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Improving the Evaluation of Building Ventilation

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INTRODUCTION

Ventilation evaluation is critical in building operation and maintenance, in building performance investigations and in building research. However, activities in these fields often do not always employ consistent or reliable approaches to ventilation evaluation. One reason for the variable consideration of building ventilation is the complexity of ventilation and air movement in large, multi-zone buildings and the wide variety of mechanical ventilation systems in these buildings. Other more specific reasons include the lack of, or in some cases the lack of use of, standardized approaches to assessing building ventilation, the cost and performance limitations of available instrumentation, and a lack of understanding of this instrumentation and its use. A project is being conducted at the National Institute of Standards and Technology (NIST) to identify approaches to improve these evaluations, to develop selected ventilation assessment protocols, and to identify research needed to make further advances in the field. This project has included a characterization of the applications of ventilation assessment in buildings, an identification of the objectives addressed by different approaches to ventilation assessment, and a review of existing protocols. This paper discusses the characterization of ventilation evaluation that was performed as part of this project and is organized into the following sections:

- Uses of Ventilation Evaluation
- Specific Evaluation Objectives
- Existing Evaluation Protocols
- Current Inadequacies: Problems, Reasons and Solutions

The first section on the uses of ventilation evaluation describes the situations in which building ventilation needs to be evaluated. These situations range from a ventilation system design analysis prior to building construction to the diagnosis of indoor air quality complaints in existing buildings. The next section discusses the various objectives of ventilation evaluation efforts. These objectives include determining the current ventilation requirements of a building, measuring system airflow rates, and inspecting the physical condition of a ventilation system. Various combinations of these goals may be applicable to the situations described in the first section. The third section of this paper describes several existing protocols, including their objectives, the required level of effort, and the appropriate level of training and expertise of the personnel implementing the protocol. The protocols discussed include those directed towards practical application and those used in research. The last section of the paper presents some of the problems with current ventilation evaluations in buildings, some reasons why these evaluations are sometimes inadequate, and some approaches to improving the reliability of ventilation evaluation in buildings.

USES OF VENTILATION EVALUATION

There are several situations in which building ventilation and ventilation system performance are evaluated. These applications are discussed in this section and include the following:

- Ventilation System Design Review
- Construction and Renovation
- Building Commissioning
- Diagnosis of IAQ Complaints
- Proactive Building Management
- Identification of Energy Conservation Opportunities
- Research

The first application is ventilation system design review in which the adequacy of a ventilation system design is assessed relative to the anticipated or existing activities in the building and to relevant building codes, standards and guidelines. It is important to conduct a design review prior to the system installation in a new building so that deficiencies can be identified while there is an opportunity to modify the design. Design reviews are also important in existing buildings to determine if building use or occupancy has changed and if the current ventilation system design is adequate to meet the new ventilation requirements of the building. The design review should include an analysis of the ventilation requirements for the building zones, the design levels of outdoor airflow to these zones, and the exhaust airflow rates from zones requiring exhaust ventilation. These requirements should be determined based on the type of space, the number of occupants and relevant building codes and standards. During a design review, the existence of special ventilation requirements in spaces such as toilets, smoking lounges and photocopy facilities can be identified. The design review can also be conducted from the perspective of those performing testing and balancing and system maintenance. This perspective would consider whether the system can be balanced, whether the system configuration is amenable to airflow rate measurements, and if system components are accessible for inspection and maintenance.

Ventilation evaluation is also appropriate during building construction and renovation, when the existence of special ventilation strategies needs to be verified. When buildings are under construction, in particular during renovation projects, special ventilation strategies are often employed to prevent contaminant build-up and migration to occupied portions of the building. These strategies include continuous ventilation system operation, maximum levels of outdoor air intake, high rates of building exhaust ventilation, and operation of temporary exhaust ventilation systems. During construction, these strategies are used to remove pollutants emitted by new building materials before they can be adsorbed onto other building surfaces for potential re-emission at a later time. During building renovation activities, ventilation strategies include isolation of the space being renovated with a temporary physical barrier, exhaust ventilation from the construction area, and the maintenance of specific pressure relationships between the renovation zone and other buildings zones. Ventilation evaluation can be employed during construction and renovation to verify that the ventilation systems are being operated as intended and that required pressure differences are being maintained in the renovation zone.

