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Author

Sherman, Max H.

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M. H. Sherman, I.S. Walker

Lawrence Berkeley National Laboratory
Environmental Energy Technologies Division
Indoor Environment Department
Energy Performance of Buildings Group
Berkeley, CA 94720

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Max H. Sherman, Ph.D. Fellow ASHRAE
Iain S. Walker, Ph.D. P.E. Member ASHRAE

Energy Performance of Buildings Group
Indoor Environment Department
Environmental Energy Technologies Division

MS 90-3074
1 Cyclotron Rd
Lawrence Berkeley National Lab
University of California
Berkeley, CA, 94720
MHSherman@lbl.gov
+1 (510) 486-4022

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ABSTRACT

Ventilation reduces occupant exposure to indoor contaminants by diluting or removing them. In a multi-zone environment such as a house, every zone will have different dilution rates and contaminant source strengths. The total ventilation rate is the most important factor in determining occupant exposure to given contaminant sources, but the zone-specific distribution of exhaust and supply air and the mixing of ventilation air can play significant roles. Different types of ventilation systems will provide different amounts of mixing depending on several factors such as air leakage, air distribution system, and contaminant source and occupant locations. Most U.S. and Canadian homes have central heating, ventilation, and air conditioning systems, which tend to mix the air; thus, the indoor air in different zones tends to be well mixed for significant fractions of the year. This article reports recent results of investigations to determine the impact of air mixing on exposures of residential occupants to prototypical contaminants of concern. We summarize existing literature and extend past analyses to determine the parameters that affect air mixing as well as the impacts of mixing on occupant exposure, and to draw conclusions that are relevant for standards development and for practitioners designing and installing home ventilation systems. The primary conclusion is that mixing will not substantially affect the mean indoor air quality across a broad population of occupants, homes, and ventilation systems, but it can reduce the number of occupants who are exposed to extreme pollutant levels. If the policy objective is to minimize the number of people exposed above a given pollutant threshold, some amount of mixing will be of net benefit even though it does not benefit average exposure. If the policy is to minimize exposure on average, then mixing air in homes is detrimental and should not be encouraged. We also conclude that most homes in the US have adequate mixing already, but that new, high-performance homes may require additional mixing. Also our results suggest that some differentiation should be made in policies and standards for systems that provide continuous exhaust, thereby reducing relative dose for occupants overall

Keywords: Air Distribution, Mixing, Mechanical Ventilation, Ventilation Effectiveness, Residential Ventilation, Indoor Air Quality

INTRODUCTION

Providing acceptable indoor air quality (IAQ) is a basic building service. Although controlling contaminant sources is the most fundamental strategy for ensuring acceptable IAQ, there is always a practical limit on source control, so some dilution from ventilation is needed. Traditionally, homes have been ventilated by air leakage through unintentional envelope airflows, augmented by some occupant-controllable opening of windows. As homes are becoming more energy efficient and as new pollutant sources are brought into them, these traditional methods are insufficient, and designed ventilation systems are becoming necessary.

In many parts of the world, regulations require designed ventilation systems for new or renovated homes. Many European and Asian countries have such requirements as do several U.S. states, and this trend is expected to continue. These requirements are not always consistent. They generally differ in terms of the required ventilation rate, the role of natural versus mechanical ventilation, and the reliance on the paradigm of whole-house vs. room-by-room ventilation. In North America, the main IAQ standard for homes is ASHRAE Standard 62.2 (2007), which primarily specifies minimum, whole-house, mechanical ventilation rates.

In contrast to the European paradigm (de Gids 2007), in which each habitable room is independently provided with ventilation, Standard 62.2 assumes that ventilation air will be well mixed throughout the home. In this study the term "mixing" is used to discuss the variability of pollutant concentrations from room to room in a home. Mixing affects occupant exposure to pollutants in two important ways: 1) if mixing is incomplete, occupant exposure will depend on the rooms in which occupants spend most of their time, and 2), the exposure of occupants who reside primarily in a particular room is affected by the degree of mixing because the air volume active in dilution changes; with no mixing, pollutants released in the room stay there, resulting in higher concentrations in that room (and zero elsewhere in the home), but, as mixing increases, the pollutants from that room are transported to other rooms with a resulting lowering of concentration in the room in which the pollutant is released. This is a different definition than is sometimes used when discussing pollutants in an individual space where mixing refers to only the air in the room of interest and is contrasted with displacement ventilation, in which mixing within the room is minimized.

The room-to-room mixing assumption in ASHRAE 62.2 is not unreasonable given the American convention of central forced-air heating and cooling systems that mix air from room to room at much higher airflows than ventilation. Currently Standard 62.2 has no requirement for such mixing, nor is there any differentiation between systems that provide more or less mixing. A better understanding of the quantitative impacts of mixing is necessary to develop robust requirements or differentiations among systems.

In this article, we review recent work and extend prior analyses on this topic to draw conclusions about the value of mixing. Although issues of source strength, mechanical ventilation rate, and interaction with air leakage can have similar-magnitude effects, we focus on what we can learn about air distribution and, in particular, the role of mixing in providing acceptable IAQ.

BACKGROUND

IAQ depends on the distribution of both contaminant sources and ventilation air. Many approaches have been used to account for these variables. One approach, for example, is to break a space up into a small number of well-mixed zones. Such a zonal model has been investigated by Feustel et al. (1989) among others.

