Ventilation Measurements in IAQ Studies: Problems and Opportunities

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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 many cases when ventilation rates are presented, the measurement approaches are not described in sufficient detail to evaluate their quality or applicability to the study design. To demonstrate this point, ventilation measurements in 26 indoor air quality studies are evaluated in terms of the methods employed and the thoroughness with which there are described. 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.

IMPLICATIONS
Significant resources are being devoted to the study of indoor air quality, but too many of these studies are neglecting the role of ventilation or are addressing it through inappropriate means. It is critical that a much better job is done in assessing ventilation and in describing the methods used to perform these assessments.

KEYWORDS *experimental design; field studies; measurement methods; study design*

INTRODUCTION
The impacts of ventilation on the health and comfort of building occupants has long been recognized through the promulgation of ventilation standards and regulations dating back to the late 19th century (Klauss, Tull et al. 1970; Janssen 1999; Stanke 1999). Current standards, such as ASHRAE Standards 62.1 and 62.2 (ASHRAE 2010; ASHRAE 2010) and analogous standards in Europe (CEN 2007), serve as the basis for current building design and regulations.

Building ventilation rates are key to understanding building IAQ. The connection between outdoor air ventilation rates and indoor concentrations is based on the mass balance theory used to analyze indoor contaminant concentrations, which can be expressed as follows for a single zone under steady state conditions:

$$C_{in} = C_{out} + \frac{S}{Q} - \frac{R}{Q}, \tag{1}$$

where C_{in} is the indoor concentration, C_{out} is the outdoor concentration, Q is the outdoor air ventilation rate, S is the indoor contaminant source strength, and R is the rate at which the contaminant is removed by filtration, air cleaning or other mechanisms. This relationship, more generally in its transient or multizone formulation, is used to analyze indoor contaminant concentrations to determine contaminant source strengths and other parameters of interest. Therefore, outdoor air ventilation rates are fundamentally important in understanding indoor contaminant transport.

In addition to research on indoor contaminant fate and transport, IAQ research also involves survey studies in which a number of buildings are studied to investigate relationships between environmental conditions, building characteristics, occupant symptoms and perceptions of the occupied space (Fisk, Mendell et al. 1993; Bluyssen, Fernandes et al. 1996; EPA 2006). Ventilation rates are one of many building characteristics included in such surveys, and is of great interest to understand how the design and operation of ventilation systems impact indoor pollutant levels and building occupants. Research continues to explore the connection between ventilation rates and occupant health effects and productivity (Wargocki, Sundell et al. 2002; Wargocki, Wyon et al. 2005; Seppanen, Fisk et al. 2006; Seppanen and Fisk 2006).

The objective of this paper is to explore the challenges related to measurement of ventilation in IAQ studies and to examine the need for improved reporting in the future. This objective is addressed through an analysis of ventilation rate measurement methods employed in a number of research papers drawn from a study of the association of ventilation rates and health impacts (Sundell, Levin et al. 2011). This study consisted of a review of peer-reviewed papers on ventilation and health, from which 26 papers were identified as informative to the goals of the study, i.e., to determine the relationship between ventilation rates and occupant health outcomes. In examining these papers, a number of different techniques were used to assess ventilation rates and a range of detail included in the description of these techniques.

METHODS

In order to evaluate how ventilation rate measurements are performed and reported, each of the 26 papers in the cited study (Sundell, Levin et al. 2011) was examined regarding the ventilation measurement method used and the manner in which it was described. The methods considered include primarily tracer gas dilution and volumetric airflow using an anemometer. Tracer gas 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 the other, or they may be similar in magnitude. There are several tracer gas methods: decay, constant concentration and constant injection (ASTM 2006). The latter method includes what is sometimes referred to as the PFT (perfluorocarbon tracer) method, but which is generally implemented with a constant tracer gas source and a sampling method that determines the average tracer gas concentration over the sampling period. The use of occupant-generated CO_2 to estimate outdoor airflow rates is essentially a constant injection method, though the assumptions required for this method to be valid are not always evaluated in many applications (Persily 1997). Some studies measure ventilation system airflows using some type of anemometer device. These measurements may occur in the supply vent to a room, in an outdoor air intake duct, or in an exhaust duct from the room. Such measurements can be accurate, but it is important to understand the system design to determine if these airflows do indeed provide a useful measure of the ventilation rate of a room or space.

In addition to a number of different measurement methods, a variety of metrics are used to characterize ventilation rates, including air change per hour, volumetric airflow rate per person or per floor area, and outdoor air fraction. Too many studies report measured CO_2

concentration as a surrogate for ventilation, despite the fact that it is a good surrogate only under very limited circumstances (Persily 1997).

RESULTS

Table 3 summarizes the measurement methods and metrics used in the 26 cited studies. The first portion of the table, Ventilation Rate Method, summarizes how each paper measured the ventilation rate, with the first subsection "Tracer Gas" referring to papers that used tracer gas methods. The use of occupant-generated CO_2 to estimate outdoor airflow rates is listed separately. "Not specified" refers to the single paper that reports the use of a tracer method, but does not indicate which one. Only one of the 12 papers using a tracer gas method includes a description of where the tracer was injected and sampled. Tracer injection and sampling are critical to the proper application of all tracer gas methods, based on the assumptions on which they are based, and should be included in any discussion of tracer gas application.