Ventilation evaluation is also an important component of building commissioning. Commissioning is the process by which the installation and performance of an HVAC system is evaluated to ensure that the system is performing as designed. While commissioning is sometimes thought of as occurring only when a building is first constructed, it should continue throughout the life of a building as system components deteriorate and as space-use and occupancy change. The American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) Guideline for Commissioning of HVAC Systems[1] describes procedures and methods for commissioning during the various phases of a building's life, i.e., predesign, design, construction, acceptance and post-acceptance. In terms of ventilation evaluation, commissioning includes testing, adjusting and balancing (TAB) of the HVAC system. TAB is a procedure in which the building HVAC systems are checked and adjusted to meet the design performance requirements. TAB involves all HVAC-related systems including air and water distribution, electrical and mechanical equipment, controls, and sound and vibration. TAB procedures and instrumentation requirements are well documented[2-6], and there are industry certification and training programs for TAB personnel. While TAB procedures should be applied in new buildings to ensure that the HVAC systems will perform as intended, systems in existing buildings also need to be recommissioned and rebalanced periodically to ensure that they are performing as intended and are meeting the current ventilation requirements of the building.

Another application of ventilation evaluation is the diagnosis of indoor air quality complaints. Ventilation evaluation is important in order to determine the role, if any, of the ventilation system in causing these complaints and to enable the interpretation of contaminant measurements made in the diagnostic effort. The ventilation evaluation procedures employed in indoor air quality diagnosis cover a broad range in terms of detail and level of effort. Similarly, the personnel involved have a broad range in their technical qualifications. Proactive building management is another application of ventilation evaluation. This approach to building management reduces the potential for indoor air quality complaints and excessive energy consumption. It involves devoting staff and resources to ensure that building systems are operated as designed, performing routine maintenance on system components, and modifying the system as required when there are changes in building use. The ventilation-evaluation aspects of proactive management include system inspections, performance evaluations involving the measurement of system airflow rates and other parameters, reassessment of ventilation system design in response to changes in building use, and testing and balancing of the system during recommissioning. Proactive building management could also involve continuous monitoring of ventilation system performance parameters, such as airflow rates and supply air temperatures, for the verification of proper operation and the early identification of performance deficiencies. Another use of ventilation evaluation, related to proactive management, is the identification of energy conservation opportunities in a building. Such efforts would include identifying situations of over-ventilation, systems operating more often than intended or needed, and control system sensors needing calibration.

Research that involves the evaluation of building ventilation falls into two categories, building ventilation research and indoor air quality research. Building ventilation research is concerned with building air change with outdoors and air movement within buildings. These studies employ a variety of techniques to measure building component airtightness, building air change rates, interzone airflow rates and ventilation system airflow rates. Indoor air quality research studies are designed to understand the factors affecting indoor contaminant levels and the response of occupants to indoor environmental conditions. Ventilation evaluations are employed in these studies to enable the interpretation of other environmental measurements.

SPECIFIC EVALUATION OBJECTIVES

Ventilation evaluations associated with the applications discussed in the previous section are designed to meet a variety of objectives. These objectives are described in this section and include the following:

- Determine ventilation requirements
- Analyze system design
- Inspect system installation
- Evaluate system operation and condition
- Measure system performance parameters
- Qualitatively assess building ventilation
- Quantitatively assess building ventilation

Given the diverse objectives of ventilation evaluations, there are numerous tasks that might be part of such evaluations. Table 1 contains a list of the different elements of ventilation evaluations and examples of the parameters associated with each element.

The first objective is to determine the ventilation requirements of a building based on the occupancy and activities in the building. Building codes and ventilation standards and guidelines contain requirements and recommendations for outdoor and supply airflow rates for different types of indoor spaces. These requirements are given in terms of airflow rates per person, per unit of floor area, per room or on some other basis. Additional requirements exist for exhaust airflow rates, pressure relationships between specific types of spaces and adjoining spaces, and air temperature and relative humidity levels. The ventilation requirements of a building and the spaces within a building are determined by first selecting the building codes, standards and guidelines on which to base the analysis. The outdoor airflow rate and any other requirements for each zone are then determined based on the use of the zone and the number of occupants. In an existing building, the analysis is based on the actual use and occupancy of the zones, while in a new building one must base the analysis on the anticipated use. The results of this analysis are used to evaluate the adequacy of the ventilation system design and performance.