It is often necessary, however, to determine the air distribution within a zone. This was an active area of research 25 years ago when the concepts of ventilation efficiency and pollutant removal efficiency were developed. Sutcliff (1990) and Brouns and Waters (1991) have reviewed the work of that period and summarize the key efforts well. Persily et al. (1994) have used ventilation efficiency approaches to make measurements in commercial buildings.

A commonly used metric developed from that time is “Age of Air,” including the concept of local mean age of air. Maldonado and Woods (1983) among others describe this metric and discuss how to measure it. Currently, ISO Standard 16000-8 (2007) describes how to determine it. The age-of-air concept assumes that contaminants are uniformly generated in each elemental volume and applies only to a single zone. It is, therefore, a good indicator of when sources are evenly distributed or whether there is enough mixing to uniformly spread actual sources, but it may not be useful when sources are localized or when mixing is problematic. Other metrics have been suggested and are in use. Sutcliff (1990) has reviewed ventilation effectiveness metrics, and Brouns and Waters (1991) have reviewed pollutant removal effectiveness metrics.

Because this study examines the effects of mixing and non-uniform source distribution, the age-of-air metric is not useful. Two other metrics that might more closely represent the source and occupancy patterns of homes have been developed by Sherman and Walker (2008): one metric is how close the house is to being perfectly mixed, and a second metric is how close the house is to perfect isolation where there is no mixing between zones.

ASHRAE Standard 62.2 establishes requirements for mechanical ventilation in low-rise residential buildings. The amount of mechanical outdoor air ventilation is defined by the dwelling’s floor area and the number of bedrooms (as a proxy for number of inhabitants).

Unfortunately the standard does not indicate whether to evenly distribute ventilation or to use other ways to ensure the outdoor air provided for ventilation results in acceptable IAQ despite the fact that past work has shown that different residential ventilation systems do not provide exactly the same performance even when providing the same nominal outside airflow rate. For example, Sherman (2008) found exposure levels within a house to be strongly dependant on the ventilation system, pollutant source distribution, and occupant location. Hendron et al. (2008) used single-tracer gas decay with multi-zone sampling to investigate ventilation air distribution. They found that an exhaust-only system provides less uniform distribution when interior doors are closed. Townsend et al. (2009a) used Hendron’s measured decay test results to calibrate a simulation model that was then used to examine other ventilation scenarios. The calibration involved modifying the air leakage network (primarily the envelope component and interzonal airflow resistance) to improve agreement between the measured and modeled airflows. As will be discussed later, Townsend found that calibrating the model greatly improved its accuracy and reduced systematic errors for the physical variations included in the calibration. Sherman and Walker (2009) found that the magnitude and location of envelope leakage and interior door opening significantly changed room-to-room ventilation performance for the same Standard 62.2 mechanical ventilation system.

Measuring Air Exchange

A tracer gas is normally used to measure age of air or other air-change-rate-related metrics in buildings. An ideal tracer gas is a substance that can be added to a volume of air (presumably in small amounts) and then accurately measured. No tracer is perfect, but a good tracer gas should be easy to measure in low concentrations, easily dispersed, and should not impact the thermo-physical properties of the air it is tracing; moreover, it should be non-toxic and environmentally friendly. Grimsrud et al. (1980) have done an

inter-comparison of different tracer gases used for such measurements. More recently, restrictions on fluoro- and halo-carbon emissions have made some tracer gases obsolete. The use of tracer gases is a well-developed experimental technique: Harrje et al. (1985) reviewed many of the approaches that use tracer gases to measure airflow-related quantities; Lagus and Persily (1985) determined airflows under field conditions to support ventilation and pollutant transport work; McWilliams (2003) reviewed airflow measurement methods covering a broad range of techniques including tracer gases; and the Air Infiltration and Ventilation Center (AIVC) (<http://www.aivc.org>) has a variety of technical publications relating to tracer gas applications.

When tracer gases are used to quantitatively estimate airflows, the concept of a “well-mixed zone” is important. A well-mixed zone is assumed to have a spatially uniform concentration of tracer gas or pollutant. Just as evaluating exposure to an air pollutant depends on knowing the concentration of that pollutant in the occupied zone, accurate estimation of airflow depends on knowing the concentration of tracer gas.

Complex buildings or complex airflow patterns require breaking the indoor space into multiple well-mixed zones. Multi-zone tracer gas measurement techniques have been developed and are summarized by Roulet et al. (1989).

The most straightforward generalization for multi-zone measurement requires that multiple, unique tracer gases be used (one for each zone). The use of a tracer for each zone allows the full range of analysis options and provides the most robust estimates of airflow.

Another issue is the time variability of ventilation. Often, mixing is not continuous because of the cycling of a central system when heating or cooling. In addition, any natural infiltration depends on ambient wind and temperature conditions that change with time. Capturing this time variability requires specific measurement techniques, such as constant injection or constant concentration rather than the tracer decay tests that are more commonly employed. Addressing time variability also introduces the concept of effective ventilation, which is the value of constant ventilation that would provide the same exposure as the actual (i.e., time-varying) ventilation.

