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Review of Literature Related to Residential Ventilation Requirements



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Review of Literature Related to Residential Ventilation Requirements

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Belgium, Czech Republic, France, Greece, Japan, Netherlands, Norway, and the United States of America.

Preface

International Energy Agency

The [International Energy Agency](#) (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an [Executive Committee](#), which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

- 1 Load Energy Determination of Buildings *
- 2 Ekistics and Advanced Community Energy Systems *
- 3 Energy Conservation in Residential Buildings *
- 4 Glasgow Commercial Building Monitoring *
- 5 Air Infiltration and Ventilation Centre
- 6 Energy Systems and Design of Communities *
- 7 Local Government Energy Planning *
- 8 Inhabitant Behaviour with Regard to Ventilation *
- 9 Minimum Ventilation Rates *
- 10 Building HVAC Systems Simulation *
- 11 Energy Auditing *
- 12 Windows and Fenestration *
- 13 Energy Management in Hospitals*
- 14 Condensation *
- 15 Energy Efficiency in Schools *
- 16 BEMS – 1: Energy Management Procedures *
- 17 BEMS – 2: Evaluation and Emulation Techniques *
- 18 Demand Controlled Ventilation Systems *
- 19 Low Slope Roof Systems *
- 20 Air Flow Patterns within Buildings *
- 21 Thermal Modelling *
- 22 Energy Efficient communities *
- 23 Multizone Air Flow Modelling (COMIS)*
- 24 Heat Air and Moisture Transfer in Envelopes *
- 25 Real Time HEVAC Simulation *
- 26 Energy Efficient Ventilation of Large Enclosures *
- 27 Evaluation and Demonstration of Residential Ventilation Systems *
- 28 Low Energy Cooling Systems *
- 29 Daylight in Buildings *
- 30 Bringing Simulation to Application *
- 31 Energy Related Environmental Impact of Buildings *
- 32 Integral Building Envelope Performance Assessment *

- 33 Advanced Local Energy Planning *
- 34 Computer-aided Evaluation of HVAC Systems Performance *
- 35 Design of Energy Hybrid Ventilation (HYBVENT) *
- 36 Retrofitting of Educational Buildings *
- 36 WG Annex 36 Working Group Extension 'The Energy Concept Adviser'
- 37 Low Exergy Systems for Heating and Cooling of Buildings *
- 38 Solar Sustainable Housing *
- 39 High Performance Insulation systems (HiPTI) *
- 40 Commissioning Building HVAC Systems for Improved Energy Performance *
- 41 Whole Building Heat, Air and Moisture Response (MOIST-EN)
- 42 The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM)
- 43 Testing and Validation of Building Energy Simulation Tools
- 44 Integrating Environmentally Responsive Elements in Buildings
- 45 Energy-Efficient Future Electric Lighting for Buildings
- 46 Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
- 47 Cost Effective Commissioning of Existing and Low Energy Buildings
- 48 Heat Pumping and Reversible Air Conditioning
- 49 Low Exergy Systems for High Performance Buildings and Communities
- 50 Prefabricated Systems for Low Energy Renovation of Residential Buildings

Annex V Air Infiltration and Ventilation Centre

The [Air Infiltration and Ventilation Centre](#) was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Czech Republic, France, Greece, Japan, The Netherlands, Norway and United States of America.

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Abstract

This paper reviews current ventilation codes and standards for residential buildings in Europe and North America. It also examines the literature related to these standards such as occupant surveys of attitudes and behavior related to ventilation, and research papers that form the technical basis of the ventilation requirements in the standards. The major findings from the literature are that ventilation is increasingly becoming recognized as an important component of a healthy dwelling, that the ventilation standards tend to cluster around common values for recommended ventilation rates, and that surveys of occupants showed that people generally think ventilation is important, but their understanding of the ventilation systems in their houses is low.

1 Introduction

With an increasing public concern about mold and other indoor air quality concerns inside their homes, many jurisdictions and institutions are looking to adopt improved ventilation codes, standards and practices. The State of California, for example, is planning to update the 2008 version of its energy code, known as “Title 24” to address this issue.

Indoor air quality (IAQ) is a complex result of occupant activities, human responses, source emission, and contaminant removal. The key issues that one can set requirements for are usually ventilation and source control. To set those requirements often requires an understanding of the materials and processes typically found in houses and the operational strategies of its occupants.

The purpose of this report is to review the published literature on existing ventilation standards and related research in order to provide a foundation for the current efforts to update Title 24 Residential Building Energy Code.

1.1 Background

Virtually every building code has requirements in it related to ventilation and indoor air quality, but an integrated approach to looking at residential indoor air quality is usually lacking. The nation’s first consensus standard on residential ventilation and indoor air quality was recently published by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ANSI/ASHRAE Standard 62.2-2003). As the first such American National Standard it forms a strong starting point; other codes and standards can be compared to that.

1.2 California Programmatic Background

The California Energy Commission (CEC) has as a funding priority a program of Research and Development (R&D) to advance the state of knowledge on residential ventilation in California. The Energy Commission will support this research through its Public Interest Energy Research (PIER) program. An important goal of this effort is to identify changes to existing residential energy efficiency standards (i.e., Title 24) that can be incorporated into the 2008 standards to maintain or to improve the indoor environment of new homes and to reduce the energy-related impacts of these homes.

To advance the state of knowledge in this field, the PIER program has established a three-part approach to the problem: 1) characterization of the indoor environments of homes built to current standards, 2) development of minimum requirements to achieve acceptable indoor air quality in future construction and 3) evaluation and development of technologies and associated descriptive algorithms for meeting minimum requirements.

These three elements act synergistically to provide the information the State needs to inform its efforts to modify Title 24. Each piece has been the subject of an independent scoping study (add references). This report provides a review of the literature necessary to achieve the following goals.

Characterization Project Goals: The broad goals of the characterization project are: 1) to determine if ventilation and indoor air quality, in a population of new, production-built, single-family, detached houses built to 2001 Title 24 energy efficiency standards, are acceptable based on available guidelines for comfort and health protection and 2) to describe the influence of selected key factors, including occupant behaviors, on ventilation rates and indoor air quality in these houses. The objective of this project is to answer a series of questions related to ventilation rates and indoor air quality (IAQ) in production-built, new, single-family, detached California homes built to the 2001 Title 24 standards. These questions focus on the topics of ventilation, indoor air quality and occupant behavior.

Requirements Project Goals: The broad goals of the requirements project are to: 1) determine the state of the art in residential ventilation codes and guidelines and their applicability to California; 2)

identify and resolve engineering-based issues necessary to define new minimum requirements; 3) determine how to extend engineering-based requirements with R&D to incorporate health protection; and 4) develop draft requirements suitable for inclusion in the 2008 version of Title 24. The objectives of the project are to focus on the technical barriers to improved residential ventilation standards and to resolve these barriers. We will closely coordinate work on this project with the characterization project to identify real-world issues and problems for ventilation and indoor air quality in new construction.

Technology Project Goals: The broad goals of the technology project are to: 1) determine the state of the art in residential ventilation methods and technologies and their application to California; 2) identify and develop suitable technologies that meet new minimum requirements and are not currently used in California; 3) develop models to evaluate the full performance of potential technology using the applicable criteria of energy, ventilation, demand, etc. and 4) work with the compliance industry to incorporate necessary algorithms into future Title 24 compliance tools.