The analysis of the design of a mechanical ventilation system, and the comparison of the design to the building ventilation requirements, is another objective of ventilation evaluations. In these efforts, one determines how the ventilation system is intended to perform based on an analysis of the design documentation. The values of specific design parameters are then compared with the corresponding values determined in the analysis of the building ventilation requirements. The analysis of the design documentation involves the determination of parameters such as design temperatures and other design assumptions, system airflow rates, and the sequence of operation of the air handlers. This information is obtained from construction and contract documents, controls and mechanical equipment submittals, operation and maintenance manuals, TAB reports, and discussions with building operators. Comparisons between system design parameters and building ventilation requirements are important in order to identify situations in which building occupancy and activities have changed without a corresponding change in the ventilation system design.

Another important objective of ventilation evaluation is to inspect the installation of a ventilation system and to compare the installation of the system and its components to the design. Inspections are an important part of building commissioning and are necessary to identify and correct errors that occur in system installation. These installation errors include reversed fans and disconnected power lines, control sensors, ducts and dampers. Despite the most conscientious efforts, it is almost impossible to install a mechanical ventilation system without some such deficiencies, making a system installation inspection critical to the subsequent performance of the system.

Ventilation evaluations are also conducted to evaluate system operation relative to the design intentions and to assess the condition of system relative to good operation and maintenance practice. These evaluations are based on visual inspections of the system, as opposed to performance measurement. The current operation is evaluated by determining the status of the system components including whether fans are operating, air is flowing in the correct direction, and dampers are in the correct position. The condition of the system is assessed through the visual inspection of system components such as the integrity of damper controls and fan housings, the cleanliness of coils and ductwork, and filter loading.

Ventilation evaluations are also performed to measure system performance parameters such as system airflow rates (supply, return, exhaust and outdoor air intake), system static pressures, and supply air temperature and relative humidity. The measurement of these parameters are performed throughout the system during testing and balancing efforts, while other evaluations involve the measurement of these parameters at only a limited number of locations in the system.

Qualitative assessments of building ventilation are conducted in order to understand how air is moving into, out of, and within a building without actually measuring the airflow rates involved. These assessments consider more than just ventilation system airflows. Examples include the use of tracer gases to demonstrate the existence of interzone airflows or exhaust air entrainment, and the use of smoke to determine the direction of airflow at loading docks and to assess mixing within a room. Building ventilation can also be assessed quantitatively by measuring whole building air change rates and interzone airflow rates using tracer gas techniques. Other types of quantitative assessments include measurements of pressure differences between building zones and airtightness measurements of the building envelopes and interior partitions.

EXISTING EVALUATION PROTOCOLS

This section describes several existing protocols for evaluating building ventilation in terms of their objectives, the associated level of effort and the personnel requirements. The discussion covers protocols developed for practical application and those intended for use in research.

Practical Application

A number of ventilation evaluation protocols exist for addressing real situations in real buildings, as opposed to protocols used to conduct research investigations. These practical applications include determining that a new ventilation system is operating as designed, evaluating the performance of an existing system, and addressing ventilation issues as part of an indoor air quality investigation.

Testing, Adjusting and Balancing.[2-6] Testing, adjusting and balancing (TAB) is a set of protocols with the objective of achieving the intended operation of an HVAC systems. TAB efforts include testing of system performance parameters to evaluate equipment and system performance, setting balancing and automatic control devices to achieve specified system performance and efficiency during operation, and balancing system fluid (air and water) to achieve desired or specified flow quantities. The level of effort associated with these protocols is a function of the complexity of the building and its HVAC systems, but generally involves tens of days. TAB personnel require extensive experience and training, and there are National Environmental Balancing Bureau (NEEB) and Associated Air Balance Council (AABC) certification programs. While TAB provides a thorough assessment of ventilation system performance, the scope does not include some other important aspects of building ventilation such as building envelope leakage and pressure relationships between zones. The required level of effort will sometimes exceed the available resources in situations requiring only a limited ventilation assessment. However, the conclusions of such a more limited assessment may be that a complete TAB effort is required.

