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Procedures and Standards for Residential Ventilation System Commissioning: An Annotated Bibliography

J. Chris Stratton and Craig P. Wray

Environmental Energy Technologies Division

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Disclaimer

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ABSTRACT

Beginning with the 2008 version of Title 24, new homes in California must comply with ANSI/ASHRAE Standard 62.2-2007 requirements for residential ventilation. Where installed, the limited data available indicate that mechanical ventilation systems do not always perform optimally or even as many codes and forecasts predict. Commissioning such systems when they are installed or during subsequent building retrofits is a step towards eliminating deficiencies and optimizing the tradeoff between energy use and acceptable IAQ. Work funded by the California Energy Commission about a decade ago at Berkeley Lab documented procedures for residential commissioning, but did not focus on ventilation systems. Since then, standards and approaches for commissioning ventilation systems have been an active area of work in Europe. This report describes our efforts to collect new literature on commissioning procedures and to identify information that can be used to support the future development of residential-ventilation-specific procedures and standards. We recommend that a standardized commissioning process and a commissioning guide for practitioners be developed, along with a combined energy and IAQ benefit assessment standard and tool, and a diagnostic guide for estimating continuous pollutant emission rates of concern in residences (including a database that lists emission test data for commercially-available labeled products).

1. Introduction

Beginning with the 2008 version of Title 24, new homes in California must comply with ANSI/ASHRAE Standard 62.2-2007 requirements for residential ventilation. These requirements include minimum airflows for whole-house mechanical ventilation, as well as minimum airflows for local ventilation, maximum total exhaust airflow for combustion safety, garage and duct airtightness, and maximum specific fan power. Designs that comply with prescriptive requirements or manufacturer's criteria do not require field verification of airflows or power, but central-fan-integrated systems do require these field tests. These requirements do not account for the fact the many homeowners already have exogenous ventilation systems running including economizers, direct evaporative coolers, dryers, or kitchen hoods. They also do not include the fact that low-emission materials may be used to reduce ventilation needs, or that high-emission materials lead to increased ventilation needs.

Currently, few California houses have mechanical ventilation systems. Where installed, the limited data available indicate that these systems do not always perform optimally or even as many codes and forecasts predict. Deficiencies occur in part because there is no consistent process to identify and correct problems, and also because the value of such activities in terms of reducing energy use and improving IAQ is unknown. Commissioning such systems when they are installed or during subsequent building retrofits is a step towards eliminating deficiencies and optimizing the tradeoff between energy use and acceptable IAQ.

Work funded by the Commission about a decade ago at Berkeley Lab documented procedures for residential commissioning and demonstrated the value of the overall process, but did not focus on ventilation systems and did not disaggregate the related potential savings. Since then, standards and approaches for commissioning ventilation systems have been an active area of work in support of European standards, and new analytical methods have been developed to assess the potential value of energy use and IAQ benefits on a common scale. To take advantage of these opportunities, this report describes our efforts to collect new literature on commissioning procedures and to identify information that can be used to support the future development of residential-ventilation-specific procedures and standards.

The following provides background about the residential ventilation commissioning process that we envision, describes our approach for the literature review, summarizes our findings and the benefits to California, and lists recommendations for future work.

2. The Residential Ventilation System Commissioning Process

Every commissioning process includes three principal elements: metrics, diagnostics, and norms. The following defines these elements and offers examples to aid understanding:

- ***Metrics***: For whole buildings, there are two broad performance objectives of interest: energy performance and indoor environmental performance (e.g., indoor air quality and comfort). Each objective can be represented by various performance metrics, which are simply defined as a quantification of the performance of relevant components or systems. Three examples are: (1) unbalanced ventilation airflow, which represents the difference between supply and exhaust ventilation airflows; (2) specific leakage area, which represents the airtightness of the building envelope; and (3) house depressurization, which is often used to represent the backdrafting potential for combustion appliances. Each of these metrics has implications in terms of energy and indoor environmental performance. However, the importance of a particular metric to each performance objective may be weighted differently, and therefore each must be able to stand on its own.
- ***Norms***: A metric itself does not indicate good or bad performance. However, when quantified, each metric forms the basis for developing the norms against which component or system performance is compared. As with the metrics, the norms will vary depending on the objective of the commissioning. They will also depend on the stage of the house in its life-cycle. For the metrics related to building performance, consider that various building standards could specify requirements for maximum airflow imbalance, for minimum or maximum specific leakage area, and for maximum house depressurization levels.
- ***Diagnostics***: Diagnostics are defined here as relatively quick short-term field procedures involving measurements and perhaps analyses to evaluate performance metrics for a system or component under functional test or actual building site conditions. While it is also possible and sometimes preferable to evaluate metrics using data taken over an entire season, time limitations make it impractical to collect and analyze such long-term

information during ventilation system commissioning. Such limitations will be largely dependent on the value of the commissioning process to the involved parties. In some rare cases, for an existing house, commissioning might be able to use readily-available historical data either as part of diagnostics or to set norms, if appropriate measurement equipment was already installed. From the building performance examples above, consider ventilation airflows. A possible diagnostic is to use airflow measuring equipment such as a commercially-available flow capture hood.

The same metrics and diagnostics can be used in new and existing houses, although some diagnostics may not be appropriate early in the construction process. However, the norms for existing houses will have to be adjusted to account for the economic viability of meeting stricter standards than those in place at the time of construction. For example, a house built in 1930 does not come close to meeting current Title 24 specifications for airtightness and mechanical ventilation. The retrofitting required to meet Title 24 airtightness levels in this example would be prohibitively expensive.

Published commissioning processes for commercial buildings are too onerous for houses. The ventilation system commissioning process that we envision is simpler and has three main phases that combine auditing, testing, and implementing improvements to enhance component and system performance:

- ***Audit and Diagnostic***: In the first phase of commissioning, metrics for the house are surveyed using instrumented and non-instrumented techniques. The results of this survey are then compared with the norms for the house. For new construction, the norms will be those of the Title 24 compliance material or of the equivalent local building codes. For an existing house, the norms may be based on design intent (in the rare cases where any was documented) or on what a particular component should be able to do compared to other similar houses.
- ***Tuning and Tweaking***: The performance of many components and systems may not meet the norms, but it will be possible to improve their performance by making minor adjustments, repairs, or retrofits on the spot. An example is adjusting airflows so that they balance. Tuning and tweaking can often provide significant performance improvements for very little marginal cost. The purpose of this step is to improve house performance to at least the design intent. Sometimes, that intent will be unknown. In those cases, the optimization will be to other norms, such as the best performance achievable without repair or retrofit.
- ***Opportunity Identification***: After tuning and tweaking, there still may be components that are not performing to their potential. This commissioning step provides the client with information about potential repair or retrofit opportunities that could be investigated further (e.g., sealing the garage-house interface). Even when components are performing to their norms, newer technology may make replacement worth considering.