2 Review of Current Codes and Standards

In developing a new standard, code or practice it is important to review what others have done. In this section we look at the ever-changing list of such documents:

The European Union is in the process of bringing the standards of the various countries into alignment with a European Standard. Many standards have already been published and others are in development. The current list of published and “in process” standards can be found at <http://www.cenorm.be/CENORM/BusinessDomains/TechnicalCommitteesWorkshops/CENTechnicalCommittees/CENTechnicalCommittees.asp?param=6138&title=CEN%2FTFC+156>

The Union has issued two directives that relate to ventilation: the Construction Product Directive (CPD) issued in 1989, and the Energy Performance of Buildings Directive (EPBD) issued in 2002 (Santamouris, 2006). The area in which the CPD relates to ventilation is that it requires construction product standards that relate to hygiene, health and the environment (among others) to be aligned within the member countries. The EPBD mainly deals with the energy efficiency of buildings, but it does contain the following reference to ventilation: “These [energy] requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation,...”. The European Committee for Standardization (CEN) is the body responsible for most of the standards relating to ventilation. They currently have a report, CR 1752: Ventilation for buildings - Design criteria for the indoor environment, however it relates only to commercial buildings, dwellings are excluded.

Table 2-2, excerpted from AIVC Technical Note 57: Residential Ventilation, gives a succinct summary of whole building and room by room ventilation rates in Europe, the U.S. and Canada (Concannon, 2002). The ASHRAE standard has been updated since the publishing of this paper. The requirements for ASHRAE Standard 62.2-2004 are shown in Table 2-1.

Table 2-1: Most Recent ASHRAE Standard

| Country and Standard Reference | Whole Building Ventilation Rates | Living Room | Bedroom | Kitchen | Bathroom + WC | WC only |
|--------------------------------|---------------------------------------|-------------|---------|--|---|---------|
| USA (ASHRAE 62.2-2004) | 0.05 * (total floor area) + 3.5 l/s/p | | | 50 l/s (inter.) or 5 ach (cont.) or openable windows | 25 l/s per room (inter.) or 10 l/s per room (cont.) or openable windows | |

Table 2-2: Ventilation Standards in Dwellings

| Country and Standard Reference | Whole Building Ventilation Rates | Living Room | Bedroom | Kitchen | Bathroom + WC | WC only |
|--------------------------------|---|--|--|--|---|---|
| Belgium (NBN D 50-001 1991) | | Supply 1 l/s/m ² Min 75 m ³ /h. May be limited to 150 m ³ /h | Supply 1 l/s/m ² Min 25 m ³ /h. May be limited to 36 m ³ /h | Exhaust 1 l/s/m ² Min 50 m ³ /h. May be limited to 75 m ³ /h | Exhaust 1 l/s/m ² Min 50 m ³ /h. May be limited to 75 m ³ /h | Exhaust 25 m ³ /h |
| Canada (CSA F326-M1989,) | >0.3 ach, 5 l/s/p | | | Exhaust 50 l/s (inter.) 30 l/s (cont.) | Exhaust 25 l/s (inter.) 15 l/s (cont.) | |
| Denmark | 0.5 ach | Supply fresh air: Hinged window, hatch or door, together with one or more fresh air valves with a total clear opening of at least 30 cm ² per 25 m ² | | Supply: Hinged window, hatch or door, or fresh air valve. Extraction: volume flow 20 l/s. The air shall be extracted through an extractor hood. | Supply: Hinged window, hatch or door, or fresh air valve. And/or opening to the access. Extraction: volume flow 15 l/s. | Supply: Hinged window, hatch or door, or fresh air valve. And/or opening to the access. Extraction: volume flow 10 l/s. |
| Finland | Exhaust figures air flows can be reduced when the spaces are not in use provided that the air change rate in the whole building is greater than 0.4 ach and min air flow rates in bedrooms and living rooms are fulfilled. | 0.5 l/s/m ² | Min 4.0 l/s/person or 0.7 l/s/m ² floor area | Exhaust air flow 20 l/s | Exhaust 15 l/s | |
| France | | | | Continuous: 20-45 m ³ /h Intermittent:: 75-135 m ³ /h | 15-30 m ³ /h | 15-30 m ³ /h |
| Germany | <50m ² up to 2 occupants Min 60 m ³ /h Total 60 m ³ /h <80 m ² up to 4 occupants Min 90 m ³ /h Total 120 m ³ /h <800 m ² up to 2 (sic 20) occupants Min 120 m ³ /h Total 180 m ³ /h | 1.0 - 1.5 ach | | Normal: 40 m ³ /h (>12 hr occupation/day) 60 m ³ /h (overall air flow) Purge: 200 m ³ /h (>12 hr occupation/day) 200 m ³ /h (overall air flow) Kitchenet: 40 m ³ /h (>12 hr occupation/day) 60 m ³ /hr (overall air flow) | 40 m ³ /h (>12 hr occupation/day) 60 m ³ /hr (overall air flow) | 20 m ³ /h (>12 hr occupation/day) 30 m ³ /hr (overall air flow) |

| Country and Standard Reference | Whole Building Ventilation Rates | Living Room | Bedroom | Kitchen | Bathroom + WC | WC only |
|---|---|--|--|---|---|--|
| Greece | Dwellings Ext 7 persons per 100 m ² of floor area. Flats Est 7 persons per 100 m ² of floor area. | Dwellings and Flats Min 8.5 m ³ /h/p Max 12-17.5 m ³ /h | | Dwellings and Flats Min 8.5 m ³ /h/p Max 50-85 m ³ /h | Dwellings and Flats Min 34 m ³ /h/p Max 50-85 m ³ /h | |
| Italy (MD 05.07.75) (Standard UNI 10339) | Naturally ventilated dwelling 0.35-0.5 ach | 15 m ³ /h/p 40 m ³ /h/p | 40 m ³ /h/p | 1.0 ach 4 ach exhaust | 2.0 ach 4 ach exhaust | |
| Netherlands Building Decree | | 0.9 dm ³ /s/m ² floor area | 0.9 dm ³ /s/m ² floor area | 21 dm ³ /s | 14 dm ³ /s | 7 dm ³ /s |
| New Zealand (ASHRAE 62-1999) | 0.34 ach but no less than 7 l/s/person Nat. vent min area of openable window as 5% of floor area in each room. | | | 50 l/s (inter..) or 12 l/s (cont.) or operable windows | 25 l/s (inter.) or 10 l/s (cont.) or operable windows | |
| Norway (Norwegian Building Code) | Not less than 0.5 ach | Supply: Openable window or inlet bigger than 100 cm ² in external wall. | Supply: Openable window or inlet bigger than 100 cm ² in external wall. | Mech. Extract 60 m ³ /h or by natural extract at least 150 cm ² duct above roof | Mech. Extract 60 m ³ /h or by natural extract at least 150 cm ² duct above roof | Mech. Extract 40 m ³ /h or by natural extract at least 100 cm ² duct above roof |
| Sweden (BFS 1988:38) | Requirements: Rooms shall have continual 0.35 l/s/m ² floor area when in use | | Recommendations: Not less than 4.0 l/s/bed place | Recommendations: Extract: 10 l/s | 10 l/s with openable window or 10 l/s with high speed rate up to 30 l/s or 15 l/s without openable window | |
| Switzerland (SIA 180:00) | 15 m ³ /h/p (non-smoking) | | | | | |
| UK (Building Regs. Approved Doc. F.) | | Rapid vent: 1/20 th floor area Background vent: 8000 mm ² | Rapid vent: 1/20 th floor area Background vent: 8000 mm ² | Rapid vent:: opening window Background vent: 4000 mm ² Extract vent rates of : 30 l/s adjacent to hob or 60 l/s elsewhere or PSV | Rapid vent:: opening window Background vent: 4000 mm ² Extract vent rates of : 15 l/s or PSV | Rapid vent:: opening window Background vent: 4000 mm ² Extract vent rates of : 15 l/s or PSV. |
| USA (ASHRAE 62-1999) | 0.34 ach but no less than 7 l/s/person Nat. vent min area of openable window as 5% of floor area in each room. | | | 50 l/s (inter..) or 12 l/s (cont.) or operable windows | 25 l/s (inter.) or 10 l/s (cont.) or operable windows | |

3 Listing of Relevant Codes and Standards

In the sections below we list the most important ventilation codes, standards and practices for dwellings.

