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ANALYSIS OF ERRORS ASSOCIATED WITH PASSIVE VENTILATION MEASUREMENT TECHNIQUES

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ABSTRACT

In small buildings where ventilation is the primary mechanism for removing indoor air pollutants, interest in converting the resulting energy load on the heating or cooling system of the building is significant. The desire of making field measurements of this time-varying quantity has led to the development of many approaches. The simplest one is called the *passive ventilation measurement technique* which typically measures the average concentration of a constantly emitted tracer gas from which the average ventilation rate can be estimated. This study relied on mathematical models combined with typical weather data to calculate how an ideal passive ventilation measurement would perform; simulations were then conducted based on two house types in four seasons and six climates. It was found that the passive technique significantly underpredicted the average ventilation and that the use of multiple tracers accomplished marginal improvement. Inadequate mixing was found to be a major impediment to the interpretation of the results and could completely invalidate the measurement. Not covered in this report are the additional errors associated with measurement uncertainty, instrumentation limitations, and non-ideal experimental conditions.

Keywords: Ventilation, Infiltration, Multizone, Passive Measurement Techniques Ventilation Efficiency.

NOMENCLATURE

A	Air change (ventilation) rate (ach) [h^{-1}]
$\mathbf{A}$	Air change rate (matrix) [h^{-1}]
C	Instantaneous tracer volume concentration [-]
$\mathbf{C}$	Multizone tracer volume concentration (matrix) [-]
ϵ	Instantaneous ventilation efficiency [-]
$\boldsymbol{\epsilon}$	Multizone ventilation efficiency (matrix) [-]
ϵ_m	Mean ventilation efficiency (for a period of time) [-]
$\boldsymbol{\epsilon}_{\mathbf{m}}$	Mean ventilation efficiency (matrix) [-]
ϵ_0	Overall multizone ventilation efficiency [-]
$\boldsymbol{\eta}$	Distribution efficiency (matrix) [-]
η_0	Overall distribution efficiency [-]
S	Instantaneous (tracer) source strength [h^{-1}]
$\mathbf{S}$	Multizone (matrix) source strength [h^{-1}]
σ_ϵ	Scatter in the multizone efficiency [-]
t	Time [h]
τ_e	Instantaneous turn over time [h]
$\boldsymbol{\tau}_{\mathbf{e}}$	Multizone (matrix) turn over time [h]
Δt	Discrete time step [h]
V_o	Total volume of the building [m^3]
$\mathbf{V}$	(Diagonal) room volume (matrix) [m^3]
$\bar{X}$	*Overbar:* The time average of the instantaneous quantity X

INTRODUCTION

In the last few years the need for a simple and accurate way of measuring the average ventilation rates of large numbers of dwellings has increased. This growing demand has spurred the development of low-cost, long-term monitors that use an emitter, to provide a constant source of a tracer gas throughout the period of measurement and a sampler to provide a time-averaged measurement of the tracer concentration. Any system that incorporates constant emission of tracer gas with a time-averaged concentration measurement, regardless of its physical details, falls into the category of a *passive ventilation measurement technique.*

Several different variations of this technique exist, but the most popular and generalizable system appears to be AIMS — the Average Infiltration Monitoring System. This system, which uses a tube filled with Perfluorocarbon Tracer (PFT) as an emitter and a diffusion-limited charcoal-like adsorber as a sampler, is the one to which most of the scientific[1], professional[2], and trade[3] refers. Although most studies reflect a fairly good understanding of the technique in highly controlled environments, large studies such as the Residential Standards Demonstration Program (RSDP) of the Bonneville Power Administration (BPA) are getting systematic differences, between the PFT and calculations based on leakage measurements, on the order of 50%[4]—a phenomenon that researches do not understand.

It is the intent of this report to discuss some of the measurement errors associated with the generic technique— specifically, to quantify the errors caused by variations occurring in ventilation during the measurement period. We believe that much of the systematic underprediction seen in the measurements obtained by these passive techniques, may be caused by this type of error.

BACKGROUND

In most small commercial buildings and virtually all residential buildings, unintentional air infiltration, or natural ventilation is the dominant mechanism for supplying fresh (i.e., outdoor) air. The rate of infiltration is caused by the interaction between the building's leakage characteristics and the external driving forces caused by the weather. Thus, infiltration varies from building to building, from climate to climate, and from hour to hour. On an annual basis, the average weather-driving forces in North America vary by a factor of three [5] and vary considerably more over shorter periods of time. The tightness of the building envelope, expressed in terms of the effective leakage area per unit of floor area, has been shown to vary over one order of magnitude [6]. Even within a single building, measured infiltration rates have a standard deviation that is typically half the size of its annual mean.

