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Measured Air Distribution Effectiveness for Residential Mechanical Ventilation Systems

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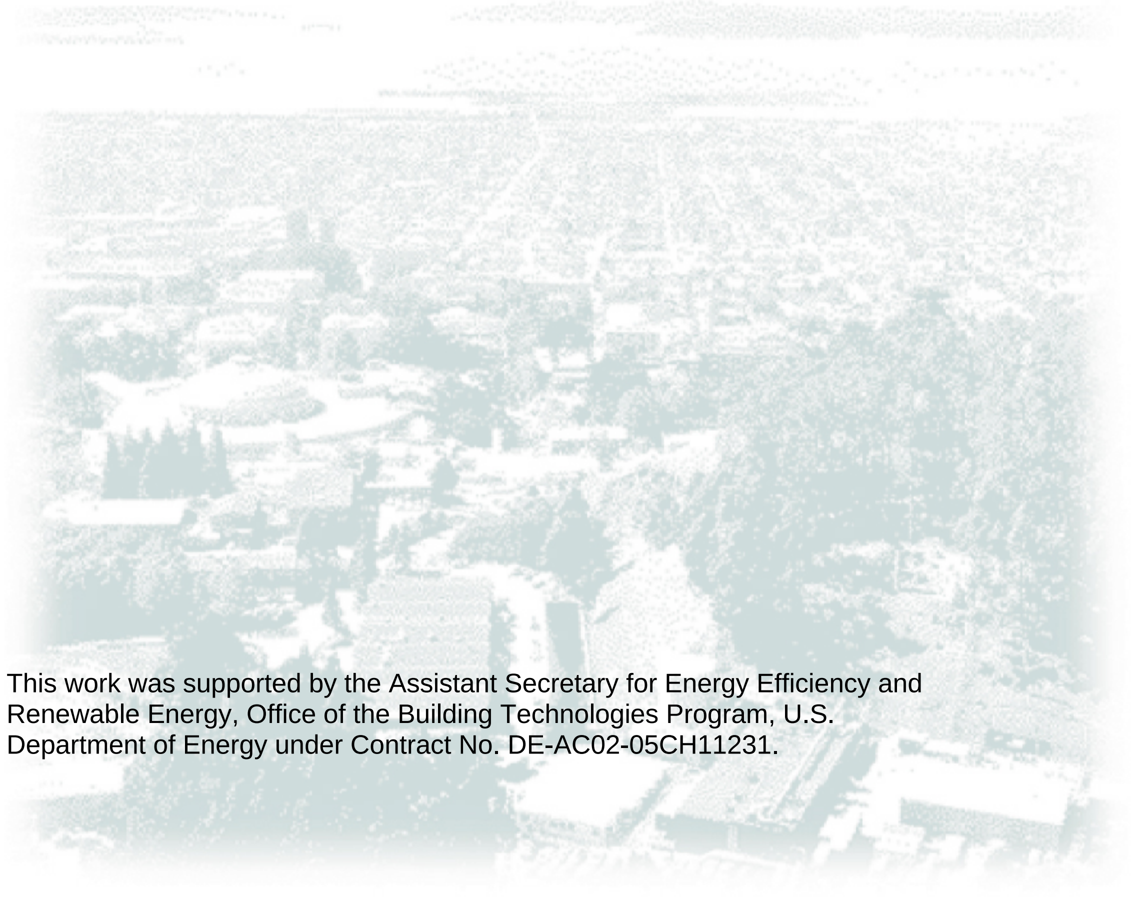

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ABSTRACT

The purpose of ventilation is dilute or remove indoor contaminants that an occupant is exposed to. In a multi-zone environment such as a house, there will be different dilution rates and different source strengths in every zone. Most US homes have central HVAC systems, which tend to mix the air thus the indoor conditions between zones. Different types of ventilation systems will provide different amounts of exposure depending on the effectiveness of their air distribution systems and the location of sources and occupants. This paper will report on field measurements using a unique multi-tracer measurement system that has the capacity to measure not only the flow of outdoor air to each zone, but zone-to-zone transport. The paper will derive seven different metrics for the evaluation of air distribution. Measured data from two homes with different levels of natural infiltration will be used to evaluate these metrics for three different ASHRAE Standard 62.2 compliant ventilation systems. Such information can be used to determine the effectiveness of different systems so that appropriate adjustments can be made in residential ventilation standards such as ASHRAE Standard 62.2.

Keywords: Air Distribution, Mechanical Ventilation, Ventilation Effectiveness, Residential Ventilation

INTRODUCTION

Ventilation, and thus the transport of contaminants and clean air, is becoming an ever more important issue as we strive to both improve energy efficiency of buildings and the indoor air quality (IAQ) within buildings. Air motion is a complex interaction of naturally and mechanically induced pressures interacting with a wide variety of air flow paths between inside and outside and from zone to zone within the building.

Because geometric details of the pathways and the magnitude, direction and space/time variability of driving pressures are difficult to determine precisely, it can be challenging to determine the quality and quantity of airflow in all but the simplest and most controlled building environments. If the entire building were very well mixed and acted like a simple single zone, extant techniques would make this determination straightforward. Buildings, however, are rarely so compliant. In fact we often wish to measure, and even sometimes use departures from, the simple situation to examine impacts of ventilation efficiency, air distribution, contaminant removal effectiveness and heat and mass exchange. When it is necessary to know how air and its constituents propagate, one must measure the air exchange using multizone tracer gas techniques that divide the building into a set of well-mixed zones.

The effectiveness of a given mechanical ventilation system will depend on air flows between each zone as well as flows to and from outside. Since it is occupant's exposure to contaminants that we are ultimately interested in, it will also depend on the distribution of those contaminants and the activity pattern of the occupants in the building.

This paper will examine different air distribution paradigms, develop some prototype air distribution metrics and apply them to two case studies done with our MultiTracer Measurement System (Sherman 1990c), which is now in its second generation (MTMS II).

TRACER GAS BACKGROUND

Tracer gas tests are used for a wide variety of diagnostic tests. Harrje et al. (1985) has reviewed many of these approaches. Their most common use in building science is to determine air flows under field conditions to support ventilation and pollutant transport work such as those described by Lagus and Persily (1985). McWilliams (2003) has more recently reviewed airflow measurement methods. The Air Infiltration and Ventilation Center (http://www.aivc.org) has a variety of technical publications relating to tracer gas applications.

When using tracer gasses to quantitatively estimate air flows the concept of a “well-mixed zone” is important. Just as exposure to an air pollutant depends on knowing the concentration of that pollutant in the occupied zone, accurate estimation of air flow depends on knowing the concentration of tracer gas.

