Evaluating Ventilation Performance

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Chapter 20-1, Handbook of Indoor Air Quality, pp. 1-39
https://doi.org/10.1007/978-981-10-5155-5_20-1
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Springer Singapore

Abstract

The evaluation of building ventilation performance is critical to understanding indoor contaminant transport dynamics and interpreting indoor contaminant measurements. However, ventilation performance involves many different issues and metrics that can make such evaluations challenging. Also, many indoor air quality research studies have not included adequate evaluation of building ventilation and its impacts on indoor contaminant concentrations. There are several reasons for this history of neglect; they include the complexity of ventilation, the cost associated with the measurements, and the lack of guidance on how to conduct such evaluations. This chapter explains what is involved in evaluating and understanding ventilation performance in buildings, with a focus on the parameters involved, how building configuration and ventilation system type impact how such evaluations are conducted, and the connection between the reasons for ventilation evaluations and the strategies employed. Among the ventilation performance parameters that are covered are whole building outdoor air change rates, ventilation system outdoor air and supply air delivery rates, and envelope infiltration rates. Some of the key points stressed in this chapter include the following: actual ventilation performance often does not match design intent; ventilation rates vary significantly with weather and system operation and therefore a single value is not particularly useful without information on the conditions during the measurement; multiple repeated measurements under different conditions are required in order to fully understand ventilation in a building; and, while indoor carbon dioxide concentrations can be a useful tool in evaluating ventilation, its application is based on multiple assumptions that must be valid.

Keywords: airflow, building performance, indoor air quality, infiltration, ventilation

Introduction

Building ventilation performance is important for several reasons, including impacts on indoor air quality (IAQ), energy use, thermal comfort, occupant health and safety, and degradation of building materials and furnishings. In some respects, the impacts are relatively straightforward. For example, the energy required for heating and cooling is based primarily on the amount of outdoor airflow into a building, the indoor-outdoor air temperature difference, and air properties such as specific heat and humidity ratio. However, the details of energy and other impacts are often more complex as they depend on the details of the relevant airflows, the heating, ventilating and air-conditioning (HVAC) equipment in the building, building and equipment operating strategies, and other factors.

Building ventilation performance cannot be characterized by a single metric but involves a range of performance issues and parameters. The next section of this chapter discusses ventilation performance in more detail, with a focus on ventilation systems and building characteristics. These performance issues include system status, envelope air leakage, ventilation system airflow rates, outdoor air change rates, interzone airflow and air distribution. A key step in understanding the significance of ventilation performance is to understand how the system is intended to perform, sometimes referred to as the design intent. To that end, building and system design information is discussed after the section on performance issues. The next section covers measurement methods to quantify performance, accounting for building configuration and system design in making these measurements, as well as capturing variations in performance over time and as a function of weather. Comparison of measurement results to the system design, as well as to relevant standards and guidelines, is also discussed.

It is important to note that many IAQ studies of buildings have done a poor job of evaluating ventilation. This is demonstrated by an analysis of the ventilation characterization approaches in a key review of 26 peer-reviewed papers on the relationship of ventilation rates and occupant health outcomes (Sundell et al. 2011). A number of different techniques were used to assess ventilation rates in these papers, and there was a range of detail included in the description of these techniques. However, an analysis of the ventilation assessment approaches in these studies revealed that about half of them do not mention the instrumentation used to make the measurements and only four report a value for the measurement uncertainty (Persily and Levin 2011). More than 10 % of the papers do not describe how the ventilation rates were determined, and about 75 % do not describe the time scale over which the measurements were made. Other common problems with the treatment of ventilation in IAQ studies is a lack of sufficient description of how the building is intended to be ventilated, information on the HVAC equipment in the building including design ventilation rates, or data on weather and equipment operation during the ventilation measurements. This chapter describes how to evaluate ventilation in buildings with different ventilation system types, and what information needs to be provided with ventilation measurement results to support their interpretation and use.

Terminology

While this chapter discusses ventilation performance parameters in some detail, it is important to note that the relevant terms are not always used consistently by researchers, practitioners and others. Figure 1 shows a mechanically ventilated building with a ventilation approach that is typical of many commercial buildings in the U.S., with several key terms displayed. Note that many of these terms are defined in ASHRAE Standard 62.1 (ASHRAE 2019a). (While a U.S. commercial building perspective exists for much of the discussion in this chapter, much of this material also applies to residential buildings and non-U.S. buildings.) Sometimes outdoor air is referred to as makeup air, often when it is needed for combustion or exhaust ventilation equipment. In many systems, outdoor air is mixed with recirculated air that flows from the ventilated space as return air. In general, a portion of the return air leaves the building as exhaust air or spill air. Some ventilation systems, sometimes referred to as 100 % dedicated outdoor air systems (DOAS), do not recirculate any air. The mixture of outdoor air and recirculated air flows through an air conditioning system where it is heated/cooled, humidified/dehumidified and filtered. The air then flows to the space as supply air, where it serves the needs of that space for outdoor air ventilation and in many cases also provides thermal conditioning. The figure does not show local mixing boxes such as variable-air-volume (VAV) boxes that are sometimes used to mix supply air (sometimes referred to primary air in such systems) with room air drawn to meet local thermal requirements. Figure 1 also shows local exhaust airflow, which is often used to remove locally-generated contaminants before they mix with air in the rest of the building. Local makeup air is sometimes provided rather than drawing air from elsewhere in the building.

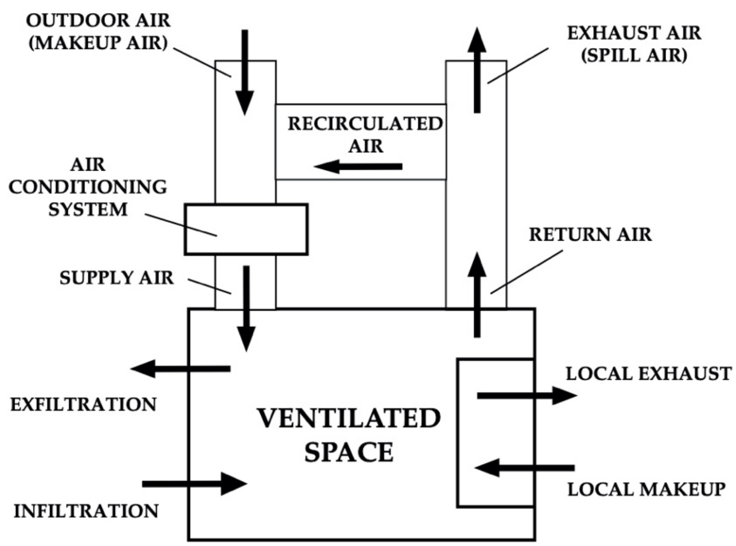

Figure 1 Schematic of Ventilated Building

It is important to note that some individuals consider ventilation to be outdoor air and others consider it to be supply air; the term “air change rate” also does not specify the type of air. To avoid confusion, it is important to clarify the air source as outdoor or supply air when discussing ventilation. ASHRAE Standard 62.1 defines ventilation as follows: the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space. This definition does not mention outdoor air but focuses on air treatment (e.g., heating, cooling and filtration), delivery and exhaust. In this chapter, when the term ventilation appears without a qualifier, it is being used in this general sense to cover outdoor and supply air delivery, air treatment and exhaust air removal.

One issue that is often not fully appreciated in considering the impacts of ventilation is the distinction between infiltration and outdoor air ventilation. Infiltration refers to uncontrolled entry of outdoor air through unintentional openings in the building envelope, i.e., leakage. Infiltration is driven by indoor-outdoor air pressure differences due to weather (wind and temperature) and the operation of building systems (e.g., exhaust fans and vented combustion equipment). Exfiltration refers to airflow from the building interior to the outdoors, again through unintentional leaks. The term infiltration is often used to describe the combined processes of infiltration and exfiltration. It is important to note that infiltration rates are not controlled, nor is the distribution of infiltration air within a building. Additionally, infiltration can have negative impacts on IAQ (since infiltration air is unfiltered), indoor moisture management, and material durability. Outdoor air ventilation refers to outdoor airflow into a building through intentional openings such as intakes, vents and open windows. Mechanical ventilation is outdoor air ventilation induced by powered equipment, i.e., fans, while natural ventilation is driven by weather. Ventilation systems, mechanical or natural, that are well designed, installed, operated and maintained are preferable to infiltration for meeting building ventilation requirements since they can provide the desired ventilation rate where it is needed, avoiding both under- and over-ventilation. Ventilation systems also provide opportunities to reduce energy impacts, such as by recovering heat or moisture from the outgoing air.

Reasons for Evaluating Ventilation

When conducting any measurement, it is essential to consider why it is being done and what will be done with the results. When deciding what to measure as part of a building ventilation evaluation, one must start with the reason for the evaluation, as well as the configuration of the building and the ventilation system design. Building and system issues are discussed later in the chapter, but the reason for the ventilation evaluation is critical. There are multiple reasons that one might evaluate ventilation in a building or a space within a building, and the reasons will impact the approach that is used including the timing of the evaluation and the financial resources and expertise required. Reasons for evaluating ventilation include: a research study of ventilation or IAQ, an effort to understand the reasons for an IAQ problem, and a commissioning effort to ensure the building and system are operating as intended. Research can range from an intense, long-term study of a single building to a survey of dozens to hundreds of buildings involving short-term (hours to days) measurements. Long-term ventilation studies of a building may be designed to characterize ventilation and infiltration rates and other performance parameters as a function of weather conditions, system operation and occupant activities, and therefore require many real-time measurements over days, weeks and perhaps seasons. To facilitate long term, real-time measurements, automated measurement and data acquisition systems are very helpful if not essential, perhaps involving a temporarily-installed tracer gas measurement system or anemometers in HVAC ductwork. Long-term research studies of indoor contaminant levels would involve similar (long-term, real-time) ventilation measurements, though they may focus on a limited number of ventilation performance parameters. At a minimum, the interpretation of long-term indoor contaminant measurements requires outdoor air change rates to understand variations in contaminant concentrations, often employing mass balance analysis.

For short-term IAQ research studies, which may involve only a single or a small number of indoor contaminant concentration measurements, it generally doesn't make sense to install instrumentation and data acquisition systems that may be justified in a longer term study. However, air change rates and perhaps other ventilation performance parameters still need to be quantified to interpret indoor contaminant concentration measurements. Such analyses may also need system supply airflows to account for contaminant removal by filtration and air cleaning equipment and infiltration rates to account for outdoor contaminant penetration (i.e., the removal of outdoor contaminants as they flow through building envelope leaks). A special case of short term IAQ studies are building surveys, in which dozens of buildings or more are studied to capture a range of performance parameters including the concentrations of different contaminants, thermal comfort conditions, non-thermal indoor environmental parameters (e.g., lighting and acoustics), and occupant symptoms and perceptions of the indoor environment. Several IAQ surveys have been conducted over the years, most of which have included some measurements of ventilation performance (EPA 2006; Bluyssen et al. 1996; Offermann 2009; Bennett et al. 2012; Bennett et al. 2011). In these studies, the cost of the measurements is critical and difficult choices often have to be made about which parameters will be measured and the level of sophistication for the various measurements. But given the first-order relationship of ventilation and IAQ, these studies need to include reliable ventilation measurements to be useful.