APPROACH

Mixing is one of many attributes that impact indoor air quality. As noted earlier, two key factors are source strength and total ventilation, but other subtle factors that can contribute to air quality are the allocation of mechanical ventilation, natural ventilation, and infiltration; the distribution of contaminant sources around the building; the variation in occupancy pattern; and the type of ventilation system. Our approach focuses on isolating the benefits of mixing from these other impacts. We combine a summary of existing literature with extended analyses that address additional mixing issues so that we can determine the impacts of mixing on occupant exposure as well as the parameters that affect mixing. We draw conclusions that are relevant for standards development (e.g., ASHRAE 62.2) and for practitioners designing and installing home ventilation systems.

To evaluate IAQ we use the concept of *relative dose*, d , introduced by Sherman and Walker (2009). The relative dose is the ratio of the dose of contaminant that an occupant would get in the current condition compared to a reference case.

Isolating the impact of mixing can be difficult because all of the above factors interact and contribute to changes in tracer gas or pollutant concentration. Three recent publications have compared measurements and a variety of simulations to highlight the

physical impacts of mixing. We reviewed these three studies in detail; the following summary highlights how their similarities and differences point to important conclusions about mixing in homes. Moreover, additional important issues related to mixing in homes were not discussed in these previous studies: trends in mean relative dose and the variability in dose resulting from mixing with a central forced-air system, identification and estimation of the magnitude of all sources of mixing, and identification of the differences between balanced and unbalanced mechanical ventilation systems. These issues are evaluated below, following the review of recent literature.

Summary of Recent Literature

Three recent publications bear directly on the subject of mixing and IAQ. In chronological order, they are: *Measured Air Distribution Effectiveness for Residential Mechanical Ventilation* by the authors of this article, Sherman and Walker (2009); *A Method for Modifying Ventilation Airflow Rates to Achieve Equivalent Occupant Exposure* by Townsend, Rudd, and Lstiburek (2009b); and *Air Distribution Effectiveness for Residential Mechanical Ventilation: Simulation and Comparison of Normalized Exposures* by Petithuguenin and Sherman (2009). Each of these publications looks at the mixing problem from a different perspective, and each has different strengths and weaknesses in its understanding of the issue. The following discussion examines the differences among the experimental procedures and analyses of each study and summarizes the conclusions that can be drawn from each.

Sherman and Walker

Sherman and Walker (2009) use a multi-gas, multi-zone tracer system in two houses to calculate, in real time, the flows to and from zones to outside and between each zone. Previous experimental work (e.g., Hendron et al. 2008) used only a single tracer gas and therefore could not resolve the entire set of airflows. The multi-zone measurements were made with three different ventilation systems: a single-point exhaust with no additional air distribution, a central-fan integrated supply system, and a single-point exhaust with continuous central forced-air fan operation for mixing. Two houses were tested: one tight (1,950 L/s [4,130 cfm] @ 50 Pa) and one leaky (635 L/s [1,345 cfm] @ 50 Pa), which had different natural infiltration rates. Both houses were tested with all interior doors open and all interior doors closed.

To analyze the data in that study, the authors used *relative dose, d*. The relative dose is the ratio of the contaminant dose that an occupant would get in the current condition compared to the dose in a reference case. The reference case used is perfectly well mixed but otherwise has the same conditions as the actual case, i.e., same total ventilation rate, air leakage, climate, occupancy patterns, and source distribution.

The relative dose is not unique to a given set of airflows because it depends on the distribution (but not magnitude) of sources and the specific occupancy pattern. Because these factors are in general unknown, Sherman and Walker applied a set of metrics that use typical source and occupancy patterns to the measured airflows to estimate the relative dose. The metrics are:

1. mean exposure where the sources and occupants are evenly distributed,
2. volume-weighted sources,
3. volume-weighted worst case where the occupant is always in the worst zone,

4. absolute worst case with all the sources in the same zone as the occupant and that zone having the least air exchange,
5. worst cross contamination with the source and occupants in different zones,
6. deviation from perfect mixing, and
7. deviation from perfect isolation of zones.

The multi-zone tracer system concentrations were used to calculate the airflows to and from each zone. The airflows were combined with the pollutant emission characteristics for each metric to determine pollutant distributions and therefore relative doses for each metric. Supply and exhaust systems were found to have similar relative doses for all metrics, indicating that they have effectively the same mixing or distribution of pollutants. Mixing led to significantly different results, however, depending on the chosen metric: some metrics showed decreased dose with mixing, but others (5 and 7) showed an increased dose with mixing. Comparing the results between the tight and leaky house shows that the total ventilation rate changes substantially but only impacts the relative dose by acting like mixing,. Open doors result in more mixing than does mechanical mixing of the air in the house.

Whether mixing reduces the relative dose or not depends on the distribution of sources and the occupancy pattern. For some of the metrics presented, mixing reduces the relative dose, but, for some metrics, mixing increases the dose.

Townsend, Rudd, and Lstiburek

Townsend et al. (2009b) take a different approach to the problem. They use a detailed numerical simulation to estimate occupant exposure based on specific assumptions. The authors also use a reference case and a test case to estimate a dimensionless factor, called the *system coefficient*, which is defined differently from the relative dose. The system coefficient is the number by which one has to multiply the mechanical ventilation rate to get the same exposure as in the test case. The system coefficient is found by interpolation or extrapolation from a set of simulation runs.