Table 3 Summary of Ventilation Measurement Methods and Metrics

VENTILATION RATE METHOD	**# of studies**
Tracer gas	**12**
Tracer gas decay	6
Constant concentration	1
Constant injection	2
Estimate from occupant generated CO_2	2
Not specified	1
Supply vent to room	**2**
Duct flow: intake only	**1**
Duct flow: exhaust only	**4**
Not described	**2**
Percent outdoor air	**3**
Tracer gas	2
Estimate from design/observation	1
CO_2 concentration	6
VENTILATION METRIC	
Air changes per hour	10
Volumetric airflow per person	14
Volumetric airflow per floor area	0
Percent outdoor air intake	3
CO_2 concentration	6
High, moderate or low	1

Several papers measured airflows in the ventilation system using an anemometer device. The table notes measurements in the supply to the room, in an outdoor air intake duct, and in the exhaust duct from the room. Two papers, noted as "Not described,' report ventilation rates but not how they were determined. Three reports present values for the percent outdoor air intake, in one case estimated from the design rather than actually measured.

As seen in the lower portion of Table 3, the papers use a variety of metrics to characterize ventilation. Some of the papers report only the outdoor air fraction. One paper simply reports the rate as high, low, moderate or some other such qualitative term. The point of this tally is that the use of different metrics makes it difficult to compare the results of different studies.

Table 4 summarizes the papers' descriptions of the measurement methods, starting with the instrumentation employed. Only half the papers identified the instrumentation, but none of them described the instrumentation in any detail, e.g. the type of detector used to determine the tracer gas concentration. Note that several papers cited references for the measurement method, where this information may be provided. Four papers describe how the instruments were calibrated, and only four report the measurement uncertainty. The lack of measurement uncertainty values is particularly striking, as a measured value cannot be interpreted without information on its accuracy. The thoroughness of the instrumentation description is summarized in the table using four categories: no mention of the instrumentation at all; mentioned but not described; described but not very well (e.g., nothing included on calibration or uncertainty); and one paper in which the hardware is described fairly well.

Since ventilation rates are in general a strong function of system operation and weather conditions, it is important to consider the variation in ventilation rates. The first step in doing so is to understand the building and its ventilation system, and how they might contribute to variations in ventilation rates. This issue was considered by noting those papers that reported only a single ventilation rate measurement, that reported more than one, and that were not clear. The duration of the measurement is also characterized first as not being described, instantaneous or short term (on the order of minutes), short term (one or several hours), and long term (more than one day). Cases where the ventilation assessment is clearly at the same time as the health effect assessment are noted as such.

Table 4 Summary of Ventilation Measurement Description

	# of studies
Instrumentation	
Measurement instrumentation identified	13
Measurement instrumentation described	0
Instrument calibration described	4
Uncertainty reported	4
Instrumentation description	
No mention of instrumentation	12
Instrumentation mentioned but not described	5
Described, but not well, e.g. nothing on calibration or uncertainty	8
Well described	1
Instrumentation possibly described in reference	10
Number of measurements	
Only one measurement	4
Measurements repeated	7
Not clear if repeated	12
Time period of measurement	
Short or long term measurement?	
0: not described	18
1: instantaneous/short term	3
2: short (hours)	0
3: long (more than 1 day)	5
Simultaneous with health evaluation	5

DISCUSSION

While only a limited number of studies were considered in this analysis, the manner in which the reported ventilation rates are described makes it difficult to interpret the results. Since these studies specifically draw conclusions with respect to the relationship of ventilation and health, one might be expect them to discuss the ventilation measurement more thoroughly. Given the importance of ventilation to IAQ and the need for better information on the association of ventilation with health impacts and indoor contaminant concentrations, the manner in which ventilation is evaluated and in which ventilation measurements are reported are in need of improvement.

When reporting ventilation measurements, the following information needs to be included:

- Measurement method employed and details on its application
- Time over which the measurement was made
- Number of measurements and associated environmental (weather) and building (system operation) conditions.
- Instrumentation and calibration method employed
- Uncertainty in measured ventilation rates

Most measurement standards, e.g. ASTM E741 for tracer gas dilution (ASTM 2006), contain reporting requirements that address these items in detail. While the need for improvement is clear, it is less clear how to change current practice in conducting ventilation measurements and reporting results. A standardized guide to conducting and reporting ventilation measurements for IAQ studies might be helpful. Journals that publish IAQ studies could state clear policies for authors on reporting ventilation rates in submitted papers.

CONCLUSIONS

This analysis, while limited to only 26 selected papers, highlights the need for better reporting of ventilation rate measurements methods in IAQ studies. For these particular papers, the lack of information provided makes it impossible to evaluate the methods employed and the quality of the results. To summarize, more than 10 % of the papers do not describe how the ventilation rates were determined and more than 10 % report the outdoor air intake fraction instead of an actual ventilation rate. About one quarter use the indoor CO_2 concentration as a metric, despite the well documented fact that it is not a good indicator of ventilation under many circumstances (Persily 1997). About 75 % do not describe the time scale over which the measurements were made, and about half of the studies are unclear as to whether the measurement was repeated or not. Just over 10 % do state that the measurement was only conducted once. Given the fact that ventilation rates vary over time, under many circumstances, a single measurement is not very informative. Finally, about half of the studies do not even mention the instrumentation used to make the measurements and only 4 of the 26 studies report a value for the measurement uncertainty.

If the field of IAQ is going 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 in these characterizations. When reporting ventilation rates, it is essential that the methods employed be well-described, that they present the details of the approach 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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