Short-term IAQ studies are also conducted to understand the cause(s) of occupant IAQ complaints or health problems. Such forensic investigations generally include an assessment of the potential role of the ventilation system and how its performance may be contributing to the problem being studied. Most of these studies are done using approaches determined by the investigator, but there is an ASTM standard for investigating residential IAQ issues that includes some aspects of ventilation performance (ASTM 2014). The specific parameters included in IAQ investigations and the manner in which they are assessed are generally a function of the building and its HVAC systems, the nature of the IAQ problem being investigated, and the contaminant sources that could be causing the problems. These investigations may require measurement of outdoor air change rates, supply airflow rates and infiltration rates. They may also merit assessment of interzone airflows that can transport contaminants from zones where key sources are located to the zones where the occupants are experiencing symptoms. This chapter does not cover the measurement of interzone airflows in detail, but it does discuss their measurement and describes some qualitative tools that can be useful.

Another reason for evaluating building ventilation is as part of a commissioning effort to ensure the system is operating as intended. Commissioning is becoming increasingly common, and is in fact required by high-performance building standards and rating systems (ASHRAE 2020). HVAC system commissioning has been part of normal practice for decades, where it is referred to as testing and balancing (TAB) (ASHRAE 2008). As noted in the foreword to ASHRAE Standard 111, "Field test results are considered essential to designers, manufacturers, and installers to better enable them to evaluate the results of their design, equipment performance, and installation techniques under actual operating conditions." TAB is typically done for new buildings and systems, but there is value in re-commissioning systems at various points in the life of a building to ensure that it is still performing as intended given the likelihood that control sensors and hardware may have degraded over time or building space use has changed.

Building and System Impacts on Ventilation Evaluation

In addition to the reasons for conducting an evaluation, the building configuration and the ventilation system design and layout are key to how a ventilation evaluation is conducted, specifically what is measured and how. Buildings and systems are extremely variable, and these variations must be considered when planning and conducting ventilation evaluations. Key building configuration parameters include building size, how the building is divided into zones, how zones are connected in terms of airflow (e.g., doorways, common hallways), and ventilation approach(es) employed. In describing the size of a building, one needs to include the building height, the number of stories, and floor area and height of each story. Zoning covers how the building is laid out into different sections or sometimes wings, which portions are handled by which ventilation systems, and how space use and occupancy vary among zones. These latter factors will determine how much outdoor air is required by ventilation standards and regulations. Other relevant building features that should be considered in the assessment include information on the climate of the building location, e.g., annual heating and cooling degree days, monthly average outdoor air temperature and wind speed, and wind exposure of the building.

The approach used to ventilate the building is key to planning a ventilation evaluation effort, and involves the following questions: Is there a mechanical ventilation system that brings in outdoor air, or is the building ventilated only by infiltration and natural ventilation? Does the ventilation system provide space conditioning (heating and cooling) only with no outdoor air intake? Does the system provide 100 % outdoor air with no recirculation? Are there local exhausts in kitchens and toilet rooms? If natural ventilation is used to ventilate the building, is it a designed system (e.g., thermal stacks and designed air inlets), or simply operable windows? If mechanically ventilated, does the building contain a central, ducted system that serves multiple rooms or zones? Or do the systems serve single zones, e.g., using through-the-wall fan coil units. When are these systems intended to operate, i.e., is operation based on time of day, controlled by a thermostat or manual? If the system provides outdoor air intake, is that intake rate varied based on weather conditions, indoor contaminant concentrations (e.g., CO_2 demand control ventilation), time of day, or some other approach? These questions must be answered in order to understand how the building is intended to be ventilated, which ventilation performance parameters are relevant, and how they should be measured.

This chapter is organized into three primary sections. The following section describes performance issues that need to be covered in conducting ventilation assessments, as well as the specific parameters used to characterize each issue. That section is followed by a description of the system design information that needs to be collected as part of ventilation assessments to support interpretation of the results. The third section focuses on the measurement methods used to determine the performance parameters described previously. The chapter concludes with some key points regarding building ventilation assessment. Note that this chapter is not a detailed guide on how to conduct such assessments, including how to make the often-challenging decisions on exactly what to measure in a specific building and how to do so. It might be considered as a heavily annotated menu rather than a how-to cookbook. The author is planning to expand this material into a much longer guidance document (the cookbook) that will contain those operational details. The reader can access a great deal of useful information on building ventilation and its measurement via the AIVC (Air Infiltration and Ventilation Centre) bibliographic database Airbase, which contains 22000 references and 16000 documents, at https://www.aivc.org/resources/airbase.

Performance issues and parameters

This section describes the performance issues that are relevant to ventilation evaluations and specific parameters under each. As noted above, the parameters that are assessed as part of a building ventilation evaluation and the manner in which they are assessed depend on the purpose of the evaluation and the details of the building and its ventilation systems. Table 1 lists key ventilation performance issues and parameters, with methods for their measurement or assessment covered later in this chapter.

Performance issue	Relevant parameters
System status	Operation
	Condition
	Maintenance
	Design documentation
Envelope air leakage	Envelope airtightness
	Building infiltration rate
	Indoor-outdoor pressure difference
Ventilation system airflow	Outdoor air intake rate
	Percent outdoor air
	Supply airflow rate (system and space level)
	Return airflow rate (system and space level)
	Exhaust airflow rate (system and space level)
	Operating status and mode of operation
Outdoor air change rate	Whole building
	Room or other building zone
Interzone airflow	Airflow rates*
	Interzone partition airtightness
	Interzone pressure differences
Air distribution	Ventilation efficiency or effectiveness*

* Measurement methods not described in this chapter

Table 1: Ventilation performance issues and parameters

The first performance issue in Table 1 is system status, which is fairly broad and mostly qualitative but extremely important. It includes whether the system is operating and the condition of the system and its components, including cleanliness and moisture damage, whether there are clearly dysfunctional or broken components (e.g., dampers) and filter condition. Another important aspect of system status is maintenance, including the intended system maintenance schedule and records of maintenance activities. Since maintenance is critical for keeping systems performing as intended, this information is key to evaluating ventilation systems. The last parameter under system status in Table 1 is the existence of system design documentation, the specifics of which are described in more detail in the next section of this chapter. It is unfortunate, but in many buildings such design documentation is nonexistent or at least not current. For example in the EPA BASE study of 100 randomly selected office spaces in the U.S., design values of minimum outdoor air intake rates were not available for roughly half of the buildings studied (Persily and Gorfain 2008).

The second performance issue in Table 1, envelope air leakage, is important because infiltration is the only outdoor air ventilation mechanism in many buildings, particularly residential buildings and some older commercial and institutional buildings. In fact, infiltration is generally a significant portion of the total outdoor air change rate in all buildings, even buildings with relatively tight envelopes (Ng et al. 2015). Infiltration impacts heating and cooling energy use and provides a path for outdoor contaminants to enter a building. As noted earlier, infiltration is not a good way to ventilate a building since the rates and air distribution are not controlled, the incoming air is not filtered, and infiltrating air can lead to indoor moisture problems and material degradation. Envelope airtightness, measured with a fan pressurization test, is a key parameter for understanding the potential for infiltration. It is usually expressed as a volumetric airflow rate or effective leakage area at a reference indoor-outdoor pressure differential and is typically normalized by the building volume or the envelope surface or floor area. Airtightness measurements can be completed relatively quickly (compared with infiltration rate measurements) and provide a single parameter that is useful for comparing buildings and for predicting airflows using computer models and other calculation tools (ASHRAE 2021; Dols and Polidoro 2020; Breen et al. 2014). There is a significant body of work on field studies of building airtightness in residential and commercial buildings that can be useful for comparing test results (Chan et al. 2012b; Chan et al. 2012a; Emmerich and Persily 2014). However, envelope airtightness measurements are conducted under imposed indoor-outdoor pressure differences to override pressures due to weather effects. Infiltration rates, on the other hand, are the rate of outdoor air entry through leaks in the envelope due to normal weather effects and the operation of local exhaust fans and vented building equipment (e.g., combustion appliances), and therefore provide a measure of the airflows that are actually occurring in the building. Infiltration rates are therefore more relevant to real-time performance, but the values still vary with weather and equipment operation and only indicate the rates for the conditions during the measurement.

Infiltration rates are typically expressed in air changes per hour or h^{-1}, which is the volumetric airflow rate of the infiltrating air divided by the building volume. These units are commonly used for air change rates, whether they are outdoor, supply or some other airflow. Some people use ACH, ACPH or other non-standard units, or refer to these airflows as air exchange rates. The author of this chapter objects to using invented units like ACH, noting that the pure SI unit for air change rate is actually s^{-1}. The term “air exchange rate” is also flawed because it implies that air is simply exchanged between the outdoors and indoors when, in fact, airflow into and out of buildings often takes very indirect and circuitous routes involving intermediary spaces such as crawl spaces, attics, wall cavities and plenums. Air change rate is preferred as simply a unit, with the type of airflow described using modifiers such outdoor air intake, supply air or infiltration.

In discussing air change rates, including infiltration, it is important to note that if a space has an outdoor air ventilation rate of one air change per hour, it doesn’t mean all of the air is replaced in one hour. One air change per hour means that a volume of air equal to the space volume enters every hour, but that entering air mixes with the air already in the space such that the air leaving is a mixture of air that entered recently and air that has been in the space for a longer time. If there is a uniform contaminant concentration in the space, the concentration decays exponentially with a time constant equal to the inverse of the air change rate. Therefore, after one time constant (1 h for one air change per hour) the contaminant concentration is reduced to 63 % of its initial value.

Measured indoor-outdoor air pressure differences across the building envelope can also be a useful indicator of envelope leakage, as their sign and magnitude provide information on where air may leak into and out of a building over its exterior surface. These pressures are not readily convertible to actual infiltration rates, but they can be helpful for understanding the direction of infiltration airflows, particularly at key locations such as entrances and areas where there are strong outdoor sources, e.g., loading docks. Indoor-outdoor pressure differences vary with location and time, and therefore they should be measured under a range of conditions to better understand the airflow dynamics. In some cases, pressurization testing or infiltration rate measurements may not be feasible, and indoor-outdoor air pressure measurements can be quick and useful even though they provide less information.

