Ventilation measurements in selected IAQ studies

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SUMMARY
Building and space ventilation rates are primary determinants of indoor pollutant levels and occupant exposures, and the impacts of ventilation on health and comfort have long been recognized in ventilation standards and regulations. Despite the importance of ventilation, its measurement is often neglected in indoor air quality studies. In cases where ventilation rates are presented, the measurement approaches are often not described in sufficient detail to evaluate their quality or applicability to the study. Ventilation measurements in 26 indoor air quality studies are evaluated in terms of the method employed, the thoroughness with which they were described, and the metrics reported. The results reveal the use of a number of different ventilation performance parameters and a generally poor description of the measurement methods. The paper also makes recommendations on the information that should be included when reporting building ventilation rate measurements.

KEYWORDS
Air change rate, Measurement, Tracer gas, Ventilation

INTRODUCTION

The impacts of ventilation on the health and comfort of building occupants has long been recognized through the promulgation of ventilation standards and codes (Klauss, Tull et al., 1970; Janssen, 1999; Stanke, 1999). More recently, research has explored the connection between ventilation rates and occupant health effects and productivity in order to better judge the adequacy of these ventilation requirements and to support future revisions (Fisk and Rosenfeld, 1997; Mendell, Lei et al., 2005; Persily, 2006; Seppanen, Fisk et al., 2006; Seppanen and Fisk, 2006). These studies are quite difficult to conduct, due in part to the challenges associated with study design, quantification of health effects and ventilation rate measurement. In particular, these and many other indoor air quality studies (IAQ) often fail to properly assess ventilation rates or to describe the measurement approaches they employ.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recently sponsored a study of the association of ventilation rates and health impacts (Sundell and Levin, 2007). This study identified over 300 peer-reviewed papers on ventilation and health, from which about 70 papers were selected for review. Twenty-six studies were eventually identified as informative to the goals of the study and are listed at the end of this paper. Among these papers, a number of different techniques were used to assess ventilation rates and a range of detail was included in the description of these techniques. This paper presents an analysis of the ventilation measurement approaches used in these studies. This analysis employs these 26 studies because they were previously assembled, but does not revisit or impact the results of the noted ventilation and health effects study.

VENTILATION CHARACTERIZATION

As background to the review of the ventilation measurement methods used in the 26 studies, it is important to understand the different ways that ventilation rates may be characterized. As described below, there are several different ways to characterize building and space ventilation, not all of which are readily comparable or of equivalent reliability. The primary factors to consider are the ventilation measurement methods, the conditions under which the measurements are made and the uncertainty associated with the measurements. If these three issues are not clearly reported, there may be reasonable concerns about the validity of the reported ventilation rates or at least the need to view them with some reservation.

Whole building

Whole building ventilation rates quantify the total amount of outdoor air entering a building, but do not characterize the distribution of this air to portions of a building or individual rooms. Depending on the uniformity of air distribution, there can be large variations in outdoor air delivery among rooms. Since people occupy rooms or spaces in buildings, whole building rates may not be good indicators of an individual's contaminant exposure.

<u>Air change rate</u>

Definition: Total rate at which outdoor air enters a building divided by the building volume, typically in units of h^{-1}.

Measurement: Whole building tracer gas dilution methods, such as those in ASTM E741 (ASTM, 2006), are the only way to make these measurements. These methods assume that the building tracer gas concentration can be characterized by a single concentration (sometimes referred to as single-zone or complete mixing), and that assumption must be verified to justify validity of the measurement results.

Comments: Building air change rates are a strong function of weather conditions (wind, outdoor temperature) and system operation (e.g. fraction of outdoor air intake, supply vs. return airflow rate, exhaust fan operation), and therefore it is essential that the measurement occur at the same time (or under the same conditions) as the IAQ assessment.

<u>Outdoor air intake rate</u>

Definition: Total rate at which outdoor air enters the building through air handling system intakes, typically in volumetric airflow units such as m^3/s or L/s.

Measurement: Outdoor air intake is most commonly measured using traditional air speed measurement methods such as pitot tube or hot wire anemometer duct traverses. There are also tracer gas methods for measuring air intake rates, but they are not as widely used.

Comments: Outdoor air intake is a strong function of system operation (e.g. heating ventilating and air-conditioning control mode, fraction of outdoor air intake), and therefore it is essential that the measurement occur at the same time (or under the same conditions) as the IAQ assessment. The measurement results do not take into account envelope infiltration, which can be as large or larger than the outdoor air intake rate. These measurements can be difficult to accomplish in the field due to limited access to ductwork and duct configurations that are inconsistent with proper air velocity profiles at the traverse location. There are no reliable estimates of the measurement uncertainty associated with duct traverses in the field, but an uncertainty of 10 % is described in some industry standards (ASHRAE, 1988) under good conditions. However, the basis for this value is unclear.