3. Literature Review Approach and Results

We carried out a topical literature review related to ventilation system commissioning and produced this annotated bibliography to build upon our past literature review (Wray et al. 2000, Bibliography Document 67) and to support related work. In searching for documents, we developed and used a set of keywords to locate information associated with ventilation system commissioning. Specifically, the search focused on metrics, diagnostics, and norms for mechanical ventilation components and systems that can be inspected to verify conformity with a specification, that can be “tweaked” or tuned during a ventilation system commissioning process, or that can be modified later to improve the energy and indoor environmental performance of a house. Key areas of interest included:

- Airflow through and pressure rise across fans
- Airflow through, pressure loss, and leakage of ducts and associated components
- Ventilation controls

A substantial amount of new information related at least peripherally to ventilation system commissioning has been published over the past decade. In particular, we identified 321 new documents, including ones from:

- Air Conditioning Contractors of America (ACCA)
- Air-Conditioning, Heating, and Refrigeration Institute (AHRI)
- American Council for an Energy-Efficient Economy (ACEEE)
- Air Infiltration and Ventilation Centre (AIVC)
- Air Movement and Control Association (AMCA)
- American Conference of Governmental Industrial Hygienists (ACGIH)
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)
- American Society for Testing and Materials (ASTM)
- Associated Air Balance Council (AABC)
- Building America (U.S. Department of Energy, DOE)
- Building Performance Institute (BPI)
- Building Research Establishment (BRE)
- Building Services Research and Information Association (BSRIA)
- Building Science Corporation
- California Energy Commission (CEC)
- Canada Mortgage and Housing Corporation (CMHC)
- Canadian General Standards Board (CGSB)
- Canadian Standards Association (CSA)
- Construction Engineering Research Laboratory (CERL)
- Environmental Protection Agency (U.S. EPA)
- European Committee for Standardization (CEN)
- Home Ventilating Institute (HVI)

- International Energy Agency (IEA) Annex 40
- Lawrence Berkeley National Laboratory reports
- Occupational Safety and Health Administration (OSHA)
- Residential Energy Services Network (RESNET)
- Various web sources

Some of the most advanced and relevant references are European[1]: the eight parts of CEN 13141 that are listed below related to "Ventilation for Buildings - Performance Testing of Components / Products for Residential Ventilation" (Bibliography Documents 46 to 53) and CEN 14134:2004 "Ventilation for Buildings – Performance Testing and Installation Checks of Residential Ventilation Systems" (Bibliography Document 34).

- CEN 13141-1:2004 "Part 1: Externally and Internally Mounted Air Transfer Devices".
- CEN 13141-2:2004 "Part 2: Exhaust and Supply Air Terminal Devices".
- CEN 13141-3:2004 "Part 3: Range Hoods for Residential Use".
- CEN 13141-4:2009 "Part 4: Fans Used in Residential Ventilation Systems".
- CEN 13141-5:2004 "Part 5: Cowls and Roof Outlet Terminal Devices".
- CEN 13141-6:2004 "Part 6: Exhaust Ventilation System Packages Used in a Single Dwelling".
- CEN 13141-7:2008 "Part 7: Performance Testing of Mechanical Supply and Exhaust Ventilation Units (including Heat Recovery) for Mechanical Ventilation Systems Intended for Single Family Dwellings".
- CEN 13141-8:2006 "Part 8: Performance Testing of Un-Ducted Mechanical Supply and Exhaust Ventilation Units (including Heat Recovery) for Mechanical Ventilation Systems Intended for a Single Room".

Each of the eight parts of CEN 13141 describes methods specifically for *laboratory* performance testing of residential ventilation components and products. The tests include (where appropriate) ones for measuring airflow through and pressure drop or rise across device(s), external and internal leakage (including filter bypass leakage), air diffusion in occupied zones, wind-related suction effects, thermal characteristics (i.e., airstream temperature ratios, occurrence of condensation or frost when intended for cold climate use), grease absorption, odor extraction, water tightness, sound power and insulation, acoustic insertion loss, and electrical power. Acoustic and electrical power tests refer to other ISO Standards for details. CEN 13141, however, does not describe field measurements and all of its parts would need to be substantially modified to be practical for field use.

CEN 14134 describes field installation completeness checks and functional tests for commissioning installed mechanical and passive ventilation systems in dwellings. It applies to

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[1] Comité Européen de Normalisation (CEN – European Committee for Standardization) members are the national standards bodies of Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

both new and existing systems, and includes all of the components in CEN 13141, plus passive stacks and filters. The functional tests include procedural outlines (but not details) and test conditions for measuring airflow (refers to 13141-1 and 13141-2), control running time, duct leakage area, sound power, and electric power.

The rest of the literature that we reviewed remains relatively devoid of field-test-related information that can be used in isolation to commission residential ventilation systems. For example, ASHRAE Standard 111-2008 "Measurement, Testing, Adjusting and Balancing of Building Heating, Ventilation and Air-Conditioning Systems" (Bibliography Document 19) describes many field diagnostic techniques for use in *commercial* building test and balance (TAB) activities. However, many of these diagnostics are not suitable for residential ventilation system commissioning because:

- The diagnostic is impractical or takes too long (e.g., pitot-static tube traverses of ducted airflows, where the ducts are often inaccessible, too short, or not straight enough),
- The information provided relates to flows that are much larger than those typically found in residential systems (i.e., it does not address increased inaccuracies at low flows), or
- The guidance is not applicable (e.g., suggestions that flow hoods cannot be relied upon for accurate measurements).

If relevant information from each of these references was combined together along with the European work and the results of follow on experimental and simulation-based work that we have conducted (Stratton et al. 2012, Turner et al. 2012; Bibliography Documents 60 to 62), it could be used as the basis to prepare a future standalone residential ventilation system commissioning guide for practitioners.

Due to resource limitations, we could only annotate a fraction of the 321 references that we collected and reviewed (about 20%). In particular, Appendix A lists annotated forms of 68 references that in our opinion contain the most relevant and comprehensive information. Appendix B lists the other 253 references, but without annotations. Those references also contain useful information, in support of the references that we list in Appendix A.

For further information, we encourage readers to also consult the broader annotated bibliography that preceded this one (Wray et al. 2000, Bibliography Document 67), as well as a comprehensive critical literature review related to combustion safety diagnostics (Rapp et al. 2012; Bibliography Document 56). The latter reference was developed as a standalone offshoot of the work reported here.

References are generally organized in alphabetic order, latest to earliest. In some cases, however, references for a particular "author" are in numeric order to facilitate finding them in the list (e.g., ASHRAE references).

4. Benefits to California

Commissioning is performed in steps, and whether or not to perform each step should be evaluated along the way. The ideal commissioning process uses appropriate, calibrated diagnostic tools and standardized procedures to determine the total energy and IAQ cost or benefit for a given home as a function of system airflow, followed by identification of the tuning options for that home, cost analysis of those options, and then finally implementing those options dependent on the cost benefit to the home owner.

Based on the home characteristics that Turner et al. (2012; Bibliography Document 62) considered, the first step of performing diagnostics appears to be justified in the majority of new homes. In particular, for low emission homes, assuming the proper use of task ventilation, tuning the airflow will always be of value so long as the price of tuning is less than the 30-year health and energy cost of an over-ventilating system. For homes with higher emission rates, currently, it would be difficult and potentially costly for a commissioning professional to perform the diagnostics required to estimate household emission rates for the pollutants of concern, especially as these are house specific and subject to change in part due to occupant behavior.

Identifying that diagnostics are needed to quantify emission rates will hopefully spur industry to develop appropriate tools and guidelines for the commissioning community. The results by Turner et al. suggest that controlling and limiting the levels of continuous emissions may also be an important tuning tool for residential ventilation systems. Labeling schemes now exist for products that meet low emission standards. Addressing emission rates in the commissioning process might be as simple as the auditor looking for labeled products in the house to help quantify the levels of continuous emissions.

5. Recommendations for Future Work

Our literature review found that commissioning of residential ventilation systems is not a common practice in California, but is being adopted in other countries. It also found that the literature is relatively devoid of field-test-related information that can be used in isolation to commission residential ventilation systems. To facilitate commissioning of these systems, we recommend the following:

1. Relevant information in the references listed in our annotated bibliography, especially CEN 14134 and CEN 13141, should be combined with the results of our diagnostic tool evaluations (Stratton et al. 2012) to develop a standardized commissioning process and a residential ventilation system commissioning guide for practitioners. The process should include audit and diagnostic, tuning and tweaking, and opportunity identification steps. The guide should provide specific information about particular metrics and diagnostics to use, and links to the norms available for comparison.
2. A combined energy and IAQ benefit assessment standard and tool should be developed. The work by Turner et al. (2012), which demonstrated how to determine the combined net present

value of the impacts on occupant health and building energy use impact of malfunctioning whole-house ventilation systems, is a useful starting point.

