ANNEX **5**

EBC

Energy in Buildings and Communities Programme

AIVC Technical Note 70
40 years to build tight and ventilate right: From infiltration to smart ventilation

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Technology Collaboration Programme

by iea

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Preface

The 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 international cooperation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely ‘Objectives’ and ‘Means’. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
– improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
– the creation of ‘low tech’, robust and affordable technologies;
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
– benefitting from ‘living labs’ to provide experience of and overcome barriers to adoption of energy efficiency measures;
– improving smart control of building services technical installations, including occupant and operator interfaces;
– addressing data issues in buildings, including non-intrusive and secure data collection;
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the ‘objectives’ themes are final goals or solutions (or part of) for an energy efficient built environment, while the ‘means’ themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)

Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
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Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group – Building Energy Codes

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1. Introduction

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The AIVC was created in 1979 and started having annual conferences in 1980. The 2019 Conference was its 40th conference and the conference theme focused on its anniversary. This Technical Note is a compendium of the contributions that the AIVC has made in its first 40 years and reflects field's evolution over time. Much of the information generated by the AIVC is of direct use today and some of the older material is good source material for future research.

The AIVC is an information dissemination project created by the International Energy Agency (IEA) as a result of a need to understand the energy impacts from air leakage in buildings for the energy crisis of the 1970s. When the Center was first created it was called the Air Infiltration Center because the focus was on energy loss due to infiltration. It was generally thought that most buildings leaked way too much air and that reducing that infiltration would reduce dependence of fossil fuels.

The mechanism the IEA uses to create projects is through implementing agreements of member nations. The AIC was the 5th project (or "annex") created by the implementing agreement on buildings and community systems, which has been renamed Energy in Buildings and Communities (EBC) at https://www.iea-ebc.org/. There have been 70 projects completed from EBC and 17 that are on-going currently. Of those, Annex V is the only information dissemination center and the only one that is active for more than a few years.

Because infiltration research was not a field of its own in the 70s, the AIC became the de-facto coordinating body for infiltration-related research around the world. It was sometimes difficult to understand each other, hence we started a series of TN named AIRGLOSS [36] in which terms and definitions were described. When investigating a new area, the first thing one must do is be able to measure it. A significant effort was put into measurement techniques both for air change rate and for air tightness. The research community is much broader now, but these are still active areas of research. Chapter 3 discusses air tightness and Chapter 4 discusses air flow measurement techniques.

Infiltration and air tightness are of course related, but quantitatively connecting air leakage and air flow, requires modeling and such models did not really exist. So along with a focus on measurement techniques, the AIC worked on infiltration modeling as discussed in Chapter 5. The first models were simple, physical models, but as computing power and the state of knowledge grew, so did the models.

After only a few years, it became clear that looking at infiltration in isolation was a sub-optimal approach. As buildings were getting tighter, there was a concern of insufficient air exchange. An optimal energy solution would then need to include both infiltration and designed ventilation. Accordingly, annex V's mandate was broadened to include ventilation systems and in the mid-80s the name was changed to the Air Infiltration and Ventilation Center as it remains.

In 1985 the AIVC began publishing technical reports (e.g. TN 17) [12] that specifically focused on optimal ventilation strategies. Many AIVC (and conference publications) have worked this problem in the last 35 years. Chapters 14 and 15 review many of the approaches used today. One of the more recent trends is to make our ventilation systems smarter and Chapter 13 looks at some aspects of that.

It was also realized during the 1980s that occupant behavior had a bit impact with respect to ventilation overall. EBC Annex VIII focused on this and resulted in 1988 in AIVC TN23[15] on the topic. Early research focused on issues such as window opening, but later work looked at how mechanical systems are perceived and ran. Chapter 10 looks at occupant impacts from today's perspective.

Ventilation for acceptable indoor air quality generally uses energy to condition the outdoor air, but there are times when ventilation can save energy, if it displaces the need for mechanical cooling. Providing ventilative cooling can be through both mechanical and natural means and can positively impact comfort. Chapter 8 discusses these issues.

As the AIVC was going to work on optimal ventilation strategies, it was important to know what the standards for acceptable ventilation were and this became another focus of the center's work. The center has published many documents related to standards such at TN26 in 1989 [17] that summarized EBC Annex IX. Ventilation standards have grown much more sophisticated since those times and are addressed in Chapter 9.

