Does Mixing Make Residential Ventilation More Effective?

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ABSTRACT

Ventilation dilutes or removes indoor contaminants to reduce occupant exposure. In a multi-zone environment such as a house, there will be different dilution rates and different source strengths in every zone. The total ventilation rate is the most important factor in determining the exposure of occupants to given sources, but the zone- specific distribution of exhaust and supply air, and the mixing of ventilation air can have significant roles. Different types of ventilation systems will provide different amounts of mixing depending on several factors such as air leakage through the building envelope, air distribution systems and the location of sources and occupants. This paper reports recent results of investigations to determine the impact that air mixing has on exposures of residential occupants to prototypical contaminants of concern. Evaluations of existing field measurements and simulations reported in the literature are combined with new analyses to provide an integrated overview of the topic. The results show that for extreme cases additional mixing can be a significant factor but for typical homes looking at average exposures mixing is not helpful and can even make exposures worse.

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, 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 with each other. They generally vary 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 the context of Standard 62.2 and this paper, mixing refers to room-to-room flows within a house and not mixing within a room. In residential situations the combination of natural convection from appliances, people and other heat sources, together with temperature differences due to indoor-outdoor temperature differences leads to significant mixing within rooms and localized variation of pollutant concentrations is not an issue. The sources of room-to-room mixing are: forced convection by mechanical ventilation systems (both distributed and local supply or exhaust), air flows due to natural infiltration, convection through open doors and central forced air heating and cooling systems.

The room-to-room mixing assumed 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 paper, we ask the question of whether mixing helps or hurts (and by how much) by reviewing recent work and extending 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.

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 and Walker (2008) found exposure levels at different locations 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; they concluded that such simulations models only worked well when they were well calibrated 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.

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. Balanced flows, such as those from an air-to-air heat exchanger interact with envelope leakage to provide a higher total ventilation rate than, for example, a continuously operating exhaust fan does. There are also ventilation system effects on room-to-room air flows depending on if the exhaust and supply air flows are localized (e.g., in a bathroom) or distributed (e.g., supply grilles in all rooms).

Approach

Our approach focuses on isolating the benefits of mixing from these other impacts of balanced vs. unbalanced, the distribution of contaminants and variation of occupancy patterns in different house configurations. We combine a summary of existing literature with an extended analyses of additional simulations and different 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 the reference case of a perfectly mixed, but otherwise identical situation—thus making the reference be the single-zone version of the multizone situation. The dose itself is the time integration of the concentration of a generic contaminant over the period of interest.

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

A detailed individual review of this literature is beyond the scope of this paper to document, but the discussion below summarizes the key issues of concern. For more details on this issue see Sherman and Walker (2010).

Comparisons of Mixing Studies

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

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. This allows a good physical understanding of the process involved. Because relative dose holds non-mixing related properties constant, it is reasonably insensitive to air leakage, climate, or a variety of other factors. That is, the main effect of air leakage is to increase the total ventilation rate and thus lower contaminants. This is a very real effect, but not the one we are investigating. The relative dose approach cancels out any *rate* effects leaving the mixing-related effects to the fore.

The system coefficient, as used only in the Townsend approach, 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 air flows 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 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 which occupants move from room to room or are absent from the house entirely. Example occupancy patterns account for differences in lifestyles. Three classic examples are: a retired couple who spend almost all their time at home and do all their own cooking and spend a lot of time in the bedrooms and common areas, a family of four with an adult and child who are home all day spending most time in common areas and an adult and child who are absent for 8/9 hours per day, and a single occupant who rarely cooks at home and spends most time in the bedroom sleeping. The overall exposure to pollutants is the aggregate from the convolution of room varying pollutant emissions and whether or not occupants are present. The occupants also interact with pollutant emissions – the occupancy generated emissions are carried from room to room by occupants, whereas uniform emissions or room specific emissions do not. The Townsend approach used four very specific, correlated occupant patterns for one specific house and chose the highest-exposure occupant pattern to determine the system coefficient.

Source Distribution

Three key source distributions are used to capture the majority of likely scenarios. They are *1. Occupant sources.* These are sources carried around by occupants. An example would be CO2 emissions. *2. Background sources.* These are emitted by building materials that are evenly distributed throughout the house, such as carpet. *3. Localized sources* that occur in specific rooms (e.g., moisture generation and storage of cleaning products in kitchens and bathrooms). Sherman and Walker examined individual specific source distributions, and the Petithuguenin approach looks at three distribution patterns separately. The Townsend approach uses a single distribution 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. None of these studies actually had an intermittent source and a related local exhaust schedule. Each study made a simplifying assumption to deal with it.

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. The local exhaust will tend to remove air with a higher concentration of pollutants emitted in the rooms with local exhaust – this leading to lower overall concentrations and reduced relative dose for these pollutants. Use of local exhaust can increase average whole-house ventilation rates and thus contribute to reduced pollutant exposure in other rooms that do not have local exhaust.