3. A diagnostic guide for estimating continuous pollutant emission rates of concern in residences should be developed. The process could be as simple as the auditor identifying and documenting labeled products in the house, but might also include methods to characterize outdoor sources of concern such as respirable particles. The guide should include information about the diagnostics, and provide related norms for comparison.
4. A database that lists emission test data for commercially-available labeled products should be developed and made available to support product emission assessments.

Appendix A: Annotated References

1. AABC. 2002. "AABC Commissioning Guideline for Building Owners, Design Professionals, and Commissioning Service Providers". Washington, DC: Associated Air Balance Council.

   Discusses cost and benefits of commissioning, AABC certification program, different phases and types of commissioning, details of processes, and responsibilities of team members. Also provides sample forms and checklists (for verification and startup), specifications, and request for proposals for commissioning services. Discusses how to select qualified commissioning agent and outlines scope of services that should be performed in each phase of process. Focuses on commercial and institutional buildings, both new and existing. Addresses both HVAC and non-HVAC system commissioning.

2. AABC. 2002. "National Standards for Total System Balance". Washington, DC: Associated Air Balance Council.

   Discusses system balancing phases (e.g., design, construction, testing and balancing (TAB), reporting, final acceptance, contractor responsibilities,). Also discusses instrumentation (e.g., anemometers, flow grids and hoods, pitot tubes, manometers, tolerances), as well as techniques (e.g., duct velocity traverse, coil traverse, density correction, calibration correction factors, damper adjustment, economizer cycle tests). Provides field observation checklist for air-handling systems and sample specifications for TAB.

3. ACCA. 2011. "Air Conditioning Contractors of America (ACCA), Quality Homes: Existing Home Evaluation and Performance Improvement Standard". Arlington, VA.

   Establishes standard for home audits, based on RESNET standard. Indicates that "auditor shall determine minimum ventilation requirement for occupants". Discusses: CO evaluation with 9 ppm limit; single-point CFM_{50} blower door envelope leakage test; visual inspection of exhaust fans and clothes dryers vented to outdoors; need to use ASHRAE 62.2-2010 or authority having jurisdiction (AHJ) methodology to determine ventilation requirements. Indicates that mechanical ventilation airflow shall be measured in accordance with section 5.2.2 of ACCA 5 QI standard. Recommends that: ventilation system complies with IECC 2009; attic ventilation shall not be installed without verifying the presence of an effective air barrier between attic and living space; existing venting for bathrooms and kitchens shall comply with International Residential Code (2009) section M1507.

4. ACCA. 2005. “2005 Standard for Air-Conditioning, Heating, and Refrigeration Institute, ANSI/AHRI Standard 1060: Performance Rating of Air-to-Air Exchangers for Energy Recovery Ventilation”. Arlington, VA.

Standard testing conditions established for heating and cooling evaluations. Provides pressure drop maximum requirements across heat exchanger. Rated airflow expressed in standard cubic feet per minute (scfm). SF_6 tracer gas test required as defined in Section 8.2 of ASHRAE Standard 84 and presented as the Exhaust Air Transfer Ratio (EATR); tracer gas test evaluates how much outgoing exhaust air leaks into incoming supply stream.

5. ACGIH. 2007. “Industrial Ventilation – A Manual of Recommended Practice for Operation and Maintenance”. Cincinnati, OH: American Conference of Governmental Industrial Hygienists, Inc.

Discusses construction and project management, commissioning (e.g., team organization, process components, forms, and proof of performance), testing and measurement of ventilation systems (e.g., measurement and instrument types, calibration, and practical issues in measurement), balancing duct systems with dampers, ventilation system monitoring and maintenance (e.g., value of predictive maintenance, risk assessment, recommended practices and documentation), troubleshooting processes (e.g., problem evaluation, system walkthrough, baseline comparisons), system modifications (e.g., changing system airflow, modifying duct system), and operator skills and training.

6. ACGIH. 1992. “Industrial Ventilation – A Manual of Recommended Practice” 21st Edition. Cincinnati, OH: American Conference of Governmental Industrial Hygienists, Inc.

Discusses general principles of ventilation, as well as exhaust system design principles (including optimum economic velocity). Also provides construction guidelines for local exhaust systems, and discusses testing of ventilation systems (e.g., pressure, air velocity, and flow measurement; instrument types and calibration; and difficulties encountered in field measurements).

7. AHRI. 2010. “ANSI/AHRI Standard 680 (I-P): 2009 Standard for Performance Rating of Residential Air Filter Equipment”. Arlington, VA.

Standard intended to evaluate performance of residential air filters. Indicates that test apparatus shall be as specified in ASHRAE Standard 52.2. Three filter categories, evaluated for initial resistance, particle size efficiency, final resistance, and dust holding capacity. Breaching test evaluates filter’s propensity to collapse, tear, or come apart under typical pressure conditions (1 in.w.c.). Ozone concentration in effluent air evaluated for electronic air cleaners.

8. AIVC. 2002. "AIR: Air Information Review: A quarterly newsletter from the IEA Air Infiltration and Ventilation Centre". Vol. 23, No. 2, March.

Review of European ventilation standards. Summaries of books about ventilation and other building science topics. Primarily focused on commercial buildings.

9. AMCA. 2007. "ANSI/AMCA 210-07 – ANSI/ASHRAE 51-07: Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating". Arlington Heights, IL: Air Movement and Control Association, Inc.

Provides laboratory test methods for fans and other air moving devices to measure performance in terms of airflow, pressure rise, power consumption, rotational speed, and efficiency for rating or guarantee purposes. Excludes ceiling and desk fans and compressors. Not intended for use in design, production, or field testing. Describes test instrument types, required accuracy and calibration, sixteen test configurations and conditions, and data analysis procedures and reporting (including examples). Includes informative appendices about checking effectiveness of airflow settling means in test chambers, for evaluating chamber leakage, and analyzing measurement uncertainty.

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

Discusses types of field tests; alternatives to field tests; system effect factors; fan system terminology; fan airflow, pressure rise, power, and speed measurements, including instruments (e.g., pitot-static tubes, double reverse tubes, static taps, manometers), methods (e.g., duct traverses, estimating drive losses), test preparation and precautions, and accuracy; and density corrections. Concludes with 23 examples of field tests on various system types (free inlet, ducted outlet; ducted inlet, ducted outlet; ducted inlet, free outlet; free inlet, free outlet; air-handling units), which include specific measurement methods, sample test data, and calculations.

11. ASHRAE. 2000. "ANSI/ASHRAE Standard 41.7: Method of Test for Measurement of Flow of Gas". Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes "recommended practices for measuring *flow of dry gas* for use in preparation of ASHRAE standards". Provides techniques for volatile refrigerants (gaseous phase), and for air under conditions where Standard 41.2 methods are "inconvenient or unsatisfactory". Dry gas is defined as a gas "wherein the amount of liquid flowing with the gas through the measuring device is less than 2% of the mass of the gas flowing". Focuses on use of square-edge orifice meters with flange taps. Requires use of mercury- or liquid-filled equal-arm manometer to measure pressure. Describes combined table lookup and graphical method to select meter and orifice size. Briefly describes calculation to convert pressure measurements to mass flow.