The next performance issue listed in Table 1 is ventilation system airflow, along with the parameters that can be used to characterize these airflows. Note that many of these are displayed in Figure 1. These parameters include: outdoor air intake rate - how much outdoor air is brought in by the system; supply air flow rate - how much air the system delivers to the occupied portion of building or to a specific room or zone; percent outdoor air intake of the system - the ratio of the outdoor air intake to the supply airflow rate; return airflow rate - how much air the system removes from the occupied portion of building or from a specific room or zone; and exhaust airflow rate - the amount of air exhausted by a central system or local exhaust. Not all of these parameters apply to all ventilation systems, e.g., some systems do not have any return airflow but rather supply only outdoor air to occupied spaces, and some systems do not have any outdoor air intake. The latter is the case for most space conditioning systems in U.S. homes, although that is changing in newer housing. The last listed parameter for ventilation system airflow (Operating status and mode of operation) is actually a number of different parameters using the overarching term operating status (e.g., is the system on or off?) and what mode of operation is currently in effect. For instance, many systems in commercial buildings have several modes of operation including minimum outdoor air intake and economizer operation.

The outdoor air change rate performance issue in Table 1 refers to the sum of the airflow rate due to infiltration and the outdoor air intake, i.e., the total rate at which outdoor air enters a building. This is the outdoor airflow rate relevant to heating and cooling loads as well as contaminant mass balance analysis. When considering contaminants with nonzero outdoor concentrations, the total outdoor air change will generally need to be considered separately for the outdoor air intake by the system and for the infiltration through the envelope. Outdoor contaminants entering via the system intake may need to account for removal due to filtration and air cleaning, and contaminant entry via infiltration may need to account for penetration losses. Infiltration is sometimes assumed to be negligible, relative to outdoor air intake rates, but in the absence of measurements or sound calculations, this assumption cannot be supported and may lead to the neglect of important air and contaminant entry into a building. Building outdoor air change rates include all of the outdoor airflows at all infiltration entry points on the envelope and the system intakes for all systems. If there are many systems, it can be challenging to measure at all of the intakes, but conceptually, whole building outdoor air change rates are clearly defined. Outdoor air change rates can be expressed as volumetric airflow rates or air changes per hour, which is the volumetric rate divided by the interior volume of the building being considered. In many cases it can be challenging to define the interior volume given that many buildings are divided into conditioned spaces, unconditioned spaces (e.g., attached garages) and semi-conditioned spaces (e.g., attics and basements), which often have significant airflows to and from the occupied and conditioned spaces. The interactions of these volumes can also complicate tracer gas measurements of air change rates as discussed below.

In many cases, researchers and practitioners are interested in outdoor air change rates for individual rooms. However, rooms in buildings exist as part of multi-zone building airflow systems, with airflows between rooms, and therefore room outdoor air change rates are not straightforward to define and less so to measure. The outdoor air change rate for a room would include outdoor air infiltration directly into the room and outdoor air delivered to the room by a ventilation system. The influence of airflow from other rooms on contaminant concentrations are more complex, and their measurement involves multizone tracer gas techniques. These techniques are mentioned in the section on Measurement Methods but are not described in detail. In some studies, CO_2 concentrations in individual rooms, often bedrooms, are used to estimate outdoor ventilation rates to the rooms. However, as discussed in the Methods section, these techniques generally neglect interzone transport of CO_2 from other rooms, resulting in uncertainties that are difficult to characterize. Note that CO_2 concentrations are not listed as a metric of ventilation in Table 1, despite their common use. As explained below and in more detail elsewhere (ASTM 2018b), CO_2 concentrations are not direct measures of ventilation. Under some circumstances they can be used to estimate per person ventilation rates using well-established tracer gas methods, but this application requires the validity and verification of several key assumptions.

The next performance issue in Table 1, interzone airflow, is important for contaminant mass balance analyses, particularly when building zones are at different concentrations, and for achieving an overall understanding of the airflow dynamics in a building. They are difficult to measure as they require the use of multizone tracer gas techniques, which are not typically employed except in research studies. In lieu of measuring interzone airflows directly, one can measure the airtightness of the partitions and the pressure differences between zones. Airtightness of interzone partitions can be assessed using fan pressurization methods and have been conducted to quantify the air leakage between attached garages and the living spaces of residences (Offermann 2009; Nirvan et al. 2012) and between rooms in low-energy homes (Guyot et al. 2016; Ng et al. 2018). Interzone pressure differences can be helpful in understanding the direction of these airflows. As in the case of indoor-outdoor pressure differences, interzone pressure differences are not easily converted to actual airflow rates, but they can be helpful for understanding the potential for contaminant transport from zones containing sources of interest to other zones. Interzone pressures vary with location and time, and therefore need to be repeated under a range of conditions to understand airflow dynamics.

The last performance issue listed in Table 1 is air distribution, which refers to the manner and uniformity with which ventilation air is delivered to a space. Some air distribution systems, for example in many U.S. office buildings, are designed to mix the supply air with air in the occupied space and are often referred to as mixing systems. Other air distribution systems are designed to ventilate a space in a manner resembling plug flow, e.g., operating rooms, in which air enters and “sweeps” through the space in an approximately one-dimensional airflow pattern. Air distribution can be quantified using various measures of ventilation effectiveness, such as age of air, which are described briefly in the Measurement Methods section.

Building and System Design Information

As noted earlier, a key factor in determining how to assess building ventilation is the design of the building and its ventilation system(s), including how the building is configured, how ventilation is intended to occur, system design airflows, and the assumptions on which the design is based. Gathering system design information is an essential part of assessing ventilation in a building, as such information is critically important as a basis for comparing the results of ventilation measurements. Field studies have shown that building ventilation performance is too often inconsistent with design intent (Persily 2016; Persily and Gorfain 2008), and such discrepancies can increase energy use and degrade IAQ. Examples of performance not matching design intent are noted later in this chapter, but the important message is that one should never assume a building is performing as intended. Measured data are essential to determining what is actually occurring regarding ventilation and airflow. It is interesting to note that many building and IAQ surveys contain entries for an HVAC description that are only a line or two. Ventilation systems are more complex than can be captured in a small amount of space and require some detail in order to document important design information. Several previous survey studies of multiple buildings have collected system design information. The EPA BASE study is of particular note, as it had detailed protocols and checklists for collecting information on the building, the portion of the building being studied, and the system serving that space (EPA 2003). A modified version of the BASE protocol was employed in a study of 37 small and medium commercial buildings in California (Bennett et al. 2011). A number of other studies of large numbers of buildings have collected building and system information (Derbez et al. 2018; Ramalho et al. 2013; Offermann 2009; Pigg et al. 2014; Weisel et al. 2005). However, standardized protocols for collecting building and system design information have not been developed, but they could be quite useful in future studies.

Table 2 contains information needed to describe a ventilation system. The items in bold font might be considered the most critical, but all of them are important. The first entry to Table 2 relates to the system status, which in the context of design involves determining whether the design documentation exists and is up-to-date. Building use and applicable standards and regulations change over time, and the design should be updated to reflect these changes, but that doesn't always happen. System maintenance schedules are also an important aspect of system design given the importance of maintenance in keeping systems performing as intended.

The next aspect of system design that needs to be captured is the approach used to ventilate the building of interest. Is the building ventilated by unintentional infiltration only? Or is there a designed mechanical or natural ventilation system? Designed natural ventilation systems are those that include elements that are arranged and sized based on engineering principles, e.g., thermal stacks and inlet vents, which are described elsewhere (CIBSE 2005; Dols et al. 2012). The term hybrid or mixed-mode ventilation is used when a building uses both mechanical and natural ventilation. Local exhaust systems are typically located in buildings zones, such as kitchens and bathrooms, with high contaminant generation rates (including moisture) in order to remove those substances before they have a chance to mix with the rest of the building air. Mechanically and naturally ventilated buildings may also have local exhausts, although they often have central exhaust systems with a single fan connected to a duct system that removes air from multiple spaces, such as toilet rooms throughout a building. Whether a building has operable windows, which would fall under natural ventilation but are typically not a designed natural ventilation system, is also part of a building's ventilation approach.

System Category	Design information
System status	**Design documentation** Maintenance schedule
Ventilation approach	**Infiltration only**
	Mechanical ventilation
	Natural ventilation
	Hybrid ventilation
	Local or central exhaust
	Operable windows
Mechanical ventilation	**Type: supply or exhaust only, 100 % outdoor air, recirculation**
	Supply airflow rate
	Minimum and maximum **outdoor air intake rate**
	Basis for minimum outdoor air intake rate (which standard or building regulation; calculations and assumptions employed)
	Particular filter locations and efficiencies
	Exhaust airflow rate: system and space level
	Space-level air distribution, e.g., use of mixing boxes and description of their controls.
	Sequence of operations
	System maintenance schedules by component
Natural ventilation	**Operable windows** (location, size of openable area)
	Purpose-provided vents (location, size)
	Engineered system, description of major elements and intended airflow patterns, primarily where air is intended to enter and leave the building and the occupied spaces, <u>and assumed operating conditions</u>
	Controls: occupant-based, automated (describe)
	Estimated ventilation rates and method of estimation
Hybrid or mixed-mode ventilation	**Design concept:** when would mechanical system operate (e.g., based on season, time of day, weather)
	Above information for both mechanical and natural

Table 2: Ventilation system design information (with most essential information in bold font)

The next section of Table 2 lists information that describes mechanical ventilation systems, the first being the type of system: supply or exhaust only, 100 % outdoor air, or having the ability to recirculate return air. There are many terms used to describe ventilation systems in terms of how they perform heating and cooling and how they distribute air to spaces, such as variable-air-volume, dual-duct and others, but those details are not covered here. Rigorous system taxonomies do not yet exist to capture this information, although EPA (2003) contains a comprehensive approach to HVAC system description that merits updating. For each air handling unit (AHU) in the mechanical ventilation system, the design will typically include fan specifications with the design supply airflow rate, the minimum outdoor air intake rate, and in some cases a maximum outdoor air intake rate that would apply when the system is operating under economizer mode. (Economizer operation refers to increased outdoor air intake to cool a building rather than using mechanical cooling equipment, i.e., chillers, as an energy efficiency option.) However, economizer operation is only feasible if the outdoor air is cool and dry enough and if elevated outdoor pollutants can be effectively removed by filtration or air cleaning. Outdoor air ventilation rates are specified during building design to comply with building regulations and standards that contain requirements for minimum ventilation rates, typically on a per occupant and per-unit floor area basis. For example, ASHRAE Standard 62.1 contains such requirements for commercial and institutional buildings, while ASHRAE Standard 62.2 contains requirements for residential buildings (ASHRAE 2019a, b). Ventilation standards exist around the world, based on the priorities and expectations of the country or region in which they are developed (CEN 2007; Limb 2001). Fan specifications or other design documentation should include the basis for the minimum outdoor air intake rates including the standard or building regulation used to determine these rates, key assumptions (e.g., floor areas and design occupancies of the spaces, occupancy category) and a record of the calculations of the minimum intake rate. However, the existence of these details is more common in commercial buildings than in residential. ASHRAE Standard 62.1 actually requires that this information be provided in writing; the standard also contains an informative appendix (not an official part of the standard) with sample tables for preparing design documentation (ASHRAE 2019a).