The reference case used for these simulations has a specific mechanical system (fully ducted, balanced, with central forced air), a specific house design, a specific set of occupants (using the worst-case occupancy pattern), a specific assumption about duct leakage, etc. To find the reference exposure level, the authors used a single air-tightness level (typical of tight new construction), and the results were averaged over climates covering all of the U.S. Department of Energy (DOE) climate zones in the contiguous 48 states. Each source distribution had its own reference value.

The study was done for source distributions and air-tightness levels for 36 ventilation system configurations. The intermediate results show that system coefficients can vary widely depending on the ventilation system configuration, building envelope air tightness, and source distribution. For example, a given system can have a system coefficient from zero to two depending on tightness levels and source distribution. Even within a specific system and for a specific air tightness, source distribution matters substantially, with some system coefficients changing by factors of three.

The authors reported system coefficients for the 36 systems for one specific source distribution pattern and one specific leakage value. The system coefficients ranged from about 3.0 to 0.50 for a reasonably airtight house. About one-quarter of the systems were as good as or better than the reference system, but the authors stated that source location and occupant patterns can have a significant impact on their system coefficients and that

the effect of house design (floor plan, number of stories, and floor area) needs to be investigated to expand the robustness of their conclusions.

Petithuguenin and Sherman

Petithuguenin and Sherman (2009) take a third approach to studying mixing, which borrows some elements of the two studies above and uses prior studies' results to focus simulation efforts. Like Townsend et al., Petithuguenin and Sherman use a numerical simulation to parametrically investigate the issue, and, like Sherman and Walker, the authors use perfect mixing as the reference case, so their results are expressed in the form of relative dose; Petithuguenin and Sherman also considered only "canonical" ventilation systems: central-fan integrated supply and single-point exhaust.

To focus on the issue of mixing, the authors removed the influence of infiltration by using a very tight envelope, which makes the analysis weather and climate independent. The situation modeled is therefore prototypical, not what one would find in the field. The purpose is to determine the physics of mixing and help isolate the effects of mixing from the effects of other parameters.

The previous studies had indicated that variations in occupancy and house design significantly change the results. Therefore, three different houses and a dozen different occupant profiles were examined. The house styles and occupancy were chosen to be representative of a wide range of the housing population. This variation created a distribution of relative dose for every system or source scenario investigated, allowing the authors to determine the mean impact as well as its variation. This procedure was done for each of three source distributions: 1) occupants as the only source, 2) source localized to kitchen and bathrooms, and 3) source uniformly spread throughout the dwelling in a volume-weighted manner. These three source-distribution patterns were chosen to capture the vast majority of likely distribution patterns in a residence.

The simulations were done with a range of mixing to see what impact mixing had on relative dose. A typical figure is shown below:

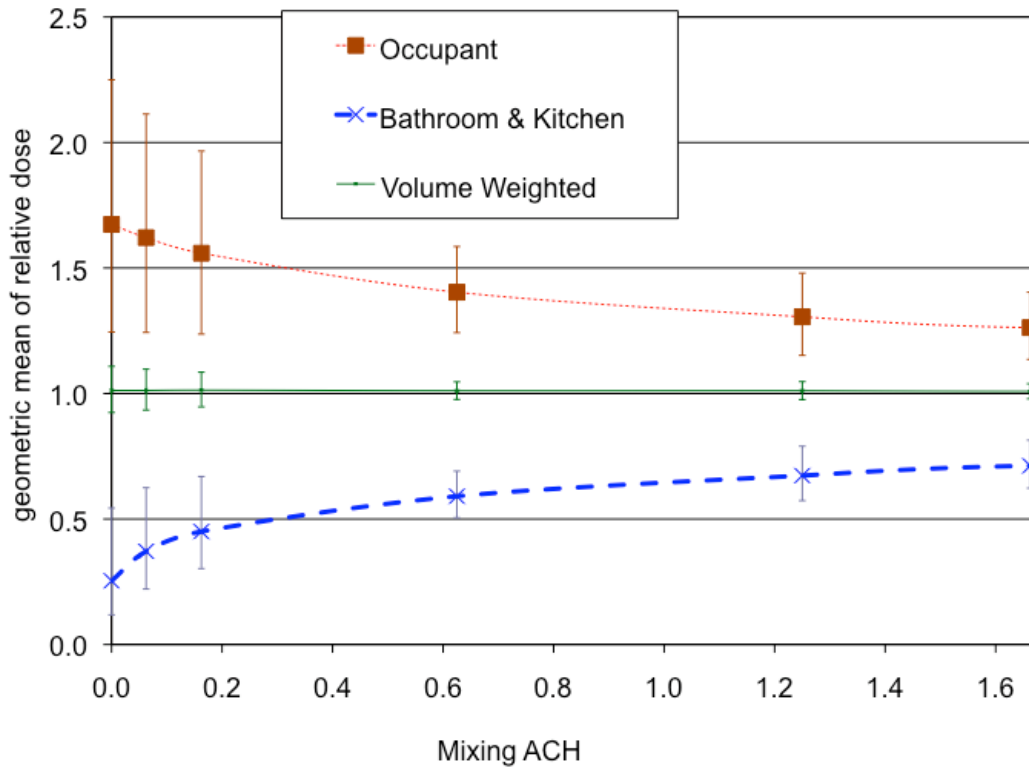


Figure 1. Mixing effects on relative dose for three pollutant source-distribution patterns using a single-point exhaust ventilation system with closed doors (from Petithuguenin and Sherman 2009)

