Air distribution effectiveness for different mechanical ventilation systems

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ABSTRACT

The purpose of ventilation is to dilute 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 conditions between zones. Different types of ventilation systems will provide different amounts of dilution depending on the effectiveness of their air distribution systems and the location of sources and occupants. This paper will report on work being done to both model the impact of different systems and measurements using a new 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 ultimate objective of this project is to determine the effectiveness of different systems so that appropriate adjustments can be made in residential ventilation standards such as ASHRAE Standard 62.2.

1. INTRODUCTION

Ventilation and the transport of both contaminants and clean air is becoming an ever more important issue as we strive to both improve energy efficiency in buildings and the indoor air quality within those buildings. Air motion is a complex interaction of naturally driven pressures and mechanically induced ones interacting with a wide variety of pathways.

The effectiveness of a given mechanical ventilation system will depend on air flows between each zone. Since it is people'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 people in building.

Because both the pathways and the motive forces are generally unknown, it can be very difficult to determine the quality and quantity of airflow in all but the simplest and most controlled building environments. When it is necessary to know how air and its constituents propagates, one must measure the air exchange using tracer gas techniques.

In this paper we will examine different air distribution paradigms, develop some prototype air distribution metrics and apply them to a single case study of a home done with our MultiTracer Measurement System (Sherman 1990c), which is now in its second generation (MTMS II).

Tracer Gas Background

The most common use of tracer gases in building science is to determine air flows under field conditions to support ventilation and pollutant transport work. 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) has reviewed the basic techniques and (1989a) analyzed the associated errors of using those techniques. ASTM E 741 (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. 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.

2. DISTRIBUTION METRIC

We would like to develop a metric to understand the value of air distribution in the control of indoor contaminants. We do that by looking at the multizone continuity equation:

$$V_i \cdot \dot{C}_i + \sum_j Q_{i,j} \cdot C_j = S_i \tag{1}$$

With this notation the diagonal elements of the air flow matrix, Q_{ii} is the total flow into or out of that zone and the Q_{ij} elements are negative and represent the flow to zone "i" from zone "j".

IAQ from the point of view of ventilation standards 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 we assume steady state which means that the concentration of the generic pollutant can be calculated for each zone.

$$\underline{C} = \mathbf{Q}^{-1} \bullet \underline{S} \quad (2)$$

If we treated the space as a single zone, we would have a similar scalar equation

$$C = \frac{S_o}{Q_o} \quad (3)$$

Where these scalar quantities are the ones we normally use and they can be used to normalize the matrix expression. (S_o is the sum of all the entries in the source vector and Q_o is the sum of all the entries in the air flow matrix.)

The above expressions allow us to calculate the relative concentration in each zone, but we are interested in the total dose which means we need to account for activity patterns. We can do this by defining a vector containing the fraction of time the occupant of concern is in each zone. The source strength matrix is normalized to add to unity and

$$\mathbf{D} \equiv Q_o \mathbf{Q}^{-1} \quad (4)$$

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 zone (i.e. no air distribution at all), the distribution matrix is diagonal; if all zones are identical, then each diagonal element is equal to the number of zones. In the other limiting case of perfect mixing, each and every element of the distribution matrix is equal to unity.

Mean Exposure

For most houses, the sources will be reasonably evenly distributed and so will the activity patterns. If we assume this is exactly true then we get the following expression:

$$d_N \simeq \frac{D_o}{N^2} \quad (5)$$

Where D_o is the sum of all the entries in the distribution matrix.

d_N is the simplest measure of how well 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 and the occupants spent an equal amount of time in each zone. Variations in source and activity distributions would translate into a distribution of relative exposures centered on the value given in Equation 5. If we knew the individual distributions we could estimate the dose distribution and then choose some fraction of the population (e.g. 80%) to use as a metric. Unfortunately, we do not know much 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. We therefore seek another metric that is not dependent on knowing the details of the source and activity patterns.