The theory and practice of using a tracer gas in a single-zone has been well developed. In addition to the references above Sherman (1990a and 1989a) has reviewed the basic techniques and analyzed the associated errors of using those techniques. ASTM (2000) has had a standard test method for making this measurement for many years.

More complex buildings or more complex air flow patterns require breaking the indoor space into multiple well-mixed zones. Multizone techniques analogous to the single-zone techniques have been developed including those discussed by Roulet et al. (1989).

The most straight-forward generalization to the multizone situation requires that multiple, unique tracer gasses be used (i.e., one for each zone). These techniques allow the full range of analysis options and provide the most robust estimates of air flow. Sherman (1990b) describes such a system. Walker (1985) reviews some issues of various approaches. Sherman (1989b) looks at some of the analysis limitations based on inverse problem theory such as that presented by Tarantola (1987).

DISTRIBUTION METRIC DEVELOPMENT

In order to understand the value of air distribution in the control of indoor contaminants we need to develop appropriate metrics. The metrics developed in this study are based on analyses using the multizone continuity equation (Equation 1).

$$\underset{\leftrightarrow}{\mathbf{V}} \bullet \underset{\leftarrow}{\dot{\mathbf{C}}} + \underset{\leftrightarrow}{\mathbf{Q}} \bullet \underset{\leftarrow}{\mathbf{C}} = \underset{\leftarrow}{\mathbf{S}} \tag{1}$$

where $\underset{\leftrightarrow}{\mathbf{V}}$ is a matrix containing the volume of each zone, [m^3]

$\underset{\leftarrow}{\dot{\mathbf{C}}}$ is the vector of the rate of change of concentration of each pollutant, [-]

$\underset{\leftrightarrow}{\mathbf{Q}}$ is the matrix of volumetric air flow rates [m^3/s]

$\underset{\leftarrow}{\mathbf{C}}$ is the concentration(vector) in each zone [-] and

$\underset{\leftarrow}{\mathbf{S}}$ is the source strength (vector)in each zone[m^3/s].

The air flow rates depend on both natural and mechanical ventilation. The source strengths vary from room to room. For example, kitchens and bathrooms tend to have strong sources from cooking, bathing and washing that occur in relatively short time frames (typically an hour or less). Conversely, in bedrooms the strongest source tends to be the occupants themselves and they emit for several hours at a time.

IAQ from the point of view of ventilation standards (e.g., ASHRAE Standard 62.2 (ASHRAE 2007)) is usually defined in terms of the total dose of some generic pollutant over a long period of time. That is, ventilation rates are not set to protect against acute (or threshold) pollutants. Accordingly, only the steady state part of the solution to the continuity equation is of interest. This implies that the concentration of the generic pollutant can be calculated for each zone using Equation 2:

$$\underset{\leftarrow}{\mathbf{C}} = \underset{\leftrightarrow}{\mathbf{Q}}^{-1} \bullet \underset{\leftarrow}{\mathbf{S}} \tag{2}$$

If the building was treated as a single zone would lead to the similar scalar Equation 3.

$$C_o = \frac{S_o}{Q_o} \tag{3}$$

Where C_o is the equivalent single zone concentration [-] and correspondingly
S_o is the sum of all the entries in the source vector [m^3/s] and
Q_o is the sum of all the entries in the air flow matrix for the whole building [m^3/s]

These scalar quantities can also be used to normalize the matrix expression.

The dose of contaminates that an occupant would be exposed to would be the concentration of the contaminants in the zone they were in times the number of hours they were in that zone. We are seeking, however, to define metrics associated with the distribution system rather than the contaminant source or the total ventilation rate. Therefore, we will develop our metrics based on a relative dose that has taken out the total ventilation rate, the total exposure time and the total contaminant emission, leaving the issues associated with air distribution.

Relative Exposure and Relative Dose

Our objective is to investigate impacts of ventilation (and source) patterns that are not uniform in space (or time) and comparing them to the perfectly-mixed constant-ventilation case. We make that comparison based on the contaminant dose that an occupant would experience compared to that they would experience in the reference case of perfectly-mixed, constant ventilation..

The relative exposure is defined as the instantaneous contaminant exposure divided by the contaminant concentration that would have resulted from the reference case:

$$\underleftarrow{\mathbf{R}} = \underleftarrow{\mathbf{C}} / C_o = \underleftarrow{\mathbf{C}} Q_o / S_o \qquad \textbf{(4)}$$

Where **R** is the relative exposure (vector) [-].

The relative exposure values are an instantaneous and local measure of how contaminated a zone is compared to the perfectly-mixed, steady-state reference. For example, a value of 2 means that the concentration in that place at that time is twice what it would be if the entire set of spaces were in equilibrium. The *relative* exposure (and relative dose) are independent of the magnitude of the sources and air exchange rates, but can be used to quantify the impacts of the spatial[1] variations intrinsic to a multizone space.

For the purposes of evaluating dilution ventilation we are not generally concerned about instantaneous exposures (or non-linear dose-response relationships). Rather we can use the total dose received by the occupants to a particular contaminant to quantify the effectiveness of the ventilation system. The *relative dose* is the integrated concentration that an occupant is exposed to divided by what they would have been exposed to in the perfectly-mixed, equilibrium case:

$$d = \frac{\int \underrightarrow{\mathbf{a}} \bullet \underleftarrow{\mathbf{C}} \, dt}{\int C_o \, dt} \qquad \textbf{(5)}$$

Where d is the relative dose [-],

$\underrightarrow{\mathbf{a}}$ is the activity (vector) normalized to sum to unity [-]

The activity vector denotes when and for how long the occupant is in each zone. This parameter allows the examination of the effect of different occupants in the same building such that it may be possible to optimize ventilation systems for different occupancy patterns. For example a retired couple who are home all day and spend more of their time in a one room watching television have a very different occupancy pattern compared to a family where the parents and children are absent from the house for a third of the day and move around from room to room, or a young, single occupant who eats out and therefore has no kitchen occupancy.

