furnishings. However, some important pollutants are directly or indirectly associated with the building occupants. Examples of direct association are carbon dioxide,[134] ammonia[135] and volatile organic compounds[136] emitted from the human body and from personal care products. Indirect association would apply for activity-related emissions, when the intensity of such activity tends to scale with the number of occupants, as would be the case for cooking. When a pollutant of concern originates directly or indirectly from occupancy, then the per-person ventilation rate (e.g., liters of outdoor air per second per person) is a better measure of ventilation for indoor air quality than is the air-change rate. This metric is commonly applied for public and commercial buildings, but the air-change rate is the more common primary ventilation metric for residences.

These two metrics of ventilation are clearly and closely related by the density of occupancy of indoor spaces. Specifically, for an indoor environment with volume per person, V_p, the flow rate per person, Q_p, is related to the air-change rate by this expression: $Q_p = a \times V_p$. So, for example, in a residence with an air-change rate of $a = 0.5\ h^{-1}$ and a per-occupant volume of $V_p = 100\ m^3$ person^{-1}, the average per-person ventilation rate would be $Q_p = 50\ m^3\ h^{-1}$ person^{-1}, or 14 L/s per person.

Although the metrics are closely related, the difference between them becomes important when comparing conditions in which occupant densities differ strongly. An example is the case of ventilation in university dormitories.[85] Table 3 reports that the wintertime air-change rates in the dormitories had a geometric mean value of 0.7 h^{-1}. Sun et al.[85] noted that "on average, six bachelors, four masters, or three PhD students share one dorm room of 20 m^2. Such dorm environment typically represents the living condition and indoor environmental exposure of college students in China." Assuming a ceiling height of 2.5 m, six students occupying a 50 m^3

space with an air-change rate of 0.7 h^{-1} would correspond to a per-person ventilation rate of only 1.6 L/s per person. So, in this case, although the air-change rate is higher than the nominal central tendency of 0.5 h^{-1}, the ventilation rate per person is relatively low compared with norms for healthful conditions.[16]

An important feature in using metabolic CO_2 to measure air-change rates seems to be not fully appreciated in the research community. This experimental approach is much better suited for evaluating per person ventilation rates of sleeping spaces than it is for determining the air-change rates of residences. Because air-change rate reporting has dominated in characterizing residential ventilation, efforts to use metabolic CO_2 as a tracer in residences have more commonly emphasized air-change rates as the reporting variable of interest. To be specific, Table 3 cites nine different studies that have used metabolic CO_2 to characterize residential ventilation. All nine reported air-change rates as the primary ventilation metric; only Sun et al.[85] reported corresponding values of ventilation rate per person.

Worth noting is that a few of the studies that used perfluorocarbon tracers reported their findings in terms of ventilation rate per person, in addition to reporting air-change rates.[31,56] Sorting data from Sweden according to year of construction, average values varied in the range 12-18 L/s per inhabitant for single-family houses and in the range 15-18 L/s per inhabitant for multi-family houses.[31] In a study of 96 single-family dwellings in Quebec City, per person ventilation rates for were reported to have GM = 7.6 L/s per person and GSD = 1.7.[56]

8. SUMMING UP AND LOOKING FORWARD

Among the measures that can be used for quantifying ventilation are the outdoor air ventilation rate, Q, the per occupant ventilation rate, Q_p, and the air-change rate, $a = Q/V = Q_p/V_p$, where V is the volume of the residence and V_p is the volume per person. Air-change rate is the most commonly measured and reported parameter for residential ventilation. As argued in §7, it is an appropriate indicator for some residential indoor air quality concerns, but not all.

The air-change rate can vary with time in any given residence and also varies across populations of buildings. Because air-pollution exposure is local and temporal, it is essential to understand not only the central tendency of air-change rates, but also the variability, both among different residences and over time within any given residence. In this report, the lognormal distribution has been employed as the most concise form of describing both central tendency and variability. Nonparametric reporting of percentile values can be a more complete and accurate representation of the distribution.