2.1 Perfect Mixing

There is only one configuration of air flows that is completely independent of the details of the source and activity distribution, and that is, perfect mixing. This suggests that we use for our metric the distance that the actual distribution matrix is from the perfect mixing matrix

$$d_{pm} \simeq 1 + \frac{1}{N}[\![\mathbf{D}, \mathbf{1}]\!] \quad (6)$$

Where the brackets represent the norm and the **1** 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:

$$d_{pm} \simeq 1 + \frac{1}{N}\sqrt{\sum_{i,j}(D_{ij}-1)^2} \quad (7)$$

This formulation 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. If our paradigm were that each zone was independently ventilated and that each zone had independent sources, we could use that matrix as the default in the norm instead of the perfect mixing matrix. Since, however, we are looking in relation to 62.2, which does not require each zone to be independently ventilated, we will not do that. $d_{pm} = 1$ would be perfect mixing and higher values of d_{pm} indicate less mixing.

2.2 Perfect Isolation

This metric examines how far the house is from the case where there is no mixing between zones and all the zones are isolated. mixing. This suggests that we use for our metric the distance that the actual distribution matrix is from the perfect isolation matrix with zero off-diagonals (**I**).

$$d_{iso} \simeq 1 + \sqrt{\frac{\sum_{i,j,i\neq j}(D_{ij}-I_{ij})^2}{N^2-N}} \quad (8)$$

This formulation penalizes the case in which each zone is perfectly mixed with all the other zones, because our paradigm is perfect isolation. d_{iso} =1 would be perfect isolation and higher values of d_{iso} indicate less isolation.

2.3 Experimental Technique

Because it is necessary to fully characterize the flows from zone to zone, we have used the full multigas, multizone measurement approach described by Sherman et al. (1990c). The case study home was divided into four zones. A different tracer gas was injected into each zone at a constant rate (the injection rates into each zone were not necessarily identical) using a mass flow controller to regulate the flow. The tracer injection rates were adjusted to result in concentrations of about 50 ppm in the zones into which the gas was injected. The tracer was injected into the airstream from an oscillating fan. Additional fans were placed in each zone to ensure good mixing within each zone. In Samples were taken from several locations - with at least one sample per zone. The tracer gas concentrations were measured using a residual gas analyzer. Samples were taken at four minute intervals over several hours to allow the tracer gas concentrations to be at or close to equilibrium. The injection rates and concentrations of each tracer gas in each zone were averaged for the last hour and used to determine the air flow and distribution matrices.

3. CASE STUDY

The metrics were evaluated in a case study of an home in Tahoe, Northern California.. The home had two stories with a forced air furnace heating both stories. 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 three other smaller bedrooms and a bathroom. The whole first floor was operated as one zone. The upstairs was separated into three zones: the two small bedrooms with the master bedroom/bathroom combined into one zone. This home was relatively leaky (Q50 = 1950 L/s) and because this test was done in late winter/early spring (March 2007) the natural infiltration was significant (averaging 132 L/s (1.2 ACH) over the week of testing). The forced air heating and cooling system has 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 is important to note because when the forced air system operates to mix air in the house it also significantly increases 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.

The house was equipped with three ASHRAE 62.2 compliant ventilation systems. The first system used an exhaust fan in the master bathroom, the second system used an exhaust fan in the downstairs bathroom and the third system used a Central Fan Integrated Supply (CFIS). The exhaust systems used auxiliary fans and flowmeters to control the exhaust flow to the minimum 21 L/s required by 62.2. The CFIS used a duct to outside connected to the return side of the forced air system. A damper operated to open this duct for 10 minutes out of every half hour. The CFIS control also turned on the distribution 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).

To examine a wide range of internal ventilation mixing scenarios we performed tests with the distribution 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 only the last mode was used). The cycling with furnace operation results are labeled “auto” in Table 1 and were about 30% to 40% fractional ontime. We also looked at the effect of interior doors being either open or closed.