If we assume the time variations of airflows and source strengths can be treated as steady-state, we can use equations 2 and 3 to define relative dose, *d*, in terms of three time-invariant factors: activity pattern describing the time in each room (**a**), distribution of sources (**s**) and the distribution matrix (**D**).

$$d = \underrightarrow{\mathbf{a}} \bullet \underleftrightarrow{\mathbf{D}} \bullet \underleftarrow{\mathbf{s}} \qquad \textbf{(6)}$$

Where $\underleftarrow{\mathbf{s}}$ is the source strength (vector) normalized to each source add to unity [-]

and the ***distribution matrix*** [-] is:

$$\underleftrightarrow{\mathbf{D}} \equiv Q_o \underleftrightarrow{\mathbf{Q}}^{\mathbf{-1}} \qquad \textbf{(7)}$$

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[1] The concepts of relative exposure and dose apply to time varying ventilation systems as well, but such a discussion is beyond the scope of this paper. Sherman (2006)

This distribution matrix contains all of the important information about how air distribution affects indoor air quality. Each element describes how emissions in one zone are coupled to exposures in any other zone. In the limiting case of non-interacting zones (i.e. no air distribution at all), the distribution matrix is diagonal. The value of each diagonal element depends on the air flow for that zone relative to the total air flow for the building and the volume of that zone. If all zones have identical flows , then each diagonal element is equal to the number of zones, *N*. When a value on a diagonal is greater than N this indicates that the zone air flow is a small fraction of the total. In the other limiting case of perfect mixing, each and every element of the distribution matrix is equal to unity. The values of individual elements can therefore be used to determine the distribution relative to perfect mixing. For example, an off-diagonal value of 2 would mean that the concentration of that particular source and zone combination is twice what it would be for the perfect mixing case.

Whatever the activity patterns, source distribution or air distribution, the relative dose, *d*, is a measure of how good or bad the IAQ is compared to the case of perfect mixing. The relative dose for a single-zone well mixed space must be equal to unity. A larger relative dose means that the occupant's exposure to contaminants is higher than if the space were perfectly mixed. If, for example, there was perfect mixing between all zones, each value of the distribution matrix would be unity and the relative dose would be unity regardless of the activity and source patterns. For any other distribution pattern, the relative dose will depend on the details of the activity and sources distribution.

If the building air flow, activity and source patterns were all known, the relative dose could be calculated, but this is rarely the case. There are many different patterns and they depend on the building and the occupants. If our purpose, however, is to determine something like a "distribution credit" in a standards environment, we need to define a process based on some assumptions about the activity and source patterns.

Potential Metrics

The concept of relative dose allows us to define metrics with which to evaluate systems if we determine the activity and sources patterns we wish to evaluate. For example, the metric could be based on either the best or worst case. This would amount to picking the smallest or largest numbers in the distribution matrix and lead to extreme answers as the system departed from perfect mixing. That is, when there is poor air distribution one can construct scenarios in which the occupant's exposure is either significantly above or below the average depending on the choices of activity patterns and source distribution.

In this study we considered seven different metrics for estimating relative dose. These metrics are not the only ones one could consider, but they span most of the ranges of concern. The Metrics 1 through 5 are based on specific source and activity patterns. Metrics 6 and 7 are not based directly on source and activity patterns, but rather are a measure of how far the actual distribution pattern is from an idealization. These two metrics do not represent a dose for some simple combinations of activity and source patterns, but their value lies in being independent of that. We will treat them as though they were actually relative dose metrics.

Metric 1: Mean Exposure

For some houses, the sources will be reasonably evenly distributed thus each entry in the source vector will be *1/N*. Similarly each value of the activity vector will be *1/N* for equal time spent in each zone. Thus, the relative dose given by Equation 6 becomes the average value of the distribution matrix.

$$d \simeq \frac{1}{N^2}\sum_{i,j} D_{i,j} = \frac{D_o}{N^2} \qquad \textbf{(8)}$$

Where D_o is the sum of all the entries in the distribution matrix and.
N is the number of zones (and i and j are indices).

This then becomes the simplest (in the sense that it is a single value) measure of how good a given spatially complex air flow pattern is at delivering IAQ. This measure of relative dose does a good job of predicting the average exposure if one had a large population of such houses and a large population of occupants in those houses.

It is probably more important to find a metric the covers a larger percentage of the population that accounts for the fact that people do not all use their homes the same way. Variations in the source and activity distributions would translate into a distribution of relative exposures centered on the value given by Equation 8. If individual distributions (i.e., values of a and s) were known the dose distribution could be calculated then the metric could be defined by choosing some fraction of the population (e.g. 80%).

Unfortunately, not much is know about the distribution of source and activities except that it is likely to be quite broad due to the large variation in the way people use their homes. Therefore we developed other metrics that are not dependent on knowing the details of the source and activity patterns.

Metric 2: Volume-weighted Sources

A variation on Metric 1 is the case in which the sources are distributed in proportion to the volume of each space instead of being exactly the same (i.e. each source vector element is V_j/NV_o). This is equivalent to assuming that the amount of contaminant was continually emitted in each elemental volume within the home. As shown by Sherman (2007) this is the source distribution assumption that is necessary if one is using age-of-air techniques.

In this case the relative dose would be as follows:

$$d \simeq \frac{1}{N^2} \sum_{i,j} D_{i,j} V_j / V_o \qquad \textbf{(9)}$$

Where V_o is the sum of all the entries in the volume matrix (i.e. the total volume). [m^3]

Metric 3: Volume-weighted Worst Case

Metric 2 assumes that the exposure is spread across all zones, but in some cases it might be necessary to assume that the occupant spends their time in a single zone (i.e. the activity pattern vector has unity in one zone and zeros elsewhere) and that is the worst zone in that case the relative dose would be

$$d \simeq Maximum(\frac{1}{N} \sum_{j} D_{i,j} V_j / V_o) \qquad \textbf{(10)}$$

Metric 4: Absolute Worst Case

The absolute worst case would be if all the sources were in the same zone as the occupant and that was the worst zone to be in because it had the least air exchange.(This means the activity and source strength vectors have are unity for the worst zone and zero for the others.) In such a case the relative does is just the largest value in the distribution matrix, which must always be on the diagonal.

$$d \simeq Maximum(D_{i,j}) \simeq Maximum(D_{i,i}) \qquad \textbf{(11)}$$

Metric 5: Worst Cross Contamination

In the worst cross-contamination case, the source and occupancy are again both concentrated, but in different zones. In such a case the relative does is just the largest off-diagonal value in the distribution matrix.

$$d \simeq Maximum(D_{i,j \neq i}) \qquad \textbf{(12)}$$

Metric 6: Perfect Mixing

There is only one configuration of air flows that is truly independent of the details of the source and activity distribution, and that is perfect mixing. This suggests that the metric is the difference between the actual distribution matrix and the perfect mixing matrix. In matrix notation this becomes,

$$d \simeq 1 + \frac{1}{N} \left[\!\left[\underset{\leftrightarrow}{\mathbf{D}}, \underset{\leftrightarrow}{\mathbf{1}} \right]\!\right] \qquad \textbf{(13)}$$

Where the brackets represent the norm and the unity **(<u>1</u>)** matrix is the perfect mixing matrix, not the identity matrix. If we use an unweighted norm, then this function can also be expressed as follows:

$$d \simeq 1 + \frac{1}{N} \sqrt{\sum_{i,j} (D_{ij} - 1)^2} \qquad \textbf{(14)}$$

This metric penalizes the case in which each zone is isolated and separately ventilated, because our paradigm is perfect mixing. Under such a paradigm the isolated zones are worse because they cannot take advantage of the extra volume offered by the other zones to dilute contaminants.