Other information needed to describe mechanical ventilation systems listed in Table 2 include the location of particulate filters and their removal efficiencies, e.g., MERV ratings. Exhaust airflow rates for central exhaust systems and exhaust vents in spaces feeding these central systems, and airflow rates for local exhaust systems are also listed. Information on space level air distribution is next, which can be quite detailed but at a minimum the existence of mixing and VAV boxes should be noted, along with a description of how they are controlled. The latter information is often contained in the so-called sequence of operations[1] for a system, which explains how the system is intended to operate, how it will respond to outdoor weather and internal thermal loads, and other aspects of system control. The sequence of operation is critical to understanding how a system is intended to operate and then to determining whether it is operating as intended. The final entry under mechanical ventilation is system maintenance, which includes schedules for visual inspection of different components, filter changing, and sensor calibration. ASHRAE Standard 62.1 contains a table of minimum ventilation system equipment maintenance activities that is useful in identifying items to record under this category.

Describing natural ventilation systems involves identifying the locations and sizes of operable windows and any purpose-provided inlet and outlet vents. If the system is engineered, rather than just providing these openings and assuming the resulting ventilation is adequate and well-distributed, the system description should include information on the major elements of the system, (e.g., inlet vents, thermal stacks) and the intended airflow patterns (e.g., where air is intended to enter and leave the building, and how it is expected to move through the building). The latter should be provided under different weather conditions, such as cold and windy, warm

[1] The ASHRAE Terminology Glossary (www.ashrae.org/ashraeterms) definition of sequence of operations includes the following: an organized narration specifying how the integrated functions of a device, system, or facility will perform. It should incorporate energy efficiency and environmental concerns with detailed, comprehensive control strategies, i.e., how each individual piece of equipment will be controlled and what information and adjustment will be available to the user. These may be provided in a combination of narratives, diagrams, and point lists for every unique type of equipment and for each system.

and mild, or other prevalent weather patterns for the climate. The manner in which the components of the natural ventilation system are controlled is also key to its design. Specifically, are the vents controlled based on occupant preferences and actions? If the system is automated based on weather conditions, indoor air temperatures, indoor contaminant concentrations, or other parameters, the manner in which these controls are intended to operate needs to be described. Finally, if the design has an estimate of the expected ventilation rates in the building or in individual spaces, these rates, including the assumed weather conditions on which the estimate is based and the method used for their estimation, should be noted.

For hybrid or mixed-mode ventilation systems, in addition to the previously-described information for mechanical and natural ventilation systems, the system description should include the design concept: When would the mechanical system operate? Is that based on season, time of day, weather conditions or some other approach? Is there an interlock that prevents the mechanical ventilation system from operating when windows or vents are opened?

While the information in Table 2 may appear to be very detailed, understanding the ventilation system design is key to building ventilation assessment. Measured ventilation rates or other performance parameters are extremely difficult to interpret without such design information.

Measurement methods

Building ventilation performance assessment methods have been available for decades and have been reviewed previously. The AIVC bibliographic database Airbase, mentioned earlier, is a helpful resource for identifying previous reviews and other relevant material. McWilliams (2002) provides a thorough bibliography of publications covering multiple measurement techniques. Nazaroff (2021) discusses several means of characterizing residential air change rates in a review of available measurement results. There is not space in this chapter for a detailed description of available assessment methods; instead, this section reviews methods of assessing the performance parameters listed in Table 1, providing references (particularly standard methods of test where available) and highlighting some key issues in their application. This section also discusses other important issues including variations in ventilation rates and deviations from design intent. As noted earlier, buildings and systems are extremely variable, and the specific features of each must be considered when planning and conducting ventilation measurements. Also, the interpretation of measurement results requires that they be compared with a baseline value, which would typically be based on the design information discussed in the previous section and results from similar buildings, as well as relevant standards and regulations.

System Status

There is no standard approach to assessing system status, although the BASE protocols mentioned earlier thoroughly cover system condition, operation and maintenance (EPA 2003). These protocols contain detailed checklists for documenting system condition and maintenance schedules. The inspection checklist (C-12) covers the operation and condition of many system components including fans, filters, drain pans, controls and terminal units. The information covered under operation includes simple matters such as whether the fan is on or off and if air is moving in the intended direction through the outdoor air intake. The system condition questions cover the presence of dirt and moisture, and the state of dampers, linkages and sensors. Assessing system operation and condition is primarily conducted by visual inspection of the system and its components using these checklists or other resources, as well as accessing information available from building automation system (BAS) interfaces. However, as useful as BAS information can be, visual inspection is essential to confirm BAS indications of system operation and to assess the condition of the system and its components, as BAS systems do not necessarily monitor cleanliness, moisture damage, dysfunctional or broken components and filter condition. The BASE protocol maintenance checklist (C-11) is useful for recording information on system maintenance procedures and schedules. The maintenance information covered by this checklist includes the frequency of air handler inspections, filter replacement, control system inspection and sensor calibration, ventilation system testing and balancing, and the inspection, cleaning and treatment of a range of specific system components. Whether one uses these detailed checklists or some other approach, system condition and maintenance are extremely important to understanding ventilation in a building. Information on maintenance practices can be obtained through discussions with building managers and operators as well as examining manuals on system operation that should be provided with the design documentation. Note that in larger buildings, the operations staff can vary in their familiarity with these procedures, and it is important to identify knowledgeable staff members.

A key aspect of assessing system status is locating the design documentation, determining if it is up-to-date, and identifying any key gaps or updates required to reflect current building use and compliance with current standards and regulations. Similarly, maintenance schedules and logs need to be identified, either hard-copies or electronic. These records should be evaluated as to whether they are current and for thoroughness in covering all the building systems and components. As noted earlier, in some buildings design and maintenance records can be hard to find and may not exist at all, although this should be less common as building and system information is increasingly in digital form. The EPA BASE protocol contains checklists (C-1 through C-10) for documenting HVAC system design information including air handlers, perimeter units, unitary systems and exhaust fans. Among these system design descriptions, minimum outdoor air intake rates are one of the most important for assessing ventilation system performance. Along with this value, the design should also describe how this minimum rate was determined, which standard or building regulation was used, the activities assumed to be taking place in the spaces served by the system, the design occupancy, and the floor area served. These assumptions are key to determining if the design outdoor air rate is still appliable to the space as it is currently being used and if a more recent ventilation standard or regulation is relevant. A previous section of this chapter, Building and System Design Information, discussed system design information in more detail, with reference to Table 2.

Envelope air leakage

As discussed earlier, infiltration is the only ventilation mechanism in many buildings, and even in tight buildings infiltration rates are comparable to mechanical ventilation rates. Characterization of air leakage involves three parameters: envelope airtightness, building infiltration rates and indoor-outdoor pressure differences. Envelope airtightness is measured with a fan pressurization test, which involves using a fan (either brought to the building or the existing air handling equipment) to temporarily impose a uniform indoor-outdoor pressure difference across the envelope and then measuring the airflow required to induce this pressure difference. Often a series of pressure differences are induced to generate an airflow versus pressure curve, which can reduce the uncertainty in the reported test result. Fan pressurization testing has been employed for about 50 years, and several standards exist that describe the equipment and instrumentation, test protocols, data reduction and reporting. There are three ASTM fan pressurization standards, with E779 (ASTM 2019) being the most general. E1827 (ASTM 2017) describes the use of an orifice blower door to conduct the test, and E3158 (ASTM 2018a) is specific to larger buildings. ISO 9972 (ISO 2015) is also a fairly general test method, while CGSB 149.15 (CGSB 1995) discusses the use a building's air handling equipment to conduct the test. Using existing air handlers has advantages over bringing a fan to the building, assuming one is able to accurately measure the airflow supplied by the system using the ventilation system airflow methods described below. Envelope airtightness is typically expressed as a volumetric airflow rate, e.g., m^3/s, at a reference indoor-outdoor pressure differential that is typically normalized by the building volume or the envelope surface area, or as an effective leakage area, which may be normalized by the building envelope or floor area (ASHRAE 2021).

In conducting whole building fan pressurization tests, it is important that all points on the exterior envelope of the building are subject to the same indoor-outdoor pressure difference. This condition can be facilitated by opening all interior doors and running tests when outdoor temperatures are mild and wind speeds are calm. The impact of indoor-outdoor air temperature differences becomes more critical as buildings get taller, since stack or buoyancy induced pressures increase with building height. The referenced test methods have criteria for weather conditions and pressure difference uniformity and describe the management of interior doors and other partitions to support achieving uniform pressure difference. Another important issue in fan pressurization testing is the need to clearly define the pressure boundary of the building that is being tested. In buildings with attics, basements and other unconditioned or partially conditioned spaces, the definition of the pressure boundary can be complex. Some of these spaces are not well-connected with either the outdoors or the building interior, leading to significant pressure differences to the outdoors or interior, interfering with the goal of a uniform indoor-outdoor pressure difference. These standards describe how to deal with such spaces, but tests in these buildings can be more complex than in simpler single zone buildings. Multi-zone buildings, in which the interior spaces are not well-connected in terms of airflow, may require more than one fan pressurization device in the different zones to meet the pressure uniformity test requirement. Another important issue in conducting fan pressurization tests is the position of vents and dampers in the exterior envelope, which is covered by the standards referenced above. If all such vents and dampers are closed and sealed, the test results provide a measure of the envelope construction quality in terms of airtightness. If those vents and dampers are open, the results are a more useful measure of the airtightness in determining infiltration rates under normal conditions of weather and building operation.

Infiltration rates, in units of air changes per hour or h^{-1}, quantify the amount of outdoor air that enters a building through unintentional openings in the building envelope. In buildings that are ventilated only by infiltration (no mechanical ventilation or open windows or doors), the tracer gas methods for measuring outdoor air change rate described below can be used to measure these rates. Given the strong dependence of infiltration rates on indoor-outdoor temperature difference, wind speed and direction, and the operation of building equipment (e.g., vented combustion appliances), multiple measurements under a range of these variables are required to characterize infiltration in a building. (Examples of such detailed measurements are shown below.) At a minimum, a reported infiltration rate must be accompanied by information on weather conditions and building equipment operation to be meaningful. In large buildings, particularly those with large horizontal footprints or otherwise divided into sections of different ages and envelope construction, different portions of the building may have different envelope leakage values and different indoor-outdoor pressure differences due to variations in wind exposure and other factors. These differences can result in different infiltration rates in these various sections of the building, which can be difficult to measure with standard tracer gas techniques but which can have significant effects on energy use, thermal conditions and indoor contaminant levels.