3.1 American National Standards

- ASHRAE 62.2-2004: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings
- ASHRAE 62.1-2004: Ventilation for Acceptable Indoor Air Quality
- ASHRAE 90.2-2003: Energy Code for New Low Rise Residential Buildings
- Uniform Building Code (1994)
- Uniform Mechanical Code (2000) *This code only deals with combustion makeup air and evaporative cooling. It references the Uniform Building Code.*

3.2 Model Codes

- International Residential Code (2003)
- International Energy Conservation Code (2003)
- CABO MEC (1996) *This code references ASHRAE 62-1989. Many state codes reference CABO MEC.*

3.3 State and Federal Regulations

- CA Title 24
- Other States
 - Washington State Ventilation and Indoor Air Quality Code (2000)
 - Minnesota Rules Chapter 7672 : Energy Code (2000) *Alternative compliance by Minnesota Rules Chapter 7670: Energy Code (1994).*
 - Florida Building Code. *This code references ASHRAE 62-1989*
 - Vermont Residential Building Energy Standard (2003)
- Department of Housing and Urban Development: Directive Number 3280.103 *This standard applies only to manufactured homes.*

3.4 International Codes and Standards

- Sweden: BFS 1998:38: Hygiene, health and the environment
- UK: The Building Regulations 1991 Document F: F1 Means of Ventilation
- France: Arrêté du 24.03.82 relatif à l'aération des logements (relating to the ventilation of residences)
- Denmark: DS 418:2002 Calculation of Heat Loss from Buildings
- Australia: AS 1668.2 – 2002: The use of Ventilation and Air Conditioning in Buildings
- Canada: Residential Mechanical Ventilation Systems CAN/CSA–F326 or alternatively the Canadian National Building Code, Section 9 – Ventilation.
- Europe: EN 13465:2004 Ventilation for buildings - Calculation methods for the determination of air flow rates in dwellings
- Europe: EN 14134:2004 Ventilation for buildings - Performance testing and installation checks of residential ventilation systems
- Europe: CEN/TR 14788:2006 Ventilation for buildings - Design and dimensioning of residential ventilation systems

3.5 Labels, Guidelines and other Voluntary Practices

- Energy Protection Agency Indoor Air Quality Standard (Proposed)
- American Lung Association Health House
- NFPA 54 National Fuel Gas Code. *This code addresses only back-drafting.*

4 Comparison of Key Requirements

Each of these documents is different, but many of them address similar aspects of the problem and consider similar types of requirements. In this section we will compare these documents across some of these requirements:

4.1 Compliance Demonstration

Many of the standards are prescriptive in nature, meaning that they prescribe that a certain airflow be provided by a mechanical ventilation system. CA Title 24, and the Florida Building Code, and are set up in this way. Testing is not required to verify that the installed system actually provides the airflow required. Some standards are mainly prescriptive with some performance component such as The American Lung Association (ALA) Health House, where the only performance component relates to the airflow of the heating and/or cooling system. In other standards, such as ASHRAE Standard 62.2, the compliance mechanism is performance, with a prescriptive alternative. The airflow required by this standard refers to the delivered airflow, as verified by a test of the installed system. As an alternative to this performance approach, the airflow rating of the fan may be used if the ductwork is also in compliance with the standard. The Canadian standard is framed in the same way, with the National Building Code requiring that ventilation systems conform to CAN/CSA F326 "Residential Mechanical Ventilation Systems", which is performance in nature, or comply with the prescriptive requirements laid out in the National Building Code. The Washington State Ventilation and Indoor Air Quality Code also has dual paths for compliance: performance or prescriptive. The Minnesota State Code and the Energy Protection Agency Indoor Air Quality (EPA IAQ) Standard require that ventilation comply with the ASHRAE Standard 62.2.

4.2 Whole-House Ventilation Rates

Whole house ventilation is needed to dilute pollutants (such as VOC's) originating from the building components and to remove pollutants (such as moisture and CO₂) that are created due to human activity. Whole house ventilation regulations are prescribed on a per area basis, a per person basis, or a combination of the two. CA Title 24 and the MN energy code are examples of codes that use a per area basis. ASHRAE Standard 62.2 and the ALA Health House use a combination of square footage and number of people. The Washington State Ventilation and Indoor Air Quality Code uses either a standard based on the number of people, or 0.35 air changes per hour (ACH), whichever is bigger. The Canadian Building Code and the Swedish Building Code specify ventilation rates that must be provided to each room. For the Canadian code the rate is 10 cfm (5 l/s) for each room except the master bedroom and basement which require 20 cfm (10 l/s). The Swedish code requires 8 cfm per square foot (0.35 l/s per square meter) of floor area in occupied rooms. In addition it requires 8.5 cfm (4 l/s) per bed space of supply capacity.

Whole house ventilation can be achieved with a continuously operating fan, or by fans operating intermittently at a higher flow rate. Most of the standards are written with the continuous fan operation requirement, and then have some allowance for how that requirement can be met with an intermittently operating fan. ASHRAE Standard 62.2, for example, requires a continuous ventilation rate of 1 cfm per 100 sq ft (0.05 l/s per m²) of building area plus 15 cfm (7.5 l/s) per person. An intermittent fan can meet this requirement if it operates at least one hour out of every twelve, provides the same volume of outdoor air as the continuous scenario plus an additional volume of air to make up for a loss in ventilation effectiveness by the intermittent fan. The current version of CA Title 24 requires 0.047 cfm/square foot (0.24 l/s per m²) of continuous mechanical ventilation if the building has a low leakage design (Specific Leakage Area (SLA) < 3), and it requires the house to be continuously pressurized to 5 Pa if the building is "unusually tight" (SLA<1.5). There is no clause about how this standard can be fulfilled by an intermittently operating fan.

4.3 Local Exhaust Rates

Most of the codes require 100 cfm (50 l/s) capacity for kitchen fans, and 50 cfm (25 l/s) capacity for bathroom fans. These codes alternatively allow the kitchen and bathroom venting to be performed by a lower capacity, continuously operating fan. The value is usually 20 cfm (10 l/s) continuous for bathrooms, and 20-30 cfm (10-15 l/s) (or 5 ACH in the case of ASHRAE Standard 62.2) for kitchens.

4.4 Infiltration

Ventilation may be provided by infiltration in only two of the standards: ASHRAE Standard 62.2 where a blower door test of the building shell allows the builder to provide some of the ventilation air through infiltration, and CA Title 24 where the mechanical ventilation requirement only holds if the building has a Specific Leakage Area (SLA) less than 3.0.

4.5 Operable Windows

The ventilation standards generally do not have specific requirements about operable windows since windows in habitable spaces are addressed in the building codes. The International Residential Code (IRC), for instance, states that all habitable rooms must have a minimum openable area to the outdoors of not less than 4 percent of the floor area. Alternatively, ventilation may be provided by a ventilation system that provides 0.35 air changes per hour to the space, or a whole-house ventilation system that supplies 15 cfm (7.5 l/s) per occupant as determined by the number of bedrooms plus one. Bathrooms are required to have at least 1.5 square feet (0.14 m²) of openable area to the outside, or a ventilation fan with 50 cfm (25 l/s) ventilation capacity or 20 cfm (10 l/s) of continuous ventilation. The IRC allows habitable spaces to have no window (operable or not) at all if the space is properly ventilated, and lighted with artificial light.