<u>Infiltration rate</u>

Definition: total rate at which outdoor air enters the building via envelope leakage divided by the building volume, typically in units of h^{-1}.

Measurement: In buildings without mechanical ventilation, the infiltration rate can be determined using tracer gas dilution methods. If the building has mechanical ventilation, then this quantity can be determined by measuring the whole building air change rate (presumably using tracer gas dilution methods) and the outdoor air intake rate as noted above, and then subtracting the intake rate from the whole building rate to determine the infiltration rate.
Comments: Infiltration rates are a strong function of weather conditions and system operation (e.g. fraction of outdoor air intake, exhaust fan operation), and therefore it is essential that the measurement occur at the same time (or under the same conditions) as the IAQ assessment.

Individual rooms

Characterizing, even defining, the ventilation rate of an individual room is extremely challenging. Given the difficulty in assessing ventilation in individual rooms, if a study reports room ventilation rates, then the methodology needs to be very well described.

System outdoor air delivery rate

Definition: Volumetric airflow rate of outdoor air entering the room via the mechanical ventilation supply outlets, typically in units of m^3/s or L/s.
Measurement: Airflow at supply air outlets can be measured using flowhoods (assuming they are properly selected and used) and then multiplied by an independent measurement of the outdoor air fraction at the air handler serving that outlet. The outdoor air fraction of the air handler can be measured using tracer gas methods (such as CO_2) or temperature.
Comments: Outdoor air delivery rates are a strong function of system operation (e.g. fraction of outdoor air intake) and system air distribution performance, and therefore it is important that the rate measurement occur at the same time (or under the same conditions) as the IAQ assessment. These values do not account for outdoor airflow into the room via envelope leakage or via transfer from adjacent spaces, and do not apply to rooms that are naturally ventilated including by infiltration.

Tracer gas decay rates

Definition: The tracer gas decay rate for an individual room is not the outdoor air ventilation rate of that room except under very unusual circumstances. As noted above, the tracer gas decay technique as commonly applied is a single zone method, generally applied to an entire building and based on the assumption of a uniform tracer gas concentration throughout.
Measurement: As generally applied, one injects tracer into the room of interest, or a larger portion of the building, and monitors the concentration decay over time.
Comments: While the tracer gas decay rate for an individual room is generally not the outdoor air ventilation rate of that room, it is often reported as the ventilation rate. The tracer gas decay rate of an individual room will equal the outdoor air ventilation rate only if air enters the room only from the outdoors directly (via windows, vents, leaks and an 100 % outdoor air ventilation system). Air entering from adjacent spaces will impact the decay rate, depending on the tracer gas concentration in those spaces Air from adjacent spaces may contain some “unused” outdoor air, which is not a well-defined concept, which tends to complicate the data interpretation even further. Multizone building systems are much more difficult to manage in terms of tracer gas testing, and most buildings behave as more than one zone.

Peak carbon dioxide concentrations

Definition: The outdoor air ventilation rate per person calculated from a single zone mass balance of CO_2 assuming that the indoor CO_2 concentration is at equilibrium (not just a plateau), the concentration is the same in all adjoining zones (or no air enters the space through these zones), the CO_2 generation rate of the occupants is known and constant, and

that the following quantities are constant: ventilation rate, number of occupants, and outdoor concentration.
Measurement: The indoor concentration is measured continuously in the space in question, and the peak value is identified for the calculation. In some cases, the concentration is measured at a single point in time and assumed to be the peak value.
Comments: Many field studies have used peak indoor CO_2 levels to estimate outdoor air ventilation rates per person, often without a solid understanding of the basis for these determinations. It is important to note that in such applications, CO_2 is just a tracer gas (with a convenient source) being applied using a constant injection method, and that one still needs to understand and validate the assumptions associated with this measurement approach. This issue has been discussed extensively (Persily, 1997), and is the subject of an ASTM standard (ASTM, 1998).

ANALYSIS

Each of the 26 papers was examined for the ventilation measurement method used and the manner in which it was described. The results are presented in Table 1, with the following parameters presented for each paper.

Ventilation rate method

This portion of the table describes how the ventilation rate was measured, with the first subsection title “Tracer Gas” referring to the use of a tracer gas method. These methods determine the sum of the intentional outdoor air intake through the ventilation system plus any unintentional infiltration through leaks in the building envelope. Depending on the building, system type and weather conditions, intake or infiltration may dominate, or they may be similar in magnitude. There are several tracer gas methods, which are distinguished in the table: decay, constant concentration and constant injection. The latter method includes what is often referred to as the PFT (perfluorocarbon tracer) method, but which is typically implemented with a constant tracer gas source and a sampling method that determines the average tracer gas concentration. The use of occupant-generated carbon dioxide (CO_2) to estimate outdoor airflow rates is noted separately. This approach is essentially a constant injection tracer gas technique, though the assumptions on which this method is based are not always evaluated or even considered in many applications. “Not specified” refers to a single paper that reports use of a tracer gas method, but does not indicate which one. Finally, only one paper includes a description of where the tracer was injected and sampled, which is critical to the proper application and therefore interpretation of all tracer gas methods.