12. ASHRAE. 1992. "ANSI/ASHRAE Standard 41.2: Standard Methods for Laboratory Airflow Measurement". Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes "recommended practices for *airflow* measurements and to provide adequate and consistent measurement procedures for use in preparation of other ASHRAE standards". Procedures are intended for "use in testing air-moving, air-handling, and air-distribution equipment and components" in "laboratory testing of heating, ventilating, air-conditioning, and refrigerating components and equipment and do not necessarily apply to field testing of installed equipment and systems". Includes "consideration of density effects on accurate measurement of flow rates" so that measurements can be expressed in terms of standard air. Does not address procedures for "testing fans, blowers, exhausters, compressors, and other air-moving devices whose principal function is to produce a stream of moving air, which fall within the scope of" ASHRAE Standard 51 / AMCA 210.

Describes use of pitot traverse or nozzle to measure flow in ducts and through products with one or more fans, use of flow straighteners and air temperature mixers, and use of flow settling and calorimetric chambers. Allows other techniques to be used, but accuracy of flow measurement "shall not exceed that corresponding to 1.2% of the discharge coefficient for a flow nozzle". Manometer accuracy "shall be ±1% or less and the precision shall be ±0.50% or less or ±0.005 in.w.c. (±1.2Pa), whichever is large". Temperature measurement accuracy for air density corrections ±2F and precision of ±1°F or better. Provides detailed calculations for determining flows from traverse and nozzle pressure measurements or from calorimetric power and temperature measurements.

13. ASHRAE. 1989. "ANSI/ASHRAE Standard 41.3: Standard Method for Pressure Measurement". Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes "recommended practices and procedures for accurately measuring steady-state, non-pulsating pressures" in 1 psia (6.9 kPa) to 500 psia (3450 kPa) range. Describes characteristics of bourdon tube, bellows, diaphragm type gauges, as well as liquid manometers and electronic (e.g., strain gauge or quartz element based) sensors. Describes calibration practices and standards (e.g., deadweight tester).

14. ASHRAE. 2011. "62.2 User's Manual - ANSI/ASHRAE Standard 62.2-2010: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings". Atlanta, GA; American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Contains explanatory material, examples and background information to aid users of Standard 62.2-2010 in designing and constructing residential buildings so that they comply with the Standard. Intended for use by residential building contractors, architects, and engineers, as well as code officials, government agencies, and homeowners. Organized to follow sections of the Standard.

15. ASHRAE. 2010. “ANSI/ASHRAE Standard 62.2: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings”. Atlanta, GA; American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Defines roles of and ***minimum*** requirements for ventilation systems (natural and mechanical) and building envelope to provide acceptable indoor air quality in low-rise residential buildings. Applies to spaces intended for human occupancy. Considers chemical, physical, and biological contaminants, but not thermal comfort. Requirements include those for whole-house and local ventilation systems. Requires measurement of outdoor airflow supplied and/or indoor exhausted by ventilation systems, using devices such as flow hood or flow grid. Also requires that HVAC system leakage be measured and be limited to no more than 6% of total fan flow at 0.1 in.w.c. (25 Pa) using procedures defined in California Title 24 Part 6, ASTM Standard E1554, or equivalent.

16. ASHRAE. 2011. ANSI/ASHRAE Addenda b, c, e, g, h, i, and l to ANSI/ASHRAE Standard 62.2-2010: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings”. Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Adds requirements to Standard 62.2-2010 for: optional use of minimum filtration as tested by AHRI 680-2009, which is based on ASHRAE Standard 52.2(addendum b); sound ratings of fans at minimum of 0.1 in.w.c. (25 Pa) static pressure, based on HVI test procedures (addendum c); filter pressure drop (and labeling) as measured using AHR Standard 680 (addendum e). Removes net exhaust flow limits for hot, humid, and very cold climates (addendum g); Adds exception to permit use of component ratings to calculate local exhaust airflows when flows cannot be measured (addendum h). Updates intermittent ventilation methodology to address impact of infiltration (addendum i). Adds requirement to install CO alarms consistent with applicable laws, codes, and standards (addendum l).

17. ASHRAE. 2006. “ANSI/ASHRAE Standard 70: Method of Testing the Performance of Air Outlets and Air Inlets”. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes laboratory methods for testing aerodynamic and sound performance of air inlets and outlets used to terminate air distribution systems. Includes specifications for test instruments, facilities, installations, procedures and methods. Measurements include: air temperature; air pressure (static and total); airflow; air velocity; throw spread, and drop; and sound. Includes procedures for isothermal and non-isothermal air streams.

18. ASHRAE. 2008. “ANSI/ASHRAE Standard 84: Method of Testing Air-to-Air Heat/Energy Exchangers”. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes laboratory methods for determining airflows, pressure drop, effectiveness, total enthalpy, and exhaust air transfer for air-to-air heat/energy exchangers. Includes specifications for test instruments, facilities, installations, procedures and methods. Measurements include: air temperature, air pressure, humidity, and tracer gas concentrations. Limited discussions regarding applications of standard in field tests (subject to achieving acceptable uncertainty in the field).

19. ASHRAE. 2008. “ANSI/ASHRAE Standard 111: Measurement, Testing, Adjusting, and Balancing of Building HVAC Systems”. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Provides ***field*** methods for determining thermodynamic, hydraulic, hydronic, mechanical, and electrical conditions, including: room air change rates, pressurization, cross contamination; adjusting outdoor ventilation rates; and validating collected data. Includes specifications for test instruments, facilities, installations, procedures and methods. Discusses: recommended uses, limitations, and calibration requirements of air-balancing instruments (inclined manometer, pitot-static and double-reverse tubes, tachometer, clamp-on volt-ammeter, vane and propeller anemometer, thermometer,, pyrometer, pressure gauge, psychrometer, smoke device). Provides recommended uses, and requirements (including accuracy) for: flow (air and hydronic) measuring and balancing devices, and for determining system effect and duct leakage. Provides report templates.

20. ASHRAE. 2008. “ANSI/ASHRAE/SMACNA Standard 120: Method of Testing to Determine Flow Resistance of HVAC Ducts and Fittings”. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes laboratory test methods for determining duct total pressure loss per unit length and fitting dynamic pressure loss coefficients. Requires use of piezometer ring (multiple pressure taps connected together) at each measurement plane to provide average static pressure at that plane. Requires pressure measurement accuracy of 1% of reading or 0.75 Pa, whichever is larger (and barometric pressure accuracy of 15 Pa). Temperature accuracy (dry and wet accuracy is 0.5°C with precision of 0.5°C). Flow measurement accuracy spec for nozzles and orifices not stated but states that these are reference devices and refers to ISO 5167-1 specs; other devices must meet 1% of full-scale or 2%

of reading, whichever is larger (need to have calibration against reference device or that is NIST-traceable). System leakage must not exceed 0.5% of minimum tests flow at maximum pressure during test.

21. ASHRAE. 2008. “ANSI/ASHRAE/SMACNA Standard 126: Method of Testing HVAC Air Ducts and Fittings”. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes laboratory leakage test method (including test setup) to determine the airtightness of ducts and connections (with caps on ends of duct section to be tested). Includes correction of airflows from actual to standard conditions. Requires flow meter accuracy of 2% (of reading). Requires compliance with ASHRAE Standards 41.1 (temperature) and 41.3 (pressure), but no accuracy specs for pressure measurement except for barometric pressure (25 Pa). Temperature accuracy (dry and wet accuracy is 0.5°C with precision of 0.25°C or better). No specification of test pressure for test section, except that it is to be specified by “sponsor”. Does not provide acceptance criteria for leakage.

22. ASHRAE. 2008. “ANSI/ASHRAE Standard 130: Method of Testing Air Terminal Units”. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Describes laboratory methods for determining airflow, leakage, mixing, condensation, and electric and sound power for constant-volume, variable-volume, and modulating integral diffuser air terminals. Includes specifications for test instruments, facilities, installations, procedures and methods. Measurements include: air temperature, air pressure, electric power, and sound power.