Air-change rates can be assessed using tracer-gas methods. The three most widely employed methods are these: (1) use of passive perfluorocarbon tracer technology, (2) either constant or pulsed injection of a tracer with time-resolved sampling, and (3) the utilization of metabolic carbon dioxide. Air-change rates may also be inferred through experimental measurement of building envelope leakage combined with a model to account for pressure-inducing forces. However, to be effective with respect to exposure, it is essential for such model evaluations to include the effects of occupancy, rather than only representing closed-residence infiltration rates.

This review has assembled, organized, and assessed evidence from a large number of field studies that have measured residential air-change rates. Because of the central concern about ventilation as a factor influencing indoor air quality and exposure, a focus has been on normally occupied dwellings. Considered cumulatively, the cross-sectional studies summarized in Tables 1, 3, and 4 encompass about 40 separate investigations of more than 10,000 dwellings. Studied households include single-family dwellings as well as apartments. Measurements have been made in residences ventilated by various means: by infiltration and occupant-controlled window use, by purpose-designed natural or passive ventilation systems, and by mechanical ventilation.

Although this body of evidence is substantial, it is important to acknowledge some limitations. In all, only nine countries are represented in the cross-sectional data. Air-change rates have been measured in more than 1000 dwellings in each of three countries: USA, Sweden, and China. The other six countries represented are Denmark, France, Canada, Norway, Finland and Slovakia. Relative to the global population, the distribution of studied households is clearly biased toward colder climates in more economically developed countries. It is important for future studies to expand the geographic scope of residential air-change rate measurements.

Probably more measurements have been made in single-family dwellings (and fewer in apartments) than their representation in the total housing stock. Also, because the record of published measurements is historically cumulative, the shift over time toward building residences with tighter envelopes, a greater reliance on mechanical ventilation, and lesser dependence on occupant-controlled window use are not fully reflected in the empirical data.

Notwithstanding these limitations, in the absence of any other information about the residential building stock, a synthesis of the large body of experimental evidence suggests that a reasonable representation for residential air-change rates is a lognormal distribution with GM = 0.5 h^{-1} and GSD = 2.0. Given the properties of lognormal distributions, these parameter values also imply an expectation that 68% of air-change rates would lie between 0.25 and 1 h^{-1}; 95% would be in the range 0.125-2 h^{-1}.

The large number of cross-sectional studies summarized in Tables 1 and 3-5 indicate that in subsets of housing the central tendency air-change rate might be as low as about GM = 0.2 h^{-1}, e.g. during winter in the cold climates of Canada and Sweden, and as high as about GM = 1 h^{-1} during periods with moderate weather or in lower income households in the US.

Weather and occupant behaviors can interact to influence air-change rates. In most studies, the air-change rates are observed to be lowest during winter, even though the indoor-outdoor temperature difference, one of the important driving factors, is largest during this season. The explanation lies in window use behavior, which is at a minimum when weather is inclement. Less extensively studied is the seasonal effect on air-change rates in hot climates. In Houston, TX, the air change rates were lowest during the hot and humid summer as compared with other seasons (see Figure 4).[102] In China, interactions have been reported, in the directions expected, among climate, window use, and overnight bedroom air-change rates.[81] Other occupancy-associated factors influencing air-change rates include use of heating or air-conditioning systems, the use of fireplaces and other flued combustion devices, and the operation of exhaust fans or appliances that increase exhaust flow.

Residential ventilation influences indoor air quality. At a broad level, concepts are well understood. Higher air-change rates tend to make indoor air more like outdoor air. With lower air-change rates, residential buildings provide more protection against pollutants of outdoor origin, while also tending to exacerbate exposures for pollutants emitted indoors. Beyond this overall qualitative description, model equations have been advanced to describe indoor-outdoor relationships for many pollutants and pollutant classes, as outlined in §7. Relative to the importance of the subject, too little work has been conducted in occupied residences to specifically assess the relationship between air-change rates and indoor pollutant concentrations. As a specific example, there is a need to study the performance of mechanically ventilated residences, not only with regard to ventilation air-change rates provided but also with regards to the relationship between ventilation system design and operation and the resulting indoor pollutant concentrations. Ideas about the nature of these relationships have been explored, mainly in theoretical studies.[130,137,138] Empirical evidence about actual behavior in occupied residences under real-life conditions is scant.[133,139]

Important challenges remain to better understand residential air-change rates. One important detail is to differentiate between the variation in air-change rates across the building stock versus variation in air-change rates over time in any individual house. The few studies that have extensively assessed the variation of air-change rates over time in individual houses (summarized in Table 2) show a degree of variability that is only moderately smaller than the variability seen in cross-sectional studies of portions of the housing stock. The relatively poor correlation for repeat measurements (in different seasons) in the RIOPA study (Table 8) also suggests that longitudinal variability of air-change rates in individual houses is potentially quite important to better understand as a factor influencing indoor air quality.