Metric 7: Perfect Isolation

The opposite paradigm to Metric 6 is that each zone is perfectly isolated and ventilated independently: In such a case all the off-diagonal elements should be zero and the relative dose metric is a measure of how far the distribution matrix is from having zero off-diagonal elements:

$$d \simeq 1 + \frac{1}{N} D_{i,j \neq i} \qquad \textbf{(15)}$$

As mentioned earlier Metrics 6 and 7 have an implicit, but unknown source and activity pattern and this is both their strength and their weakness as metrics.

FIELD STUDIES

The seven metrics were evaluated in two case studies of homes in Tahoe, Northern California and Sparks, Nevada. Both were two story homes with forced air heating systems. Diagnostic tests of both homes were carried out to characterize the homes in terms of envelope leakage, duct leakage, volume of each room, and ventilation system air flows. The houses were divided into several zones and tracer gas injection and air sampling tubing was placed in each zone. Larger zones used multiple sample and injection points. Each zone was well mixed using fans. MTMS II was used to determine the air flows between zones and to and from outside for each zone. A different tracer was injected at a continuous rate into each zone. A sample was taken from each zone every 4 minutes. These samples were analyzed using a residual gas analyzer to determine the concentration of each gas in each zone. In each house several experiments were conducted that changed the mechanical ventilation system in use, open and closed interior doors and operation of the *Central fan*[2]. Each experiment lasted several hours such that quasi-steady-state concentrations were achieved in each zone.

The following analysis technique was applied to the multigas tracer concentration data to estimate the air flow matrix and then the distribution matrix for every test. The distribution matrixes were then used to determine the seven metrics.

Experimental Analysis Technique

Because it is necessary to fully characterize the flows from zone to zone in order to calculate the distribution matrix, we have used the full multigas, multizone measurement approach described by Sherman et al. (1990c).

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[2] The "Central fan" may also be known as the air handler, the blower or the central forced air system. It is that system that supplies air to various rooms of the house and picks up its return air from one or more returns around the house.

The primary data from MTMS is the injection rates and concentrations of each tracer gas in each zone at house temperature and pressure conditions. Zone temperatures and additional concentrations will be measured, but not made use of in the real-time analysis It is assumed that we know the volumes of each zone for the real time analysis.

In the experimental protocol used, the homes were in a single configuration for only a few hours. Rather than use a very general analysis technique such as used by Sherman (1989b), we sought a technique that would treat the air flows as slowly varying, but allow us to see real time results as the data was taken.

A point-by-point analysis of the continuity equation does not yield satisfactory results because the inherent noise in the concentration signal (generated more by mixing issues than instrumentation issues) is magnified in the time derivative term. Integrating over an appropriate time period greatly reduces the errors induced by signal noise. The longer the time period, the more stable the results are, but the less able one is to see short-term temporal variations in the air flows. Typically we chose averaging times on the order of an hour.

The averaging approach we took was to use a first order (i.e. single-pole) low-pass, recursive filter to condition the data. This reduces high frequency noise better than, for example, a moving average. It has the advantage that as each new point is taken output results can be immediately recalculated.

Formally, such a filter applied to the data is equivalent to a Laplace transform of the data. For discrete time series data the continuous Laplace transform of any function can be converted to the computationally efficient and robust form of a single-pole recursive low-pass filter of the discrete data:

$$\mathrm{L}(X_t) \equiv \frac{1}{\tau}\int_0^\infty e^{-t'/\tau} X(t-t')\,dt' = \left(1-e^{-\Delta t/\tau}\right)\mathrm{L}(X_{t-1}) + e^{-\Delta t/\tau} X_t \qquad \textbf{(16)}$$

Where Δt is the time step (i.e. the time between the measurements at steps t and $t-1$) and τ is the averaging time of the filter.

To see how to use the filtered measurements within the context of the continuity equation we can apply a Laplace transform to it:

$$\mathrm{L}(X) \equiv \frac{1}{\tau}\int_0^\infty e^{-t'/\tau} X(t-t')\,dt' : \quad \underset{\leftrightarrow}{\mathbf{V}}\bullet\underset{\leftarrow}{\dot{\mathbf{C}}} + \underset{\leftrightarrow}{\mathbf{Q}}\bullet\underset{\leftarrow}{\mathbf{C}} = \underset{\leftarrow}{\mathbf{S}} \qquad \textbf{(17)}$$

We assume that the volumes and flows are independent of the concentrations and injection rates and treat them as pseudo-steady state to move those parameters outside the transform.

$$\underset{\leftrightarrow}{\mathbf{V}}\bullet\mathrm{L}(\underset{\leftarrow}{\dot{\mathbf{C}}}) + \underset{\leftrightarrow}{\mathbf{Q}}\bullet\mathrm{L}(\underset{\leftarrow}{\mathbf{C}}) = \mathrm{L}(\underset{\leftarrow}{\mathbf{S}}) \qquad \textbf{(18)}$$

The Laplace transfer of the derivative becomes a more manageable difference:

$$\mathrm{L}(\underset{\leftarrow}{\dot{\mathbf{C}}}) = \frac{1}{\tau}\left(\underset{\leftarrow}{\mathbf{C}} - \mathrm{L}(\underset{\leftarrow}{\mathbf{C}})\right) \qquad \textbf{(19)}$$

From which we get

$$\underset{\leftrightarrow}{\mathbf{Q}}\bullet\mathrm{L}(\underset{\leftarrow}{\mathbf{C}}) = \mathrm{L}(\underset{\leftarrow}{\mathbf{S}}) + \frac{\underset{\leftrightarrow}{\mathbf{V}}}{\tau}\bullet\left(\mathrm{L}(\underset{\leftarrow}{\mathbf{C}}) - \underset{\leftarrow}{\mathbf{C}}\right) \qquad \textbf{(20)}$$

This equation cannot be directly solved as it stands because we do not have enough information. However, it can be solved if expanded from a vector equation to a matrix equation by running sufficient simultaneous experiments. That is, a complete system is evaluated using as many tracer gasses as zones, then it can be solved directly. Thus the vector of concentrations and injection rates because a square matrix of them and provides sufficient information to solve the system of equations.

The system is solved using matrix inversion, but not any matrix can be inverted. For example injecting all the tracers in the same zone and no other zone can lead to a poorly conditioned matrix. The most robust approach is to inject one tracer in one and only one zone. To minimize mixing problems the injection rates should be reasonably steady over time.