23. ASHRAE. 2005. “ANSI/ASHRAE Guideline 0: The Commissioning Process”. Atlanta, GA; American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Describes detailed process for verifying that facility and systems meet Owner’s project requirements. Intended for application to non-residential buildings. Provides overview of activities. Describes processes in each phase (pre-design, design, construction, occupancy and operations). Provides requirements for acceptance, and documentation, and training.

24. ASHRAE. 2007. “ANSI/ASHRAE Guideline 1.1: HVAC&R Technical Requirements for The Commissioning Process”. Atlanta, GA; American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Describes technical requirements for the application of Guideline 0. Appendices include information on: basis of design, project specifications, communication structures, roles

and responsibilities, process scheduling and flow charts, meetings, review criteria and processes, construction checklists, test procedures, training, and correspondence.

25. ASHRAE. 2010. “ANSI/ASHRAE Guideline 2: HVAC&R Technical Requirements for The Commissioning Process”. Atlanta, GA; American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Provide guidelines for planning, analyzing data, and reporting uncertainty of experiments. Describes terminology and provides recommended procedures and formulas for applying statistical methods to experimental data. Addresses: experimental measurement categories, planning, and processes; data validation; regression analysis; propagation of uncertainties for single and multi-sample data; results reporting.

26. ASHRAE. 2009. “ANSI/ASHRAE Guideline 11: Field Testing of HVAC Controls Components”. Atlanta, GA; American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Provides methods for testing and adjusting HVAC system control components. Includes procedures (system preparation), test conditions, instrumentation, and formats for evaluating and documenting performance. Describes tiered strategy: installation verification and basic performance testing; repeatability and stability testing; and diagnostic quantitative testing. Addresses room, duct/equipment mounted, and outdoor sensors” temperature, pressure, humidity, air and water flow, “air quality” (CO_2, CO, VOC). Also addresses dampers and valves (including those in terminal boxes), as well as PI loop tuning, electrical tests, rotating equipment tests, and sequence of operation tests. Includes single- and multi-zone systems.

27. ASHRAE. 2008. “ANSI/ASHRAE Guideline 24: Ventilation and Indoor Air Quality in Low-Rise Residential Buildings”. Atlanta, GA; American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Provides information relevant to ventilation and indoor air quality on envelope and system design, material selection, commissioning, installation, operation, and maintenance, which may go ***beyond*** minimum requirements. Scope is broader than Standard 62.2. Describes contaminant regulations and guidelines pertinent to indoor environments; building airflow fundamentals; outdoor air migration, filtration, and acceptability; moisture generation, transport, and control; contaminant generation and transport; mechanical and natural ventilation system design; verification of equipment performance (focused on flow tests); and operations and maintenance documentation.

28. Baker, R.C. 2000. “Flow Measurement Handbook: Industrial Designs, Operating Principles, Performance, and Applications”. New York: Cambridge University Press.

Discusses why flow meters are needed, accuracy and sensitivity coefficients, fluid flow fundamentals, and flow meter selection and calibration. Also discusses flow meter types in detail (e.g., orifice plates, venturis, nozzles), including theory, design, commercially-available devices, application, installation effects, operation, and advantages and disadvantages. Concludes with a discussion of flow meter manufacturing, production, markets, and potential future developments.

29. Barles, P., P. Vialle, and M. Lemaire. 2005. “Diagvent” Guidebook – Checking the Performance of Ventilation Systems”. Les Arcs, France.

Advocates requirement of regular inspection of ventilation systems in France. Intended for use as practical tool for: engineering consultants, inspectors, installers, maintenance companies. Modeled on Swedish document. Found duct leakage in French homes on order of 15-45%. Advocates visual inspection and performance measurement – mostly airflow, duct leakage, and fan power. Commercial-building focused.

30. Bernard, A., A. Tissot, and P. Barles. 2007. “Impact of Ventilation Systems on Energy and IAQ Performance”. Helsinki, Finland: Proceedings of Clima 2007 WellBeing Indoors.

Seeks to quantify impact of ventilation system retrofits from perspectives of energy, IAQ, and health. Also considers CO_2 emission reduction potential of retrofitting ventilation systems in French residential and commercial buildings.

31. Concannon, P. 2002. “Technical Note AIVC 57: Residential Ventilation”. Brussels, Belgium: Air Infiltration and Ventilation Centre.

Claims that ventilation energy consumption in OECD countries can be reduced by factor of twelve without reduction in services that ventilation provides to buildings’ occupants and systems. States that natural ventilation remains most common form of ventilation in OECD countries, and that countries with cold climates have more rigorous standards both for building envelopes and HVAC systems.

32. Cory. W.T.W. 2005. “Fans and Ventilation – A Practical Guide”. London, UK: Elsevier.

Discusses fluid flow principles; fan types, materials, and performance standards; duct system components, design, and balancing; flow regulation; drive components and motors; fan noise and vibration principle and measurement; and fan selection, installation, economics, and operation/maintenance.

33. Durier, F. 2008. “Trends in the French Building Ventilation Market and Drivers for Change”. Ventilation Information Paper No. 19. Brussels, Belgium: Air Infiltration and Ventilation Centre.

Describes French housing stock as of 2006. 1982 French standards require whole building ventilation and kitchen and bathroom exhaust. Ventilation requirements are based on number of rooms in dwelling (for both single and multi-family housing). Some demand-controlled ventilation in residential buildings. Recent study showed that 40 to 50% of homes tested did not meet required ventilation rates. 2005 standards have source energy use intensity requirements, also fan power use requirements. Tradable energy savings certificates schemes, required by government of energy suppliers. 215-home study found mean envelope leakage of 3 ACH50. Duct leakage also considered. Upcoming requirements on sound level of ventilation equipment, to ensure its usage and reduce annoyance of residents.

34. European Committee for Standardization. 2004. “Ventilation for buildings – Performance testing and installation checks of residential ventilation systems”. EN 14134. Brussels, Belgium: European Committee for Standardization.

Describes test and check procedures, including requirements for operation manual; checks for component presence and compliance with regulations (natural and mechanical systems); functional checks for fans, filters, dampers, and air terminals, control devices, and cowls (checks include airflow rate and direction, control run times, ductwork air leakage, sound pressure levels, and electric power).

35. Gladstone, J. and Bevirt, W.D. 1997. “HVAC Testing Adjusting, and Balancing Manual”. Boston, MA: McGraw-Hill.

Discusses general test and balance (TAB) procedures (e.g., duct velocity traverses, recording TAB data); airflow measurement, fan, and system curve equations; use of TAB instruments (anemometers, flow hoods, pitot tubes, manometers, thermometers); damper adjustments; effects of air densities; and energy recovery device fundamentals, configurations, and problems. Also discusses sound and vibration fundamentals and measurement. Concludes with discussion of troubleshooting process and provides troubleshooting charts (e.g., for fans).

36. Grob, R.F. and M. Madjidi. 2007. “Commissioning and Fault Detection of HVAC Systems by Using Simulation Models Based on Characteristic Curves”. Helsinki, Finland: Proceedings of Clima 2007 WellBeing Indoors.

Discusses use of modeling to “commission” a proposed building ventilation system. Model can provide benchmark against which actual measured system performance can be compared and evaluated.

37. Heinz, J.A. and Casault, R.B. 2004. "The Building Commissioning Handbook". Second Edition. Alexandria, VA: Association of Higher Education Facilities Officers (APPA).

Provides overview of commissioning (e.g., goals, benefits, which system should be commissioned). Discusses commissioning team and processes (e.g., predesign, design, construction, and occupancy phase planning, communications, and reviews), and differences between commissioning, recommissioning, and retrocommissioning. Also, discusses economics of commissioning (e.g., costs of not commissioning, costs and benefits, and budgeting for commissioning). Concludes with case study of commercial building commissioning.