The mixing is expressed in terms of air changes per hour (ACH) determined by taking the total airflow through the central forced-air system over an hour and dividing by the total house volume. The points and bars represent the geometric¹ mean (of the relative dose of the configurations at the same mixing ACH) and standard deviation of the relative dose for each of the three source-distribution patterns for a single-point exhaust system. The deviation is due to differences in results caused by occupancy pattern changes and house geometry (1, 2, and 3 story). The behavior of the means varies substantially with the source-distribution pattern: when the source is carried by the occupants, doses are high, and mixing reduces the relative dose; when the sources are in rooms not commonly frequented by the occupants (in this case bathrooms and kitchens), doses are low, and mixing increases relative dose. When the source is uniformly spread throughout the dwelling, additional mixing does not change the relative dose. The standard deviations tend to decrease with increased mixing because the mixing removes extremes of both high and low concentrations and therefore dose.

The results above assume closed doors and the use of a central forced-air system to provide the mixing. Repeating the simulations with open doors and small temperature

¹ The geometric mean is the appropriate statistic for ratios such as the ones we are considering because they are positive definite and expected to be distributed log normally.

differences between zones results in substantial mixing. Open doors are equivalent to about 2 ACH of mixing in this analysis.

The single-point exhaust systems generally performed slightly better than or equivalent to distributed supply systems. The improvement is because, when a source is in a zone with an operating exhaust fan, the exhaust fan has high pollutant removal effectiveness, which lowers pollutant concentrations in the rest of the house. For example, an occupant in the bathroom running an exhaust fan will remove whole-house pollutants directly. This will not just lower that occupant's exposure (compared to a supply system), but it will lower that of the other occupants. A central supply system, in contrast, transports the pollutants to the rest of the house and mixes them rather than exhausting them directly. Comparing the single-point exhaust to distributed supply showed that, for a single-point exhaust, the forced-air infiltration throughout the envelope (which travels throughout the house to the exhaust fan) creates mixing that is roughly equivalent to operation of a central forced-air system at a rate of 0.2 ACH.

The report also studied whether the metrics previously proposed produced the right trends and values for the cases studied. Some of the metrics were much more extreme than the cases simulated, but some followed the general trends and thus were reasonable for those cases. The report proposed new, more complicated, metrics that better matched the cases simulated.

COMPARISONS OF MIXING STUDIES

Although the three studies above are all trying to address the problem of mixing, they differ in definitions and assumptions. We evaluate those differences:

Relative Dose vs. System Coefficient

Although relative dose and system coefficients metrics are similar, they differ in important ways related to the reference cases they each use and how each is applied. Relative dose uses a reference case in which only the single factor under investigation (i.e., the mixing system) is varied while all else is held constant. This allows a good physical understanding of the process involved. Because relative dose holds most non-mixing related properties constant, it is reasonably insensitive to air leakage, climate, or a variety of other factors.

The system coefficient is designed to be directly applied to the mechanical ventilation rate to achieve the same exposure as the reference case. This is, in one sense, a more practical value because it can be directly applied to system design to achieve the desired end result, but it is problematic when one is trying to understand the individual contributions of mixing vs. other parameters because the system coefficient is very sensitive to the actual value of relevant quantities like air tightness, climate, duct leakage, and other quantities that might be different in the real house vs. the reference house.

Occupant Activity Patterns

The three studies' approaches make different assumptions about occupant activity patterns. In the metric-based approaches (i.e., the ones based on prototypical flow rates), occupant activity patterns are not part of the analysis but are part of the choice of metric and therefore exogenously determined. Each metric makes a different assumption about occupant patterns, and it is up to the user of the metrics to find the appropriate one for a given application.

The Townsend approach used four very specific, correlated occupant patterns for one specific house configuration and chose the highest-exposure occupant pattern as representative. This builds in a specific choice of occupant profile. Unlike the metric-based approaches, however, it offers no alternative choices to compare to.

The Petithuguenin approach used a distribution of house configurations and occupant profiles rather than selecting a single pattern, and generates a distribution of results. This distribution reasonably overlapped the results of the other approaches, indicating that results can be very sensitive to the choice of specific parameters. A distribution approach allows one to understand what happens in the mean ranges of possible outcomes. Without the distribution, the results can be true for the specific case studied but might not be true in general, which would lead to erroneous conclusions.

Source Distribution

The handling of source distribution is very similar to the handling of occupant activity in that the Sherman and Walker and Townsend approaches utilize individual specific source distributions, and the Petithuguenin approach looks at three distribution patterns separately as shown in Figure 1. The Townsend approach uses a single source emission that is an equal mix of the three patterns.

Local Exhaust Assumptions

Local exhaust is common in wet rooms such as kitchens and bathrooms, and it is required in many codes and standards. Use of local exhaust affects the exposure to pollutants generated by short-term occupant activities in those spaces. Any pollutants left behind by occupant activities (e.g., cleaning products) and arising from storage of chemicals (e.g., detergents and other cleaning products) are also exhausted, leading to reduced exposure. Because we assume that pollutant sources that contribute to the need for whole-house ventilation may be concentrated in those spaces for at least part of the time, acceptable IAQ will be sensitive to how these systems are operated. Use of local exhaust increases average whole-house ventilation rates and thus contributes to reduced pollutant exposure in other rooms that do not have local exhaust.