Three of the ventilation standards do have regulations regarding operable windows: ASHRAE Standard 62.2, which states that each habitable room, and each toilet or utility room must have an operable window, the Swedish standard where every habitable space must have an operable window, and the Belgian standard where there is a minimum openable area to the outdoors of not less than 6.4 percent of the floor area if windows are located in only 1 wall of the space and not less than 3.2 percent if the windows are approximately equally located in 2 walls of the space for living rooms, bedrooms and offices. The ASHRAE and Swedish standards do not account for new houses that are designed with an interior bath (meaning all the bathroom walls are interior partition walls) where their requirements cannot be met.

4.6 Air Distribution and Duct Leakage

In an ideal ventilation system, fresh air would be provided to every room in the house, and polluted air would be drawn from the rooms in which it is produced. When a mechanical ventilation system is required, virtually every code specifies that a certain volume of air be exhausted from the bathroom and kitchen, however, few codes have requirements for distributing fresh air throughout the dwelling. The exceptions to this are Canada, where fresh air must be distributed throughout the dwelling¹, and Sweden, where 8 cfm per square foot (0.35 l/s per square meter) of floor area must be provided continuously in occupied rooms. The rate may be reduced when the room is unoccupied. Some codes have the requirement of air inlets in every room (ASHRAE 62.2, Washington State, Minnesota), but there must be a negative pressure in the room in order to bring air in through the inlet. So whether the inlets actually provide distributed fresh air depends on equal depressurization of the building by the exhaust system.

¹ Residential Mechanical Ventilation Systems, CAN/CSA-F326, requires 10 cfm (5 l/s) for each room except the master bedroom and basement which require 20 cfm (10 l/s), however the National Building Code only specifies that the fresh air be distributed. Compliance in Canada can be met by satisfying either of these codes.

4.7 Combustion Equipment

All combustion equipment including furnaces, boilers, hot water heaters, wood stoves, fireplaces, gas cooking appliances, etc. need a certain volume of air as an ingredient for combustion, and to carry the combustion products away from the house occupants. This volume of air is called “combustion air”. Safety problems can arise when air does not follow the intended path through the appliance and out the flue. Downdrafting is when outdoor air enters the house by downward movement through the flue when no combustion is occurring. Backdrafting occurs when the combustion appliance is unable to reverse this flow when firing, causing spillage, or entry of combustion gasses into the indoor air. (Wray, 2001)

Some combustion appliances are sealed combustion, meaning that the air supply and exhaust for the appliance does not mix with the air in the house. In these types of appliances spillage cannot occur. Other appliances have a dedicated air inlet to supply combustion air, but are not completely sealed from the house air, and still others take the combustion air directly from the air in the house. Spillage may occur in these appliances if the pressure conditions cause backdrafting. Mechanical ventilation can cause depressurization of the zone around the combustion appliance increasing the likelihood of backdrafting, therefore ventilation standards sometimes include safeguards to prevent this from happening. Many of the newer furnaces are induced draft, meaning that they have a fan to aid the combustion gasses in exiting the flue. Backdrafting is less likely in this type of furnace.

The NFPA 54: National Fuel Gas Code regulates the installation of gas appliances. It states that “A venting system shall be designed and constructed so as to develop a positive flow adequate to remove flue or vent gases to the outside atmosphere.” The standard addresses IAQ by requiring that combustion product exhausts must be located at least 6-12 (depending on size of combustion equipment) inches (15-30 cm) away from air intakes. Makeup air is stipulated by 50 ft³ per 1000 Btu/hour (4.8 m³/kW) minimum required room volume for a combustion appliance that uses room air for combustion in a building where infiltration is unknown. If the infiltration rate is known, another method can be used if the air exchange rate is less than 0.60 ach, and must be used if the exchange rate is less than 0.40 ach. This second method stipulates 21 ft³ (0.59 m³) (or 15 ft³ (0.42 m³) if the appliance has fan assisted draft) divided by the air change rate per 1000 Btu/hour (293 W). If the makeup-air volume requirement cannot be met then a permanent opening must be installed between the combustion appliance space and the outside.

Many codes require makeup air to reduce negative pressure caused by exhaust fans or testing for spillage. The ALA Health house simply states to “reduce the depressurization of the building.” ASHRAE Standard 62.2 states that the net flow, at full capacity, of the largest two exhaust fans cannot be greater than 15 cfm/100 ft² (0.75 l/s per m²) of occupiable space. If this condition is not met, compensating airflow must be provided, maximum flow reduced, or atmospherically vented combustion appliances inside the conditioned space must be tested for spillage. CA title 24 requires that glass doors and an air inlet be provide for each fireplace and each wood, pellet or gas stove. The Minnesota code limits "excessive depressurization" except when all appliances are sealed combustion and 3 biggest exhaust fans have a combined flow less than 425 cfm (200 l/s). There are 4 prescriptive paths or a performance test to show compliance. The Canadian code requires make up air for exhaust flow greater than 150 cfm (70 l/s) if there is a chimney vented oil or gas appliance in the house. The EPA IAQ standard goes even farther to require a direct vent water heater. It also requires a direct vent furnace if the house is located in a climate with more than 4000 Heating Degree Days (HDD).

4.8 Filtration and Air Cleaning

Since the main purpose of ventilation is to provide clean air for people to breathe, filtration can be an important component of a ventilation system. ASHRAE Standard 62.2 requires a heating or cooling system to have at least a MERV 6 filter. The EPA IAQ standard requires MERV 8 filters, and no filter bypass is allowed. A neoprene gasket is required on one side of filter rack to bring the filter into contact with the rack. The ALA Health House requires at least a MERV 10 filter in the heating or cooling system. In Sweden, they require that the return air is filtered, and that there is no return air from bathrooms, kitchens, or other apartments. (The requirement of no return air from bathrooms and

kitchens are standard in building codes, and are contained in the IRC.) It is also required that the ducts be clean-able.

4.9 Other Source Control Measures

Clothes dryers are required to be vented to the outside in the IRC, in the Washington State code, and in the ALA Health House. Additionally, the Washington State code requires a pool or spa area to be vented. The EPA IAQ standard requires 100 cfm (47 l/s) of continuous exhaust from the garage. ASHRAE Standard 62.2 limits HVAC return duct leakage to 6% of total fan flow in ducts that run inside garage spaces, and it requires that the walls and ceiling between the garage and the house be sealed before insulation is installed, and that doors be gasketed between the garage and living space.

4.10 Other Occupants Issues

The major occupant issue that is addressed in the ventilation standards is control of the system. A French survey of 10,000 households (Lemaire et al. 2000) found that occupants are more satisfied with ventilation systems that offer occupant control. ASHRAE Standard 62.2, The Minnesota Energy Code and the Canadian Building code all require that the occupant be given override (if not total) control of the ventilation system.

There was only one code that addressed an occupant comfort issue: Swedish code requires the velocity of air supplied to an occupied zone to be less than or equal to 0.15 m/s (0.5 ft/s) in heating mode and less than or equal to 0.25 m/s (0.8 ft/s) in cooling mode.

4.11 Other Equipment Issues

Several codes addressed the issue of fan noise. ASHRAE Standard 62.2 gives a maximum noise rating of 1 sone for continuous fans, and 3 sones for intermittent fans. The philosophy is that quiet, unobtrusive fans will get left on, while noisy ones will be turned off by the occupant. Fans with flow greater than 400 cfm are exempt from the noise requirements. This exemption allows noisy (and high flow) kitchen range hood fans to be installed. The Washington ventilation code limits fan noise for ventilation systems where the fan is within 4 feet (1.2 m) of the grille at 1.5 sones. The ALA Health House also has the limit of 1.5 sones for fan noise. The Minnesota code has a maximum of 1 sone for surface mounted fans.

The EPA IAQ guideline requires a carbon monoxide alarm outside each sleeping area in homes with combustion appliances.