One thing common to most ventilation standards over that period is that they assume that outdoor air is clean, or at least substantially better than indoor air. In such a case one can use it to dilute indoor-generated contaminants without worry. We know that in many cases this assumption is wrong, but it is not always clear what to do. Chapter 12 looks at the issue of outdoor air more broadly.

Outdoor air contains moisture, but water vapor is a rather unique kind of contaminant: it has both an indoor and outdoor source and we neither want too much of it nor too little. Control of moisture has been a priority for the AIVC since it had a workshop in New Zealand (TN20) in 1987 [13]. Chapter 7 provides an overview the issue today.

Another unique kind of constituent is carbon dioxide. CO_2 is a product of combustion including human metabolism and therefore is unavoidable in indoor spaces. At high enough concentrations CO_2 can become deadly, but it is not a contaminant of concern in typical buildings. It is, however, a good indicator that can be used in ventilation systems. Use and misuse of CO_2 is a quite topical issue today. Chapter 11 discusses the role of CO_2 in buildings.

Since the turn of the century, it has been clear that the purpose of ventilation is acceptable indoor air quality and one cannot determine acceptable indoor air quality without looking at health. A growing part of the more recent efforts of the AIVC have been focused on understanding this health linkage and optimizing systems accordingly. Chapters 6 and 13 address what the AIVC has been doing in this area and form a basis for future activities.

From the editors

We, the editors, have been involved with the AIVC since its first conference in 1980 and have been active participants in both its management and execution of its research program. We hope you find this compendium of value.

Each chapter is relatively short and points to a lot of key references from the AIVC and elsewhere. Each chapter was put together by a separate team of experts who are knowledgeable of the field and of the AIVC and each team made its own choice as to how to describe their area of expertise.

The chapters by themselves are not an exhaustive description of the field but focus instead on contributions made by or needed by the AIVC. When the AIVC first started almost all contributions in the field were through the AIVC. The fact that that fraction is much smaller is a testament of the success of the center motivating the broader research community and showing the AIVC has been doing its job.

The chapter authors are listed for each chapter and we would like to give them personal thanks for working through this complicated effort. We would also like thank those that helped edit and format the document including Maria Kapsalaki and Manfred Plagmann.

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2. Air Infiltration. The start and progress over 40 years of AI(V)C

Willem de Gids, VentGuide, Netherlands

2.1. The beginning of AIC

Before the formation of Annex 5 Air Infiltration Centre in 1979, ventilation and infiltration was in most cases the unknown factor in energy balances. Ventilation could be reasonably estimated but infiltration was the real unknown. Therefore, IEA organized a meeting in Paris with specialists from around the world to discuss the influence of ventilation and infiltration on the energy use of buildings. One of the actions from that meeting was to try to collect all information on infiltration around the world and so Annex 5 the Air Infiltration Centre (called AIC) was created. In 1986 the name AIC was changed in AIVC. This was due to the fact that the interaction between infiltration and ventilation was more and more dominating the type of research in the participating countries.

Infiltration was in some countries seen as ventilation or at least as a part of the desired ventilation. In other countries infiltration was seen as a disturbance of the planned or designed ventilation. Infiltration counted in the cold countries for a remarkable part of the energy use. One of the first things was to try to speak the same language.TN 5 Air Infiltration Glossary, 1981 [26] with about 1000 terms was one of the first products of AIC. Later this Glossary was translated in four other languages: German, French, Italian and Dutch.

2.2. Definitions of infiltration and air leakage

The definitions changed a bit over the years because of the need to better understand and to be more precise.

In TN 5 Air Glossary from 1981 the definition of air infiltration was:

"The uncontrolled inward air leakage through cracks and interstices in any building element and around windows and doors of a building, caused by the pressure effects of the wind and/or the effect of differences in the indoor and outdoor air density, measured as an air change rate. (CIB Report "Units and Definitions", Publication 53, 1978)"

The definition was changed in TN 36 1992:

"The uncontrolled inward leakage of outdoor air through cracks, interstices, and other unintentional openings of a building, caused by the pressure effects of the wind and/or stack effect"

The difference between the definition of infiltration 1981 and the later replaced version in TN 36 1992 was that the cause of the infiltration was only specified by pressure and the unnecessary sentence about measurement was skipped. Because the infiltration to a building could also come from an adjacent building, the term *inward air leakage* changed to *inward air leakage of outdoor air*.