When estimating energy loads related to ventilation, the quantity of interest is the amount of energy required to condition the incoming air. In this situation, ventilation plays the same role as heat conductance because in both calculations its product with the inside-outside temperature difference yields the energy loss; because the infiltration depends on the temperature difference, however, the relationship is nonlinear. On the other hand, when estimating the ventilation component that contributes to indoor air quality, it is the effective dilution of pollutants rather than the average ventilation which is the important quantity to determine.

Many mathematical models exist for predicting infiltration. They range in complexity from single-zone methods useful for houses to complex network models common to large commercial or multifamily buildings. The *Air Infiltration and Ventilation Centre* in England has prepared a guide for selecting the appropriate model [7]. In the sections to follow, we will refer to the model, AIRMOV, which is the ventilation and air movement model incorporated in the Thermal Analysis Research Program (TARP) developed by the National Bureau of Standards (NBS) [8] for simulating ventilation on an hourly basis.

Any time a simulation model is used to draw generalizable conclusions, the assumptions it uses are open to criticism; the NBS programs are no exception. It should be noted, however, that we are using these programs only to generate *typical* infiltration-rate profiles. The absolute values of air flows are factored out and only variations and percentage differences are finally reported. In other words, the conclusions we present are independent of the simulation program used.

VENTILATION EFFICIENCY

Of the many methods used for predicting ventilation rates, virtually all involve measuring the dilution of a tracer gas by the ventilation air[9-11]; these techniques are essentially independent of the specific tracer used[12]. With the exception of the passive technique most tracer techniques take multiple air samples in a time not longer than it takes for the air in the room to be exchanged with outdoor air (i.e. the turn-over time). Thus, these techniques actually measure the *instantaneous* ventilation; to get an average ventilation value the instantaneous measurements much be repeated many times over the period of interest. Any technique, including the passive technique, that averages the concentration of tracer gas over a long period of time will not be able to measure the average ventilation over that period of time accurately—except in the case of unvarying ventilation rates.

One of our earlier studies[13] showed systematic underpredictions* in average ventilation, because the tracer under study and ventilation are not linearly related. However, when estimating pollutant exposures of constant source strength, the ventilation measured from an average concentration *is* the *effective* ventilation. For this earlier work, we used the *mass conservation equation,*

$$\dot{C}(t) + A(t)\,C(t) = S(t) \tag{1}$$

to derive a characteristic *turn over time*, τ_e,

$$\tau_e(t) \equiv \int_{-\infty}^{t} e^{\int_{t}^{t'} A(t'')\,dt''}\,dt' \tag{2}$$

that couples the concentration of a tracer (or pollutant) to its source strength (assuming a relatively steady term):

$$C(t) = \tau_e(t)\;S(t)$$

* Fundamentally, this underprediction is caused by the fact that the ventilation and concentration are inversely related and that the average of the inverse is not the inverse of the average.

This turn over time is the characteristic time for the tracer concentration to approach steady state and has been defined similarly by Sandberg [14,15].

We can define the *ventilation efficiency*, ϵ, this way — so as to allow the mean concentration to be related to the mean source strength and ventilation—

$$\epsilon(t) \equiv \frac{1}{A(t)\tau_e(t)} \tag{3.1}$$

and the *mean-ventilation efficiency* for a period of time as

$$\epsilon_m \equiv \frac{1}{\overline{A}\,\overline{\tau_e}} \tag{3.2}$$

The average concentration of a pollutant or tracer can thus be related to the average ventilation rate and the average emission rate through the mean-ventilation efficiency:

$$\overline{C} = \frac{\overline{S}}{\epsilon_m\,\overline{A}} \tag{4}$$

(It should be kept in mind that the ventilation efficiency represents a *temporal* efficiency and considers only the time variation of the ventilation, not the local inefficiencies associated with the imperfect mixing of contaminants with incoming air.)

It is in this expression that a systematic error can creep into the passive ventilation measurement. For example, $\overline{S}$ represents the known emission rate of the tracer, $\overline{C}$ is its measured average concentration, and $\overline{A}$ is the quantity of interest—the average ventilation rate; if the ventilation rate varies over the measurement period, ϵ_m will, in general, be less than unity. Given that the usual goal is to measure the average ventilation and that ventilation efficiency is unknown, the difference between actual and effective ventilation represents a systematic error or *bias* in the measurement technique. For indoor air quality measurements, however, we might prefer to know the product $\epsilon_m\,\overline{A}$, which is the *effective* ventilation rate, and in this case the passive technique gives us exactly what we want.