3.1 Measurement Results

Applying the analysis approach to the multigas tracer data we estimated the air flow matrix and then the distribution matrix for each of the 18 cases. From the distribution matrix we calculated the three metrics.

The cases in italics are not mechanically ventilated. Cases 17 and 18 use alternative exhaust point locations, but show no appreciable difference in distribution.

4. DISCUSSION

The first clear result is that closing the doors makes the house less mixed and all the open door cases 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 cases.

Table 1. Distribution metric results

Case	Ex.	Furn.	CFIS	door[1]	d_N[2]	d_{pm}	d_{iso}
1	*off*	*off*	*off*	*O*	*1.1*	*1.8*	*1.9*
2	*off*	*auto*	*off*	*O*	*1.1*	*1.9*	*1.8*
3	on	off	off	O	1.1	1.9	1.9
4	on	off	off	C	1.6	4.2	1.5
5	*off*	*auto*	*off*	*C*	*1.4*	*3.2*	*1.5*
6	on	auto	off	C	1.5	3.5	1.5
7	*off*	*off*	*off*	*C*	*1.5*	*3.8*	*1.5*
8	on	1/3	off	O	1.0	1.7	1.8
9	on	1/3	off	C	1.4	3.3	1.5
10	on	on	off	O	1.1	1.7	1.9
11	on	on	off	C	1.2	2.5	1.6
12	on	auto	off	O	1.1	1.9	1.8
13	off	1/3	on	O	1.2	1.8	2.0
14	off	1/3	on	C	1.4	3.3	1.5
15	*off*	*off*	*off*	*O*	*1.0*	*1.5*	*1.9*

16	*off*	*on*	*off*	*O*	*1.1*	*1.5*	*1.9*
17[2]	on	off	off	O	1.2	1.8	2.0
18[2]	on	off	off	C	1.9	4.8	1.5

1. O = open, C = closed. 2. Different exhaust location

Comparing cases 3 and 4 (exhaust cases) shows how closing the doors reduces interzonal mixing. The two distribution matrixes further illustrate this point, with the off-diagonal values reduced significantly for the doors closed case.

$$\begin{pmatrix} 1.19 & 0.05 & 0.12 & 0.13 \\ 0.99 & 1.34 & 0.63 & 0.66 \\ 0.98 & 0.34 & 3.25 & 1.40 \\ 0.97 & 0.34 & 1.88 & 2.70 \end{pmatrix}$$

Distribution Matrix for exhaust with open doors (case 3)

Case 4 shares the lowest value of isolation with the other closed door cases.

$$\begin{pmatrix} 1.23 & 0.01 & 0.01 & 0.03 \\ 0.83 & 2.07 & 0.03 & 0.04 \\ 1.03 & 0.03 & 10.8 & 0.22 \\ 1.03 & 0.03 & 0.15 & 8.86 \end{pmatrix}$$

Distribution Matrix for exhaust with closed doors (case 4)

These results are further illustrated in Figures 1 and 2 that show the concentration data for the tracer released in zone one in all the four zones. Theses figures clearly show how the distribution 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 2 for the concentration in zone 1 is due to the central fan cycling on and off. The four zones are not identical in Figure 2 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.