In buildings with outdoor air mechanical ventilation, infiltration rates can be estimated by subtraction; one measures the whole building outdoor air change rate using a tracer gas dilution method and subtracts the system outdoor air intake rate measured using the system airflow rate measurement techniques described below. This approach is not common, but was applied in a commercial building by Persily and Norford (1987), who studied the variation in infiltration and intake rates as a function of weather and ventilation system control mode. However, ventilation system operation can induce indoor-outdoor pressure differences that will impact the infiltration rate. Even if the ventilation system is balanced, i.e., the system outdoor air intake and exhaust rates are equal, operating the system can induce local pressure effects that will impact infiltration rates. Infiltration rates in mechanically ventilated buildings can also be measured by conducting a tracer gas test with the system off, as was done in a very, tight residential building by Ng et al. (2015). However, conducting tracer gas tests with the system off can interfere with achieving uniform tracer concentrations, which are required for accurate measurements as discussed below.

As noted earlier, measuring indoor-outdoor air pressure differences across the building envelope can be useful in understanding envelope leakage. There are no standards that describe how to make these measurements and interpret the results, although there have been some useful articles in building industry trade publications. Standards exist that describe air pressure measurements and instrumentation in detail (ASHRAE 2014, 1988). Indoor-outdoor pressure differences can be measured at key locations over the building envelope, either one-time or periodically with a hand-held device or automatically over an extended period of time to capture inevitable variations in these pressure differences. Since these pressures will vary with location and time, they should be measured under a range of weather and system operation conditions to understand the airflow dynamics of the building being studied. Consistent pressure difference values over the entire building envelope or locally can be an indication that a specific building or system operating mode is inducing higher infiltration rates than others, or that there is an airflow imbalance between the supply and exhaust airflows for a space. The latter conclusion should be confirmed by measuring those system flows and comparing them to their design values.

Ventilation system airflow

Depending on the type and configuration of a ventilation system, it will be associated with several different airflows as described in Table 1 and shown in Figure 1: outdoor air intake, supply, return and exhaust. For systems serving multiple spaces, the latter three are relevant at both the system level and in individual rooms or ventilated spaces. As noted earlier, not all of these parameters apply to all ventilation systems, e.g., some have no return airflow and some have no outdoor air intake. The rate at which outdoor air is brought into the ventilation system can also be characterized by the percent outdoor air or outdoor air fraction, which is the outdoor air intake rate divided by the supply airflow rate. Percent outdoor air values vary from 0 % (no intake) to 100 % (no return air being recirculated). Exhaust airflow rates, both at the system and space level, are relevant to systems whose sole function is to draw air from single or multiple spaces, e.g. toilet rooms, and exhaust that air to the outdoors. As noted earlier, system airflow rates depend on the system operating status and mode of operation, which need to be considered in planning these measurements and included with reported measurement results.

System airflow rates can be measured in ducts or at outdoor air intakes using standard air speed traverse methods employing pitot tubes or hot-wire anemometers (ASHRAE 2008; NEBB 2005; SMACNA 2002). Traverse measurements involve multiple air speed measurements across a cross section of a duct, with the number of measurement points depending on the duct size. The average air speed is then multiplied by the cross-sectional area of the duct to yield the volumetric airflow rate in units of L/s or cfm. Accurate traverse measurements require uniform velocity profiles in the ducts, and the referenced standards and guides contain criteria for evaluating whether the profile is acceptable. These documents typically claim a measurement accuracy of +/- 10 % under good conditions, but the basis of these accuracy estimates is not provided. In order to meet the requirements for a uniform velocity profile, there needs to be a sufficient number of lengths of ductwork downstream of transitions (as a multiple of duct diameter) upstream of the measurement plane. However, in many system configurations, such lengths do not exist, making these measurements less accurate. This is especially true at outdoor air intakes, where there may be very few duct diameters before the outdoor airstream mixes with the return air (Fisk et al. 2002). Some ventilation systems have permanently installed airflow monitoring stations, which include an array of thermal anemometers or other sensors to provide a continuous airflow rate measurement, which is often accessible via the BAS. While these systems can be fairly accurate under ideal conditions, they should be calibrated as installed as every system installation is unique and may affect the measurements. Technologies exist to measure outdoor air intake rates by incorporating air speed or pressure sensors into outdoor air intake louvers. Studies into the performance of such devices show promise, with potential measurement errors from 10 % to 30 %, but each louver and sensor configuration needs to be tested to verify its accuracy, which tends to degrade at lower airflow rates (Fisk et al. 2004; Fisk et al. 2008).

Outdoor air intake rates can be determined by separately measuring the supply airflow rate (using a duct traverse) and multiplying it by the percent outdoor air intake rate. Percent outdoor air can be estimated based on measurements of the air temperature in the return, supply and outdoor airstreams of the air handler (ASHRAE 2008). Accurate measurements using this approach requires that the three air temperatures are sufficiently different relative to the air temperature measurement uncertainty and that there is no heating or cooling of the air between these temperature measurement locations. Alternately, one can estimate the percent outdoor air based on the CO_2 concentration in these three airstreams, which is discussed in ASTM Standard D6245 (ASTM 2018b). This method also requires that the three CO_2 concentrations are sufficiently different relative to the concentration measurement uncertainty, with the referenced standard describing how to estimate the associated measurement error.

Airflow rates in ducts can also be measured with tracer gas methods as described in ASTM E2029 (ASTM 2011a). This method involves injecting tracer gas into a duct at a constant rate and measuring the concentration upstream and downstream of the injection point. The airflow rate is equal to the tracer gas injection rate divided by the increase in tracer gas concentration from upstream of the injection to the downstream location. As described in the referenced standard, care must be exercised in injecting the tracer gas to facilitate good mixing with the duct airstream, and the downstream concentration measurements must provide a good estimate of the average downstream concentration.

Supply airflow rates into, and return and exhaust airflow rates out of, individual ventilated spaces can be measured using flow hoods. These devices use a conical or other shaped hood to collect all of the air from a supply vent and guide it over an airflow measuring device that employs vane anemometers or pressure difference based gauges (ASHRAE 2008; SMACNA 2002; NEBB 2005). Flow hoods can also be used in reverse at return and exhaust vents. The referenced standard and manufacturers' literature provide limits on air speeds, calibration requirements, cautions on directional effects related to supply air discharge pattens, and potential impacts of pressure drops associated with the flow measurement device itself.

Ventilation system operating status and mode of operation needs to be checked and recorded whenever measuring system airflow rates. This involves more than just whether the system is on or off but also the outdoor air intake mode, e.g. morning warm up during the heating season when outdoor air fractions will be reduced or even zero, or economizer operation when outdoor air intake is maximized for cooling the building without using mechanical cooling equipment. Modern ventilation systems in commercial building typically have multiple modes of operation, and describing their operating status requires an understanding of the system design and sequence of operation as described earlier.

Ventilation system airflow measurements must be planned based on the building layout, the number of systems and an understanding of which portions of the building are served by each. Part of this planning relates to logistics, scheduling and instrumentation deployment, as these systems can be located at significant distances from each other in different mechanical rooms throughout a large building. If system airflow rate measurements are going to be related to airflow measurements at supply, return or exhaust vents in the occupied space, the spaces served by the system must be identified prior to making the measurements through the examination of the building mechanical drawings and floor plans. Situations in which this can be useful include comparisons of the supply airflow rate at the system to the sum of all the supply airflow rates at the individual vents, which can help to verify the supply airflow rate value and perhaps also to provide an indication of duct leakage between the air handler and the vents. Another example is multiplying the percent outdoor air fraction at the air handler by local supply airflow rate measurements to estimate the outdoor air delivery to the ventilated space.

When evaluating buildings with multiple air handling systems, ventilation measurements in the different systems need to be coordinated to ensure that they are conducted under sufficiently similar weather, occupancy and operation conditions such that the results can be combined in a meaningful way to yield total supply and outdoor air intake rates for the building. For example, measuring outdoor air intake in some systems during the cool part of a morning when outdoor air intake fractions are high, and other systems during warmer periods in the afternoon when outdoor air intake are more likely to be at minimum values, will not allow a meaningful determination of the total outdoor air intake of the building.

Outdoor air change rate

Outdoor air change rates, envelope infiltration plus outdoor air intake, impact the amount of energy required for heating and cooling a building and indoor contaminant concentrations. Infiltration is often assumed to be negligible, but in the absence of measurements or physics-based analysis, this assumption cannot be supported. Also, as noted earlier, infiltration is the only means of outdoor air ventilation in many buildings.

Total outdoor air change rates can be measured using tracer gas dilution methods as described in ASTM Standard E741and ISO 12569 (ISO 2017; ASTM 2011b). In fact, tracer gas methods are the only way to measure building outdoor air change rates except in the unusual case in which a building is so extremely tight that all of the airflows into and out of the building are known to take place via the ventilation system ductwork. In these cases, the system airflows can be measured using duct airflow measurement techniques described above. Both referenced tracer gas standards are single-zone techniques, which means the tracer gas concentration throughout the building being tested can be characterized by a single value. Some discussions refer to this as perfect mixing, but the key issue is actually tracer gas concentration uniformity. The referenced ASTM standard requires that concentrations in the test space differ by less than 10 % of the average concentration to achieve a test precision and bias of 10 %. There are three tracer gas dilution methods: decay, constant concentration and constant injection. In the decay method, a quantity of tracer gas is released directly into the test space or supplied via the ventilation system and allowed to mix with the interior air until the concentration is sufficiently uniform. Sometimes portable mixing fans are installed in the space to enhance mixing, but these should not be relied on to mix the air and tracer between rooms in a building. Air handling systems can be used to enhance distribution and mixing of the tracer gas between rooms. However, if these systems are left on during the actual decay, they can create indoor-outdoor pressure differences across the building envelope that impact the infiltration rates. Once the tracer gas concentration is sufficiently uniform, the concentration decay over time is monitored and used to estimate the air change rate, with ASTM E741 providing detail on sampling, analysis and reporting. Some tracer gas decay studies have been conducted by monitoring the decay rate in a single room, such as a bedroom, and referring to that as the air change rate of that room. However, this approach ignores air and tracer transport from adjoining spaces, and unless there is explicitly accounting for interzone transport in the tracer gas mass balance analysis, single-room decay rates in multizone buildings should not be referred to as outdoor air change rates. They can be informative but should only be referred to as room decay rates as they generally do not provide accurate outdoor air change rates for a test space or the whole building.