MULTIZONE VENTILATION EFFICIENCY

The analysis above was based on the assumption that the building could be treated as a single, well-mixed zone. Very often, however, it is necessary to assess the ventilation in a multizone building. Just as spatial efficiency concepts can be expanded to multiple zones [16], so can temporal efficiency concepts. Each of the quantities in the defining relations become matrices reflecting the multizone configuration of the building. The continuity equation becomes the following:

$$\dot{\mathbf{C}}(t) + \mathbf{A}(t) \cdot \mathbf{C}(t) = \mathbf{S}(t) \tag{5}$$

where:

$\mathbf{A}$ has a row and column for each zone and

$\mathbf{C}$ and $\mathbf{S}$ have a row for each zone and a column for each species of tracer.

The multizone ventilation-rate matrix, A, has positive diagonal elements that, when suitably volume weighted, represent the total air flow in and out of that zone to all other zones and the outside; the off-diagonal elements are the negative of the flow from one zone to another. Note that there can be flow both from zone i to zone j as well as from zone j

to zone i. The sum of a row or column yields the flow to or from the outside (which is not explicitly treated as a zone), and the sum of all elements yields the total ventilation of the building.

The tracer concentration is related to its source strength through matrix multiplication,

$$\mathbb{C}(t) = \mathcal{T}_{\mathbf{e}}(t) \cdot \mathbb{S}(t)$$

where we have solved* the multizone continuity equation to get an expression for the multizone *turn over time* :

$$\mathcal{T}_{\mathbf{e}}(t) \equiv \int_{-\infty}^{t} e^{\int_{t}^{t'} \mathbb{A}(t'')\,dt''}\,dt' \tag{6}$$

We can similarly define the *ventilation efficiency matrices as*

$$\epsilon \equiv \left(\mathbb{A} \cdot \mathcal{T}_{\mathbf{e}}\right)^{-1} \tag{7.1}$$

$$\epsilon_{\mathbf{m}} \equiv \left(\overline{\mathbb{A}} \cdot \overline{\mathcal{T}_{\mathbf{e}}}\right)^{-1} \tag{7.2}$$

to yield the expression,

$$\overline{\mathbb{C}} = \left(\epsilon_{\mathbf{m}} \cdot \overline{\mathbb{A}}\right)^{-1} \cdot \overline{\mathbb{S}} \tag{8}$$

The ventilation efficiency matrix serves the same function in a multizone environment that the ventilation efficiency served in the single-zone situation but is more difficult to interpret because, it splits and (through its off-diagonal terms) mixes flows from different chambers. Although this matrix is the full descriptor of the efficiency, it may be more useful to have a scalar quantity to use as an overall indicator of the ventilation efficiency in multizone situations. The *overall multizone ventilation efficiency*, ϵ_0, serves this function:

$$\epsilon_0 \equiv \frac{\sum \mathbb{V} \cdot \epsilon_{\mathbf{m}} \cdot \overline{\mathbb{A}}}{\sum \mathbb{V} \cdot \overline{\mathbb{A}}} \tag{9}$$

(where the sum is over all elements of the resulting matrices).

For the multizone case then, this efficiency, ϵ_0, is directly analogous to the single-zone efficiency, ϵ_m. However, because the multizone case is represented by a matrix of efficiency values, we can estimate the variation of the individual elements of the efficiency by taking the root mean square value of the difference between the efficiency matrix and unity:

$$\sigma_\epsilon \equiv RMS\left\{\mathbb{I} - \epsilon_{\mathbf{m}}\right\} \tag{10}$$

where RMS indicates the root mean square sum over all elements in the matrix.

* The matrix differential equation is not generally soluble in closed form; this expression for the turn over time is true only if the ventilation matrix commutes with its derivative. We can, however, use this expression whenever the derivative is small compared to the ventilation or by breaking it into segments in which the ventilation rate can be assumed constant. (The exponential of a matrix is defined through its Taylor series expansion.)