AMCA 203-90 Field Performance Measurement of Fan Systems.[7] The Air Movement and Control Association publication AMCA 203-90 is a set of protocols for measuring the installed performance of fan systems. These protocols include pitot tube traverse measurements of fan airflow rates, and the measurement of fan input power, fan speed and fan static pressure at inlets and outlets. The level of effort is a function of the number and configuration of fans tested, but is generally on the order of several days. The testing personnel require familiarity with fans, fan installations, and the measurement procedures and instrumentation described in the document. These procedures address very specific fan performance parameters and provide no information on a range of other relevant information including outdoor airflow rates.

AMCA 202-88 Troubleshooting.[8] AMCA 202-88 is a set of protocols for determining why an air moving system is not achieving its design performance. The document includes a fan inspection checklist that covers installation, condition of equipment, cleanliness, obstructions, system effects and leaks. It also describes how to analyze performance using fan curves and contains appendices on specific problems (e.g., noise, insufficient airflow, too much airflow, wrong static pressure, high power, and fan not operational) and probable causes of these problems. The level of effort is a function of the number and configuration of fans tested, but is generally on the order of several days. The personnel using these protocols need to be familiar with fans and fan installations.

ASHRAE Commissioning Guideline.[1] ASHRAE Guideline 1, Guideline for Commissioning of HVAC Systems, describes procedures for documenting and verifying the performance of HVAC systems to ensure that they operate according to the design intent. This guideline, discussed earlier in this paper, is meant to assist in formulating procedures for documenting building occupancy requirements and system design assumptions, conducting performance testing of the system and adjusting the system to meet the actual occupancy needs. It does not contain the procedures themselves, but identifies the procedures that must be implemented in an HVAC commissioning program and how such a program should be structured to be successful. It contains brief sections on documenting design requirements, system verification procedures and commissioning documentation, and provides an example HVAC commissioning plan and schedule. The guideline refers to TAB standards for ventilation evaluation. The level of effort associated with an HVAC commissioning effort is a function of the complexity of the building and its HVAC systems and spans from pre-design throughout the occupancy of a building. As described in the guideline, the personnel on the commissioning team include the building owner, designer, contractor, supplier, operator, and the so-called commissioning authority.

NIST Ventilation Assessment Manual.[9] This document contains multiple protocols for obtaining basic information on ventilation system performance and other aspects of building ventilation. These protocols include measurement techniques to determine system performance parameters including system airflow rates and building air change rates, and procedures to assess building space use and to evaluate system design and performance. While this document is a collection of techniques and procedures, it does not contain a general strategy for selecting protocols for specific situations. The approaches in this manual are much less detailed than a full TAB effort. The level of effort required for these procedures is a function of the complexity of the building and its HVAC systems and the objectives of the evaluation. Depending on these factors, the level of effort can range from a few days to tens of days. The personnel using these protocols must be familiar with buildings, HVAC systems, and airflow rate measurement.

AIVC Measurement Techniques Guide.[10] This document, published by the Air Infiltration and Ventilation Centre (AIVC), is a collection of measurement procedures to evaluate building infiltration and ventilation parameters including air change rates, interzonal airflow rates, and the airtightness of building components. It describes available procedures for measuring these parameters, instrumentation for doing so, and measurement standards. There is also a section describing the selection of appropriate measurement techniques. The level of effort depends on the parameter being measured and the complexity of the building and its ventilation systems. It is assumed that the personnel using these techniques are familiar with buildings, ventilation systems, and the instrumentation.

ASTM E741.[11] American Society for Testing and Materials Standard E741 is a test method for determining whole building air change rates using tracer gas decay, constant injection, or constant concentration. The results of these measurements include the combined effects of mechanical system intake and envelope leakage, and provide the air change rate for the conditions of weather and system operation that exist during the measurement. To fully characterize the dependence of building air change rates on weather and system operation, a large number of measurements are required under a wide range of conditions. The level of effort required to make these measurements depends on the complexity of the building and its ventilation systems. A single measurement can require a day or less. The personnel making these measurements need to be familiar with buildings, ventilation systems and tracer gas measurement equipment. This is the only procedure for determining whole building air change rates, as distinguished from outdoor air intake rates.