The field measurements in the Walker and Sherman study did not involve any local exhaust operation. Petithuguenin's study follows the intent of ASHRAE Standard 62.2 that exhaust fans will operate when someone is in spaces that have local exhaust. The Townsend study does not have the exhaust fans operate when people are in those spaces but instead has the fans scheduled to operate for a much more limited time. This assumption is critical for evaluating the impacts of mixing when pollutant sources are occupant-based or kitchen- and bath-based.

Open Doors

Open doors can supply substantial mixing because very small temperature differences alone can induce significant and usually two-way flow through large open areas. Thus, when evaluating impacts of mixing, it is important to include not just mechanically induced mixing but also naturally induced mixing from open doors.

Petithuguenin's simulations and Sherman and Walker's tracer gas measurements examined open- and closed-door configurations separately. As expected, open doors provided substantial mixing. Mixing resulting from airflow through open doors has been observed in measurements by other researchers: Weber and Kearney (1980), Kiel and

Wilson (1986) and Blomqvist and Sandberg (1996) as well as in analyses by Walton (1984) and Allard and Utsumi (1992). The mixing effect of open doors is tempered by the fact that doors may also be closed for extensive periods, e.g., bedroom doors at night, so not all of the possible open-door mixing benefit is available at all times.

In Townsend's simulations, doors were open and closed on a schedule. However, the simulation program was modified to reduce the open-door flow rate to better fit concentration data in some houses. Because simulation programs use open-door flow rates that are well supported by measurements in several studies (referenced above), the Townsend modification has the effect of underestimating the mixing resulting from open doors and perhaps overestimating the mixing resulting from other causes.

Infiltration and Air Leakage

The interaction of air leakage and climate leads to infiltration, and infiltration induces mixing from zone to zone (either horizontally from wind effects or vertically from stack effects). This mixing can be observed strongly in multi-zone tracer measurements and to some degree in Townsend's simulations by comparing tight and leaky configurations. Infiltration has two effects. First, infiltration airflows increase dilution of pollutants. Second, the mixing from infiltration makes pollutant concentrations more uniform throughout the building.

DISCUSSION

After examining the three studies summarized above, we identified the following issues that need further consideration: trends in mean relative dose and the variability in dose resulting from mixing with a central forced-air system, identification and estimation of the magnitude of all sources of mixing, and identification of the differences between balanced and unbalanced mechanical ventilation systems. We addressed these three issues by reanalyzing the data from the Petithugenin study.

Examining Trends in Mean Relative Dose with Additional Mixing

Because residential buildings have a broad range of pollutant sources and are highly diverse with respect to layout and occupancy patterns, we have to consider multiple pollutant sources and occupancy patterns if we are to conclusions suitable for use in codes, standards, policies, and ventilation system designs. The Petithugenin study exercised the appropriate variables over reasonable ranges. Linking the Petithugenin data across house type, occupancy pattern, and pollutant sources yields the results shown in Figure 2 (for closed interior doors).

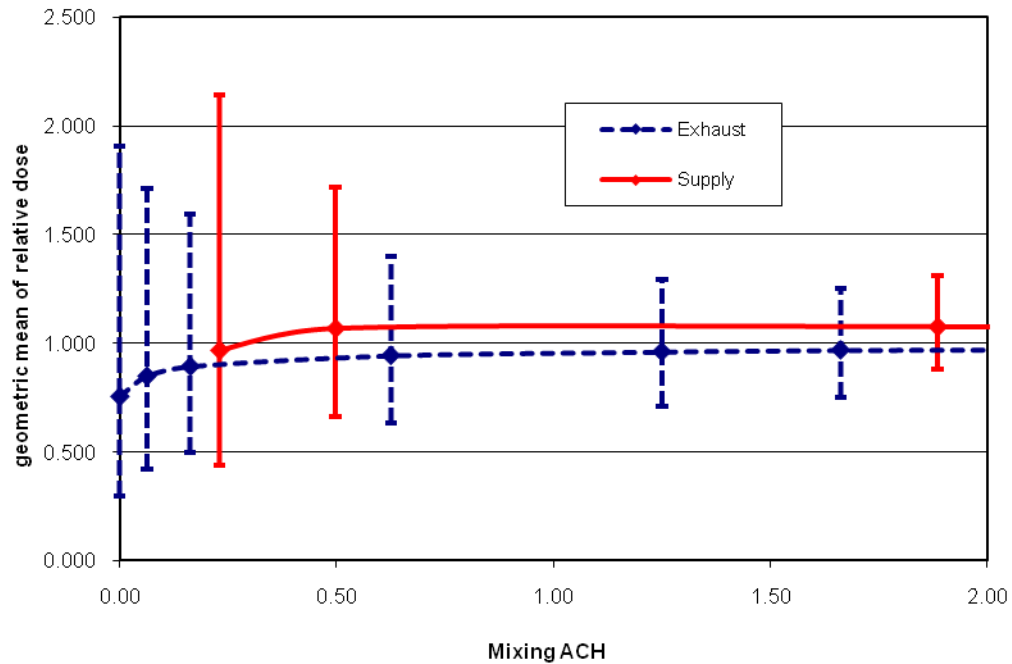


Figure 2. Dependence of geometric mean and variability of relative dose on mixing rates for a point exhaust and distributed supply ventilation system with closed doors.