DISTRIBUTION EFFICIENCY

Another important concept which becomes an important factor in multizone environments is that of *distribution efficiency*—that is, the amount of a tracer or pollutant in one zone compared to a perfectly mixed single-zone. This factor involves both spatial and temporal *efficiencies* and is crucial in determining how concentrations from a single source can vary within a building. The distribution efficiency* is defined to be the ratio of the concentration of a gas in a zone to the concentration that would have occurred had the entire building been a single well-mixed zone; it is a matrix. From our definitions of turn over time it is a straight forward task to write down the expression for distribution efficiency:

$$\eta \equiv \frac{V_0}{\tau_e} \tau_{\mathbf{e}} \cdot \mathbf{V}^{-1} \tag{11}$$

The turn-over time in the denominator, τ_e, is the turn-over time for the building calculated as a whole. The inverse volume term enters the equation because we have assumed that there is an equal amount of tracer gas injected into each zone yielding an S-matrix that is proportional to the inverse volume.

The average value of the elements of this matrix, which we designate by η_0, represents the average concentration of the tracer gas in the building assuming equal emission from each zone. Without active control of or advance knowledge about the ventilation in a multizone environment, the best one can do with a single tracer gas is to inject and sample in each zone to get a distribution efficiency of η_0. Even when cruder strategies are used, the distribution matrix can often be used to evaluate the magnitude of the inefficiencies so created.

The average value of a *column* of the distribution matrix is the distribution efficiency for the zone-averaged concentration given emission into a single-zone. The Root Mean-Square (RMS) deviation of this average (from η_0) is a measure of the error associated with using a single emitter and multiple samplers. Similarly the average value of a *row* of the matrix is the distribution efficiency obtained when emitting into all zones and sampling in a given zone; and the RMS deviation of this average (from η_0) is a measure of the error associated with using multiple emitters and a single sampler.

The RMS deviation of all elements of the matrix from η_0 represents the distribution error associated with making a measurement using single sampler randomly placed and a single random placed emitter. Although this may be closest to the sampling strategy used in single family homes—which are often considered as a single zone even though they may have strong multizone character—the sampler is not normally placed in the same zone as the injector. It would be useful, therefore, to separate the distribution efficiency into two groups of sampling in the same or different zones as emitting. Because each subset need not have the same mean distribution efficiency, the average for these two situations is separately recalculated the average for these two situations.

* The distribution efficiency can be greater than unity. Some authors prefer to make a distinction between "efficiency" and "effectiveness" based on whether or not the quantity is constrained to be between zero and unity. Since this distinction is not relevant here, the cleaner term "efficiency" is used in this report.

APPLICATION TO THE PASSIVE TECHNIQUE

The efficiency techniques described above can be directly applied to the passive ventilation measurement technique. If the building can be treated as a single, well-mixed zone, a single tracer gas emitter and a single sampler can be used to estimate the average ventilation rate. This rate would be in error by the difference between the actual ventilation efficiency and the assumed ventilation efficiency (i.e., unity). If the building is broken into a set of internally well-mixed zones that exchange air with one another, then a multizone technique must be employed using one unique tracer gas and one sampler for each zone to get a concentration matrix (zones by gases) from which the average ventilation matrix can be estimated. Again this matrix will be in error by the difference between the efficiency and actual ventilation matrix.

The value of an effective ventilation or distribution efficiency matrix will depend upon the specifics of the problem including the weather, the building type, and the building environment. Because of the large number of factors and the numerical complexities involved in a calculation, the most practical method of demonstrating the variations in the passive technique is to simulate the ventilation behavior for some typical cases. Typical hourly weather data[17-19] was used to calculate the ventilation efficiencies for the six cities of Chicago, Illinois, Edmonton, Alberta Canada, Los Angeles, California, Miami Florida, Seattle, Washington, and Washington, District of Columbia. These data combined with two typical single-family floor plans and the AIRMOV program [8] to generate all of the hourly air flows for an entire year. These twelve sets of data were then used to generate the single-zone and multizone ventilation efficiencies and distribution efficiencies for the four seasons (denoted by the four quarters of the calendar year). The results of these 48 datasets are presented in Table 1.

Two house types were chosen for this simulation: single-story and two-story. In both cases external envelope (wall) leakages totaling approximately 900 cm^2 were assumed so as to achieve typical natural air change rates in the range of 0.3 to 1.0 ach. More specifically, the houses were patterned after typical North American house types: the *Ranch* house, (single-story) and the *Colonial* house, (two-story). A short description of each follows:

The **Ranch house** is a single-story slab-on-grade house broken into five zones (two bed/bath zones, two living zones, and a hall). All of the zones are connected to other zones by open doorways except for one bedroom which connects only to the hall by a closed doorway.

The **Colonial house** is a two-story house with central stairwell and full basement. It was assumed that each level was a well-mixed zone. (This assumption is justified *a posteriori* by looking at the mixing of a single story with open doors connecting the zones.) Approximately 400, 300, and 200 cm^2 of leakage area were assumed for the top floor, main floor, and basement, respectively. A central open stairwell connects the top and main levels and a closed door connects the main level to the basement.