Instrumentation Manuals. The manuals provided with measurement instruments constitute a collection of general protocols that describe the use of particular instruments for assessing some aspect of building ventilation. They contain specific instructions on how to use the instrument to measure a specific quantity, such as temperature or air speed, and may also include instructions on how to relate the measurements to a somewhat bigger performance issue, e.g., compliance to ASHRAE Standard 62.[12] The level of effort associated with the protocols in these manuals is a function of the complexity of instrument and of the building and its HVAC systems. In general, these protocols will require a few hours to a few days of effort. The use of these protocols requires familiarity with the particular instrument, measurement principles related to the quantity being measured, buildings and HVAC systems. These protocols include a variety of techniques and procedures that depend on the instrument and the completeness of the manual. They usually do not constitute a comprehensive ventilation assessment, and sometimes imply greater simplicity of measurement and interpretation than may actually exist.

EPA/NIOSH Building Air Quality.[13] This document, published by the U.S. Environmental Protection Agency and the National Institute of Occupational Safety and Health, contains a collection of protocols intended for evaluating ventilation system design, operation, condition and performance as part of efforts to prevent or resolve IAQ problems. The protocols include descriptions of the following: evaluating the design of ventilation systems; checking maintenance records and inspecting system condition and operation; collecting information on pollutant pathways and driving forces; and, performing measurements of thermal comfort, carbon dioxide levels, and outdoor air delivery rates based on percent outdoor air. The required level of effort is a function of the complexity of the building and its ventilation systems. Generally, these procedures require about one or two days. The personnel using these protocols need to be familiar with buildings, HVAC systems, indoor air quality, and measurement instruments. The descriptions of measurement procedures, and the checklists of HVAC system description and inspection, are not intended to be complete.

Private IAQ and HVAC Consultants. Private-sector consultants employ individually-developed protocols in their investigations. The objective of these protocols is usually to assist in diagnosing indoor air quality problems, but in some cases they are also used to address comfort and energy problems. They may also be used to assess building ventilation as part of a preventive maintenance program. These protocols include a wide range of procedures used to evaluate system design, installation, operation, and performance that vary in terms of the depth and technical detail of the investigation. They usually consist of relatively short-term assessments that can range from well-established procedures to "gut-level" evaluations based on the experience of the individual. The level of effort is a function of the complexity of the building and its HVAC systems, as well as the detail of the investigation, and can cover a wide range from a fraction of a day to tens of days. The personnel using these protocols are generally very experienced in indoor air quality and/or HVAC systems.

Research

Additional ventilation evaluation protocols exist for use in research investigations. These investigations include studies of building ventilation as well as indoor air quality studies in which building ventilation is assessed in order to allow interpretation of other indoor environmental measurements.

EPA BASE Protocol for Building and HVAC Characterization The so-called BASE (Building Assessment Survey and Evaluation) research project is being conducted by EPA to define the status of the existing office building stock with respect to factors affecting indoor air quality and occupant perceptions of the indoor environment.[14] The overall BASE protocol is intended for the evaluation of a so-called test space in a building and contains a subset of protocols for obtaining information on ventilation system design and performance. The scope of the building and ventilation protocols includes the following items: description of the building and the test space being studied; description of the HVAC system serving the test space; and HVAC performance measurements including supply airflow rate, percent outdoor air, outdoor air intake and diffuser supply flows.[15] These procedures require two days of effort by two people who are familiar with buildings, ventilation systems, airflow rate measurement, and indoor contaminant measurement. These protocols were developed for this particular research effort, and not for the diagnosis of indoor air quality complaints.

Air Change Effectiveness. Air change effectiveness, defined in terms of age of air, is measured with tracer gas techniques[16-18], and is the subject of a draft ASHRAE test method (designation 129P). The protocol describes how to measure the average age of air at several locations in the occupied space and how to compare the average value to outdoor air intake rate into a building or test zone. The protocol places severe restrictions on the type of space to which it applies, making it generally inapplicable to field situations. This procedure is placed in the research category because there is limited experience with its use in the field.[19,20] The level of effort required to perform these measurements is a function of the complexity of the building and its ventilation systems. A single measurement requires roughly one or two days. The personnel conducting these measurements must be familiar with buildings, ventilation systems, and tracer gas measurement equipment.

CURRENT INADEQUACIES: PROBLEMS, REASONS AND SOLUTIONS

The overall objective of this project is to increase the availability and use of appropriate and reliable approaches to ventilation evaluation in buildings. In order to achieve this end, it is important to begin with a characterization of the existing problems and the reasons that they exist. Based on this assessment, several approaches to improving the current situation can be identified.