Open Doors

Open doors can supply substantial mixing because very small pressure differences (such as those resulting from small room-to-room temperature differences on the order of 1°C, or less) can induce significant (the same magnitude as whole-house ventilation air flow rates or individual room flows from central forced air systems) flow through large openings (as shown in many previous studies, e.g., Weber and Kearney (1980)). In vertical openings, such as doors, this can be two-way flow. The results of Petithuguenin and Sherman showed that open doors were equivalent to about 2 Air Changes per Hour [ACH] of mixing. 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. 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.

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 was observed in the multi-zone tracer measurements of Sherman and Walker (2009) 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, infiltration induced room-to-room air flows result in significant mixing. Mixing can move contaminants from pollutant zones to un-pollutated zones, but the air flows associated with infiltration are generally smaller than those associated with mechanical mixing.

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.

Discussion

Examining Trends in Mean Relative Dose with Additional Mixing

Additional mixing was supplied in the simulations by operating a central forced air system fan at various air flow rates. The air flows are converted into air changes per hour by dividing the volume of air moved in an hour by the volume of the home. At each additional mixing air flow rate the results from all the simulations (following Petithuguenin we used combinations of two different ventilation systems, three house configurations, three occupancy profiles and three emission profiles at five different mixing rates) were combined and their geometric means [1]and standard deviations for relative dose were calculated. The results are summarized in Figure 1.

The trend for both supply and exhaust systems is that at low mixing rates the mean values of relative dose are below unity and these approach unity at higher mixing rates with the supply systems seeming to average just above unity. This indicates that mixing, on average, is not beneficial. In fact, mixing, on average, can reduce air quality. This effect is 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.

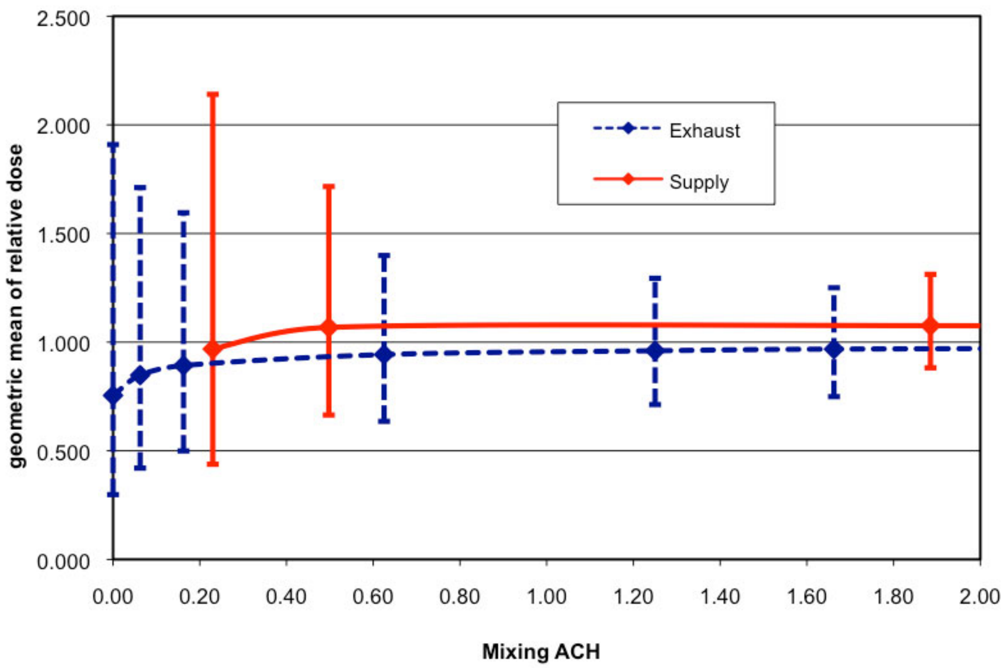
As expected the distribution appears to be skewed high, but is not substantially skewed. That is, a factor of two above the mean and a factor of two below the mean are equally likely. And indeed we saw some very high ratios (e.g. 5) and very low ratios (.2).

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.

[1] The geometric mean was used because relative dose is a positive-definite ratio and therefore is expected to follow log-normal statistics.

Figure 1. Dependence of Geometric Mean and Variability of Relative Dose on Mixing Rates for a Point Exhaust and Distributed Supply Ventilation System with Closed Doors



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 of relative dose 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.

Suggested Mixing Requirement to Limit High Exposures

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 leakage is too localized. This is equivalent to about one quarter of an ACH or about half of the suggested mixing.
- *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 on average would supply the 0.5 ACH required.
- *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; and consequently it is not reliable.
- *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 no central forced air system – either because forced air is not used or the system is individually zoned for each room. 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.

Conclusions

The question posed in this paper is whether mixing improves residential ventilation. In most North American homes the simple answer is "No:" Increasing mixing will not substantially affect the mean indoor air quality across a broad population of occupants, homes, and ventilation systems. However, mixing can reduce 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, for example, energy efficient houses with very little infiltration or no (or small) central forced-air systems, extra mixing or increased outdoor ventilation might be helpful.

Ventilation systems that induce flow between zones (such as single-point local exhaust or supply (rather than a distributed system with supplies or exhausts from multiple rooms), or a balanced system where the exhaust and supplies are in different spaces) induce some mixing, which can be more than if ventilation air was ducted to each room. 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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