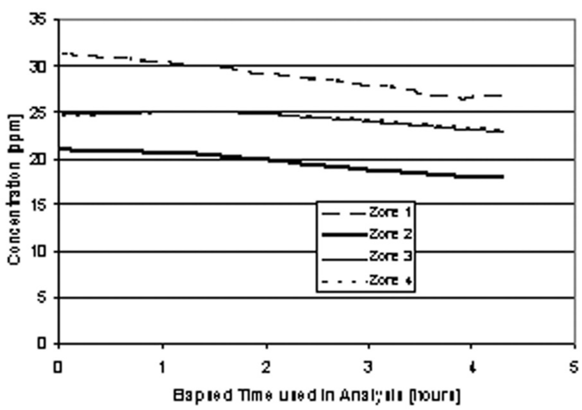

Figure 1. Exhaust Ventilation Doors Closed

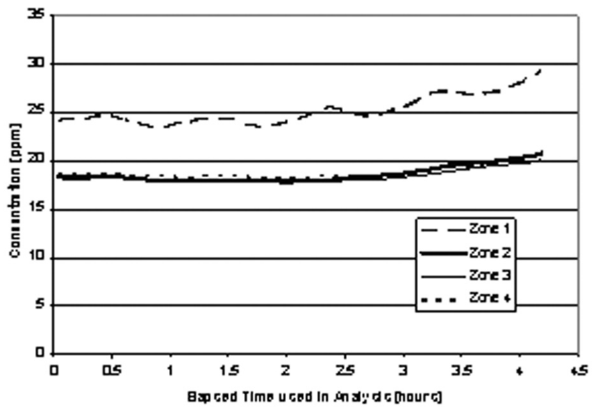

Figure 2. Exhaust Ventilation Doors Closed With Central Furnace Blower Punning1/3 of the time

However it is unlikely that all doors will be always open so the following discussion focuses on doors closed cases. For the exhaust system, operating the distribution fan leads to more mixing, although not as much as with open doors.

$$\begin{pmatrix} 1.29 & 0.25 & 0.42 & 0.52 \\ 0.94 & 1.53 & 0.42 & 0.51 \\ 0.94 & 0.27 & 4.44 & 0.48 \\ 0.93 & 0.24 & 0.42 & 5.27 \end{pmatrix}$$

Distribution Matrix for exhaust with closed doors and distribution fan operating continuously (case 11)

The CFIS system operates the distribution fan for 1/3 of the time. Comparing the CFIS to the exhaust with 1/3 operation shows that they have the same d_N and d_{pm} and their distribution matrixes are similar. This implies that the mixing due to the operation of the distribution 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.

$$\begin{pmatrix} 1.32 & 0.12 & 0.20 & 0.19 \\ 0.83 & 2.09 & 0.18 & 0.16 \\ 0.88 & 0.11 & 7.12 & 0.15 \\ 0.90 & 0.12 & 0.21 & 7.22 \end{pmatrix}$$

Distribution Matrix for CFI with closed doors (Case 14)

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

Distribution Matrix for exhaust with closed doors and 1/3 furnace fan operation (Case 9)

As might be expected, the intermediate amount of distribution fan operation in Case 9 falls between no operation and 100% operation. Whether this fraction mixing due to fraction operation of the distribution fan is sufficient mixing is not clear.

The distribution fan auto cases, where the distribution 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.

Finally, because this is a relatively leaky house with high natural infiltration, the influence of the mechanical ventilation systems is weak. The best results occurred for cases with the highest ventilation rates, lowest exposure and best mixing - and these were natural infiltration cases. This is because the leaky envelope and high driving forces for natural infiltration made this a natural infiltration dominated home. The results shown here may not be representative of tighter homes.

In terms of isolation, all the door closed cases has low values of d_{iso} indicating that the rooms are isolated from each other. Even having the furnace fan operate continuously could not increase d_{iso} with the doors closed.

The difference between perfect mixing and isolation may be important when a zone contains a relatively concentrated source. For sample, if zone 2 had a large source, then closed door exhaust (case 4) would be superior to systems with central fan mixing (e.g. cases 9,11 or 14) because they redistribute the pollutant.

5. CONCLUSIONS

Open or closed doors have a dominant effect on distribution and mixing of pollutants - even greater than operation of a distribution fan. However, the distribution fan did effectively mix the house. For this house with its high natural infiltration continuous distribution fan operation was necessary to achieve good mixing and low pollutant exposure when doors were closed.

The distribution performance of the single point exhaust with mixing by the distribution fan and CFIS systems are indistinguishable, therefore there is no reason to treat these systems differently in applications or codes/standards. If you do not want to mix pollutants throughout a house, or you have non-uniform occupancy patterns then the room isolation provided by a single point exhaust is advantageous - even in this leaky natural infiltration dominated home.

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