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PANEL DISCUSSION

Measuring Ventilation Rates

IAQ consultants often include ventilation rate measurements in their IAQ investigations. In theory, this is a sound strategy; the amount of outdoor air an HVAC system supplies to a building's occupants is a key factor in maintaining good IAQ. In practice, however, measuring ventilation rates can be problematic. If the measurements are incorrect, the investigator's recommendations may be ineffective. ***IAQU*** recently asked several IAQ professionals, *What is the best practical way to measure ventilation rates?* While their responses varied, they had one clear message: choose your measurement techniques according to the requirements and specifics of the situation. (For background information on measuring ventilation rates, see ***IAQU***, November and December 1989.)

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The determination of the best way to measure ventilation rates depends on both what is meant by "best" and the specific conditions of the building and its HVAC systems.

If the definition of best refers to the technique that is the easiest to perform, then of the three methods available, CO_2 measurements will be the best way. In order for this method to provide meaningful results, however, there needs to be an accounting of both the number of people present and the duration of their occupancy, in addition to the quantification in the increase in concentrations after occupancy. It should also be determined how this actual occupancy compares with the potential maximum occupancy for that space. Although CO_2 measurement is a powerful tool for determining ventilation rates, there are certain limitations to its use. First of all, CO_2 generation rates vary from individual to individual as a function of diet and level of activity. There is also the problem that occurs when an afternoon peak value is incorrectly assumed to represent an equilibrium value. If this happens, then this technique will yield overestimates of ventilation rates.

If the goal is a more accurate determination of the ventilation rates and ventilation characteristics, then sulfur hexafluoride [SF_6] is the best method. Compared with the CO_2 method, the SF_6 tracer technique also has the advantage that the parameters of the HVAC system do not need to be maintained in a constant condition for as long an interval of time.

A third method is based on a determination of both the percentage of outdoor air in the supply air and the volume of air being delivered from each supply register in the zone under evaluation. This technique will be the best method when the goal is to evaluate a particular portion of a building that is served by several AHUs, which also serve other areas of the building.

When using any of these three techniques, it is important to remember that the first step is to document the condition of the HVAC equipment. Most important, the position of the outdoor air damper needs to be inspected. There also needs to be recognition that this position can change by time of day or season of the year as a function of the relationship between the outdoor temperature and the indoor thermal loads.

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The best practical way to measure ventilation rates depends on what you want to measure, the desired measurement accuracy, and the type of ventilation system in the building. Do you want to measure the total ventilation rate (i.e., mechanical and infiltration) in the building, or just the mechanical portion? Do you want to measure the ventilation rate of the entire building, from a single air handler, or at a specific location in the occupied zone? Do you want to measure the average ventilation rate over a period of time or the ventilation rate as a function of time?

There are a number of ways to measure ventilation rates, including mechanical flow rate methods, tracer gas techniques, and combinations of both. Mechanical flow rate methods measure air speed with pitot tubes and manometers or hot wire anemometers. The ventilation rate is calculated as the product of the speed and area of the airstream. Tracer gas techniques involve releasing a nontoxic inert gas such as sulfur hexafluoride into the building and measuring the tracer gas concentration as a function of time at strategic locations in the building and in the ventilation system. The ventilation rate is then calculated from this data using the mass balance theory.

A combination mechanical/tracer gas method that is increasingly being used in IAQ investigations involves multiplying the supply air flow rate from diffusers times the percentage of outside air in the supply airstream. The supply air flow rates are measured with air flow hoods, and the percentage of outside air is determined from measurements of the flow rate, weighted concentration of tracer gas in the return and supply air streams, and the outdoor air. Since the mixing of tracer gas in the air streams is often far from perfect, a multi-point sample is required to determine the flow-weight average tracer gas concentration. While mechanical and mechanical/tracer gas methods measure the amount of ventilation air being delivered to the building or a portion of the building, tracer gas methods are the only way to accurately determine the distribution of ventilation air through the building.