Another tracer gas dilution approach, also described in ASTM E741, is the constant concentration tracer technique, which involves varying the tracer gas injection rate to maintain a constant indoor tracer gas concentration using automated feedback control. This approach can be advantageous in multi-zone buildings where zones have different outdoor air change rates, in which a decay test would not be able to maintain a uniform tracer gas concentration throughout the building. However, this approach requires more complex instrumentation than the decay method and is not used often except in research studies (Takaki et al. 2005).

The third single-zone tracer gas dilution method is the constant injection method, which involves injecting tracer gas at a constant rate into the space being tested and monitoring the concentration response. Assuming the outdoor concentration is zero and the injection rate is constant, the single-zone mass balance can be integrated to yield an expression for the outdoor air change rate that requires the average of the inverse of the tracer gas concentration. If the airflow rate is constant, the tracer gas concentration will eventually reach steady state, at which point the outdoor airflow rate equals the tracer gas injection rate divided by the steady-state tracer gas concentration. The constant injection approach can be useful for measuring airflow rates in ducts per ASTM E2029 as discussed earlier, and the steady-state formulation serves as the basis for the use of peak CO_2 concentrations for estimating ventilation rates, which is discussed below.

The constant injection tracer approach is the basis of the so-called perfluorocarbon tracer (PFT) method, in which a PFT is injected using passive devices, typically over measurement periods of days to weeks or longer. Passive samplers are then deployed throughout the building being tested to determine the average tracer gas concentration during the sampling period. This approach has the advantage of being relatively inexpensive since the samplers are analyzed in a laboratory facility after the field test, and it has been used in a number of residential field surveys (Offermann 2009; Yamamoto et al. 2010). This technique employs a transient tracer gas mass balance, since the air change rate cannot be assumed to be constant over typical sampling periods given variations in weather, equipment operation and occupant activities. The fact that the sampling technique determines the average concentration, not the average of the inverse concentration, introduces bias into the measurement results. Specifically, there is a tendency to overestimate the average air change rate, which has been shown to be as high as 15 % to 35 % for seasonal average air change rates (Sherman 1989). In tight buildings with very low infiltration rates and fairly constant mechanical ventilation rates, this bias is less of a concern. In those cases, a short-term tracer gas measurement may suffice.

The peak CO_2 approach has been used for decades, purportedly as an inexpensive and simple means of estimating outdoor air change rates in buildings and sometimes spaces within buildings. However, it has been misapplied in many cases due to a lack of recognition that it is fundamentally a single-zone, constant injection steady-state tracer technique and thus must abide by several key assumptions to yield valid air change rates. These assumptions include: the CO_2 generation rate is known, constant, and uniform throughout the building being tested; the CO_2 concentration is uniform throughout the building and has achieved steady state; the outdoor CO_2 concentration is known and constant; and the outdoor air ventilation rate is constant (ASTM

2018b). Also, because it is a single-zone approach, it can only be used to determine the air change rate of an entire building with a uniform CO_2 concentration. If the CO_2 concentration varies among rooms, the single-zone mass balance is no longer valid and one must employ a multizone mass balance of CO_2 that accounts for the airflows between zones. The assumption that the CO_2 generation rate is known, constant and uniform throughout the building translates to the occupancy level also being known, constant, and uniform. It also requires that the occupant levels of physical activity are relativity constant as physical activity impacts CO_2 generation rates (Persily and de Jonge 2017). The requirement for the CO_2 concentration to be at steady state translates to conditions being constant for long enough that a steady-state concentration is achieved. As described in ASTM D6245 (ASTM 2018b), the time required to achieve steady state depends on the air change rate of the building. For a given air change rate, the concentration will be within 95 % of steady state after three time constants, where the time constant is the inverse of the air change rate. For an air change rate of 1 h^{-1}, it will therefore take 3 h to reach 95 % of the steady-state concentration. For an air change rate of 0.5 h^{-1}, it will take 6 h. During this time, the ventilation rate, occupancy, and outdoor CO_2 concentration must all be constant, which will not be the case in some buildings. Using a CO_2 concentration before steady state has been achieved will overestimate the air change rate, in some cases by significant amounts.

As noted above in the discussion of the tracer gas decay technique, the peak CO_2 approach has also been applied in single rooms, such as bedrooms, with the result being referred to as the air change rate of that room. However, the tracer gas methods on which this approach is based apply only to single zones. Using peak CO_2 in bedrooms ignores interzone air and CO_2 transport from other indoor spaces such as adjoining rooms and hallways. The impacts of such transport on the measurement results are difficult to characterize unless interzone transport is explicitly accounted for in the tracer gas mass balance analysis. Only then can CO_2 concentrations in a bedroom be used to calculate outdoor air change rates. Several studies have converted peak CO_2 concentrations in bedrooms to outdoor air change rates without speaking to the issue of interzone transport and the inaccuracies in this approach. Maximum CO_2 concentrations in bedrooms and other spaces in multizone buildings can be informative, but they are not outdoor air change rates.

It needs to be noted that that single-zone, tracer gas dilution methods for measuring outdoor air change rates are challenging in naturally ventilated buildings. Specifically, when there are large openings, e.g., open windows, the large and localized airflows into the building at zero outdoor tracer gas concentrations will interfere with the tracer gas concentration uniformity requirements of these test protocols (Jones and Kirby 2010; Nikolopoulos et al. 2012). Some studies have measured air speeds in ventilation openings, but these approaches have not been well studied nor will they capture infiltration through unintentional leaks.

The tracer gas dilution methods discussed so far are for measuring building outdoor air change rates. In some circumstances, one is also interested in airflow rates between zones, commonly referred to as interzone airflows. Also, as noted earlier, larger buildings with sections that are different in terms of construction, wind exposure or ventilation system design or operation, can have different air change rates. The single-zone tracer decay and constant injection methods are not able to quantify differences between building sections and may be challenging to implement given the lack of tracer gas concentration uniformity that is likely to exist. Measuring airflows in such situations requires multizone tracer techniques that are discussed briefly below.

Interzone airflow

Interzone airflows are an important aspect of ventilation assessment in many applications, particularly when one needs to perform a contaminant mass balance analysis for building zones at different contaminant concentrations or to understand the overall airflow dynamics in a building. Interzone airflows, as well as differences in airflows to and from outdoors in different sections of a building, become more important as buildings are larger and configured such that different portions of the building vary in their construction and ventilation systems. The constant concentration method discussed above can be used to determine the outdoor airflow rate into individual zones but not interzone airflow rates. Multizone tracer gas methods exist for estimating interzone airflows, but they are complex and have typically only been used in research studies going back four decades (I'Anson et al. 1982). More recent applications of multizone tracer techniques (Dodson et al. 2007; Du et al. 2015; Du et al. 2012; Bekö et al. 2016) are discussed by Nazaroff (2021). These references involve studies to estimate airflows to and from basement zones or garages to the living space, or bedrooms to and from the rest of the building. Interzone airflow measurements are scarce in commercial buildings, with one study conducted by the author almost 30 years ago (Persily and Axley 1990). In contrast to the single-zone tracer gas techniques discussed above, multizone tracer gas techniques have not been standardized, are more complex and costly, and are subject to potentially large uncertainties, which are some of the reasons they have not been widely applied.

As alternatives to tracer gas measurements of interzone airflows, the airtightness of partitions between zones and pressure differences between zones can be measured more easily. The former can be measured using fan pressurization methods, while the latter can be measured with differential pressure gauges, but neither approach has been standardized and general guidance on their application is lacking. Measurement of the airtightness of interzone partitions can be useful for understanding the potential for interzone airflows, but without values of the pressure difference across the partitions, they cannot be related to actual airflow rates. However, these interzone airtightness values can be used for airflow modeling.

As noted above in the discussion of indoor-outdoor pressure differences, standards exist that describe air pressure measurements and instrumentation (ASHRAE 2014, 1988). Again, the concept is to measure interzone pressure differences at locations of interest in the building to better understand the direction of these airflows, and more specifically the pressure relationships between zones. The measurement locations should relate to the goals of the building study being carried out, which might include concerns regarding airflows to and from zones with elevated contaminant concentrations (e.g., toilet rooms and attached garages) or stack-driven pressures within a building via stairwells and other vertical stacks. These pressures can be measured one-time with a hand-held device or automatically over an extended period of time to capture variations. They should be measured under a range of weather and system operation conditions as they will vary with location and time.

Air distribution

Air distribution refers to the manner and uniformity with which ventilation air is delivered to a space, specifically the portions of the space where occupants are located. A variety of metrics and definitions have been employed over the years to quantify air distribution including age of air, pollutant removal efficiency, ventilation effectiveness and ventilation efficiency. The specific terms and definitions are not always used consistently, but published experimental and simulations studies are generally clear on what is being measured or calculated. Most air distribution measurements involve tracer gas methods, though some are based on air speed, temperature and contaminant levels (Fisk et al. 2005; Rim and Novoselac 2010; Karimipanah et al. 2007; Zhai 2005; Faulkner et al. 2004; Chao and Wan 2004). The air diffusion performance index (ADPI) is used to characterize the performance of air diffusers in spaces based on air speed and temperature distribution in the context of thermal comfort and depends on the geometry and cooling load of the space, but it is does not characterize outdoor air distribution (ASHRAE 2013). An ASHRAE standard for measuring air change effectiveness using a tracer gas to quantify the effectiveness of outdoor air distribution was approved in 1997, and reaffirmed in 2002, but hasn't been updated since (ASHRAE 1997).

Other Considerations

Variation in Ventilation

As noted earlier, many of the performance parameters listed in Table 1 vary with weather, system operation, and occupant activities. The existence and extent of these variations in ventilation performance have been seen in multiple building studies of infiltration rates, mechanical ventilation system airflows and total outdoor air change rates (Persily 2016). Given these variations, one needs to understand the building and its system before planning a ventilation measurement effort, and multiple measurements under a range of conditions are needed to characterize ventilation in a building. Even if one is only interested in the outdoor air change during a specific period of time, for example in conjunction with indoor contaminant measurements, it is critical to report weather, system status and other factors along with the outdoor air change rate measurement. Space does not permit an extensive discussion of the many studies showing these variations, but three examples are highlighted here.

One example is a study involving multiple measurements of outdoor air change rates in a three-bedroom manufactured house used for IAQ research, before and after an airtightening retrofit (Nabinger and Persily 2011). The retrofits included sealing of ducts and floor penetrations over a vented crawlspace and installation of a house wrap under the exterior siding, resulting in an overall reduction of 24 % in the envelope airtightness based on whole building pressurization tests. Figures 2 and 3 are plots of the air change rate versus indoor-outdoor temperature difference with the forced-air heating and cooling fan off and on, respectively. Each plot distinguishes between the measurements before and after the airtightening retrofit. Note in Figure 2 that the air change rate varies over a range of about 5 to 1 based on temperature difference with the fan off; the range of variation with wind speed is similar in magnitude. Also, the dependence on temperature difference has an entirely different form with the fan on in Figure 3, and this dependence changes dramatically after the retrofit. These data highlight the importance of accounting for weather, system operation and building status when measuring and reporting air change rates.