Air infiltration is as the definition says inward air leakage. So, air leakage also needed to be defined.

In TN 5 1981, the definition of air leakage was:

"The uncontrolled flow of air through a component of the building envelope, or the building envelope itself, when a pressure difference is applied across the component."

Later in TN 36 1992 this was changed to:

"The leakage of air in or out of a building or space usually driven by artificially induced pressures."

For air leakage the definitions changed to be more suitable for the measurement pressurization test.

The measurement of leakage of a building is described in chapter 3.

2.3. Impact of infiltration/exfiltration

The focus in the building industry is always on the infiltration of air but the counterpart exfiltration can also be important, mostly in terms of damage of the building construction or in terms of energy.

The energy impact of infiltration was very important at the beginning of AIC. Because most buildings became more airtight the relative importance of infiltration went down. From 1980 to 1990 the contribution to the heating demand could easily go up to about 60%. Nowadays it can still be up to around 20% of the heating loss.

Infiltration of air in buildings has several consequences such as:

- Energy losses
  - Cold or mild climates:
    - When infiltration of air is higher than the desired airflow, the infiltrated air must be heated
    - Since more and more ventilation systems in buildings become balanced ventilation systems, infiltration and exfiltration cannot be neglected in terms of energy use. The reason for it is that where the same amount of air is supplied and exhausted mechanically, all infiltration must be exfiltrated to the building envelope and hence is an energy penalty. (AIR Phaff, de Gids)
- Effect on ventilation
  - In the years around the launch of AIC there were many countries around the world where infiltration was accepted as part of the ventilation necessary to provide enough air exchange to control the indoor environment. Even nowadays in the more mild or warm climates, many countries infiltration still counts as part of the required air change between outside and inside
  - Influencing the ventilation pattern, positive as part of the desired ventilation in case of (mechanical) extract systems, the infiltration air contributes to the dilution of indoor produced contaminants
- Comfort
  - It might have negative effects because of local leaks causing draught problems
  - Warm and/or humid climates
    - The infiltration air may disturb the indoor climate and may cause extra cooling capacity or even dehumidification

Over the AIVC years the role of infiltration is understood better and better. Infiltration of air may locally cool down construction parts and so cold bridging may occur, which may lead to mold problems. Exfiltrated air may cause interstitial condensation in the construction parts, which is not desirable either. It may affect the insulation, the construction itself and can cause mold problems.

Sweden was the first country in AIVC who had produced a handbook on airtight dwellings. In 1983 AIC published a handbook [1] with the title: Air infiltration Control in Housing. A Guide to International Practice. Arne Elmroth and Per Levin were the editors.

Some figures from this Guide are given below.

The slogan “Build tight, Ventilate right” is nowadays more important than ever before.