Seven papers measured airflows in the ventilation system using an anemometer device. As noted in the table, these measurements occur in the supply vent to the room, an outdoor air intake duct, or an exhaust duct. Such measurements can be reliable, but it is important to understand the system design to determine if these airflows provide a useful measure of the ventilation rate of a room or space. Three papers report an outdoor air intake fraction rather than a ventilation rate. Two use tracer gas concentration measurements in the outdoor, supply and recirculation airstreams, and one employs an estimate based on design and observation. One paper reports ventilation rates but does not describe how they were determined, as noted in the “Not described” category.

Ventilation metric

The papers also use a variety of parameters to characterize the ventilation rate, such as air change per hour, volumetric airflow rate per person or per floor area, and percent outdoor air. Many use the measured CO_2 concentration as a surrogate for ventilation, with no actual measurement of the ventilation rate. One paper simply reports the rate as low, moderate or high. The use of different metrics in different studies makes it difficult to compare the results.

Table 1. Ventilation measurements.

	# of studies
VENTILATION RATE METHOD	
Tracer gas	13
Tracer gas decay	6
Constant concentration	1
Constant injection (includes PFT)	3
Estimated from occupant generated CO_2	2
Not specified	1
Tracer gas injection and sampling described	1
Supply vent to room	2
Duct flow: intake only	1
Duct flow: exhaust only	4
Percent outdoor air	3
Tracer gas	2
Estimate from design/observation	1
Not described	1
VENTILATION METRIC	
Air changes per hour	9
Volumetric airflow per person	14
Percent outdoor air	3
CO_2 concentration	6
Low, moderate or high	1
OTHER FACTORS	
Reference another paper for method	14
Reference measurement standard	1
Study in chamber	1
Repeat measurements	
Only one measurement	4
Measurement repeated	8
Not clear if repeated	14
Short or long term measurement	
Not described	17
Instantaneous or short term	3
Long term	6
Instrumentation	
Not mentioned	12
Measurement hardware identified but not described	13
Hardware calibration described	4
Uncertainty reported	5
Hardware presumably described in reference	11
SUMMARY	
No measured rates, only percent outdoor air	1
CO_2 concentration, poor description of method	2
CO_2 concentration, good description of method	4
Measurement method barely or not described	9
Measurement method marginally described	10

Other factors
Several papers, while perhaps not very descriptive of the measurement method employed, do reference another paper or a measurement standard for more information. A single paper describes a study in a laboratory chamber, where ventilation characterization is more straightforward than in an actual building.

Since ventilation rates are strongly dependent on system operation and weather conditions, it is important to consider the variation in ventilation rates, particularly when interested in the rates that occur during an IAQ assessment. This issue was considered by noting those studies that reported only a single ventilation rate measurement, that reported more than one, and that did not make it clear whether or not the measurements were repeated. Most of the studies fell into the latter category. The duration of the measurement is another important factor and is characterized as not being described, instantaneous or short term (on the order of minutes to a few hours), and long term (more than one day). Again, most of the studies did not describe the duration of the measurement period.

The final category considered is the instrumentation used to measure ventilation. Papers are noted where the instrumentation was not described at all, where it was identified but not described, and where it was described in some detail. Four papers mentioned how the instrumentation was calibrated and five reported the measurement uncertainty. There are eleven papers where the instrumentation is presumably described in a reference.

RESULTS
A summary of the results for the 26 papers is presented at the bottom of Table 1. About 25 % of the studies use the indoor CO_2 concentration as a ventilation metric, despite the questions raised by Persily (1997) regarding its usefulness in this application. Of those studies, one-third do not describe the CO_2 measurements well. Out of the total number of studies, about one-third do not describe the ventilation measurement method at all or provide only a minimal description. Just slightly more provide a marginal description of the measurements conducted. Among the 26 studies, almost half are unclear as to whether the measurement was repeated or not and about 15 % included only a single measurement. About 65 % do not describe the time scale over which measurements were made, and about half do not mention the instrumentation used to make the measurements.

DISCUSSION AND CONCLUSIONS
While only a limited number of studies were considered in this analysis, there is no reason to expect that they are different in their treatment of ventilation than other IAQ studies. In fact, since these studies were selected as part of an effort to examine ventilation and health, one might expect them to be better than most. For the field of IAQ to advance in its understanding of ventilation impacts on indoor pollutant levels and occupant exposure, it needs to do a better job in characterizing building ventilation and reporting on the methods used. When reporting ventilation rates, it is essential that the methods employed be well-described, including where and when the measurements were made, the state of the building during the measurements, the instrumentation employed and the uncertainty of the measurement results. Journals should stress the importance of such reporting in their paper acceptance criteria and hold authors to these requirements before accepting papers for publication.

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