Using matrix inversion the expanded equation is solved for the air flows to get

$$\underset{\leftrightarrow}{\mathbf{Q}} = \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{S}}) + \frac{\underset{\leftrightarrow}{\mathbf{V}}}{\tau} \bullet \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{C}}) - \underset{\leftrightarrow}{\mathbf{C}} \right) \right) \bullet \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{C}}) \right)^{-1} \tag{21}$$

Or equivalently

$$\underset{\leftrightarrow}{\mathbf{Q}} = \frac{\underset{\leftrightarrow}{\mathbf{V}}}{\tau} + \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{S}}) - \frac{\underset{\leftrightarrow}{\mathbf{V}}}{\tau} \bullet \underset{\leftrightarrow}{\mathbf{C}} \right) \bullet \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{C}}) \right)^{-1} \tag{22}$$

The main concern in this study is the distribution matrix which is related to the inverse of the air flow matrix. Computationally, it can be better to calculate that directly:

$$\underset{\leftrightarrow}{\mathbf{Q}}^{-1} = \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{C}}) \right) \cdot \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{S}}) + \frac{\underset{\leftrightarrow}{\mathbf{V}}}{\tau} \bullet \left(\mathrm{L}(\underset{\leftrightarrow}{\mathbf{C}}) - \underset{\leftrightarrow}{\mathbf{C}} \right) \right)^{-1} \tag{23}$$

For a system near steady-state the calculation of the inverse flow matrix (and hence the distribution matrix) is more accurate, but the error analysis necessary to demonstrate this is beyond the scope of this report.

These equations can be solved using field data by replacing the Laplace transforms with the single-pole, low-pass recursive filters as indicated above, providing real time estimates of the flows and/or distribution matrix.

Ventilation Systems

In order to compare the various tests in the two case studies we used three different mechanical ventilation systems that met ASHRAE Standard 62.2 minimum requirements. All the systems were operated in two modes: with the interior doors being either open or closed.

System 1: Continuous Exhaust; No mixing

This system uses a continuously operating exhaust fan at the rate specified by ASHRAE Standard 62.2-2007. The Central fans were not operated for System 1 tests. System 1 corresponds to a house without an air distribution system or to times when the Central fan is not operating.

System 2: Central Fan Integrated Supply

This system uses supply ventilation integrated into the return system of the central forced air system. The Central fan is run at the fraction of time necessary such that the supply air flow meets the rate specified by ASHRAE Standard 62.2-2007.

System 3: Continuous Exhaust; Full mixing

This system uses a continuously operating exhaust fan at the rate specified by ASHRAE Standard 62.2-2007. The Central fan runs continuously. This system corresponds to a house in which the “fan on” switch is used and represents the maximum amount of mixing possible using the CFA system.

Case Study 1: Leaky Home

This 134 m^2 home (see Figure 1) was relatively leaky: 1950 L/s at 50Pa envelope pressure difference. Because this test was done in late winter/early spring (March 2007) in the cool climate of Lake Tahoe, CA., the natural infiltration was significant, averaging 132 L/s (1.2 ACH) over all the tests. The forced air heating and cooling system had most of the ducts in the attached garage and crawlspace with 60 L/s of supply duct leakage and 105 L/s of return duct leakage out of a total forced air system flow of 400 L/s. This duct leakage was important because when the Central fan operated it significantly increased the ventilation rate: with 105 L/s directly from outside through the return duct plus the effect of the imbalance between supply and return leakage on the envelope air flows.

For ventilation Systems 1 and 3 the exhaust fan in the master bathroom was used whose flow was set to the ASHRAE 62.2 level and confirmed using a powered flow hood. Additional tests were performed using the exhaust fan in the downstairs bathroom. The downstairs exhaust systems used auxiliary fans and integral flow meters to control and monitor the exhaust flow at the minimum 21 L/s required by ASHRAE Standard 62.2. System 2 used a Central Fan Integrated Supply (CFIS) where a 0.25 m diameter duct was installed to supply air from outside to the return plenum in the crawlspace under the house. The air flow through the CFIS was controlled and monitored using an in-line fan and flowmeter. The CFIS control system used a damper to open the duct for 10 minutes out of every half hour and turned on the Central fan to distribute the air in the house. Because the CFIS only operated one third of the time its operating air flow was controlled to be three times the 62.2 required minimum (62 L/s).

The first story had an open-plan kitchen, living room and dining area as well as a small bathroom. The second story had a large master bedroom with its own master bathroom and two other smaller bedrooms and a bathroom. Because any real home is going to have more rooms than can be practically measured, several rooms may be grouped into a single zone. The whole first floor was operated as one zone (zone 1). The upstairs was separated into three zones: the two small bedrooms (zones 3 & 4) with the master bedroom/bathroom combined into one zone (zone 2).

In addition to evaluating the seven metrics for three ASHRAE 62.2-2007 compliant systems, tests were performed with the Central fan always off, always on, cycling with furnace operation (controlled by the demand of the house for heat) and operating for 10 minutes out of every 30 (for the CFIS). The cycling with furnace operation results were about 30% to 40% fractional ontime. These extra tests were used to provide additional insight.

Figure 1.Leaky home in cool climate of Lake Tahoe, CA.

Measurement Results

For each of the three systems tested we have generated a distribution matrix for the door open configuration and for the door closed configuration. We show below as an example the distribution matrices for the continuous exhaust system (System 1).

$$\underset{\leftrightarrow}{D}_{open} = \begin{pmatrix} 1.19 & 0.05 & 0.12 & 0.13 \\ 0.99 & 1.34 & 0.63 & 0.66 \\ 0.98 & 0.34 & 3.25 & 1.40 \\ 0.97 & 0.34 & 1.88 & 2.70 \end{pmatrix}$$

Distribution Matrix for exhaust with open doors

$$\underset{\leftrightarrow}{D}_{closed} = \begin{pmatrix} 1.23 & 0.01 & 0.01 & 0.03 \\ 0.83 & 2.07 & 0.03 & 0.04 \\ 1.03 & 0.03 & 10.8 & 0.22 \\ 1.03 & 0.03 & 0.15 & 8.86 \end{pmatrix}$$

Distribution Matrix for exhaust with closed doors

Looking at this pair of distribution matrices we can see that the off-diagonal terms are reduced when the doors are closed—thus indicating more separation between zones, just as one might imagine. The values near unity in the first column indicate that the contaminant released in zone 1 appears roughly equally in all the zones (physically, this corresponds to internal stack driven air flows for this leaky house in a cool climate). The large on-diagonal terms for zones 3 and 4 show how the air flows for these zones are small compared to the total air flow for the building.