In both examples one of the internal doorways was assumed to be closed and all of the others were open. These doorways represent the only leakage paths (i.e. connections) between the different zones. If short term tests are made on houses, the internal doors are usually opened; in the passive technique, however, the doors are operated normally by the occupants and it is quite likely that one or more will be closed for much of the

TABLE 1a: OVERALL VENTILATION RATES AND EFFICIENCIES for a Ranch House

City	*Season*	*Ventilation Rate* $\bar{A}$ [h^{-1}]	*Single-Zone Efficiency* ϵ_m [%]	*Multizone Efficiency* ϵ_0 [%]	*Multizone Error* σ_ϵ [%]
Chicago	Winter	0.922	75.5	75.8	14.6
	Spring	0.772	72.3	74.0	14.7
	Summer	0.616	70.7	71.3	14.9
	Fall	0.844	75.6	75.9	13.2
Edmonton	Winter	0.812	81.2	81.3	8.9
	Spring	0.660	69.4	69.1	13.0
	Summer	0.556	70.5	70.0	12.5
	Fall	0.688	77.8	77.4	9.2
Los Angeles	Winter	0.610	68.2	67.6	21.1
	Spring	0.644	74.2	72.4	21.1
	Summer	0.576	74.8	72.6	21.1
	Fall	0.471	76.3	75.1	17.8
Miami	Winter	0.646	74.1	74.4	13.5
	Spring	0.538	77.0	77.4	12.5
	Summer	0.449	81.8	81.3	11.1
	Fall	0.728	77.9	79.1	11.2
Seattle	Winter	0.803	72.9	73.7	16.6
	Spring	0.669	80.7	81.4	12.8
	Summer	0.564	80.4	81.4	12.5
	Fall	0.789	71.2	71.7	14.3
Washington, D.C.	Winter	0.907	75.2	76.2	12.7
	Spring	0.738	77.5	78.3	11.9
	Summer	0.530	80.9	81.5	11.5
	Fall	0.623	70.9	71.4	12.0

measurement period. Sensitivity tests showed only a mild effect of closing a door on the overall ventilation efficiencies, but a large percentage effect on the interzonal flows and associated distribution efficiencies.

The ventilation rate in Table 1 is the overall ventilation rate produced by the simulation. The single-zone ventilation efficiency (ϵ_m) is the ratio of the air change rate that the passive technique would have measured to the actual air change rate, assuming a single-zone building having the same air flows through the envelope as in a multizone building. The next column, ϵ_0, is the ratio of the overall air change rate that a multitracer passive technique would have measured to the actual air change rate.

The last column in Table 1, σ_ϵ, is a measure of the uncertainty of an individual multizone term (i.e., the ventilation between one zone and another) caused by the temporal variation in ventilation. It should be noted that this uncertainty represents a *mixing* of the actual ventilation terms and that the error, therefore, cannot be interpreted as a

TABLE 1b: OVERALL VENTILATION RATES AND EFFICIENCIES for a Colonial House

City	*Season*	*Ventilation Rate* $\bar{A}$ *[h^-1]*	*Single-Zone Efficiency* ϵ_m *[%]*	*Multizone Efficiency* ϵ_0 *[%]*	*Multizone Error* σ_ϵ *[%]*
Chicago	Winter	0.807	78.4	84.6	9.5
	Spring	0.678	75.2	82.8	11.6
	Summer	0.537	72.6	78.8	15.1
	Fall	0.722	77.3	85.6	9.8
Edmonton	Winter	0.674	84.6	92.9	6.7
	Spring	0.552	73.7	80.3	12.6
	Summer	0.471	73.3	79.7	13.5
	Fall	0.565	80.9	88.6	9.1
Los Angeles	Winter	0.543	73.3	76.1	12.5
	Spring	0.562	75.6	77.6	11.9
	Summer	0.499	76.6	78.5	11.4
	Fall	0.422	79.9	83.0	9.3
Miami	Winter	0.557	75.9	83.7	12.6
	Spring	0.464	77.9	82.7	13.6
	Summer	0.406	85.2	88.0	9.2
	Fall	0.633	77.7	83.7	11.8
Seattle	Winter	0.666	74.2	81.3	15.7
	Spring	0.551	81.2	88.7	11.5
	Summer	0.470	82.9	89.5	9.5
	Fall	0.646	73.3	80.7	15.6
Washington, D.C.	Winter	0.763	77.6	85.5	12.0
	Spring	0.628	79.4	87.5	10.2
	Summer	0.457	83.1	89.8	10.2
	Fall	0.524	74.5	81.4	12.4

percentage of an individual measured interzone flow but rather it should be considered as a percentage of the total flow to or from those zones. The error expressed as a percentage of the actual flow between two zones will be quite large for low flows and may be infinite since the measured flows are almost always non-zero while the actual flows may be zero (e.g., if the flow is unidirectional between two zones there would be a zero entry in the matrix).