38. Holden, V.D. 2007. "Protecting the HVAC System During Construction: An Industry Standard of Care for Contractors". Helsinki, Finland: Proceedings of Clima 2007 WellBeing Indoors.

Indicates that construction activities can adversely affect the performance of HVAC systems. Provides guidelines for protecting HVAC system components during building construction and renovation projects. HVAC systems need to be protected from water, dust, and debris during construction activities. Should choose duct materials that are corrosion-resistant and easy to clean (flexible ducts are difficult to clean). Time elapsed between delivery and installation of materials should be minimized. Protect HVAC components from moisture exposure during construction. Location of outdoor air intakes (OAIs) should be chosen carefully to ensure that air is relatively clean and dry and that inlet is easily accessed for cleaning and maintenance. During construction, microbial risk assessment should be performed on HVAC system. Primarily focused on commercial buildings, but principles are also applicable to residential.

39. Kolokotroni, M. 2008. "Trends in the Building Ventilation Market in England and Drivers for Change". Ventilation Information Paper No. 17. Brussels, Belgium: Air Infiltration and Ventilation Centre.

States that ventilation and energy consumption standards in England in 2006 are performance-based and specify amount of ventilation required but not means by which that performance is achieved. Ventilation control is also included. For dwellings, whole building ventilation rates are required, calculated based on the number of bedrooms. Local exhaust is required for kitchens, laundry rooms, and bathrooms as well. Any proven ventilation system that meets these performance requirements may be installed, but outlines four commonly-used systems: background ventilators and intermittent exhaust fans; passive stack; continuous mechanical exhaust; continuous mechanical supply and exhaust with heat recovery. Two energy and emissions metrics are used to characterize building performance (CO_2 emissions and energy consumption per square foot) – these are used as asset rating for building.

40. Liddament, M. 2006. "Technologies & Sustainable Policies for a Radical Decrease of the Energy Consumption in Buildings: Report of the 27th AVIC Conference". Brussels, Belgium: Air Infiltration and Ventilation Centre.

Discusses importance of ventilation for health and comfort of building occupants and acknowledges energy and environmental costs of thermally conditioning incoming ventilation air and electricity needed to drive ventilation flows. States that ventilation typically responsible for 50% of building energy use and 40% of building operation-related greenhouse gas emissions.

Summarizes conference papers on topics such as: outdoor gaseous pollutants; fungal spores; system maintenance; workplace productivity; environmental tobacco smoke; energy labeling; airflow modeling; ventilation controls; natural ventilation; ventilation measurements; PFT tracer techniques to determine ventilation rates.

41. Liddament, M.W. 1996. "A Guide to Energy Efficient Ventilation". Brussels, Belgium: Air Infiltration and Ventilation Centre.

Describes basics of ventilation and discusses energy/health tradeoff dynamics. States that roughly third of all building operation energy consumption is due to ventilation. Focuses on ventilation solutions in relation to pollutants, building type, air tightness, thermal environment, and outdoor climate. Intended for non-specialists.

42. Limb, M.J. 2001. "Balancing Ventilation Systems: An Annotated Bibliography". Brussels, Belgium: Air Infiltration and Ventilation Centre.

Explains methods of balancing ventilation systems, including "proportional method", "traverse method", and "alternative methods". Discusses study by Foltz examining six field airflow measurement devices. Relies on pitot-tube traverse for reference flow comparison. References ASHRAE Standard 111. Describes importance of HVAC commissioning.

43. Liptak, B.G. 2003. "Instrument Engineers' Handbook – Process measurement and Analysis – Volume I". Fourth Edition. Boca Raton, FL: CRC Press LLC.

Discusses system accuracy; uncertainty calculations; instrument terminology, installation, and calibration; instrument response time and drift; instrument evaluation; and flow measurement device methods and selection (e.g., anemometers, pitot tubes, elbow taps, orifice plates, venturis, nozzles). Also, discusses pressure measurement devices (e.g., differential pressure instruments and manometers), as well as snubbers, calibrators, and manifolds.

44. Merzkirch, W. 2005. “Fluid Mechanics of Flow Metering”. Berlin, Germany: Springer-Verlag.

Discusses fundamentals of flow meters, including: decay of disturbances and optimal characteristic parameters in turbulent pipe flow, measurement of velocity and turbulence downstream of flow conditioners, effect of area changes in swirling flow, designing a flow meter based on drag principles, ultrasound-related flow metering, and correcting flow meter readings in pipe flow disturbed by installation effects.

45. Miller, R.W. 1996. “Flow Measurement Engineering Handbook”. Third Edition. Boston, MA: McGraw-Hill.

Discusses general fluid flow and measurement principles, accuracy, influence quantities (e.g., velocity profile, pulsations), flow meter selection and installation, and engineering equations and design information for differential producer devices (e.g., pitot tubes and multiport averaging devices, elbow taps, orifice plates, venturis, nozzles).

46. NEN. 2004. “Ventilation for Buildings - Performance Testing of Components/Products for Residential Ventilation - Part 1: Externally and Internally Mounted Air Transfer Devices”. NEN-EN 13141-1. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Specifies laboratory methods for testing _**externally and internally mounted air transfer devices**_ operating under pressure differences. Applies to devices located between two spaces (between one room and outside, or between two rooms) of following types: devices with fixed opening(s); devices with manually adjustable opening(s); devices with pressure difference controlled opening(s); and window openings specifically designed to act as an air transfer device. Describes tests intended to characterize following: flow rate/pressure; non-reverse flow ability; “air tightness when closed” (for closeable externally mounted air transfer device); geometrical free area; air diffusion in occupied zone; sound insulation; and water tightness.

47. NEN. 2010. “Ventilation for Buildings - Performance Testing of Components/Products for Residential Ventilation - Part 2: Exhaust and Supply Air Terminal Devices”. NEN-EN 13141-2. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Specifies laboratory methods for testing _**exhaust and supply air terminal devices**_ operating under pressure differences. Applies to devices used in mechanical and natural residential ventilation systems, of following types: device with a manually adjustable opening; device with a fixed opening; or pressure difference controlled device. Describes tests intended to characterize: flow rate/pressure; air diffusion characteristics (for supply air terminal devices); noise production for components of systems; insertion loss of component of systems; and sound insulation.

48. NEN. 2004. “Ventilation for Buildings - Performance Testing of Components/Products for Residential Ventilation – Part 3: Range Hoods for Residential Use”. NEN-EN 13141-3. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Specifies laboratory methods for measuring performance characteristics of ***range hoods*** for residential use. Applies to recirculating range hoods, and to air extraction range hoods with or without a fan. Describes tests intended to characterize: flow rate/pressure (based on EN 13141-4); noise production; acoustic insertion loss; grease absorption; and electrical power.

49. NEN. 2009. “Ventilation for Buildings – Performance Testing of Components/Products for Residential Ventilation – Part 4: Fans Used in Residential Ventilation Systems”. NEN-EN 13141-4. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Specifies laboratory test methods for fans used in residential ventilation. Indicates that performance characteristics strongly influenced by upstream flow conditions (velocity profile, possible presence of swirl and wind). Downstream conditions do not usually affect fan operation, but nature of flow downstream from fan, especially swirl, can have effect on losses in circuit and should be taken into account during installation design. Lists four categories of installations (as defined in ISO 5801:1997): category A, free inlet and free outlet; category B, free inlet and ducted outlet; category C, ducted inlet and free outlet; and category D, ducted inlet and outlet.

Test methods primarily concern: exhaust fans installed on wall or in window without any duct; ventilation fans installed in duct (upstream or downstream of fan, such as roof exhaust fans); and encased ventilation fans having several inlets. Describes tests intended to characterize: flow rate/pressure; sound power; and electrical power. For acoustic performance testing, indicates that one of following methods is to be used: in duct method; reverberant field method; or free field or semi-reverberant method.