For each distribution matrix we can calculate our seven metrics and compare them. Table 1 summarizes the relative dose for the leaky house for the 21 combinations of evaluation metric and mechanical ventilation systems.

Table 1. Relative dose for a leaky house and forced air duct system for three ASHRAE 62.2 Compliant Ventilation Systems

	Exhaust: no mixing		Central Fan Integrated		Exhaust: full mixing	
Metric	**Doors Open**	**Doors Closed**	**Doors Open**	**Doors Closed**	**Doors Open**	**Doors Closed**
1	1.06	1.64	1.16	1.36	1.13	1.18
2	0.95	1.14	1.01	1.04	1.00	0.99
3	1.05	1.59	1.06	1.18	1.06	1.05
4	3.25	10.85	2.96	7.22	3.14	5.19
5	1.88	1.04	2.04	0.90	1.28	0.94
6	1.89	4.20	1.80	3.29	1.69	2.45
7	1.77	1.43	1.83	1.40	1.74	1.51

The first clear result is that closing the doors makes the house less mixed; all the open door tests are about the same and are independent of the 62.2 ventilation system or distribution fan operation. Similarly, the mean exposure is higher for the door closed tests[3].

The next significant result is that Central fan operation for doors closed tests leads to lower dose (except for case 7). This is illustrated in more detail Figures 2 and 3 that show the concentration data for the tracer released in zone one in all the four zones. Theses figures show how the Central fan operation makes the concentrations of gas from zone 1 in zones 2, 3 and 4 essentially the same. The concentration is still higher in the zone the gas is released in. The waviness in Figure 3 for the concentration in zone 1 is due to the central fan cycling on and off, but then filtered out by the data processing. The four zones are

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[3] The exception is the result for Metric 5, where closing doors reduces exposure because this metric looks at cross-contamination between one zone where the pollutant is and a different one where the occupant is. In this case closing the doors achieves better separation between the source and occupant zones and therefore less exposure.

not identical in Figure 3 because the high natural infiltration rate (140 L/s) is a significant fraction of the mixing air flow rate of 400 L/s and so even with 100% distribution fan runtime the four zones do not reach identical concentrations.

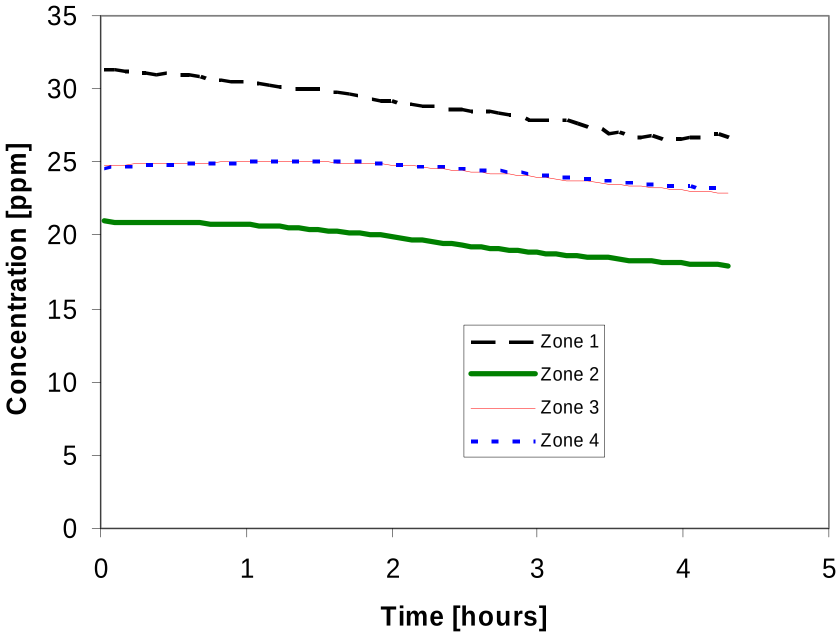

Figure 2. Concentration of gas injected into Zone 1in four zones for Exhaust Ventilation with Doors Closed

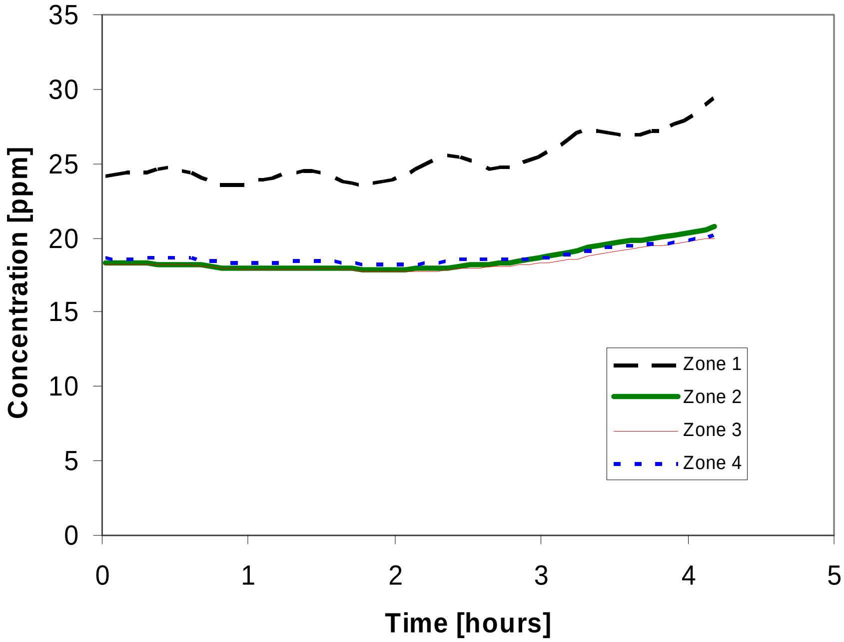

Figure 3. Exhaust Ventilation Doors Closed With Central Furnace Blower Running 1/3 of the time

We can see some interesting results when we compare the distribution matrices of the tests using the CFI and exhaust systems when both have closed doors and the central-fan operating 10 minutes out of every 30 minutes.

$$\underset{\leftrightarrow}{D}_{CFI\_closed} = \begin{pmatrix} 1.32 & 0.12 & 0.20 & 0.19 \\ 0.83 & 2.09 & 0.18 & 0.16 \\ 0.88 & 0.11 & 7.12 & 0.15 \\ 0.90 & 0.12 & 0.21 & 7.22 \end{pmatrix}$$

Distribution Matrix for CFIS with closed doors

$$\underset{\leftrightarrow}{D}_{closed} = \begin{pmatrix} 1.23 & 0.09 & 0.21 & 0.25 \\ 0.91 & 1.86 & 0.28 & 0.32 \\ 0.90 & 0.12 & 7.27 & 0.31 \\ 0.92 & 0.11 & 0.29 & 7.31 \end{pmatrix}$$

Distribution Matrix for exhaust with closed doors.