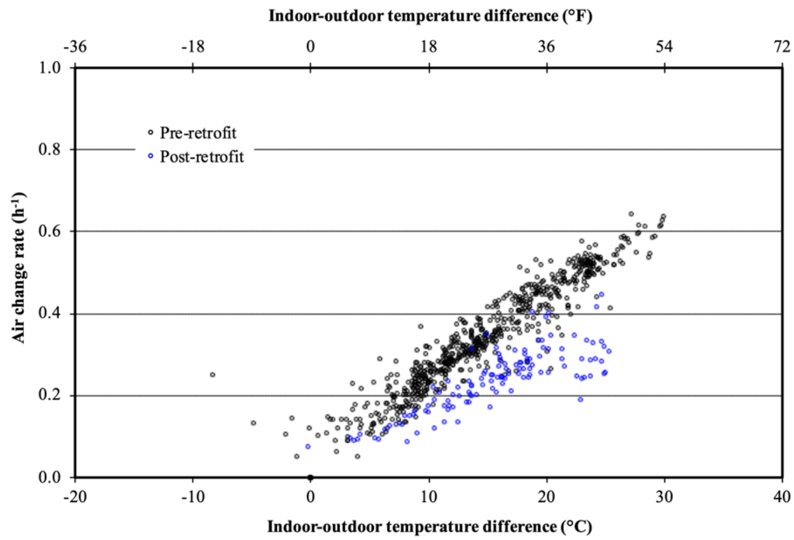

Figure 2. Air change rates vs. indoor–outdoor temperature in manufactured house, forced-air system off

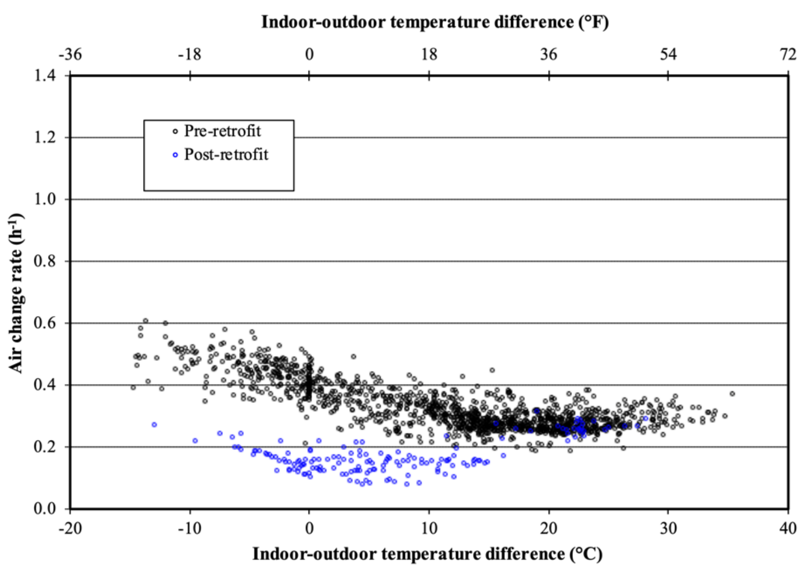

Figure 3. Air change rates vs. indoor–outdoor temperature in manufactured house, forced-air system on

An earlier, year-long study of air change rates in an occupied townhouse also shows variations with weather and occupant actions, specifically exhaust and attic fan operation and window opening (Wallace et al. 2001). About 4500 hourly-average air change rates were measured, with a mean air change rate of 0.65 h^{-1} and a standard deviation of 0.56 h^{-1}. Figure 4 is a frequency distribution of the measured rates, revealing a lognormal distribution, which is typical for air change rates in single buildings and collections of buildings. Once again, we see a roughly 5 to 1 variation in air change rates. Window opening had a strong influence on the air change rates, with operation of an attic fan having a smaller influence. The indoor–outdoor air temperature difference impacted the air change rates, but wind speed had very little effect on this house due in part due its location in a wooded area.

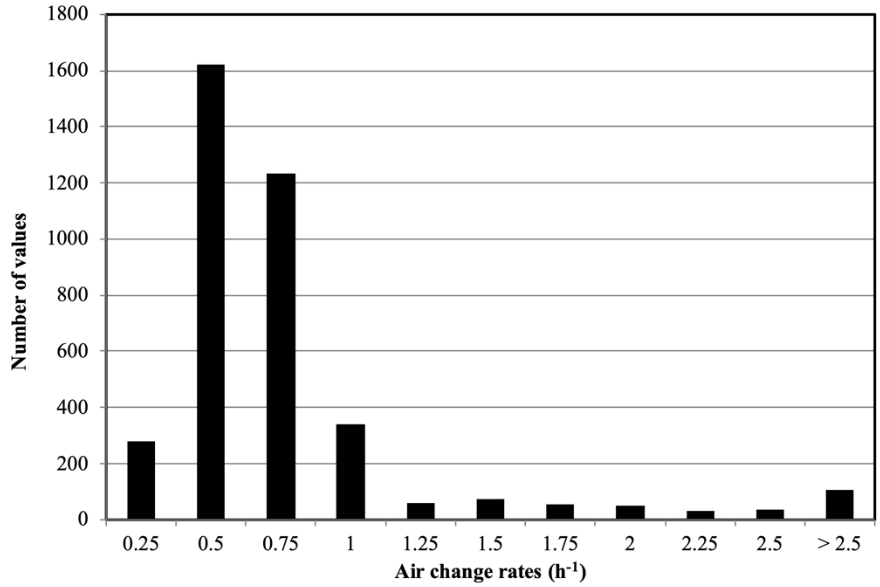

Figure 4. Distribution of air change rates over one year in an occupied town house

Another example is a long-term study of fourteen mechanically ventilated office buildings in the U.S. (Persily 1989). These studies involved automated tracer gas decay measurements over multiple seasons of the year to get a fairly complete picture of air change rate variations with weather and system operation in each building. Figure 5 shows whole building air change rates for one of those buildings with the mechanical ventilation system operating over a wide range of outdoor air temperatures (Persily et al. 1992). These data exhibit the economizer cycle common in U.S. commercial buildings, in which the system operates at minimum outdoor air intake during warm weather (about 20 °C and higher) when mechanical cooling is required. At cooler temperatures, the outdoor air intake rate is increased dramatically to use outdoor air to cool the building rather than the mechanical cooling equipment as an energy efficiency measure. At lower outdoor air temperatures, the HVAC control system reduces the outdoor air fraction as less outdoor air is needed to cool the building. The outdoor air rate varies over a range of 5 to 1 based on the control system function, with a range of about 2 to 1 at a single outdoor temperature, presumably due to wind effects, measurement error and other factors.

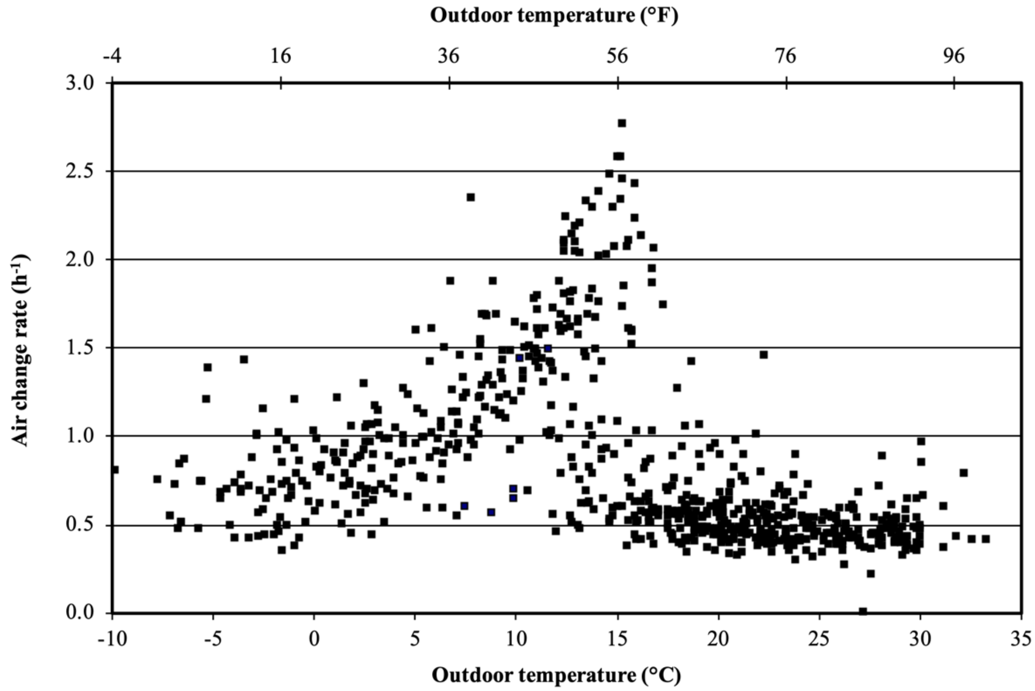

Figure 5. Air change rates vs. indoor–outdoor temperature in an office building (Persily et al. 1992)

Figure 6 is a frequency distribution of outdoor air change rate measurements in 14 U.S. office buildings (Persily 1989). This plot shows more than 3000 individual measurements, each corresponding to a tracer gas decay test lasting an hour or two, conducted over a wide range of weather and system operating conditions. The air change rates vary over a range of 10 to 1, with the rates in the individual buildings typically covering a narrower range depending on the weather during each building's tests and its individual characteristics such as airtightness. It is important to note that about 40 % of the measured values were below the outdoor air ventilation requirement of 10 L/s per person for office buildings in ASHRAE Standard 62-1989, which was in effect at the time. Also, about 50 % of the measurements were below the minimum outdoor air intake specification in the respective building's design documentation. This deviation from design is more notable since these air change rates include infiltration through envelope leakage, while the requirements in the standard and the design value are only for intentional intake. Presumably, if the system outdoor air intake rates were measured separately, even a higher fraction would be below the design value.