50. NEN. 2004. “Ventilation for Buildings – Performance Testing of Components/Products for Residential Ventilation – Part 5: Cowls and Roof Outlet Terminal Devices”. NEN-EN 13141-5. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Specifies laboratory test methods for measuring performance characteristics of terminal devices used in both natural and mechanical ventilation that project above the roof (cowls and roof outlets). Only cowls (including fan assisted ones) and roof outlets fitted onto ducts that project above roof surface are covered by standard; standard does not address non-fan-assisted cowls such as injection assisted cowls. Performance testing of "assistance" provided by auxiliary fan of assisted cowl is excluded from scope of standard. Describes tests intended to characterize: pressure drop; suction effect of cowl; flow rate/pressure (based on EN 13141-4); sound power; and electrical power.

51. NEN. 2004. “Ventilation for Buildings – Performance Testing of Components/Products for Residential Ventilation – Part 6: Exhaust Ventilation System Packages used in a Single Dwelling”. NEN-EN 13141-6. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Specifies laboratory test methods for multi-branch system to “avoid the necessity of testing each component separately”. If component is not physically linked to others (e.g., externally/internally mounted air transfer devices), then it is expected that component will be tested according to specific test method related to it. Describes tests intended to characterize: flow rate/pressure; sound power; and electrical power.

52. NEN. 2004. “Ventilation for Buildings – Performance Testing of Components/Products for Residential Ventilation – Part 7: Performance Testing of a Mechanical Supply and Exhaust Ventilation Units (including Heat Recovery) for Mechanical Ventilation Systems Intended for Single Family Dwellings”. NEN-EN 13141-7. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Applies to ***whole-house*** ventilation units, which in general consist of supply and exhaust fans, air filters, an air-to-air heat exchanger with or without a heat pump for exhaust air heat recovery, and a control system (provided as one or more assemblies designed to be used together). Does not address heat pump testing. Describes tests intended to characterize: flow rate/pressure; internal and external air leakage; airstream temperature ratios; sound power; and electrical power.

53. NEN. 2006. “Ventilation for Buildings – Performance Testing of Components/Products for Residential Ventilation – Part 8: Performance Testing of Un-Ducted Mechanical Supply and Exhaust Ventilation Units (including Heat Recovery) for Mechanical Ventilation Systems Intended for a Single Room”. NEN-EN 13141-8. Delft, Netherlands: Nederlands Normalisatie-Instituut.

Similar to Part 7, but applies to units serving only a ***single room*** and does not address ducted units or units with heat pumps.

54. Pasanen, P., R. Holopainen, B. Muller, J. Railio, H. Ripatti, O. Berglund, and K. Haapalainen. 2007. “Cleanliness of Ventilation Systems – a REHVA guidebook”. Helsinki, Finland: Proceedings of Clima 2007 WellBeing Indoors.

Provides information about design features, criteria for cleanliness, inspection, and cleaning instructions of ventilation systems, primarily in commercial buildings.

55. Railio, J. and P. Makinen. 2007. "Specific Fan Power – A Tool for Better Performance of Air Handling Systems". Helsinki, Finland: Proceedings of Clima 2007 WellBeing Indoors.

Study discusses electrical energy needed for ventilation fans and air handling units (AHU). Traditional level is between 5-10 kW/(m^3 s); authors claim it's currently technically feasible to use 2 kW/(m^3 s) or less, with proper design and equipment. Specific fan power (SFP) is name given to this metric, as expressed in units of kW/(m^3 s). References standard EN 13779, which stipulates typical SFP value between 2-3 kW/(m^3 s). Indicates that higher duct pressures and increased filtering efficiency will increase these values.

56. Rapp, V.H., J.C. Stratton, B.C. Singer, and C.P. Wray. 2012. "Task 2.12: Building Airtightness Through Appliance Venting Standards: Assessment of Literature and Simulation Software Related to Combustion Appliance Venting Systems". April. LBNL-5798E. Berkeley, CA: Lawrence Berkeley National Laboratory.

States that, in many residential building retrofit programs, air tightening to increase home energy efficiency is constrained by concerns about related impacts on the safety of naturally vented combustion appliances. Tighter homes more readily depressurize when exhaust equipment is operated, making combustion appliances more prone to backdraft or spillage. Several test methods purportedly assess the potential for depressurization-induced backdrafting and spillage, but these tests are not necessarily reliable and repeatable predictors of venting performance, in part because they do not fully capture weather effects on venting performance.

Summarizes related codes and standards, the litany of combustion safety test methods, evaluations of these methods, and also discusses research related to wind effects and the simulation of vent system performance. Gaps in existing knowledge that require further research and development are also highlighted.

57. Raymer, P.H. 2010. "Residential Ventilation Handbook: Ventilation to Improve Indoor Air Quality". New York: McGraw-Hill.

Discusses code requirements (e.g., IMC, IBC, IRC, IPMC), system design and installation (new and existing homes), testing and balancing, and maintenance and troubleshooting. Includes many picture of components and schematics of systems to illustrate operational issues.

Discusses supply and exhaust termination types (e.g., vents, hoods, wall caps). Discusses passive vent types (e.g., transfer ducts, trickle vents) and make up air tempering. Discusses system control types (e.g., manually operated and motorized dampers, switches with and without timers).

Discusses types and use of flow and pressure test equipment (e.g., pieces of paper as flow status indicator, garbage bag flow meter, hot-wire and vane anemometers, flow capture hoods, pressure pan, pitot-static and static pressure tubes). Provides limited description of procedures for flow measurement. Discusses other cx issues such as checking condensate drains, owner education, documentation needs, flow visualization using smoke, humidity and contaminant monitoring. Discusses product testing in laboratories (e.g., HVI, TEES, Bodycote) and performance/safety certification (e.g., UL, ETL, CSA, Met Lab).

Discusses laboratory sound level measurements and refers to HVI Loudness and Rating Procedure (Publication 915).

Discusses issues to consider if system airflow is insufficient (e.g., is the fan on, have controls been set improperly or failed, are inlets, outlets, filters, heat exchangers, or ducts plugged, damaged, or too restrictive), system produces drafts (e.g., stuck open or missing dampers), or system is noisy (e.g., motor hum, damper rattles, airflow restrictions, vibration transfer to structural components). Includes troubleshooting tables.

Discusses ventilation product life expectancy.

58. RESNET. 2012. Mortgage Industry National Home Energy Rating Systems Standards. Residential Energy Services Network and National Association of State Energy Officials. RESNET: Oceanside, CA. July 30.

Describes equipment characteristics and procedures for measuring mechanical ventilation system flows (Section 804).

59. Sherman, M.H. 2006. “Technical Note AVIC 60: Efficacy of Intermittent Ventilation for Providing Acceptable Indoor Air Quality, International Energy Agency Energy Conservation in Buildings and Community Systems Programme”. Brussels, Belgium: Air Infiltration and Ventilation Centre.

Report establishes methodology for providing adequate air quality for low-density building through intermittent ventilation. Identifies three factors that can be used to establish appropriate intermittent ventilation regime for given building: ventilation efficacy, nominal air-turnover (the inverse of air change rate), and under-ventilation time factor. Intermittent ventilation allows energy load shifting, because of variation in outdoor air quality, time-of-day variation in energy cost, or other factors. Cites ASHRAE Standards 62.2 and 62.1 as ventilation norms. References ASHRAE Standard 136, which is now combined with Standard 62.2. To achieve same IAQ level, number of daily air changes required for intermittent ventilation typically exceeds number of daily air changes required for continuous ventilation.

60. Stratton, J.C., I.S. Walker, and C.P. Wray. 2012. “Measuring Residential Ventilation Systems Airflows: Part 2 - Field Evaluation of Airflow Meter Devices and System Flow Verification”. October. LBNL-5982E. Berkeley, CA: Lawrence Berkeley National Laboratory Report.