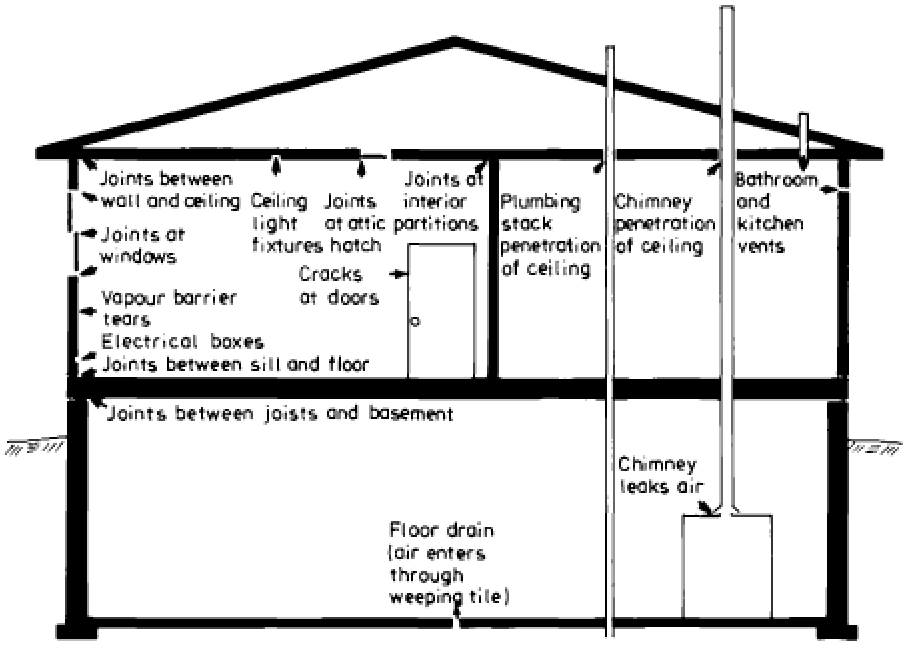

Figure 1: Locations of air leakages in a dwelling

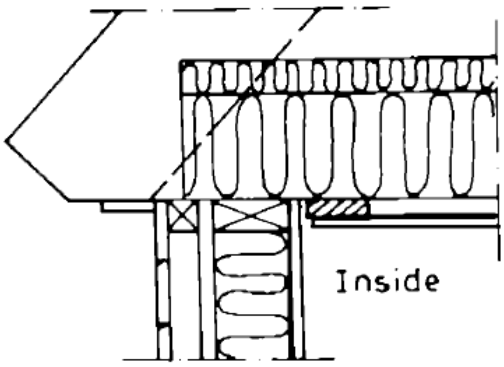

Figure 2: Detail of a wall roof junction

2.4. Flow equations

In the beginning years of AIC, the flow equation was one of the most frequent discussions between international researchers. It is clear that infiltration is caused by pressure differences. From theory we know that flow can have a turbulent character or a laminar character. In reality the situation is almost never one or the other.. From measurements one could see a relation between pressure and infiltration flow that is neither laminar nor fully turbulent. The more physics oriented researcher therefore preferred an equation in which the turbulent and laminar flow components are separated.

$\Delta p = a * Q + b * Q^2$

the AIVC Calculation Guide from 1986 [2] gives some explanation for this equation. This equation is mainly used before 1990 by some UK researchers.

The equation which follows is more obvious:

$Q = C * (\Delta p)^n$

Although theoretically and physically not completely correct, the last equation is now used by most people carrying out infiltration and ventilation studies in the world. The flow exponent n is always between 1 for complete laminar and 0.5 for full turbulent flow. In practice it is in most cases around 0.65. The reason why this last equation is used is twofold:

- It is a result of the used measurement technique for pressurization and/or depressurization test
- The laminar part is important at very low pressure differences where hence the flow is also very low and in most cases outside the scope of our studies

2.5. Estimation of infiltration; calculation techniques

The most rough and crude method is the role of thumb used from the beginning of AIC/AIVC.

In the Guide to Energy Efficient Ventilation 1996 [5] this rule of thumb is described. It is based on the air leakage measurement result N50, which means an air change rate between inside and outside at 50 Pa pressure difference, here called ach(50).

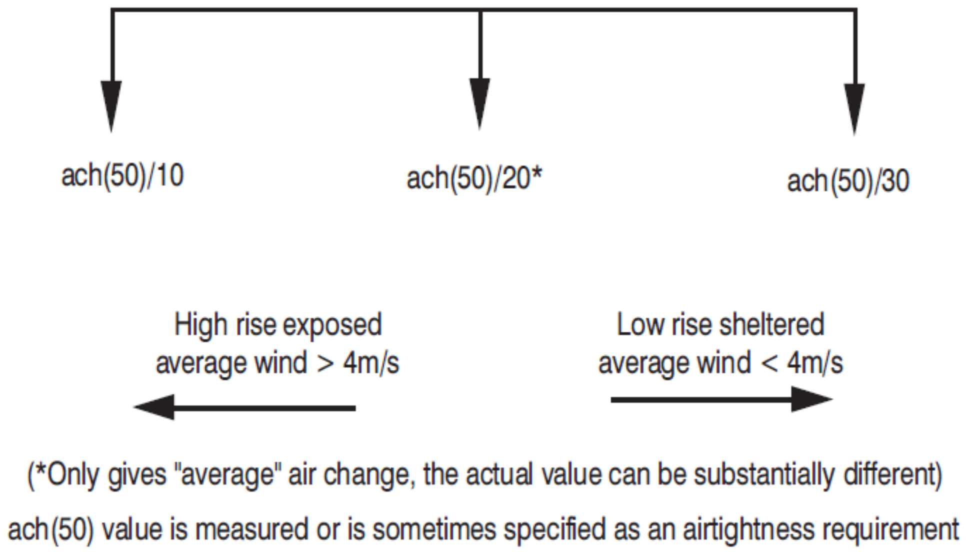

Figure 3: From air change at 50 Pa to an average air change over a year for a dwelling

As an example:

N50 is 10 ach for a dwelling for average conditions. The average value dividing 10 over 20 leads to an average air exchange for the whole dwelling of 0,5 air changes per hour.