The accuracy of both mechanical and tracer gas methods may vary from 5% to greater than 50% uncertainty depending upon the instrument accuracy and the practicality of applying the method to specific buildings. The use of carbon dioxide measurements as an indicator of ventilation rates is not very accurate due to the significant uncertainties associated with the emission rate of carbon dioxide per person and whether or not an equilibrium concentration has been reached. Carbon dioxide measurements are a better indicator of people pollution (e.g., body odor) at that time and place and only a crude indicator of the amount of ventilation air per person.

With respect to standards for measuring ventilation rates, ASHRAE has two standards for measuring air flow rates, Standard 41.2-1987 for laboratories, and Standard III-1988 for buildings. ASTM has a standard for measuring air exchange rates using tracer gases, E-741-1983. This ASTM method assumes that the building air is perfectly mixed, which in real buildings may result in significant errors. ASHRAE SPC-129P is currently drafting a tracer gas method for measuring both ventilation rates and ventilation effectiveness that does *not* assume that the building air is perfectly mixed.

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The most appropriate technique for measuring ventilation in a building depends on the information that is needed and the available resources. Is one interested in the rate of outdoor air intake through the air handling system, the rate of air leakage through the building envelope, or the total building air change rate including both intake and infiltration? Are the resources available to fully characterize the dependence of ventilation on weather conditions and building operation? If only limited resources are available, under what conditions will the measurements be made and how will the inevitable incompleteness of the characterization affect the effort?

While there are many techniques for assessing ventilation, the only way to determine the total air change rate of a building is with tracer gas techniques. While tracer gas techniques are described as excessively sophisticated by some and as exceedingly simple by others, neither generalization is appropriate. There is also confusion between the tracer gas monitor and the measurement protocol. It is relatively straightforward to measure the concentration of a tracer gas in air. The much more difficult issue is, given a specific building, where and how does one inject the tracer gas, where and how does one sample the tracer gas concentration, and how will the concentration data be analyzed? The latter issues of protocol are much more difficult than is generally appreciated.

There has been much discussion on the use of carbon dioxide measurements for assessing ventilation. Many of these discussions have concentrated on issues of the accuracy of the concentration monitors, but this misses the point. Of all the constituents of indoor air that we consider, carbon dioxide is the easiest to measure. Accurate measurements require careful calibration and good experimental technique, and there is no way around that.

The critical issue with carbon dioxide measurements is the lack of acknowledgement of the assumptions implicit in the use of peak carbon dioxide concentrations to determine ventilation rates. In order to calculate ventilation rates from peak concentrations, the carbon dioxide generation rate (building occupancy) must be constant, the concentration must be uniform throughout the building, and the carbon dioxide concentration in the building must be at equilibrium.

Unfortunately the equilibrium assumption is too often not appreciated. Depending on the building ventilation rate, it takes several hours for the concentration to attain equilibrium. At one air change per hour (ach), it takes about 4 hours for the carbon dioxide concentration to reach equilibrium. At 0.5 ach, it takes 8 hours. And the building occupancy must be constant throughout this period of time. In many buildings, particularly office buildings, the occupancy is not constant for sufficiently long periods of time. The use of a pre-equilibrium concentration will lead to an overestimation of the building ventilation rate.

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I will start off by saying that I do not think there is a best practical way to measure ventilation rates. Every situation is different, and one must choose the best method for the particular installation. I say this from the perspective of an engineer and an IAQ investigator with sophisticated instrumentation at my disposal. For most people in the field, the options are limited. Another thing to consider is whether this is to be a "screening" investigation or an advanced IAQ/engineering analysis. As a screening measure, carbon dioxide measurements and percent outdoor air (% OA) determinations are probably adequate. Be aware of the following:

1) CO_2: Make the measurement in the late morning or late afternoon (the concept assumes steady-state conditions that are rarely reached). Also, since the occupants are the producers of CO_2, if there are significantly fewer occupants in the space than normal, the measurement is useless. In addition, remember that the CO_2 measurement is influenced by infiltration, natural ventilation, interzonal mixing, and mechanical ventilation. Bear in mind that infiltration and natural ventilation are highly weather-dependent (i.e., air temperature and wind velocity).