The additional tests led to the following results:

- The CFIS and exhaust system with 1/3 Central fan operation have the same central-fan runtimes using Metrics 1 and 6, and their distribution matrixes shown above are similar, i.e., they are dominated by the values on the diagonal with off diagonal terms being less then one. Each corresponding matrix entry for both CFIS and exhaust is the almost the same - showing the same trends where the off-diagonal terms in the first column are close to unity and the other diagonal terms are about 0.1 to 0.3 in magnitude. Similarly, the diagonal terms are within a few percent of each other. This implies that the mixing due to the operation of the central fan is the important part of the CFIS system and the distribution of the outdoor air via the forced air distribution system (compared to the central exhaust that only exhausts from one location) does not have a significant impact.
- The Central fan auto tests, where the Central fan only operated when heating was required, show that some mixing does occur - but the effectiveness of this mixing depends strongly on runtime. This suggests that a minimum runtime (as adopted by the CFIS system) is a good idea if mixing is desired.
- Because this is a relatively leaky house with high natural infiltration, the influence of the mechanical ventilation systems is relatively weak compared to the tight house results discussed later.
- The alternative exhaust point locations showed no appreciable difference in distribution.
- In terms of isolation, all the door closed tests has low values using Metric 7 indicating that the rooms are isolated from each other. Even having the furnace fan operate continuously could not increase the Metric 7 results with the doors closed.

Case Study 2: Tight House

This 270 m^2 home (see Figure 4) was relatively tight (635 L/s at 50Pa envelope pressure difference) and because the local climate in Sparks, NV. is mild[4] at the time of year of testing (April 2007) the natural infiltration was much lower than for the leaky house, averaging 22 L/s (0.1 ACH) for natural infiltration and 44 L/s (0.2 ACH) with the three mechanical ventilation systems operating over the week of testing. The forced air heating and cooling system was located inside the conditioned space. This resulted in low duct leakage to outside of 6 L/s of supply duct leakage and 9 L/s of return duct leakage out of a total forced air system flow of 708 L/s.

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[4] Because indoor and outdoor temperatures were almost the same during the testing the forced air system rarely operated to heat or cool the house (testing over a period of about 6 hours led to no heating or cooling required for most of the tests) so we were not able to replicate all the normal heating and cooling operation testing that was performed at the Lake Tahoe house.

For ventilation Systems 1 and 3 the exhaust fan in the master bathroom was used. The exhaust fan flow was set at the minimum 31 L/s required by ASHRAE Standard 62.2 and was measured using a powered flow hood. System 2 used a Central Fan Integrated Supply (CFIS) where a 0.15 m diameter duct supplied air from outside to the return plenum from a roof mounted vent. The air flow through the CFIS was controlled and monitored using an in-line fan and flowmeter. The CFIS control system used a damper to open the duct for 15 minutes out of every half hour and turned on the Central fan to distribute the air in the house. Because the CFIS only operated one half of the time its operating air flow was controlled to be twice the 62.2 required minimum (62 L/s).

The first story had an open-plan kitchen, living room, family room and dining room as well as a small bathroom. The second story had a large master bedroom with its own master bathroom and three other smaller bedrooms, a bathroom and a laundry room. The whole first floor was operated as one zone. The upstairs was separated into four zones: the three small bedrooms and the master bedroom/bathroom combined into one zone. The upstairs hallway was well mixed with the open plan space below via a large open space the full height of the house using several large mixing fans. There were jump ducts from the bedrooms to the hall to minimize pressure differences when the central fan operated.

Figure 4. Tight home in mild climate of Reno, NV.

Figure 5 shows the locations of tracer gas injection (i) and sampling (S) locations for the ground floor that is treated as one zone. Figure 6 shows the injection and sampling locations together with the boundaries of each zone for the second floor.

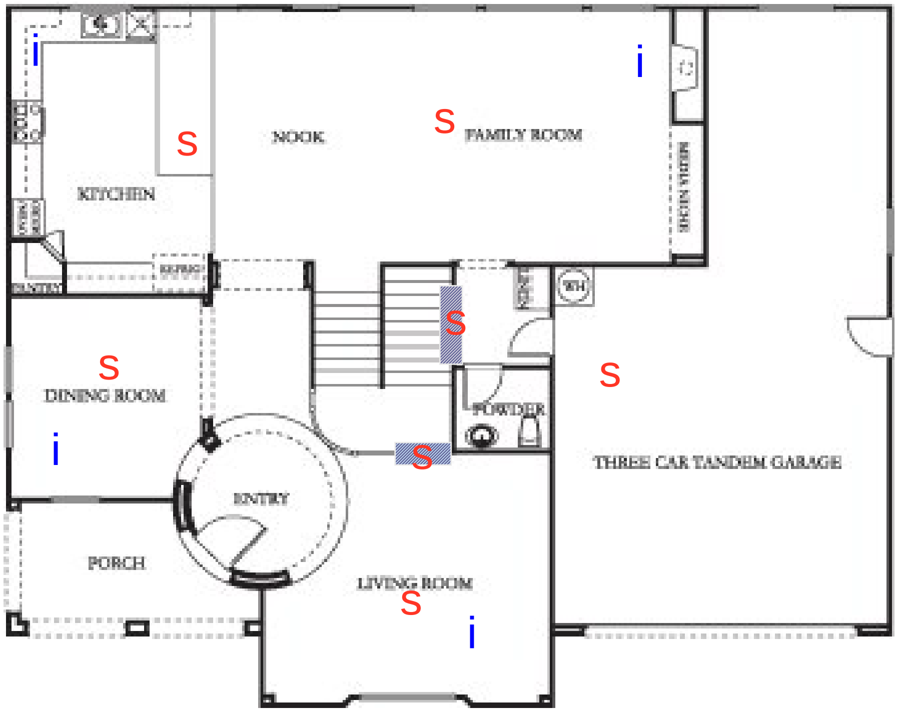

Figure 5. Ground floor plan for tight house showing injection (i) and sampling (s) locations.