4.12 Outdoor Air

Outdoor air is always a part of a ventilation system, whether it enters the house through dedicated inlets, supply fans, or through unintentional openings in the building shell. The standards that require dedicated air inlets are ASHRAE 62.2, Washington State, Minnesota, Canada and Sweden. Inlets must be 10 feet (3 m) from known contamination such as exhausts vents, stack pipes and vehicle exhaust in ASHRAE 62.2, EPA IAQ, ALA Health House, and the IRC.

4.13 Energy and Demand Impacts

Some of the ventilation standards have maximum energy requirements, and others leave the energy regulations to standards dedicated to energy use in buildings. The ventilation standards that have specific requirements for energy usage are the ALA Health House that specifies a maximum of 0.5 watt per cfm (1 W per l/s) for exhaust fans, and 1 watt per cfm (2 W per l/s) for HRV's. Minnesota requires a maximum of 0.8 W per cfm (1.6 W per l/s) for residential (constant air volume) systems.

California Title 24 is an energy standard so it dictates that when mechanical ventilation is installed, the power of the fans is and the extra infiltration load is added to the building energy usage for performance compliance.

4.14 Climatic or Regional Differences

The climates that are significantly different such that they receive special attention from a ventilation perspective are cold climates and warm-humid climates. Cold climates have the issue that ventilation air entering the building shell in the winter will be uncomfortable for the occupants unless it is tempered before it reaches them. Canada, Minnesota, and the EPA IAQ guideline have requirements for tempering incoming air. ASHRAE 62.2 has the requirement that mechanical supply systems exceeding 7.5 cfm/100 ft² (0.38 l/s per m²) shall not be used in severe cold climates, which include most of Canada, and the upper half of most US states that border Canada.

In warm-humid climates the concern is humidity which can damage building components, if forced into walls. ASHRAE 62.2 has the requirement that mechanical exhaust systems exceeding 7.5 cfm/100 ft² (0.38 l/s per m²) shall not be used in hot-humid climates, which include areas that border the Gulf of Mexico. The ALA Health house states that vinyl wallpaper may not be used in hot-humid climates due to the concern about mold and mildew growth when water condenses on the back of the vinyl. The EPA IAQ guideline contains three options for controlling humidity inside dwellings in warm-humid climates: controls that ensure humid outdoor air is not supplied to the interior, whole house dehumidification, or enthalpy exchange equipment.

5 Occupant Acceptability, Control and Behavior

The purpose of the codes, standards and guidelines we review are generally to provide a minimum amount of health, safety and comfort for the occupants. A part of that is subjective because it involves the perceived acceptability of the indoor environment to those occupants. This section reviews the literature related to ventilation and IAQ-related behaviors and attitudes of residential occupants.

Determining occupant behavior can sometimes be done through objective scientific measurements, but determining occupant acceptability usually requires the use of surveys, questionnaires, etc.

5.1 Occupant Surveys

The Energy Commission, through the California Air Resources Board, is currently conducting an occupant survey in new California homes. The results of this survey are not yet available, but that survey is based on other surveys of a similar nature.

The surveys that have been done can be broadly divided into those having to do with occupant perception of the ventilation and IAQ of their residence, and the occupant behavior with respect to the ventilation of the residence. Occupant behavior has been extensively studied, by means of interviews and questionnaires and also by more quantitative means such as activity diaries, direct observation, and sensors to monitor for specific behavior. The interviews and questionnaires in the behavior studies sometimes include questions related to perception of the ventilation and IAQ since the perception influences the behavior. All the studies having to do with people's perception of the ventilation in their homes also had a behavior component.

People generally believe that ventilation systems are beneficial. In Canada 60 homes were surveyed to determine the performance and people's perception of heat recovery ventilators (Hill, 1998). Most of the occupants thought the heat recovery ventilator was beneficial and understood the general purpose of the equipment. In the state of Washington 235 households were surveyed (Devine, 1999) to reveal attitudes about ventilations systems such as: "people are concerned about indoor air quality and believe fresh air is important for health." The reasons given for why occupants ventilate (Dubrul, 1988) are: to get fresh air into bedrooms and living rooms, to remove odor, to remove stale air and condensation, to 'air' the dwelling during residential activities, and to remove tobacco smoke. The reasons given for not ventilating are: to prevent draughts, to maintain a preferred temperature, to protect against cold and rain, to maintain privacy and safety, and to reduce external noise and pollution.

The understanding that people have of their ventilation systems is generally fairly low. In a Canadian study, the occupants' knowledge of how to operate and maintain the system was found to be very low (Hill, 1998). In the Washington study (Devine, 1999) one quarter of the people surveyed were not aware that their house had a mechanical ventilation system, perhaps because many of the mechanical ventilation systems were integrated with the forced air heating system. In another Canadian study of exhaust only ventilation systems, almost 10% of the people surveyed had no idea how they operated their ventilation system. Another 70% of those surveyed operated the system incorrectly (Fugler, 2004). A study of 43 Minnesota homes found that people need more information and guidance about the operation and maintenance of their ventilation systems (Sheltersource, 2002).

When considering satisfaction with system, 20% of respondents in a Washington study "considered noise, drafts and/or energy waste a problem with their system" (Devine, 1999.) In a study of 10,000 French households (Lemaire and Trotignon et al. 2000), only 9.2% of people with balanced ventilation systems found noise to be a problem, and 6.7% of people with single flow ventilation systems (exhaust or supply only) found noise a problem. This study also found that overall, 81% of the survey respondents were satisfied with their ventilation systems. Satisfaction increased with the age of the head of the household, household income, number of rooms in the dwelling, and surface area of dwelling. Higher satisfaction is also correlated with people who clean their vents, and with systems that allow occupant control. 22% of the survey respondents reported problems with their ventilation systems such as condensation from humidity, dampness on walls, persistent odors, ventilation noise, cold drafts, or dust/stains due to ventilation. Fewer problems were reported in owner occupied houses (about half the rate of problems reported in rental properties), and in dwellings where the ventilation system could be switched off. The number of problems reported was found to be inversely related to length of time since move in.

Occupant behavior has been widely studied as it relates to ventilation. AIVC Technical Note 53, Occupant Impact on Ventilation (Liddament 2000), offers a comprehensive review on occupant interaction with ventilation systems in residential and non-residential buildings.

Liddament examines:

- basic statistics on housing occupation and ventilation systems
- basic ventilation and indoor climate needs
- observed occupancy interaction with ventilation systems and controls
- occupant impact on the total ventilation/ air exchange rate
- occupant impact on energy consumption
- and lessons learnt and procedures for optimizing occupant interaction

His key findings were:

- Dwellings are often occupied 24 hours a day
- Ventilation is necessary to provide air for metabolism, dilute and remove pollutants, and provide combustion air for fossil fuel heating appliances.
- Pollutants that need to be vented include metabolic CO₂ and odor, moisture from bathing, cooking and clothes washing, combustion products from unvented gas cooking appliances, and tobacco products.
- Occupant behavior has a significant effect on ventilation, particularly in relation to window opening.
- Finally, he provides a set of occupant guidelines to provide good indoor air quality and comfort without excessive energy usage.

Windows have historically been a main source of ventilation in dwellings. 71% of households in California report door or window opening for longer than 1-2 minutes a day according to Phillips et al. (1990) and Wiley (1991). Less window opening was found during the winter (57%), and less was found in the non-costal regions (32%). The conclusion of this survey was that adequate supply of fresh air was not supplied to a substantial portion of homes, particularly during the colder seasons of the

year, and in colder climates. It is important to note that when the temperature is cold outside, infiltrative ventilation is increased. This contributes to the decreased need for window opening when it is cold. (Kelly et al. 1993) In a New York state study of 141 households, 30% were found to open windows in the winter, and 78% opened them in the summer. IEA Annex 8 summarized findings from numerous studies on window opening reported in Table 5-1.