Current Problems

There are several problems with ventilation evaluations in buildings and the approaches being used in these evaluations. Some of the current problems include the following items:

- Lack of ventilation evaluation
- Inadequate calibration and treatment of measurement uncertainty
- Difficulties in measuring outdoor air intake rates
- Misuse and misunderstanding of indoor carbon dioxide concentrations

Lack of ventilation evaluation refers to fact that building ventilation is sometimes not considered in situations where it plays a critical role. For example, many investigations of indoor air quality complaints do not consider the impact of the ventilation system on the indoor environment. Also, building ventilation rates are not always measured in some indoor air quality research studies, making it impossible to interpret indoor contaminant concentration measurements. Other examples of the lack of consideration of ventilation are building management programs that do not involve ventilation system inspection.

When ventilation system performance parameters are measured, the equipment used in these measurements is not always properly calibrated by the user. Many users are not sufficiently aware of the need to calibrate their instruments and tend to rely too much on manufacturer's claims regarding accuracy and the lack of need to calibrate. The equipment used to evaluate ventilation needs to be calibrated, in many cases including on-site checks in the field. In addition, the uncertainties of these measurements are often not reported or are not reported in a statistically sound manner. Many field measurements do not adequately address the critical issue of measurement uncertainty, making it impossible to interpret the measurement results. Another problem is the difficulty in measuring outdoor air intake rates at air handling units due to the configuration of these units. The geometry of the intakes often precludes the use of standard velocity traverse procedures based on the lack of a uniform velocity profile at or near the intake. Many intakes are unducted or do not contain a sufficiently long length of straight duct for a uniform profile to develop before the outdoor airstream mixes with the return airstream. This problem is particularly true for smaller systems and packaged units.

The misuse and misunderstanding of indoor carbon dioxide concentration measurements is another problem related to ventilation evaluation. While indoor carbon dioxide concentrations can be useful in evaluating indoor air quality and building ventilation, the limitations of the procedures for doing so are often not acknowledged or understood.[21] Specifically, indoor concentrations are often used to estimate outdoor air ventilation rates per person without realizing that this approach requires the indoor carbon dioxide level to be at equilibrium. In many situations, the indoor concentration does not reach equilibrium, resulting in an overestimation of the ventilation rate.

Reasons

There are many reasons for these problems with building ventilation evaluation. The following list includes some of the reasons, listed in order from general to specific:

- Complexity of ventilation and air movement in mechanically ventilated buildings
- Variability in background and objectives of people performing and requiring evaluations
- Lack of standardized protocols for ventilation evaluation
- No requirement for ventilation evaluation
- Lack of training/experience
- Lack of information on measurement uncertainty
- Air handler configurations that inhibit inspection and measurement
- Instrumentation: reliability, cost, and ease-of-use
- Lack of reliable techniques for troublesome parameters

The first item refers to the inherent complexity of ventilation and air movement in multi-zone mechanically ventilated buildings. Airflow within such buildings is a complex process, involving many individual airflow rates and many factors affecting these rates. In addition, there is great variability among ventilation systems in their design and operation. This complexity and variability makes it difficult to develop and apply consistent evaluation procedures to all buildings and systems. In addition, there is also significant variability in the background and objectives of the people performing and requiring ventilation evaluations. As discussed previously in this paper, ventilation is evaluated in buildings for many different reasons and by individuals with different backgrounds including building operators, indoor air quality investigators, industrial hygienists, and researchers.

Another reason for some of the problems with ventilation evaluation is a lack of standardized protocols that cover the range of applications and users. As identified earlier, existing protocols cover only a range of the users of ventilation evaluations and their objectives. The lack of protocols covering the full range of needs results in the use of some incomplete and inappropriate procedures. Another reason for inconsistent or missing ventilation evaluations is the fact that they are seldom required. While ventilation evaluation is important in many applications, such as building investigations, it is not always required of the parties conducting the investigation. This lack of any requirement makes it hard for the investigator to perform this work while remaining economically competitive. Also, there is a lack of training and experience on the part of many potential users in terms of building ventilation, system design and operation, and approaches to ventilation evaluation. Inadequate training results in a lack of appreciation of the importance of ventilation and the inability to perform the evaluation procedures.

There is also a lack of information on the measurement uncertainty for many of the instruments and techniques used in ventilation evaluations. For example, there is little information on the measurement uncertainty expected in the field for flowhood measurements of supply airflow rates at diffusers or for pitot traverse measurements of airflow rates in ducts. The lack of uncertainty estimates is due in part to the fact that the careful experimental work required to make these estimates has not been done.