3. Airtightness measurement

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3.1. Introduction: Importance of topic of the chapter

Airtight construction lies at the heart of achieving high energy performance in buildings, in combination with the installation of dedicated energy efficient ventilation systems to provide good indoor air quality. In order to minimize convective heat losses or disturbance of designed air flow patterns as a result of air leakage, it is important to achieve both an airtight building envelope as well as airtight ductwork of ventilation and HVAC systems.

Controlling air leakage requires building or ductwork assemblies to contain air barrier systems. This is a combination of materials (boards, films, plasters, sealants, gaskets…) which establishes a continuous plane of airtightness at all joints and intersections over the service life of the system. Because of the difficulty to predict the airtightness performance based on material properties and design drawings, and the dependency of the performance on workmanship, it is crucial to test the building and ductwork airtightness using measurements at commissioning, after building construction is completed.

Over the last decades, evaluation of the overall airtightness of the building envelope by means of measurements has become standard practice in high performance buildings, and, in some countries, mandatory for all new built. The role of airtightness testing in construction has increased in many countries as a result of the introduction of energy performance standards and regulations, and the evolution of requirements towards nearly zero energy buildings in recent years. As a result of the more widespread use of testing, various countries took initiatives to increase the reliability of air leakage tests in practice, because of the potentially large impact of erroneous results (TN67 2012) [54]. These initiatives include the development of test standards and specifications, competent tester schemes and trainings, centralized test data collection, and quality management approaches.

3.2. Historic role of AIVC: Contributions over the last 40 years

The discussion and dissemination of research work on air tightness measurement techniques was one of the central objectives of the AIVC since the very start of the Centre. In the 1980's a great deal of effort was devoted to the advancement of measurement techniques for air infiltration and ventilation, as the fundamental means of acquiring a greater understanding of these phenomena (Charlesworth, 1988) [3]. Over the last 40 years, annual AIVC conferences (1980-2019) have been a major exchange platform to address building airtightness measurements, but often during the conferences in the 1980's air infiltration instrumentation, measuring techniques and standard development were central themes. Measuring techniques and analysis methods still available to researchers and practitioners today were already discussed during the 1st conference in 1980: tracer gas techniques, fan pressurization testing under steady state and alternating pressurization (Conference proceedings 1, 1980). As a result of the considerable progress being made at the time in the development of measuring techniques to the point where their more general application in building practice became possible, the information on measuring techniques was brought together in 2 review reports (TN10 1983 [7], TN24 1988 [16]) and culminated in an applications guide (Charlesworth 1988)[3], which was updated and expanded in a technical report a few years later (TN34 1991)[24]. The role of these guides was to increase general awareness of air exchange rate measurement techniques and their applications, meeting the needs of both academics and consultants. Around the same time several countries developed standards relating to on site measurements of building airtightness using fan pressurization methods. As a result, the interest in building airtightness measuring methods decreased a little in the 1990's and early 2000's. However later studies on the development and application of alternative test methods overcoming disadvantages of the standard methods have been presented regularly at AIVC conferences (Cooper et al. 2015, Lanooy et al. 2019).

While in the first 10 years of AIVC, publications on airtightness measurement techniques related almost exclusively to the building envelope, later on ductwork airtightness gained more attention. The technical reports TN34 (1991) [24] and TN56 (2002) [43] contained a section discussing airtightness measurements of ducts and networks, based on pressurization. The first Ventilation Information Paper (VIP1, 2003) [56], which was recently updated dealt specifically with airtightness of ventilation ducts, including standardized measurement and classification methods.