Table 1 expresses the ventilation efficiencies and ventilation efficiency errors for a multizone building where one unique tracer gas is used for each zone. In most field situations only a single tracer is employed although there may be multiple injection and sampling points. Because the distribution efficiency relates the concentration so measured to what one would have measured had the building been a single, well-mixed zone, it is the indicator of choice for understanding errors due to the use of a single (passive) tracer in a multizone environment.

TABLE 2a: DISTRIBUTION EFFICIENCY AND ERRORS for a Ranch House

City	Season	*Distrib Eff.* η_0 *[%]*	*Uncertainties for* *I All S One* *[%]*	*I One S All* *[%]*	*I One S One* *[%]*	*Eff.±Uncer. Inject One* *S Same* *[%]*	*S Diff.* *[%]*
Chicago	Winter	104.5	16.1	12.5	74.7	216.3±65.0	76.6±44.9
	Spring	102.6	12.2	11.5	68.7	202.1±65.8	77.7±41.5
	Summer	103.7	13.5	11.8	69.0	198.0±62.9	80.2±46.7
	Fall	105.3	22.7	10.4	71.9	209.7±54.2	79.2±48.1
Edmonton	Winter	107.2	28.6	11.9	75.2	215.5±48.5	80.1±53.0
	Spring	106.2	21.8	10.9	69.8	201.4±53.1	82.4±50.6
	Summer	106.2	19.3	11.5	67.4	196.1±53.0	83.7±49.4
	Fall	107.2	28.8	10.3	71.9	206.4±45.5	82.4±53.5
Los Angeles	Winter	104.2	11.0	10.4	70.3	200.7±69.6	80.2±45.4
	Spring	108.7	24.5	11.5	68.9	202.6±44.5	85.2±51.8
	Summer	109.3	22.7	12.6	68.1	200.7±45.4	86.5±51.7
	Fall	104.9	10.2	10.9	68.8	197.0±68.3	81.8±45.8
Miami	Winter	103.4	8.2	12.7	74.8	206.7±78.7	77.6±45.9
	Spring	101.9	4.9	13.7	71.9	198.9±76.3	77.7±45.4
	Summer	102.2	5.1	12.5	75.2	200.8±84.4	77.5±47.5
	Fall	99.8	12.9	14.7	78.2	208.1±93.8	72.7±42.0
Seattle	Winter	103.9	17.5	10.5	70.8	206.4±58.8	78.3±46.0
	Spring	104.2	20.3	9.2	67.4	200.3±53.0	80.1±45.7
	Summer	103.2	12.4	9.9	65.8	195.9±63.3	80.1±41.6
	Fall	104.7	17.2	11.8	72.4	208.0±60.3	78.8±48.0
Washington	Winter	103.9	16.3	12.3	72.7	212.3±62.5	76.9±44.3
	Spring	105.1	16.6	13.2	69.8	205.2±58.0	80.1±46.0
	Summer	104.1	12.2	12.9	67.4	196.6±61.5	80.9±45.3
	Fall	103.5	16.2	8.6	66.5	196.0±60.0	80.5±44.2

Table 2 summarizes the distribution efficiencies for the same set of conditions assumed in Table 1. The distribution efficiency, η_0, represents the ratio of the average concentration one would measure if emitters and samplers were in all chambers to the equivalent single-zone (i.e., well-mixed) situation. In addition to this bias, an extra amount of uncertainty will be associated with strategies that do not involve injecting and sampling in all zones. The next three fields of the table indicate the extra uncertainties associated with the non-ideal mixing of a single tracer gas, based on such sampling strategies: the "*I All/S One*" column gives the additional random error associated with the strategy of injecting in all zones and then making a single measurement tracer gas of concentration; the "*I One/S All*" column gives the additional random error associated with the strategy of injecting in a single zone and then averaging the concentrations from all of the zones; the "*I One/S One*" column gives the additional random error associated with the strategy of injecting in a single zone and sampling in a single zone.