Figure 2 displays the distribution of relative dose as a function of the amount of central forced-air-induced mixing, assuming the home's internal doors are closed. The dashed line is for a single-point exhaust system (normally located in the master bathroom); the solid line is for a central-fan integrated supply system. The error bars represent the standard deviation of the more than 100 combinations of house type, and occupancy patterns for each of the three source distributions.

The trend for both systems is that, at low mixing rates, the mean values are below unity, but they trend upward toward near-unity as an asymptote at higher mixing rates. This indicates that mixing, on average, is not beneficial. In fact, mixing, on average, can reduce air quality. This effect is likely attributable to the fact that, on average, there tend to be more pollutant sources in zones with local exhaust systems. Without mixing, more of those pollutants are exhausted directly when the local exhaust operates; with mixing, some of those pollutants are redistributed to other zones rather than exhausted.

On average, whole-house exhaust is slightly better than whole-house supply. This is for the same reason as above: the whole-house exhaust comes from a zone that has higher-than-average pollutant concentration. This increases the system's effectiveness in removing pollutants from the home, resulting in lower occupant dose.

This result might seem counter-intuitive because it seems reasonable that supplying clean air should provide better indoor air quality. If the air were supplied only to zones that were occupied, that would be true. The key issue is not supplying outdoor air (i.e., to meet oxygen needs), but rather diluting pollutants from indoor sources so that occupant exposures are minimized. Thus, exhausting above-average concentrations of pollutants

will improve IAQ, and exhaust systems have a better opportunity to do that than supply systems.

Some of these results might seem to disagree with Townsend's results, but a careful review shows that the differences can be explained. There are a few systematic differences, for example that the Townsend simulation reduces the impact of open doors in the simulation and does not use local exhaust fans when occupants are scheduled to be in the kitchens or bathrooms. This latter assumption is quite important in view of the results discussed above. The Townsend study results do not distinguish among several factors that appear to be conflated with mixing one of the most important examples of this is the inclusion of air leakage and the interactions between mechanical ventilation and natural infiltration. Townsend's use of a system coefficient based on a fixed air leakage means that a balanced system will generally have a lower system coefficient, not because of mixing but because balanced systems interact differently with infiltration than unbalanced systems and have higher overall ventilation rates.

As Townsend (2009a) reports, the simulation approach is quite sensitive to details such as enclosure leakage distribution and must be calibrated for results to be robust. The simulation results quoted here (Townsend 2009b) were not calibrated and therefore could be expected to have the systematic errors cited in Townsend (2009a). However, perhaps a larger discrepancy results from the narrow focus of the Townsend simulations on a single house and occupant configuration and on the worst-case result; by contrast, the Petithuguenin study takes a more general approach that is applicable to more homes, based on mean values and standard deviations over a broad range of house and occupant configurations.

Reducing Variability of Dose using Mixing

If we were only interested in an average or typical situation, mean values would tell us what we need to know: overall, mixing is slightly detrimental, and exhaust is slightly better than supply. But there is more information in the distribution than just the mean values. It is important to look at what mixing can do to the shape of the distribution and specifically to the high exposure tails.

At the lowest mixing values, one can see that the standard deviation is quite large. One standard deviation changes the relative dose by a factor of more than two. This indicates that even though the average might be below unity, the relative dose is greater than two in a substantial number of situations where occupants are experiencing poor air quality.

Mixing helps reduce the variability. As mixing increases, the standard deviation goes down and approaches a limit of about 25% at higher mixing rates. Most of the improvement happens at relatively low mixing rates. Some amount of mixing could, therefore, be profitably used to reduce the tail of the distribution and minimize the frequency of high relative doses.

The upper standard deviation could be kept to a reasonable limit of 1.5 with a moderate amount of mixing. For single-point exhaust systems, this is roughly a mixing rate of 0.2-0.3 ACH; for central-fan integrated supply systems, this would be a mixing rate of about 0.5-0.7 ACH.

We speculate that the difference between these values is mostly due to the difference between single-point and fully ducted systems. The former are applied here to exhaust and the latter to the supply. A single-point exhaust system requires that air move from

leakage sites around the envelope to a central exhaust. This acts like mixing because it requires that air move from zone to zone. The same would be true of a single-point supply system, as air flowed from a central point to exfiltration sites. Thus, all else being equal, a single-point system has less variation than a fully ducted system.

This result also seems counter-intuitive. To see how it arises, consider the fully ducted case for a zone that has no (or a below-average number of) sources in it. Ventilation air will be delivered there and then exhausted without being mixed with any other zone. Thus the ventilation air will not participate as much in diluting pollutants. If the system were single point, the air would have to transit through multiple zones and would have more opportunities to dilute pollutants before being exhausted. Presumably, this effective mixing would also take place in balanced systems where the exhausts were in different zones from the supplies so that air would need to mix throughout the house.

This result would not be true for all air leakage distributions. Both Townsend and Petithuguenin distributed air leakage evenly around the envelope. Had the air leakage been concentrated, leaving some zones completely sealed, the result would have been different. In typical homes, there will almost always be diffuse leakage, but in tighter new homes, the leakage might be small enough that the likelihood of it being concentrated is large, so we should not necessarily rely on this effect. A system commonly used in Europe is to have central exhaust with designed air inlets in the habitable rooms; such a system would mean we would not have to worry about concentrated leakage, and a lower range of mixing could be required to keep the upper standard deviation below a set limit.