Even when using appropriate procedures, the configuration of many air handlers inhibits their inspection and the measurement of important parameters. These problems include inaccessible equipment, the lack of access doors for inspecting system components, and ductwork configurations that prevent reliable velocity traverse measurements of airflow rates. While instrumentation is available to measure most of the required parameters, there are needs for new instruments with increased reliability, lower cost, and easier use in the field. Also, reliable measurement techniques do not exist to measure some parameters. For example, it is difficult to measure outdoor air intake rates at air handlers and supply airflow rates at diffusers, and the techniques commonly used to measure these parameters are not always reliable.

Solutions

An important objective of this project is to identify approaches to improving the reliability of building ventilation evaluations. Based on the problems identified above, the following solutions are presented:

- Development of standardized protocols for ventilation evaluation
- Requirements for ventilation evaluation
- Guidance on ventilation system design to facilitate inspection and measurement
- Research
- Improved instrument application manuals
- New instrumentation and measurement techniques
- Training

One approach to eliminating some of the current problems with ventilation evaluation is the development of standardized protocols. While there may not be established procedures covering all applications that are ready for standardization, there are important protocols that could be standardized by ASHRAE, ASTM, and other standards-writing organizations. These standards could range from general guides on ventilation evaluation to specific test methods. For example, a guide to the use of indoor carbon dioxide concentrations for evaluating building ventilation and indoor air quality would help to eliminate some of the current confusion. Other examples include a test method for measuring percent outdoor air intake using tracer gases and a guide to ventilation system inspection.

Requiring ventilation evaluation would increase the frequency at which these evaluations are performed, and ideally their reliability would improve as well. Such requirements could take many forms including regulations, contract requirements, and guidelines for building operation and building investigations. The appropriate means for implementing requirements for ventilation evaluation would be situation specific.

Research is needed that would address some of the problems in ventilation evaluation. These research needs could be divided into two groups: the development and demonstration of new technologies, and the evaluation of existing measurement procedures. The latter category includes the determination of measurement errors in the field for commonly used procedures such as airflow rate measurement in ducts using pitot tube traverses and supply airflow rate measurements at diffusers using flowhoods.

The last three options listed are self-explanatory. They include the improvement of instrument application manuals, the development of new instrumentation and measurement techniques, and the development and use of guidance on ventilation system design to facilitate inspection and measurement. Training is needed that covers the range of applications and users. In addition, these users need to recognize the limitations of their training and experience, and not attempt to conduct evaluations for which they are not qualified.

CONCLUSIONS

This paper has summarized the current state-of-the-art of ventilation evaluation in buildings, including when they are used and the objectives of these evaluations. A variety of existing evaluation protocols were also described. The fact that ventilation evaluation is sometime inadequate was discussed in terms of some of the specific problems, the reasons for these inadequacies, and some approaches to improving the current situation.

REFERENCES

1. ASHRAE, Guideline for Commissioning of HVAC Systems, ASHRAE Guideline 1-1989, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, GA, 1989.

2. AABC, National Standards for Testing and Balancing Heating, Ventilating, and Air Conditioning Systems, Fifth Edition, Associated Air Balance Council, Washington, DC, 1989.

3. ASHRAE, Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning, and Refrigeration Systems, ANSI/ASHRAE Standard 111-1988, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, GA, 1988.

4. W.D.Bevirt, Environmental Systems Technology, National Environmental Balancing Bureau, Rockville, MD, 1984.

5. NEBB, Procedural Standards for Testing Adjusting Balancing of Environmental Systems, Fifth Edition, National Environmental Balancing Bureau, Rockville, MD, 1991.

6. SMACNA, HVAC Systems, Testing, Adjusting & Balancing, Sheet Metal and Air Conditioning Contractors National Association, Inc., Chantilly, VA, 1983.

7. AMCA, Field Performance Measurement of Fan Systems, Publication 203-90, Air Movement and Control Association, Inc., Arlington Heights, IL, 1990.

8. AMCA, Troubleshooting, Publication 202-88, Air Movement and Control Association, Inc., Arlington Heights, IL, 1988.

9. A.K. Persily, Manual for Ventilation Assessment in Mechanically Ventilated Commercial Buildings, NISTIR 5329, National Institute of Standards and Technology, Gaithersburg, MD, 1994.