TABLE 2b: DISTRIBUTION EFFICIENCY AND ERRORS for a Colonial House

City	Season	Distrib Eff. η_0 [%]	Uncertainties for I All S One [%]	I One S All [%]	I One S One [%]	Eff.±Uncer. Inject One S Same [%]	S Diff. [%]
Chicago	Winter	114.2	49.0	71.7	161.	275.3±192.4	33.7±30.9
	Spring	112.1	51.7	56.6	158.	280.8±179.8	27.9±19.2
	Summer	111.0	52.3	47.7	154.	279.9±167.3	26.6±18.4
	Fall	114.5	51.4	66.7	164.	283.5±192.4	30.0±22.8
Edmonton	Winter	117.8	49.8	80.7	164.	276.3±203.5	38.6±33.5
	Spring	116.5	54.0	73.0	168.	283.6±203.5	32.9±27.8
	Summer	115.6	54.5	67.0	165.	283.9±196.7	31.5±24.3
	Fall	117.6	49.3	79.8	163.	276.0±201.5	38.5±33.2
Los Angeles	Winter	114.3	48.6	66.1	160.	281.4±184.0	30.8±31.3
	Spring	115.5	48.6	57.1	164.	297.8±174.6	24.4±24.4
	Summer	115.3	50.6	50.6	166.	303.3±169.8	21.3±20.9
	Fall	114.1	49.2	62.5	160.	283.3±180.7	29.5±29.1
Miami	Winter	111.1	53.2	52.8	160.	283.5±178.5	24.9±19.7
	Spring	108.1	46.7	36.3	142.	271.1±140.7	26.6±21.5
	Summer	107.4	57.1	40.1	142.	258.4±156.0	31.9±34.6
	Fall	109.6	48.0	46.6	153.	280.3±161.0	24.3±21.2
Seattle	Winter	112.9	44.5	65.2	154.	272.8±177.7	33.0±25.3
	Spring	113.4	50.2	59.8	161.	285.6±182.7	27.3±20.2
	Summer	113.5	52.6	58.0	163.	287.8±184.3	26.4±22.3
	Fall	113.8	47.2	67.8	158.	275.0±186.0	33.2±25.9
Washington	Winter	114.9	51.6	69.9	165.	281.2±196.9	31.8±26.7
	Spring	113.1	55.5	56.2	163.	285.3±186.4	27.1±19.1
	Summer	110.4	53.6	42.7	150.	274.7±161.6	28.2±21.5
	Fall	116.4	54.7	71.4	167.	283.1±202.9	33.1±26.2

The last two columns of Table 2 are an expansion on the single injection/single sample strategy. Although this strategy may be used often, the sampled zone is not normally the same as the injected zone. The middle three columns of Table 2 are all uncertainties around the same mean distribution efficiency (η_0). When the sampled zone is the same as the injected zone, the mean distribution efficiency is generally going to be higher than the η_0 and, conversely, when the sampled zone and the injected zone are different then it will be lower. Therefore, the distribution efficiency and its uncertainty have been recalculated for these two cases and results are given in the last two columns: "*S Same*" indicates that the sampling has taken place in the same zone as the injection (i.e., the diagonal element of distribution efficiency matrix); and "*S Diff*" indicates that the sampling has taken place in a zone other than the injection zone (i.e., off diagonal).

DISCUSSION

Passive ventilation measurement techniques tend to underestimate the average ventilation of even a well-mixed (i.e., single-zone) building if the ventilation varies over time. For the two building types and six climates investigated, the seasonal ventilation tended to be low by from 15% to 35% (See ϵ_m column of Table 1.) Earlier modeling of a specific two-zone environment suggests a similar size effect[20]. Although the size of this underprediction is affected by weather, construction details, duration of measurement period, absolute ventilation rate, etc. (see ref. 13), the trend toward significantly low measurement is clear.

Although this low bias may have a significant impact on the ventilation rate used for such purposes as calculating energy load, it has no impact on the ventilation rate used to determine the indoor pollutant exposure caused by constant sources. That is, the *effective ventilation rate* measured by the passive technique is the appropriate ventilation rate to couple a pollutant source strength to the average concentration in the building. The ventilation efficiency is the ratio of this effective ventilation to the average ventilation and is a direct measure of the bias in the passive ventilation measurement technique.

In a multizone building the situation is qualitatively similar but quantitatively more complex. There are two additional ways that the passive technique can be used in a multizone building: in full multigas, multizone mode, or in a single-gas mode. The former allows all interzonal flows to be estimated whereas the latter is intended to get only the overall ventilation of the building.