2) % OA: The % OA can be determined by measuring temperature or CO_2 in the outdoor air, return air, and mixed air. To obtain %OA, take the difference between the mixed air and return air concentration (or temperature) and divide that number by the difference between the outdoor air and return air concentration (or temperature). CO_2 is often easier to use because of the difficulty in measuring (accurately) the mixed air temperature, and if the outdoor, return, and mixed air temperatures are all close to the same value, an accurate determination is impossible. Cubic feet per minute (cfm) of outdoor air is then determined by using the % OA and the fan cfm from the mechanical prints or some other source (often not readily available). Bear in mind that the cfm on the mechanical prints and the actual cfm could differ significantly.

For any advanced investigation, a velocity traverse of the duct should be conducted, or tracer gas techniques should be used. [Editor's Note: for "traverse" studies, air speed is directly measured at a number of points lying in a cross section of the duct (a traverse), and the results integrated to give the volume flow rate.] It is often difficult to gain access to the duct to conduct a velocity traverse, but a tracer gas technique can be employed relatively easily. Things to be aware of: 1) For velocity traverses, choose an adequate number of grid points (most velocity probe manuals provide guidelines); and 2) Take precautions to assure that the tracer gas thoroughly mixes with the air stream (e.g., if the tracer is introduced at a single point, incomplete mixing of tracer can still be evident even after passing through a fan).

Most practical? For screening, use CO_2. For advanced investigations, do velocity traverses.

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Any ventilation measurement should be performed with a specific purpose: first, the problem should be clearly stated, then the information required to solve the problem should be listed. Finally, measurement techniques should be selected, when required, to obtain the missing data. The best technique is the cheapest method allowing for collection of the required information.

A CO_2 concentration measurement may be the best way to quantify IAQ in an assembly hall, provided there are no other contaminants than those emitted by the occupants. However, this technique cannot give any accurate value of the air flow rate. For that purpose, tracer gas techniques, marking the air to be measured, are unavoidable.

Several such techniques exist, which have different domains of application, and different costs. They are described in detail in the AIVC [Air Infiltration and Ventilation Centre] technical note 34, "Air Flow Patterns Within Buildings: Measurement Techniques." Until now, multitracer techniques involving active, controlled tracer injection and active air sampling were used essentially for research purposes, while passive techniques using perfluorated tracers (PFT) or active single tracer methods were used more and more in field audits. Such techniques are not only useful for air flow rate measurements, but also provide information on the performance of a mechanical ventilation system and on ventilation efficiency. Tracer gas measurement techniques have proven to be useful for assessing several physical quantities related to indoor air quality. Moreover, harmless, easily analyzable tracer gases can be used to simulate contaminants that may be more dangerous and difficult to measure. The contaminant removal effectiveness of any system can be measured this way.

These techniques, however, have not yet been generally implemented and are not broadly used. Thus, ventilation systems are not properly commissioned, the actual ventilation in buildings is not really well known, and the causes invoked to explain poor IAQ may be the wrong ones. Most of the few audited ventilation systems have been found to have significantly different performances than those specified in the design values. Therefore, standards on ways of commissioning systems could be very useful, when applied, both for improving IAQ and for saving energy.

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I split the issue of ventilation rate measurements into two categories: a) measurements in occupied residential buildings, and b) measurements in commercial buildings. In occupied residential buildings I consider the passive perfluorocarbon tracer method (PFT-method) to be the best available method for wide-scale surveys. The main advantages of this method are inexpensive and harmless-to-occupant field instruments. The PFT-method measures the long-term (from a few days to several months) outdoor air flow rate to a building. The accuracy of the method varies between 20% and 30% relative error, which I find reasonable considering that the method reveals new information on occupant and weather effects on ventilation. The disadvantage of the PFT-method is the expensive laboratory equipment. The availability of commercial analysis services is, of course, dependent on the demand for such services.