10. P.S. Charlesworth, Air Exchange Rate and Airtightness Measurement Techniques - An Applications Guide, Air Infiltration and Ventilation Centre, Coventry, Great Britain, 1988.

11. ASTM, Standard Test Method for Determining Air Change in a Single Zone by Means of Tracer Gas Dilution, E741, American Society for Testing and Materials, Philadelphia, 1993.

12. ASHRAE, Ventilation for Acceptable Indoor Air Quality, Standard 62-1989, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 1989.

13. EPA/NIOSH, Building Air Quality, A Guide for Building Owners and Facility Managers, EPA/400/1-91/033, U.S. Environmental Protection Agency, Washington, DC, DHHS (NIOSH) Publication No. 91-114, National Institute for Occupational Safety and Health, Cincinnati, OH, 1991.

14. S.E. Womble, R. Axelrad, J.R. Girman, R. Thompson, and R. Highsmith, "EPA BASE Program - Collecting Baseline Information on Indoor Air Quality," in Proceedings of Sixth International Conference on Indoor Air Quality and Climate, Helsinki, Finland, 1993, Vol. 1, pp 821-825.

15 A.K. Persily, Building and HVAC Characterization for Commercial Building Indoor Air Quality Investigations, NISTIR 4979, National Institute of Standards and Technology, Gaithersburg, MD, 1993.

16. M. Sandberg, "Ventilation Efficiency as a Guide to Design," ASHRAE Transactions, 89(2): (1983).

17. M. Sandberg and M. Sjoberg, "The Use of Moments for Assessing Air Quality in Ventilated Rooms," Building and Environment, 18(4): 181 (1983).

18. A. K. Persily, "Assessing Ventilation Effectiveness in Mechanically Ventilated Office Buildings," in Proceedings of International Symposium on Room Air Convection and Ventilation Effectiveness, Tokyo, Japan, 1992, pp 201.

19. A. K. Persily and W. S. Dols, "Field Measurements of Ventilation and Ventilation Effectiveness in an Office/Library Building," Indoor Air, 1(3): 229 (1991).

20. A. K. Persily, W.S. Dols, and S.J. Nabinger, "Air Change Effectiveness Measurements in Two Modern Office Buildings," Indoor Air, 4(1): 40 (1994).

21. A. K. Persily, "Ventilation, Carbon Dioxide and ASHRAE Standard 62-1989." ASHRAE Journal, 35(7): 40 (1993).

Table 1 Elements of ventilation evaluations and examples of each element

- **Determination of ventilation requirements based on analysis of space use**
  - Supply, outdoor and exhaust airflow rates
  - Pressure relationships between zones
- **Analysis of system design**
  - Design conditions in space: Air temperature and relative humidity
  - Air handler specifications
    - Supply airflow capacity
    - Supply air temperature and relative humidity
    - Minimum outdoor air intake
  - Air handler control
    - Sequence of operations
    - Supply airflow rate control
    - Control of outdoor air intake rate
  - Exhaust and return fan specifications: Airflow rate and sequence of operations
- **Inspection of system installation**
  - Air handlers, controls, ductwork, exhaust fans, fan coil units, and terminal units
- **Inspection of system operation**
  - Fan operation
  - Direction of airflow
  - Damper position
- **Inspection of system condition**
  - Mechanical room
  - Supply, return and exhaust fans
  - Outdoor air intakes
  - Air handler components: e.g., sound liners, dampers, coils, filters, drain pans
  - Ductwork
  - Fan coil units
  - Terminal units
- **System performance measurement.**
  - Supply airflow rate: air handler, distribution ductwork, ventilated space
  - Supply air properties (temperature and relative humidity)
  - Outdoor airflow rate: air handler, distribution ductwork, ventilated space, work station
  - Exhaust airflow rate: fan, ventilated space
  - Air handler airflow rates and controls
  - Terminal unit airflow rates and controls
  - Duct leakage
- **Qualitative assessment of building ventilation**
  - Interzone airflow patterns
  - Airflow direction at exterior openings
  - Exhaust air entrainment
  - Air mixing within rooms
- **Quantitative assessment of building ventilation**
  - Whole building air change rates
  - Interzone airflow rates and pressure differences
  - Airflow rates and pressure differences at interior and exterior openings
  - Envelope airtightness