Table 5-1: Factors Relating to Window Opening Behavior

| Factor | Observed Trend |
|-------------------------|--|
| Occupancy density | Window opening increases with number of occupants present. |
| Occupant's age | The amount of window opening and ventilation reduces with the increasing age of the occupants. |
| Outdoor air temperature | Window opening decreases with decreasing outdoor air temperature, although a significant number are still opened at temperatures as low as -5 deg. C. |
| Sunshine | More windows tend to be open on the sunny side of buildings than on the opposite side. |
| Wind speed | Window opening decreases with increasing wind speed. |
| Day time opening | Windows are usually closed when the building is unoccupied during the day. |
| Night time opening | A significant number of windows are kept open in bedrooms at night, even in cold weather. |
| Weekend opening | Windows are open more frequently on weekends than during the rest of the week. |
| Thermostat setting | The higher a household sets its heating thermostat, the less often windows are opened. |
| Residential activities | Reasons given for window opening include vacuum cleaning, and airing of bed-clothes, cooking, odour and moisture problems. |
| Smoking | Windows are opened twice as frequently in smoking households than in non-smoking households. |
| Energy use | There is only a weak correlation between energy saving intentions and window opening. More window opening tends to take place in buildings in which heating energy is not separately metered to occupants. |

Another question of interest, which has been widely studied, is **“Do people use their ventilation systems?”** Buildings may have no intended ventilation system, or they may have one of three types of systems: passive systems, mechanical systems with unidirectional flow, or bidirectional mechanical systems. The French study (Lemaire and Trotignon, 1998) reported that 46% of dwellings have passive ventilation systems, meaning intentional air inlets and/or outlets but no fan. In the UK, a study (Oseland 1995) showed that 7-8% of passive stacks were blocked up compared to 13% of all vents (mechanical and natural) reported to be blocked in the French study. The fraction of blocked vents drops to 6-7% in dwellings built after 1982. This shows that most of the passive systems that are installed are in daily use.

Unidirectional mechanical systems consist of exhaust only systems or supply only systems. Exhaust only systems are much more common, and more appropriate in cold climates where cold dry air brought in through leaks in the building shell will not damage the building components, and will be tempered before it gets to the living space. Supply only systems are rarely used, but are appropriate when it is advantageous for the building shell to be pressurized, as in a moist climate where outdoor air must be dehumidified before entering the house, for the comfort of the occupant as well as for the health of the building. In Canada, Fugler (2004) found exhaust only ventilation (EOV) systems as the most common, installed in 76% of the houses. 30% of the EOV system owners never used the system and most of the other owners used the system only for bathroom ventilation, although a significant number of homeowners had window condensation or stuffiness in the house. In California, Phillips et al. (1990) and Wiley (1991) found that only a 3% of the statewide population used exhaust fans. Slightly higher percentages were found in the winter (5%) and in the San Francisco region (7%). In France, 17% of dwellings were found to have extract ventilation (Lemaire and Trotignon, 1998). Almost one quarter of those systems could not be turned off by the occupant, about half of the systems could be turned off, but were rarely or never turned off by the occupant, and another quarter of the systems were often or fairly often turned off.

Bidirectional flow or balanced mechanical ventilation systems are becoming more popular in France. Lemaire and Trotignon (1998) report that 9% of dwellings built since 1989 have this type of system as

opposed to 1.5% in buildings built before 1948. Balanced systems are most common in cold countries such as Canada and Scandinavia, where heat recovery ventilators are used to temper the air coming into the house, and to recover the heat from the air leaving. In Canada, Hill reports that 17% of the houses surveyed had blocked their air intakes (1998), much higher than the number of intakes blocked in the UK and in France, but this may have to do with the colder climate. More than half, 60%, of the houses surveyed had substandard ventilation due to poorly maintained systems. As in the EOV study in Canada, 55% of the occupants who's systems required running the furnace fan at the same time to distribute the air, were not aware of this.

6 Key Issues

In our review of codes and standards above, several key issues were identified. In this section we review the literature on those key issues.

6.1 Definition of Contaminant sources

Airborne indoor contaminants have two types of sources: indoor sources and outdoor sources. Indoor sources should be removed from the dwelling or the air contaminated by the source should be vented to outdoors as close to the source as possible, whereas outdoor sources should be removed from the air as much as possible before the air is brought inside the house. Indoor sources include mold and mites, carbon dioxide, indoor generated particulates, tobacco smoke, formaldehyde and other volatile organic compounds (VOC's), and combustion products. The chapter on the affect of ventilation on health in the Ventilation: A State of the Art Review (Santamouris, 2006) describes sources of air pollutants that affect human health, and is summarized below:

Mold and mites both produce substances that are respiratory irritants and allergens. Both populations increase with increasing building humidity, so source venting of humidity (showers, and cooking) is important to reducing these allergens in the building. In climates and seasons when outdoor humidity is significantly higher than indoor humidity simple ventilation is not sufficient to control indoor humidity. Air conditioning systems are generally used to continuously dehumidify indoor air.

Water vapor and carbon dioxide are both products of metabolism, and are released during respiration. It is impractical to vent these pollutants at the source, so whole house ventilation is needed. This explains why many standards are written in terms of a minimum ventilation rate per person.

Indoor particulates are commonly known as dust. Particles smaller than 5 μm do not settle by gravity, and those that are smaller than 0.3 μm are particularly dangerous because they can go deep into the lungs. These particles are removed more effectively with a filter or vacuum cleaner than by ventilation.

Tobacco smoke is most effectively controlled by removing the smoker from the house. The ventilation rate required to dilute tobacco smoke to a safe level is 555 l/s (1168 cfm) per a smoked cigarette in an hour (Santamouris, 2006). This rate is unreasonable to achieve in practice, and this is why the ventilation standards implicitly or explicitly do not address dwellings with smokers.

In the last ten years, research has shown that almost all materials (varnishes, paints, floor coverings, furniture, partitions, sealants, etc...) emit hazardous chemical pollutants. Rates of emission have reduced due to recent labeling systems, but ventilation is still necessary, particularly in new or recently remodeled dwellings to dilute the off-gassed chemicals.

Combustion products that are harmful to health are nitrous oxides (NO_x) and carbon monoxide (CO). Carbon monoxide is formed in the case of incomplete combustion when not enough oxygen is supplied. Ideally, combustion products would be exhausted directly without mixing with inside air. This is how most water heaters and furnaces are designed, and generally function. Range hoods are

necessary to exhaust combustion products of gas cook tops, although the capture efficiency of these hoods is generally about 60% (Santamouris, 2006).

Outdoor air brought into the building should contain as few contaminants as possible. This may mean filtering the air, or placing the inlet vents where they will not bring in contaminated air. Outdoor sources are pollen, combustion products, (nitrogen oxides, carbon monoxide), and ozone. Pollen can be easily filtered out of incoming air because the particle size is large. In the presence of humidity pollen can germinate creating smaller allergenic particles which are harder to remove from the air. The most likely outdoor source of combustion products are gasoline powered cars and trucks. Combustion products are controlled by placing inlet vents away from roads, driveways, and parking lots. Ozone generally has a higher concentration outdoors than indoors. It may react with other compounds indoors resulting in harmful chemicals. Ozone can also be produced by electrostatic filters.

6.2 Whole-House Ventilation Rates

Ventilation rates were first stipulated by a physician named Billings in the 1890's at a minimum whole house rate of 30 cfm (15 l/s) per person (Roberson, 2004). The concern at this time was about airborne spread of diseases such as tuberculosis. This rate was adopted by the American Society of Heating and Ventilation Engineers (ASHVE) in 1914, although in this early version it was not clear what percentage of the ventilation air should come from outdoors. Subsequent research by Yaglou and others found that only 15 cfm (7.5 l/s) per occupant of outdoor air was necessary (Janssen, 1994). During the 1970's the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, ASHVE changed names with the advent of refrigeration technology, adopted ASHRAE standard 62-1975 which reduced the recommended ventilation rate to 5 cfm (2.5 l/s) per person. In the 1980's the accepted standard again became 15 cfm per person after experimental work by Ole Fanger showed that this level was necessary in order to control odors indoors. ASHRAE Standard 62-1989 specified a minimum ventilation rate of 0.35 ach or 15 cfm (7.5 l/s) per person, whichever was greater.