The simplest comparison one can make between a single-zone and multizone building is in the ventilation efficiency (ϵ_m, ϵ_0 respectively). For the ranch-style house these two numbers are very close. This closeness indicates that for a house with relatively good communication between zones, the overall ventilation efficiency measured with multiple tracer gasses yields the same result as if additional internal mixing were induced (i.e., as if the building were made effectively single zone).

The agreement between the two overall ventilation efficiencies is not so close for the colonial-style house. Although the individual zones may have large openings between them, the presence of the stack effect tends to make the airflows go in a single direction; therefore, the communication is not as good as that in a single-story building. It should be noted that while the single-zone efficiencies for the two building types are approximately the same, the multizone ventilation efficiency for the colonial-style house is higher. In short, it is an advantage to use multiple tracer gases in multistory buildings.

If multiple tracer gases are used, interzonal airflows can be calculated by the passive technique. From this analysis the uncertainty of any of these values, σ_ϵ, is 10% to 20% of the value of the zone is total. Thus, even for moderate interzonal flows the value of those flows may be off by a large amount. The passive method can accurately determine only the largest flow from any zone; at best only qualitative indications of other air flows can be gleaned from this technique.

In general, the information gained by using multiple tracers will not be worth the effort required; accordingly, it is important to understand the errors induced by using a single tracer gas in a multizone environment. That is, the distribution efficiency must be taken into account. (Note that all of the following arguments are valid whether the ventilation rate is stationary or time-varying.)

The overall distribution efficiency, η_0, is an estimate of the bias involved in estimating the overall ventilation efficiency from single tracer-gas information. Specifically, it is the ratio of the average concentration obtained by injecting into every zone to the concentration obtained when injecting into a single, well-mixed zone. For the ranch-style house the average concentration is 0-5% higher than that associated with the equivalent single-zone building and for the colonial-style house the concentration is 8-18% higher. These values parallel the ratio of the overall multizone ventilation efficiency to the single-zone ventilation efficiency and are similarly caused.

If a less than ideal injection/sampling pattern is used, there will be a large uncertainty in the result in addition to the bias mentioned in the paragraph above. For the ranch-style house there will be an extra 10-25% uncertainty in the estimated tracer concentration (and hence ventilation), if either the sampling or injecting is not done in every zone. The analogous figures are much higher for the colonial-style house (i.e., 40-80%) because of the poor communication from one story to the next.

If injection and sampling are done in a single zone only, both the biases and uncertainties become unacceptably large. In cases where experimental design prohibits using many samplers or injectors in a building, additional mixing must be provided to increase the communication between zones. The fan from a typical central HVAC system can supply more than enough mixing to convert a multizone building into a single-zone building, and, as long as the fan does not induce any extra infiltration, one design strategy is to run the fan continuously during the experiment.

CONCLUSIONS

Ease of use does offer a clear advantage to the passive ventilation measurement technique. Unfortunately, its simplicity is gained at the expense of some accuracy. The theoretical description of the phenomenon and the results in Tables 1 and 2 have been used to draw the following conclusions about these errors and the appropriateness of the technique.

- *The passive technique underpredicts the average ventilation.* Time-varying ventilation causes the (temporal) ventilation efficiency to be less than unity for the averaging times associated with the passive ventilation measurement technique. The examples presented indicate a seasonal underprediction in the range of 20-30%.
- *The passive technique is appropriate for indoor air quality measurements.* The effective ventilation measured by the passive technique can be used directly to estimate the average concentration of any pollutant of (known) constant source strength.
- *Multiple injectors and samplers should be used.* Mixing of tracer gases throughout the test space is critical. Without good tracer distribution, the uncertainty in the results could easily be 100% in a multizone building. Even with good injector/sampler coverage there will be a bias on the order of 10%. If possible, internal mixing should be added.
- *Multiple tracer gases for unidirectional flow.* In some buildings the internal air flow tends to flow continuously in one direction (e.g., stack-dominated buildings or houses in heavy prevailing winds). The use of a different tracer gas in each zone will improve the estimate of the average ventilation, as in the example of the colonial-

style house, where the underprediction was cut by one third.

- *Interzonal airflows are unreliable.* Multiple tracer gases ostensibly allow the estimation of average interzonal airflows. The uncertainties on all but the largest flows are sufficient to make these estimates quantitatively useless. As noted above, however, these values may be useful in predicting the average concentration level in one zone due to a pollutant source in another zone.

These conclusions are based on simulation runs on two housing types in six climates. Although such calculations cannot be considered exhaustive, they do span the typical range of conditions found in single-family homes. These simulations lay the groundwork for both future theoretical and experimental research.

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