Considering residential buildings, there are other methods as well. Other tracer gas techniques (e.g., decay technique using CO_2, SF_6, etc.) give high accuracy in empty buildings, but little information on real-life situations. More conventional techniques for measuring air flows in ducts and grills totally ignore the ventilation due to infiltration. Attempts to estimate infiltration must be recognized as only estimates, even at their best.

It is our extensive experience that it is only with long-term ventilation measurements (as opposed to short-term measurements and infiltration models) that the actual real-life ventilation rates can be determined. Occupant effects can be so drastic that short-term measurements are of little value. Various infiltration models may give reliable average results for a large stock of buildings, but when it comes to determining the ventilation rate of a certain building, I find these models rather unreliable.

While I consider the issue of residential buildings solved (using the PFT-method), the problems are more complicated in commercial buildings. The application of the PFT-method in commercial buildings still requires some basic research. In these buildings, the conventional air flow measurement techniques are often the most practical way of measuring ventilation rates. Again, the effects of infiltration must be considered, but infiltration in fully mechanical systems is not so dominant as in residential buildings.

Another important issue is recirculation air flow. This can be solved by tracing the return air and measuring the ratio of tracer gas concentration in the supply to that in the return. This can be done using the carbon dioxide produced in the building as the tracer. Indicator tubes are accurate enough for measuring the concentration in this case, as the absolute CO_2 levels are not needed. Whole-building tracer gas measurements are usually rather expensive, which limits their use in wide-scale surveys.

Standardization of field measurement methods is an extremely important issue. Otherwise the measurements in various samples cannot be compared. It may, however, be a difficult job to include all types of buildings and measurements in one standard. The approach should rather be splitting the stock into smaller parts. In the Nordic countries, several measurement methods have already been standardized by NORDTEST, an "internordic" agency that promotes development in the field of technical testing. Currently, I am writing a standard proposal for single-zone PFT-measurement in residential buildings. In the US, ASHRAE is the appropriate body to implement this type of standard.

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During the course of providing indoor air quality services for clients nationally, we routinely need to assess the actual quantity of outdoor air being supplied to the occupants, and the overall effectiveness of the ventilation distribution system. We employ a variety of techniques (often in combination) to accomplish a definitive analysis as needed. These include actual outside air flow measurements; time-shared simultaneously recorded carbon dioxide measurements for supply air and return air as a surrogate for ventilation; and low-level sulfur hexafluoride tracer gas assessments utilizing a special dedicated portable gas chromatograph. One method alone is typically not sufficient.

We select the particular method or methods by considering several items, including the design parameters of the HVAC system; the occupant density available during the planned assessment period; designed and desired intrazonal pressure relationships within the facility; and the number of air handlers to be addressed. We would also consider the owner's budget, the severity of any indoor air quality complaints, and whether the results of our evaluation are destined for legal use.

Most of our clients expect a set of very specific engineering recommendations on how to mitigate the deficiencies that are identified. Thus we strive to learn as much as we can in the shortest time period concerning the intricacies of how the HVAC system does or does not work and why. An accurate ventilation assessment is a crucial part of our building diagnostic services. This diagnostic information, along with a clear understanding of the sources of contaminants and how the occupants use the facility, is then utilized to develop a mitigation plan as warranted, such that acceptable air quality and thermal comfort can be provided to the occupants.

We have recently explored the use of our laser particle counter to assess the ventilation efficiency that is provided to an occupied space. This is an experimental technique that is being explored by some professionals in the field; however, it has not been widely utilized. We are considering utilizing this method in our own new office building, which is currently under design.

The use of a specific method should be left up to the expertise of the diagnostician based on the parameters that I have outlined. Most importantly, the results must be defendable and useful in developing a cost-effective solution.

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