The whole house ventilation may be provided by mechanical ventilation (local or distributed) or natural ventilation, i.e. unintentional openings (infiltration) or intentional openings (windows, passive vents). Each of these options are examined in more detail in the following paragraphs.

6.3 Local Exhaust Rates

The first local exhaust was a hole in the roof to let smoke out of the building. Fans were invented by Leonardo DiVinci circa 1500 (Kuhnl-Kinell, 2000), however exhaust fans didn't become widely used until the 20th century (Kaplan, 1986). Exhaust rate regulations probably entered the standards as rules of thumb that were introduced into the building codes. Exhaust rates were first regulated by ASHRAE in Standard 62-2001.

6.4 Air Distribution and Duct Leakage

Ventilation efficiency is a concept that has been discussed in the literature as the ratio of the integrals of the concentrations of tracer gas in the different zones (Maldonado, 1983). One zone is generally taken as the reference zone, and each of the other zones are compared to that zone. It has been found that when an air handler for a whole house air distribution system is running, the zones are well mixed, but when the air handler turns off the zones start to diverge. The rate of divergence depends on temperature and wind conditions as well as the physical characteristics of the building.

Ventilation strategies have been developed which use an exhaust fan at one location to extract air, and require an air distribution system to be turned on to evenly distribute the fresh air brought in through the building shell (Fugler, 2004). Although this strategy offers evenly distributed fresh air at a low initial cost to the builder, it has several drawbacks such as the excessive fan energy required to mix the air (most HVAC fans draw 500W), the likelihood that the HVAC fan will not be turned on as designed unless a control system exists to turn it on, and the energy penalty associated with duct leaks, which scales with the duration of HVAC fan operation.

6.5 Infiltration

Infiltration has historically been the main source of ventilation in residential buildings, and in some buildings it still is. There has been an ongoing debate within the research community over which type of ventilation is better. Liddament (1988) compares the two strategies in Table 6-1.

While it is a choice in building a new house, to make it tight or conventionally leaky, existing construction does not have this option. Very few existing houses are below the minimum recommended ventilation level, and in most houses it is difficult to seal them enough to bring them below this level.

The major problem with using a leaky building envelope to provide ventilation is that the direction of airflow is uncontrolled. Ideally, polluted air is exhausted from the house close to the source of pollution, and it enters the house evenly in all other areas. This airflow pattern is unachievable with a leaky envelope, even when exhaust fans are installed to aid in air extraction from rooms with source pollutants (Roberson, 2004). In addition, infiltration is wind and temperature driven so the magnitude of air exchange will change seasonally. This will lead to over-ventilation or under-ventilation during certain seasons. However, if the house has the right permeability to provide good IAQ in winter, then additional ventilation can be provided by window opening in mild weather (Howard-Reed et al., 2002).

Table 6-1: Comparison of Tight Envelope versus Average Envelope with respect to Ventilation

| 'Tight' Building | Possible considerations and/or points of attention | 'Less Tight' Building |
|---|---|--|
| Mechanical extract and balanced ventilation systems can be dimensioned to perform reliably with minimum interference from prevailing weather conditions | Ventilation Strategy | Basic ventilation may be dominated by air infiltration Passive stacks and/or local extract fans, combined with user controllable trickle ventilators may be used to 'top up' ventilation. |
| Heat recovery systems can be effective. Uncontrollable draughts energy loss avoided. | Advantages | A measure of 'safe background' ventilation is provided by airflow through the natural porosity of the building |
| Severe risk of inadequate ventilation if occupant seals air supply return terminals or switches system off. | Disadvantages | Mechanical systems and heat recovery will perform unreliably because of interference from fabric leakage. |
| Fan energy needed either to overcome high under-pressure (e.g. 10-20 Pa room + 200Pa duct) with an extract system or to operate two fans (balanced system – e.g. 200Pa for each duct network) | | Risk of excessive air change especially when driving forces are high (e.g. high temperature difference (winter) and high wind speeds.) |
| Method of purging needed, either by substantial ventilation boost or by openable windows | Control Strategy (People are not capable of correctly managing ventilation devices) | User can control trickle ventilators, fans and openable windows as needed |
| Adjustable ventilation grilles should not close completely since these represent the only significant source of air supply. | | Adjustable openings needed otherwise, if fixed, the occupant might permanently seal them. Air infiltration provides a measure of safety. |
| Cooler climates where high infiltration losses lead to discomfort and energy loss and where the benefit of heat recovery can be maximized. | Applications | Milder climates where cold draughts are less of a problem and heat recovery is economically difficult to justify. |
| Outcome: By good design and with a thorough understanding of the interaction of air-tightness and climate with ventilation both approaches could lead to good air quality and energy efficient solutions. | | |

6.6 Windows and Passive Vents

Natural ventilation is the subject of one chapter of *Ventilation: A State of the Art Review* (Santamouris, 2006). The physics of airflow in urban areas is discussed in detail, and examines the issues of noise and pollution as barriers to using natural ventilation in urban areas. Noise is attenuated by balconies and with increasing height above street level. After a certain threshold level, the level of pollution in an urban area is inversely related to the economic development of the area.

The main problem of using windows for ventilation is that occupants and weather conditions control the ventilation rate, and these are less predictable than a motorized fan. Occupants open windows generally to dilute odor in the dwelling, but research has shown that odor is not necessarily a good predictor of the need for ventilation since contaminants such as radon and carbon monoxide are odorless (Liddament, 1996). Window opening behavior varies among individuals, and with weather conditions so there is no way of ensuring that adequate ventilation is provided by window opening. When windows are open, however, they can ventilate the house as much as or more than infiltration caused by weather effects (Howard-Reed et al., 2002). Window opening in mild weather confounds the theory that natural ventilation is lower in mild weather.

Passive vents may be a solution for natural ventilation that is not controlled by the occupant. It has been shown that constant area passive vents either do not provide adequate ventilation in mild weather (spring and fall) or they over-ventilate in winter (Wilson and Walker, 1992). Some air inlets automatically adjust the size of the opening such that it is larger when the outdoor air is warm and smaller when outdoor air is cold. Other air inlets can be centrally controlled to open or closed in coordinated way with the other ventilation system components (Dorer, 2004). The Residential Hybrid Ventilation project proposes four hybrid (combined passive and active) ventilation systems, designed for severe cold, cold, moderate and mild climates. All of the designs propose outdoor air supplied to the living spaces and extracted from the bathrooms and kitchen, and all propose a central control system linked to occupancy and humidity sensors in order to provide just the ventilation that is needed and no more.

6.7 Combustion Equipment

Substantial work has been done in the United States and Canada to understand backdrafting and spillage, and the relation of these events to the operation of ventilation equipment, but in spite of these efforts we still cannot reliably predict when backdrafting and spillage will occur, and if the quantity of contaminants released into the house will be harmful to the occupants (Nagda et al, 1995)

6.8 Filtration and Air Cleaning

Filtration is generally thought of as the solution to removing particulate pollution in indoor air. In “A guide to Energy Efficient Ventilation” Liddament includes a chapter entitled “Air Cleaning by Filtration” where he describes types of particulates, and types of filters for addressing various particle size and chemical composition. He discusses the European rating system for filtration efficiency ranging from EU1 with a dust spot efficiency of 10% to 20% to EU14 that has a dust spot efficiency of greater than 90%. The equivalent rating system in the United States is the MERV rating, defined in ASHRAE Standard 52.2-1999. This scale ranges from MERV 1 with average particle size efficiency (E_3) of less than 20% to MERV 16 with E_3 greater than 95%.