Two methodological issues in air-change rate measurements remain as important challenges for future progress for indoor air quality studies in occupied residences. The first concern is the proper treatment of time-varying air-change rates, especially when using time-averaged sampling, as with the passive PFT technology. That this method measures the harmonic mean rather than the arithmetic average air-change rate can be seen as a virtue when trying to understand the relationship between emissions and ventilation for pollutants that are primarily derived from continuous indoor sources. On the other hand, when trying to understand how indoor pollutants of outdoor origin are influenced by ventilation, there is a mismatch between the proper time averaging of ventilation’s influence for those pollutants and the time-average attained from a constantly emitted indoor tracer. The potential for such a mismatch to matter is potentially large when trying to use time-averaged sampling methods to infer rates of dynamic processes, such as the deposition loss rate coefficient of particulate matter indoors. It can also introduce errors when trying to apportion indoor particulate matter and associated exposures to sources.

The second major challenge concerns the multizone character of residences. The challenge here is exacerbated by factors that influence interzonal airflows in a time varying manner. Specific circumstances commonly encountered include intermittent operation of central, forced-air heating and cooling systems; interior doors that may be variably open or closed; and stable versus unstable temperature structure in residences with multiple floor levels. Treating a residential unit as a multizone environment is challenging in part because there are no well-established criteria for selecting an appropriate number of zones or for defining their spatial extent. The use of time-averaged sampling, as with the passive PFT method, provides ambiguous information in the presence of time-varying air-change rates and/or time-varying interzonal flows. To date, no studies have overcome the difficulties of using tracer gases so as to accurately characterize multizone flows in normally occupied residences.

The available evidence suggests that the single-zone representation of residences remains useful as an approximate description of this most important class of indoor environments. The limitations that arise because of a single-zone representation of a multizone environment may be important at times and should be further studied, but these limitations do not erase the value of the existing empirical evidence about residential air-change rates.

To address the multizone aspects of residential environments, a rethinking of the use of tracer gases has merit. Air-change rates and interzonal flows are not of primordial importance; rather they are important factors influencing indoor air quality, exposure, and associated health risks. Tracer gases are used to characterize air-change rates and interzonal flows for the purpose of better understanding indoor air quality. Some of the complexity can be bypassed if, rather than focusing on flow characterization, some use of tracer gases is oriented toward direct characterization of source-to-exposure relationships. For example, when a tracer is released at a constant rate from a residential basement, the concentration measured in the living space can be the basis of evaluating a transfer factor (concentration per unit emission rate) that is directly pertinent for assessing how continuous contaminant releases in the basement affect exposure concentrations in the living space. Extending this concept, one can envision tracer releases with specific spatial or temporal patterns that would then be used to make a more direct assessment of the transport features influencing exposures from selected source categories. Analogously, rather than relying on spatially fixed sampling sites, active personal-sampling equipment could be employed to more accurately assess how air-change rates and interzonal flows influence the relationship between pollutant emissions and occupant exposures. Existing tracer gas technologies constitute a strong platform for further developments that could help the research community overcome some of the important limitations in characterizing residential air-change rates and their influence on occupant's exposures to pollutants in their homes.

ACKNOWLEDGEMENTS

Some early phases of this review were undertaken as part of a joint project with Charles Weschler. I appreciate his encouragement to pursue this specific topic independently along with helpful suggestions that he made at the outset. I'm grateful to the University of California for a pension sufficient to pursue work like this without specific funding. I'm also grateful that the university allows full access to its outstanding library system for retired members of its faculty. The work needed to prepare this review was greatly facilitated by having access to digital copies of research articles and reports along with excellent on-line bibliographic tools, including Clarivate Analytics' Web of Science and Google Scholar.

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