The measuring techniques applications guide and reports, mentioned previously, paid systematic attention to accuracy and calibration of air tightness measuring equipment, and influence of ambient conditions on the validity and accuracy of test results. The quantification of uncertainty in airtightness testing has however really gained in popularity since 2010. Numerous very specific papers have been presented at AIVC conferences, building on earlier work by Sherman & Palmiter (1995). Also, methods to understand and improve reproducibility and reliability of airtightness test results received attention in the last decade. TN 67 (2012) [54] developed recommendations for testing, reporting and quality schemes for airtightness measurements, to make large scale testing applicable in a compliance framework. Such schemes can be a solid basis for the development of airtightness databases, which allow to monitor building and ductwork airtightness evolutions, and play a role in quality assurance of competent tester schemes (TN66 2012 [53], VIP37 2017[92]).

3.3. Airtightness Test Methods (TN34 1991) [24]

If a pressure difference is applied across a leakage path, the resulting air flow rate may be approximated by the well-known power law equation:

$$Q = C \cdot \Delta p^n$$

with Q the air flow rate (m^3/h), C the leakage coefficient ($m^3h^{-1}Pa^{-n}$), Δp the applied pressure difference (Pa) and n the airflow exponent (-).

This principle is widely used to measure air leakage characteristics of buildings and ductwork, either on site, by whole building, compartment or component pressurization, or in the laboratory for testing of specific components. Measurements are made by using a fan to create incremental steady-state pressure differences across the test object (building or component) in the 10-100 Pa range. For each pressure increment the corresponding air flow rate through the fan is measured. For whole building testing on site, the fan is typically positioned in the opening of a door for the duration of the test. This type of test and testing device is therefore often referred to as 'blower door'. The standard methods used for quantification of building airtightness assume the same principle and are described in ISO 9972 (2015).

Although building components are on average subject to pressure differences in the order of 0-10 Pa, it has become standard practice to use the measured air leakage at a pressure difference of 50 Pa as a performance metric against which the airtightness performance of buildings may be compared. ISO 9972 gives a regression method to derive the flow rate at a reference pressure difference (e.g., 50 Pa) from the measured flow rates at the incremental pressure differences applied during the test. In some countries lower reference pressures are used, e.g., 4 Pa, closer to pressures representative for average environmental conditions.

The maximum volume of enclosure which may be pressurized depends on the overall airtightness of the building and the size of the available fan. While blower door tests are typically performed in small residential buildings, for the examination of large buildings either multiple blower door devices must be combined or large trailer mounted fans are to be used. As an alternative the building's existing air handling system could be used to create the required pressure differentials. Essentially, during the test supply fans are operated while all return and extract fans are turned off, with all return dampers closed (or vice versa for depressurization). Since this technique requires the system to be operated in a non-standard manner, not all air handling systems are suitable. Also, in case of large and complex systems, the technique may require more effort and expertise to obtain accurate results than in the case of measurement with a set of multiple blower doors (Szymanski et al. 2014). The applicability of the technique has also been assessed for dwellings, as a cheaper and faster alternative for blower door testing (Lanooy et al. 2019).

Given the practical difficulties of measuring the airtightness of large and multi-family buildings, it is also possible to measure the airtightness of individual zones separately (e.g., individual apartments in multi-family buildings). In some countries sampling rules have been defined to choose the units/parts that must be tested in a compliance framework to avoid systematic testing of all individual zones of the building (TN67 2012) [54].

The steady-state pressurization test methods discussed above are subject to the disturbing influence of natural pressure fluctuations created by the wind. To overcome this the tests are performed at pressure differentials far above those created by natural forces, avoiding testing under strong winds. However, this may lead to inaccuracies if the results are extrapolated to lower pressure differentials. Dynamic pressurization methods allow building airtightness to be examined at similar pressure differentials as under climatic forces, but with minimal interference. Two dynamic methods are described in TN34 [24]. In the first, so-called AC technique, a small cyclically varying pressure difference is created across the building envelope, using a piston. By measuring the amplitude of the pressure response in the building and the phase relationship between this pressure and the velocity of the piston, the air flow through the envelope can be evaluated. In the second, so-called pulse pressurization method, the pressure is suddenly enhanced in the measured volume, and the subsequent pressure decay is recorded. The leakage flow rate is identified by fitting the measured pressure decay on theoretical values. The latter method has been developed into a quick-to-use method, applicable in practice using a portable and automated device (Cooper et al. 2015).