Liddament refers to filtration systems for all types of buildings, but he gives the following requirements for an effective filtration system, which are applicable to residential buildings:

- It must not be used as a substitute for ventilation air needed for occupants, or for combustion appliances.
- It must be designed to remove the particular problem pollutant (e.g. Tobacco smoke, industrial emissions etc.).

- Recirculatory systems must have sufficient flow rate, e.g. two to three times greater than the ventilation rate to make a sensible reduction of pollutant concentration. This rules out any useful performance from desk top “air fresheners”.
- It must be well sited to intercept the polluted air.
- It must be inexpensive and easy to maintain, and preferably give a clear indication of when filter replacement or cleaning is needed.
- It should be free of operational noise.
- It should be energy efficient.
- It should not cause excessive draughts.
- It should be designed to ensure that filtered air is not directly short circuited back into the air intake.
- It should conform to relevant requirements and performance standards.
- Filters should be well sealed into the assembly frame to ensure that particles do not bypass the filter.
- Ductwork should have provision for cleaning. Contamination of a building with dust and bacteriological products can occur if ductwork and filters are not regularly cleaned.
- Air distribution across a filter should be uniform, otherwise local clogging and premature filter failure will occur.

A recent study by the Canada Mortgage and Housing Corporation (CMHC), Fugler (2000), shows that filtration may not be as effective as we think in removing pollutants from the air. The filter’s effectiveness is maximized when the filtration fan runs all the time, however, this is rarely the case in residences where the filter is generally part of the central heating and cooling system. In addition, airborne pollutants are increased by human activity such as getting out of bed, walking across the carpet, and making toast. People walk around in a “personal cloud” of pollutants, and furnace filters do little to reduce this cloud. Fugler recommends reducing particulates by:

- Removing footwear on entry;
- Keeping major dust generators (smoking, pets, and so forth) out of the house;
- Keeping dust collecting surfaces (open shelves, carpets, upholstered furniture) to a minimum;
- Vacuuming diligently and frequently with an efficient vacuum cleaner (a HEPA vacuum or a central vacuum work best at not re-blowing household dust back into the home.)
- Reducing the entry of particulate-laden outdoor air by closing windows, improving house airtightness, and installing an intake filter on the air supply; and
- Using as effective a furnace filter as the homeowner’s budget permits.

6.9 Other Equipment Issues – Noise

The Home Ventilating Institute (HVI) publishes noise and energy use data for fans of their members (VHI, 2005), and several of the standards incorporate maximum sound levels for fans. The general opinion in the research community is that noisy fans will not be used, although in practice this may not be true. Kitchen range hood fans are sold to consumers with the implication that “the more noise it makes, the better it must be working”, although nothing could be farther from the truth. Noise is often generated by forcing large airflow through too small a duct (reference). Bathroom fans serve a dual purpose: ventilate odors and humidity from the bathroom and to make noise for privacy reasons. When asked to install a bath fan, one builder replied, “Would you like a quiet fan or a noisy fan?” The noise function of bathroom fans is real, but is often ignored by the research community.

6.10 Energy Impacts

Energy is of concern in ventilation in two ways: energy is required to operate the ventilation system, and energy is required to condition the air that is exchanged by the ventilation system. The first way to reduce energy costs for ventilation is to not over-ventilate by natural or mechanical means. Most of the existing housing stock is over-ventilated by infiltration (Sherman and Dickerhoff, 1994). An average infiltration rate of 29.7 air changes per hour at 50 Pascals was reported which corresponds to a natural air change rate of about 1.5¹. Most new houses are not over-ventilated by infiltration (Sherman and Matson, 2002). The average infiltration rate for new houses was found to be 5 air changes per hour at 50 Pascals, corresponding to a natural air change rate of 0.25. Additional energy may be saved by recovering the heat in the exiting air stream. Research has shown that heat recovery in the building envelope from infiltration air is minimal in insulated walls (Walker, 2003). Therefore, minimizing infiltration and supplying ventilation air with a ducted system can save energy by using a heat exchanger to condition the incoming air by removing heat from the outgoing air stream. Heat recovery ventilators are generally cost effective (and frequently used) in severe cold climates.

The energy required to operate a ventilation system can be minimized by making use of passive ventilation whenever possible and by decreasing fan energy by minimizing pressure drop in ducts by using larger diameter, shorter length ducts with a smooth interior surface. The Residential Hybrid Ventilation project (previously mentioned) (Dorer, 2004) gives examples of proposed hybrid (combined passive and active) ventilation systems that minimize the electrical energy needed to operate the ventilation system, as well as minimizing the ventilation rate by using occupancy and humidity sensors in order to provide just the ventilation that is needed for good indoor air quality.

In “A guide to Energy Efficient Ventilation”, (Liddament, 1996) the author devotes a chapter to the energy impact of ventilation and infiltration. He estimates the energy impact of ventilation (intentional and unintentional) for 11 European countries, the United States, and Canada. The delivered air change energy ranges from 40 GJ for the United States to 8 GJ in Sweden, with the majority of the countries using about 20 GJ.

Wray et al. (2000) examined the energy cost of four ventilation strategies: infiltration, central exhaust, heat recovery ventilator, and forced air cyclor system. They found that the lowest cost system, central exhaust only, would add a marginal cost of \$0.50 a day for a typical new house in the United States. This can be compared to the typical cost of \$2.00 a day to condition the infiltration air of a typical existing house. Designed passive ventilation systems and hybrid ventilation systems were not investigated.

¹ The natural air change rate is dependent on climate, represented by the variable N, which ranges between 16 and 24 for climates in the United States. The value of N=20 has been used for these conversions.

7 Discussion of Literature Gaps

The most significant area where research is needed to fill gaps in our knowledge is in ventilation impact on electricity demand. This type of study would require detailed information about the exact times that the ventilation system is in use and the number of systems operating are necessary inputs for such an analysis, thus making it difficult to carry out. The study would have to be linked to a specific ventilation standard or ventilation strategy and a specific geographic area.

8 Key Findings

Ventilation is increasingly becoming recognized as an important component of a healthy dwelling. The states of Washington, Minnesota and Vermont now require mechanical ventilation in dwellings, and the state of Maine is considering such a regulation. New guidelines from the American Lung association and Energy Star include mechanical ventilation requirements. Canada requires mechanical ventilation, and many European countries have a ventilation requirement that may be satisfied without a mechanical system.

All the ventilation standards tend to cluster around common values for recommended ventilation rates. Whole house ventilation rates are generally 0.35 ach, although some standards do stipulate values as high as 1.0 ach. Kitchens are often required to be vented at a rate of 50 l/s (100 cfm), intermittently or at some lower continuous value. The continuous ventilation requirement is as high as 30 l/s (60 cfm) (in Canada and the UK) or as low as 6 l/s (12 cfm) (in France.) Regulations for bathrooms are similarly prescribed with a higher intermittent rate, often 25 l/s (50 cfm), and a lower continuous rate, with a range of 15 l/s to 4 l/s (30 cfm to 8 cfm).

Surveys of occupants showed that people generally think that ventilation is important, but that their understanding of the ventilation systems in their houses is low. The majority of people are satisfied with their ventilation systems. As to whether people actually use their ventilation systems, studies showed that 90% of passive ventilation systems were in use, as opposed to mechanical systems which are used much less often. The use of such systems varied widely between studies from 3% (bath fans) in a California study to 70% (exhaust only ventilation system) in a Canadian study to 82% (HRV system) in another Canadian study.

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