Evaluates a sample of fifteen new California homes for ASHRAE 62.2-2007 compliance. Flows measured using six commercially available flow hoods, and accuracy and usability of these flow hoods were evaluated based on results of field measurements. Only two of fifteen homes tested met all ASHRAE 62.2 requirements for whole-building ventilation and local exhaust. Because of physical constraints, range hood flows were especially difficult to measure; flows for only five of thirteen homes could be evaluated. Consistent with laboratory findings of previous studies, powered flow hoods were found to provide more accurate field measurements than non-powered flow hoods. Errors for powered flow hood measurements were around 6%, whereas those for non-powered flow hoods ranged from 11% to 25%.

61. Stratton, J.C., W.J.N. Turner, C.P. Wray, and I.S. Walker. 2012. “Measuring Residential Ventilation System Airflows: Part 1 - Laboratory Evaluation of Airflow Meter Devices”. November. LBNL-5983E. Berkeley, CA: Lawrence Berkeley National Laboratory Report.

States that building codes increasingly require tighter homes and mechanical ventilation per ASHRAE Standard 62.2. These ventilation flows must be measured so that energy is not wasted with over ventilation and occupants’ health is not compromised by under ventilation. Flow hoods are used to measure ventilation flows, but there is currently no standard specifying measurement procedure and measurement devices that should be used.

Evaluates accuracy of six commercially available flow hoods under laboratory conditions configured to emulate a residential mechanical ventilation duct system. Measurements taken with flow hoods compared to simultaneous measurements taken by an in-line reference flow meter having known uncertainty. Results indicate that powered flow hoods yield more accurate measurements than non-powered flow hoods, and that majority of flow hoods measured inlet flows more accurately than outlet flows. In several cases, there was little resemblance between manufacturers’ stated accuracy and the accuracy found in laboratory measurements.

States that current flow hood calibration procedures may not consider field application variables such as flow asymmetry, flow angle, and flow direction. Indicates that new flow hood measurement standard that takes ‘real world’ conditions into account should be developed to ensure that residential buildings receive intended ventilation flows.

62. Turner, W.J., J.M. Logue, and C.P. Wray. 2013. "A Combined Energy and IAQ Assessment of the Potential Value of Commissioning Residential Mechanical Ventilation Systems". Building and Environment, Vol. 60, February. LBNL-5969E.

Goal was to determine potential value of commissioning residential whole-house ventilation systems that are intended to comply with California's Title 24 residential ventilation requirements. Computer modeling approach was used to assess impact on occupant health and building energy use of malfunctioning whole-house ventilation systems. Energy and IAQ impacts were quantified and then compared by using Time Dependent Valuation (TDV) approach for energy and Disability Adjusted Life Year (DALY) approach for IAQ.

Results showed that health benefits dominated energy benefits independently of house size and climate. States that metric for commissioning whole-house ventilation systems should be net present value of the combined energy and IAQ benefits to the consumer. Also states that commissioning cost decisions should be made relative to that value even if that means ventilating to exceed the ASHRAE 62.2 minimum

63. Utsumi, Y., S. Hayakawa, T. Kurabuchi, and H. Yoshino. 2007. "Proposal of Japanese Standard of the Measuring Method of Airflow Rates of Building Equipments". Helsinki, Finland: Proceedings of Clima 2007 WellBeing Indoors.

Identifies four categories of airflow measurement devices/methods: anemometer sampling array, tracer gas, flow hoods (passive and powered), k-factor method. Proposed standard will indicate expected uncertainty for each airflow measurement category method, along with measurement report template.

64. Visier, J.C. 2003. "Developing Tools to Improve HVAC Commissioning: The Annex 40 Approach". Paris, France: Centre Scientifique et Technique du Batiment.

Indicates that Energy Conservation in Building and Community Systems program of International Energy Agency set up research working group (Annex 40) on commissioning of HVAC systems for improved energy performance. Purpose is to develop, validate, and document commissioning tools. References Japanese SHASE Standards.

Discusses: needs for commissioning; building energy management systems (BEMS); development of commissioning plans; Dutch "model quality control matrix": program, design, elaboration, realization, and operation, with definitions of each. Discusses development of customized commissioning plan for individual buildings. Describes pros and cons of commissioning authority structure options. Discusses use of models in commissioning and utility of comparing modeled performance to actual measured data. Commercial-building focused.

65. Wouters, P., N. Heijmans, C. Delmotte, P. Van den Bossche, and D. Wuyts. 2008. “Trends in the Belgian Building Ventilation Market and Drivers for Change”. Ventilation Information Paper No. 18. Brussels, Belgium: Air Infiltration and Ventilation Centre.

States that, historically, compliance with ventilation standards was not required in Belgium; merely considered “good practice”. Bathroom exhaust fans rare, and kitchen exhaust more or less non-existent. 2006 EPB regulations made ventilation compulsory, and fines were assessed for buildings whose ventilation was insufficient. No ventilation requirements for non-residential buildings. Idea of ventilating buildings is reportedly new in Belgium.

66. Wouters, P., C. Delmotte, J. Faysse, P. Barles, P. Bulsing, C. Filleux, P. Hardegger, A. Blomsterberg, K. Pennycook, P. Jackman, E. Moldonado, V. Leal, and W. de Gids. 1998. “Towards Improved Performance of Mechanical Ventilation Systems (TIP-Vent)”. Brussels, Belgium: European Commission’s JOULE Programme.

Intended to provide better understanding of impact of ventilation rates on energy consumption and of real performance of existing ventilation systems, to provide an overview of European ventilation standards, and to transfer ventilation research findings into professional practice.

67. Wray, C.P., M.A. Piette, M.H. Sherman, R.M. Levinson, N.E. Matson, D.A. Driscoll, J.A. McWilliams, T.T. Xu, and W.W. Delp. 2000. “Residential Commissioning: A Review of Related Literature”. March 3. LBNL-44535. Berkeley, CA: Lawrence Berkeley National Laboratory.

Literature review was first step in project to lay groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. Intent of review was to facilitate access to existing literature related to residential commissioning published over past 20 years, which represents period of time over which building commissioning and closely related issues have been actively reported.

Discusses status of commercial building commissioning and compares it with residential commissioning. Based on an extensive review of 469 readily available documents, it summarizes existing metrics, diagnostics, and norms for all building types that are relevant for evaluating, tuning, and retrofitting various aspects of new and existing houses. Relevant areas of concern for California houses included: Building Envelope, Cooling Equipment and Heat Pumps, Air Distribution Systems, Indoor Air Quality, Combustion Appliances, Controls, and Other Electrical Appliances.

Concludes by highlighting gaps in existing knowledge that require further research and development. Relevant areas in particular need of work include: metrics, diagnostics, and norms for moisture-damage susceptibility; diagnostics and norms for ventilation

effectiveness and efficiency; diagnostics to evaluate the potential for backdrafting and combustion gas spillage; and metrics, diagnostics, and norms for controls and other electrical appliances.

Only 33 of 469 papers reviewed specifically addressed house as system of interacting components, although many mentioned that this is an important issue.

68. Yoshino, H. 2008. “The Current of Air-tightness and Ventilation System in Houses in Japan”. Kyoto, Japan: AIVC 29th Conference: Advanced building ventilation and environmental technology for addressing climate change issues.

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Cites ventilation system commissioning to ensure proper performance as one strategy to improve indoor air quality. Includes plot of required ventilation airflow rates per standards of 10 OCED countries; range from 0.35 ACH (USA) to 1.0 ACH (Belgium), with most around 0.5 ACH. Shows airflow rates in ACH before and after ventilation system cleaning.

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