Sources of Mixing

The variability analysis suggests that, despite the detrimental effect of mixing on average, a modicum of mixing might be a good idea to reduce the high exposure tail. In establishing ventilation standards such as ASHRAE Standard 62.2, there is a preference for the simplicity of having a single value. Half an air change of mixing seems to be a reasonable value to keep extreme events from being problematic. .. However, because the physical factors listed below induce or are equivalent to mixing, there will be significant periods of the year when no additional mechanical mixing will be needed:

- *Single-point systems:* As shown above, single-point systems can contribute to mixing roughly at the typical size of their flow rate unless the envelope is too tight.
- *Central forced-air systems:* When any central forced-air system operates, it provides mixing. Typical forced-air systems provide about 6 ACH if operated continuously. Therefore, operating for about 5 minutes out of each hour would supply the 0.5 ACH required to provide reasonable control over the upper limit for dose (mean plus one standard deviation)
- *Infiltration:* As shown by both simulation and measurement, infiltration has the same effect as mixing. The effect is highly variable depending on total envelope leakage, leakage distribution, and weather.
- *Open doors:* Fully open doors have the same effect as mixing (approximately 2 ACH), but doors are not open all time and thus are not always a reliable mixing mechanism.

The above factors combined mean that there will be substantial fractions of the year for which no additional mechanical mixing is needed. In some situations, however, it could be important to provide extra mechanical mixing above and beyond these factors. One situation would be for a tight home having zone space conditioning (i.e., no central

forced-air system). In this case there is a combination of no central system, little infiltration, and doors that will tend to be closed because of the zone space conditioning. One solution for this example would be to use a fully ducted supply system that blended the ventilation air 3:1 or 4:1 with indoor air. This blending would both temper the ventilation air and provide the necessary mixing.

A similar situation would arise in a tight home with a central forced-air system if it were well insulated and used a fully ducted supply ventilation system. An additional option in this instance would be to operate the central forced-air system for a few minutes each hour (independent of the need for heating or cooling) to meet minimum mixing requirements.

Balanced vs. Unbalanced Ventilation Systems

The Townsend study was the only one of the three studies reviewed above that investigated the differences between balanced and unbalanced systems. In general, Townsend found that the calculated system coefficients were higher for unbalanced systems. This trend is expected because the total ventilation rate is higher for a balanced system than an unbalanced system when it interacts with envelope air leakage. The *ASHRAE Handbook of fundamentals* (ASHRAE 2009), Sherman (1992), and Wilson and Walker (1990) describe this superposition effect in more detail. The differences found by Townsend are roughly in the range one would estimate from this interaction. Petithuguenin did not examine the difference between these two systems because the primary impact—the rate effect—would be normalized out of the relative dose values.

Although the difference between balanced and unbalanced ventilation systems is quite real and should be considered in the overall design of a ventilation system (or a ventilation standard), it is not primarily an air distribution or mixing issue. The way in which a balanced system is implemented might, however, impact mixing. For example, a balanced system that had a supply and return in every zone would be fully ducted and would not provide any additional mixing, but a balanced system that supplied or exhausted (but not both) from every zone would provide extra mixing.

CONCLUSIONS

The fundamental conclusion of this work is that increasing the mixing of air in most homes will not substantially affect the mean indoor air quality across a broad population of occupants, homes, and ventilation systems, but it can reduce the number of occupants who are exposed to extreme pollutant levels. If the policy objective is to minimize the number of people exposed above some pollutant threshold, then the fact that mixing might raise the exposure of those people whose exposures are substantially below the threshold is unimportant. In other words, some amount of mixing will be of net benefit even though it does not benefit average exposure. If the policy is to minimize exposure on average, then mixing air in homes is detrimental and should not be encouraged.

Our analysis for whole-house ventilation flow rates typical of ASHRAE Standard 62.2 suggests that a mixing rate of approximately one-half of an ACH captures the vast majority of benefit that mixing can provide. One way to think of the mixing rate is as the total air change rate of each zone exchanged with outside or any inside zone. This mixing rate requirement is typically met in European or Asian homes that do not have central forced-air systems because of the higher outdoor air exchange rates that are used (typically 0.5 ACH compared to the 0.15 to 0.2 ACH used in U.S. systems).

One should not infer, however, that *additional* mixing is typically necessary or beneficial in American homes intending to meet ASHRAE 62.2. In most homes, the combination of open doors, infiltration, a central forced-air system, and exhaust fans all operating intermittently and independently will provide sufficient mixing. In some cases, however, for example houses with very little infiltration and no (or small) central forced-air systems, extra mixing or increased outdoor ventilation might be necessary.

Other interesting conclusions can be drawn from our study. Ventilation systems that induce flow between zones (such as single-point exhaust or supply, or a balanced system where the exhaust and supplies are indifferent spaces) induce some mixing, which can be more than if ventilation air was ducted to each zone. That is why much of the mixing we recommend can be provided by systems such as a single-point exhaust with air inlets, as is often used in Europe.

Finally, well-designed exhaust systems (or exhaust parts of balanced systems) can improve IAQ. When continuous exhaust is provided from spaces that normally have higher-than-average pollutant loads (e.g., kitchens, laundry rooms, bathrooms), the relative dose for occupants is reduced overall. This suggests that some differentiations should be made for such systems in setting policy or writing standards.

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