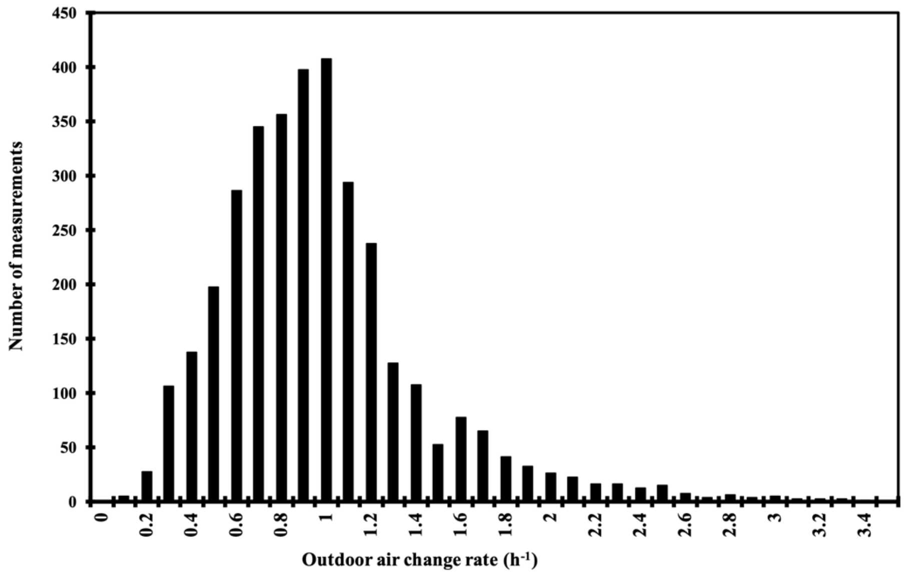

Figure 6. Frequency distribution of outdoor air change rates in 14 U.S. office buildings (Persily 1989)

Deviations from Design Intent

As noted above, actual ventilation performance can be significantly different from design intent. Such deviations in ventilation performance have been seen in studies of mechanical ventilation system airflows and total outdoor air change rates (Persily 2016). One example of that deviation is from the EPA BASE study of 100 U.S. office buildings mentioned earlier. That study included ventilation measurements during a one-week study period in each building (Persily and Gorfain 2008). The mean measured outdoor air ventilation rate was 49 L/s per person based on volumetric airflow measurements at the air handlers and measured occupant densities, which is high relative to the minimum outdoor air requirements in almost all ventilation standards. However, these high air change rates were due in part to frequent operation in economizer mode and the actual space occupancies being on average 80 % of the design occupancy. Nevertheless, about 17 % of the ventilation measurements were still below the 10 L/s per person requirement in ASHRAE Standard 62-1999, the version of the standard that was in effect at the time of the analysis (ASHRAE 1999). Considering only measurements made under minimum outdoor air intake and accounting for the actual occupancy levels, the mean ventilation rate was roughly 11 L/s per person and about one-half of the values were below the minimum requirement in Standard 62-1999. These results demonstrate the need to consider building occupancy and system operation when interpreting ventilation measurement results, as well as the deviation of measured ventilation rates from expectations based on design values or standard requirements.

Another finding of the BASE ventilation study, highlighted in Figure 7, is the deviation of the measured outdoor air intake rate from the corresponding design value, shown here exclusively for measurements conducted when systems were running at minimum outdoor air intake. The horizontal axis is simply the individual measurement result, and the vertical axis is the ratio of the measured value to the design value. If the systems were operating as designed, the ratios would all equal 1.0, subject to some variation due to measurement error. However, many values are less than one, reflecting systems operating with less outdoor air intake than intended, which can have a negative impact on IAQ. There are also many values greater than one, indicating higher outdoor air intake rates than intended, which leads to unplanned energy cost and potentially other problems, e.g., excessive indoor moisture.

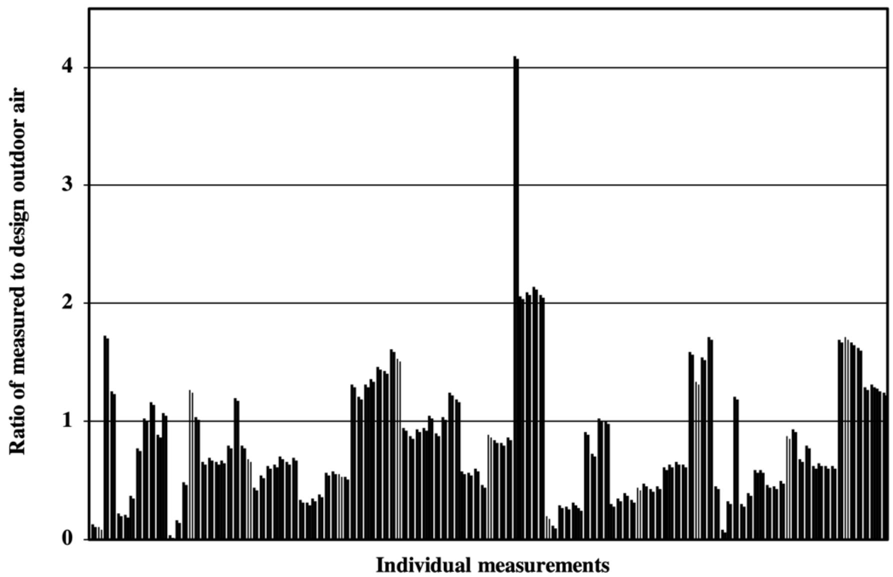

Figure 7. Ratio of measured minimum outdoor air intake to design value ((Persily 2016))

Another field study in 108 new, single-family homes in California included measurements of air change rates using the steady-state PFT approach and outdoor air intake measurements using flow hoods or hot wire anemometers (Offermann 2009). This study evaluated the performance of ducted outdoor air ventilation systems, which typically operated intermittently in conjunction with the forced air space conditioning system fan, and of heat recovery ventilators that typically ran 24 h per day. Sixty-four percent of the ducted outdoor air systems failed to meet the California Energy Commission's 2008 Building Energy Efficiency Standards, which was attributed to a combination of low airflow rates and short operating times. All of the heat recovery ventilator systems met the 2008 standards. The median 24-h outdoor air change rate was 0.26 h^{-1}, with a range of 0.09 h^{-1} to 5.3 h^{-1}, and 67 % of the homes had outdoor air change rates below the minimum California Building Code requirement of 0.35 h^{-1}. The report attributed the lower air change rates to relatively tight envelope construction and limited window use by the building occupants. This study again highlights the impacts of system operation and occupant action, as well as the deviation of performance from design standards.

Conclusions

Assessing building ventilation performance, including the measurement of ventilation rates, is essential for interpreting indoor contaminant concentrations, accounting for the impacts of outdoor air entry on energy use, and understanding building airflow dynamics. This chapter has stressed that building ventilation assessment is not about a single quantity but covers several parameters, some of which are qualitative but still important. The quantitative parameters include but are not limited to outdoor air intake rates, system supply and exhaust airflow rates, envelope infiltration rates, and indoor-outdoor and interzone pressure differences, while the qualitative features include building design information, operational status and condition, and maintenance schedules. While ventilation assessment is important in field studies of IAQ and other building performance issues, it is not always obvious how to best characterize ventilation performance in any given building. Ultimately, the approaches employed will depend on the reasons for the measurements, the characteristics of the building and its system(s), the available time and resources, the required level of accuracy, and how the measurement results will be used. Buildings and systems are extremely variable, and these variations must be considered when planning and conducting ventilation assessments. Examples of important building characteristics affecting ventilation assessment include building size, how the building is divided into zones, how zones are connected in terms of airflow, the ventilation approach(es) employed in the building, and the ventilation system design. While this summary does not repeat all of the discussion of ventilation performance parameters and measurement methods, the critical points are that they be measured, that the measurement methods be well-described and that the measurements be repeated to establish uncertainty of the results and to capture temporal and seasonal changes.

This chapter makes several important points about ventilation performance assessment, which are reiterated here:

- Ventilation rates vary significantly with weather and system operation, with weather effects easily leading to variations on the order of 5 to 1 for an individual building. Therefore a single value is not particularly informative without additional information on the conditions during the measurement. In order to fully understand ventilation in a building, multiple repeated measurements under different conditions are required. Also, a single value will be subject to unknown measurement errors unless the measurements are repeated, or otherwise planned and conducted to provide a sound uncertainty estimate. Extrapolating ventilation measurements from one set of conditions to another is potentially associated with significant uncertainty, but can be performed with reasonable accuracy using models, especially if the model predictions have been validated using other measured data.

- Ventilation performance often does not match design intent due to the realities of building construction, system installation, operation and maintenance. Interpretation of measurement results requires an understanding of how the system is intended to perform, e.g., when it is supposed to be operating and design outdoor air intake rates. Rather than reporting a measured ventilation rate as low or high, it is much more informative to say it’s below the design value or the outdoor air requirements in a specific ventilation standard.

- Many of the measurement methods described in this chapter can be challenging to apply in the field given the complexities of real buildings and systems. Therefore, it can be helpful to use more than one measurement method to increase one's confidence in the results, i.e., air speed traverse in a supply duct combined with measurements of supply airflow rates out of individual diffusers. While indoor CO_2 concentrations can be a useful tool in evaluating ventilation, using peak CO_2 (which is in essence a steady-state, constant injection tracer gas method) to estimate per person outdoor air ventilation rates must be done with a full understanding of the assumptions involved.

The discussion in this chapter leads to suggestions for the development of standards and guidance. One such need is a standardized approach to describing buildings and systems. As described in this chapter, the EPA BASE protocol is the only such approach that currently exists, but it is quite detailed and bears updating given that it was developed more than 25 years ago (EPA 2003). Another area where additional guidance, or even standardization is needed, is the measurement and interpretation of indoor-outdoor and interzone pressure differences. Also, while tracer gas and building pressurization measurement standards include reporting requirements, standards or guidance for reporting the results of a ventilation assessment would be helpful. The following list includes some suggestions on what should be reported when documenting the results of ventilation assessments and measurements:

- <u>Building</u>: Age, height, measured envelope airtightness, activities in building and occupancy levels, geographical location
- <u>System</u>: Type(s), ventilation approach(es), availability of design documentation, design outdoor air ventilation rate, design exhaust airflow rate (with the latter two at both the system and space level)
- <u>Space</u>: Floor area and ceiling height, activity and occupancy levels, system(s) serving it
- <u>Assessments performed</u>: quantities measured, measurement method(s), instrumentation employed including its measurement uncertainty, number of measurements, conditions during measurement (e.g., weather, system operating status)
- <u>Results</u>: values including the test conditions and their overall measurement uncertainty

A standard or guideline on reporting ventilation assessments might present different levels of detail from the minimum essential in all cases to more comprehensive.

Building ventilation performance is important, and while it can be difficult to measure, that is not a valid reason not to perform these assessments or not to do them properly. IAQ researchers and others need to do a better job characterizing ventilation of the buildings and spaces they are studying to understand their measurement results and to report them thoroughly enough to allow comparability between studies and enable others to interpret their results. This chapter has described just a portion of the large amount of knowledge available on building ventilation assessment that has been generated over the years. As the building community strives for improved understanding of IAQ in buildings and overall better building performance, the role of ventilation must be addressed through the use of sound approaches to ventilation assessment.

Acknowledgements
The author expresses his appreciation to James Lo, Lisa Ng and David Yashar for their very helpful review comments.

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