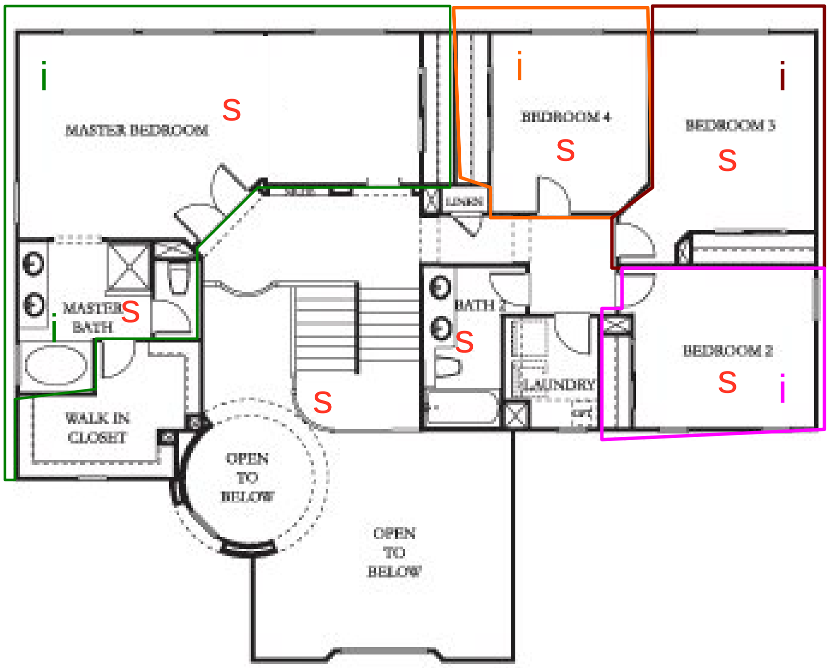

Figure 6. Second floor plan for tight house showing injection (i) and sampling (s) locations.

Measurement Results

The results in Table 2 show that for the tight home, unlike the leaky home, some mixing always leads to lower doses. This is because the adventitious effects of high infiltration rates are reduced in the tight house. The door closing effects are greater for the no mixing system compared to the leaky house. Conversely, the mixing systems show very little door closing effect. This difference between tight and leaky house response to door closing is particularly pronounced for Metric 4. The metrics that look for extreme values (3, 4 and 5) show higher doses than for the loose house. This is also due to the reduced mixing effects attributable to infiltration.

Table 2. Relative dose for a tight house and forced air duct system for three ASHRAE 62.2 Compliant Ventilation Systems

	Exhaust: no mixing		Central Fan Integrated		Exhaust: full mixing	
Metric	**Doors Open**	**Doors Closed**	**Doors Open**	**Doors Closed**	**Doors Open**	**Doors closed**
1	1.37	2.43	1.01	1.10	1.03	1.05
2	1.05	1.20	1.00	1.00	1.00	0.99
3	1.09	1.83	1.01	1.03	1.01	1.02
4	4.25	24.80	1.94	2.83	1.88	2.21
5	2.95	2.53	1.20	1.16	1.14	1.13
6	1.96	6.32	1.28	1.57	1.28	1.40
7	2.25	1.84	1.84	1.81	1.85	1.82

DISCUSSION

Several observations can be made by examining the results in Tables 1 and 2:

- Despite the fact that the overall ventilation rates are factors of 5 to 10 different, the relative dose values do not change nearly this much (typically 50% or less) between the tight and leaky houses.
- The one time that the relative dose is significantly below unity is for Metric 2 of the leaky house with an exhaust fan and no mixing. The leaky envelope and strong stack effect caused by large indoor-outdoor temperature differences leads to large quantities of air entering the first floor and exiting at the second floor. This acts as displacement ventilation that leads to improved air distribution. For this situation adding mixing actually increases the relative dose.
- Generally there is little variation in relative dose between the three ventilation systems when the sources and occupancy patterns are broad (i.e., metrics 1,2 and 3) , but the variation can be large (a factor of ten) when the sources and occupancy patterns are narrow and correlated (4 and 5).
- The greater air leakage of the Tahoe house acts to reduce the variation from system to system. Specifically it brings down the relative dose in the worst cases. It also may disrupt mixing if there is sufficient stack driven infiltration to develop displacement flows within the house.
- Most metrics show reduced relative dose for the systems that provide increased mixing, but metrics 5 and 7 show worse results with increased mixing. These two metrics benefit from enhanced separation.
- Open doors substantially enhance mixing and reduce separation. Jump ducts (e.g. a duct around a bedroom door) and transfer grilles, which can greatly reduce pressure differences between zones, do not substitute for open doors as far as mixing is concerned.

Supply vs. Exhaust

While there are differences in relative doses between the supply and exhaust systems analyzed above, most of that difference is due to the differences in the mixing supplied by infiltration and/or the Central fan. It is not clear from the results if there is any impact on the relative dose due to the difference between supply and exhaust systems per se.

Bear in mind that a large difference is not expected unless there were no mixing and no infiltration. In rough numbers the Central fan induces mixing of approximately four air changes per hour (ACH). The air change rate for the ASHRAE 62.2 minimum mechanical ventilation is roughly a factor of 20 smaller than that. Thus if the Central fan runs any significant fraction of the time, it will sufficiently mix the air and it does not matter where the air entered. A similar effect happens when infiltration is operating causing air to be distributed between the rooms.

To minimize relative dose exhaust systems would ideally exhaust from the zones of highest contaminant concentration and supply systems would provide air to where there was current occupancy. If there is not enough mixing to homogenize the concentration of contaminants then location of exhaust fans is important. A more detailed examination of how much Central fan operation is required to eliminate the effects of the source of supply air and then the location of exhaust points is beyond the scope of this study but is an interesting topic for future work. Such parametric analysis requires simulation techniques that can be calibrated using the data from these case studies.

Contaminant Sources

The results above look at a single contaminant source pattern. Different source types may have very different distribution patterns. Therefore the appropriate metric to use may be different for each one. For example, occupant generated contaminates would correlate highly with activity patterns and therefore metric 4 might be appropriate. Emissions from building materials might be spread out evenly and metric 2 might be appropriate. Emissions from specific contaminants may be localized in non-habitable rooms and metric 5 might be the most appropriate. In most real situations a combination of appropriate metrics may need to be considered. This is a topic for future research efforts.

CONCLUSIONS

This study successfully used a multigas tracer gas system to make detailed air flow measurements in two multizone houses in order to evaluate the effect of air distribution on occupant exposure for a variety of system configurations. This MTMS technique has proven invaluable for making such field measurements.

This study demonstrated that open or closed doors have a dominant effect on distribution and mixing of pollutants. Unless there is substantial and continuous mechanical mixing (e.g. from a central forced air system fan), open and closed door configurations need to be considered when looking at multizone air distribution effectiveness in houses.

This study used first principles to develop (and demonstrate using field data) seven metrics for evaluating air distribution effectiveness. These metrics cover a wide range of home and occupant characteristics and give different results for relative exposure. Policy makers need to decide the paradigm of choice, and hence the metric of choice, before credit for different air distribution methods can be given.

ACKNOWLEDGEMENTS

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