3.4. Uncertainty

With more widespread use of building airtightness tests, it has become increasingly important to understand and quantify the reliability of these tests. While the test principle of the standard fan pressurization test is simple, experience shows that there can be wide differences in the derived quantities, also when standard protocols for building preparation and testing are followed (TN67 2012) [54]. Many sources of error can affect the measurement of building airtightness. If human errors are reduced by means of competent tester and quality assurance schemes, the main ones are the following:

- Equipment uncertainty (flow and pressure measurements).
- Wind and stack effects (pressure non-uniformity and fluctuations).
- Analysis method (regression model).

These sources of errors can be subdivided in the errors associated with making the measurements themselves, and the errors associated with the use of a model to extrapolate the measured behavior during the pressurization test to the desired quantity, this is the leakage flow rate at low pressure differentials (Sherman & Palmiter 1995). The measurement error is made up of the precision error and bias error. Besides traditional mathematical analysis of the problem, a contribution to a better knowledge of random measurement error (precision) of airtightness measurements of buildings can be made through determination of their repeatability and reproducibility in practice. Repeatability and reproducibility are the two extremes of precision, the first describing the minimum and the second the maximum variability in results, caused by different operators and equipment. Delmotte (2011) showed standard protocols can give reproducible results, with a reproducibility standard deviation of 2.4% at 50 Pa pressure difference, but noticeably higher deviation at pressure differences below 10 Pa.

Traditional mathematical analysis of measurement uncertainty consists of propagating identified sources of error through the calculation. This approach has been explored by different authors through the years. The analysis of the problem has highlighted the need to reconsider the relevance of unweighted ordinary linear regression if measurement uncertainty is to be taken into account. There are practical suggestions from Okuyama and Onishi (2012) and Delmotte (2017) to apply methods of weighting for regression to obtain a significant reduction of standard deviation of estimated air flow rates at low and high pressures.

According to Sherman and Palmiter (1995), “wind is probably the most pernicious source of experimental error in field situations because it can cause both precision and bias errors”. VIP41 (2021) gives an overview of research on the quantification of the impact of wind on air tightness test results and gives guidance to reduce the wind impact and improve test standards, including recommendations on the pressure difference measurement method, the location of pressure taps, and the regression method. Integrating the impact of wind in uncertainty analyses would allow testers to perform tests under windier conditions than specified in ISO 9972 yet keeping confidence in the results (VIP37 2017) [92]. Integrating information technology in airtightness software could also improve the reliability of tests and help central data collection.

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4. Airflow measurement techniques

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4.1. Introduction

When the AI(V)C was started in 1979, no one knew what the air change in buildings really was despite the occasional measurements dating back almost 50 years. Most buildings were dominated by infiltration and natural ventilation and although some decay-type tests had been done, there were no good techniques for quantifying the flows. Knowing ventilation rates is not only useful for understanding energy use and indoor air quality in buildings, but it is also needed to validate airflow models. Developing and validating airflow measurement techniques has been a priority for the Center since its formation.

4.2. Overview of work over 40 years AIVC

4.2.1. Tracer Gas Techniques

When one has a uniform flow such as in a duct, there are well known techniques such as a pitot-tube traverse to determine airflow rates. Air flows through building envelopes, however, cannot be measured with these techniques because the sites of infiltration and exfiltration are rarely known. And even if all the airflow pathways were known, they are not likely to be accessible for air speed measurements.

Tracer gas techniques can determine the air change rate without the need to know the airflow pathways and thus is ideal for determining infiltration. Investigating techniques for measuring infiltration and ventilation rates directly using tracer gases was a major focus of the research community and the Center in the early 1980s.

In 1983, the Center published an authoritative review on measurement techniques (TN 10) [7], which is still a key resource for anyone wishing to review the early work on tracer gas measurement techniques. Tracer technique research continued through 1980s with many papers published in AIVC and other proceedings such as ASTM (1990). At the 10th AIVC Conference in Finland, for example, Sherman (1989) presented an evaluation of tracer techniques currently in use. In 2001, the AIVC published a literature list (LL13) and then in 2003 an annotated bibliography (BIB12) of airflow measurement techniques that included both tracer and non-tracer techniques.

Starting in the late 1980s, the focus turned to looking at how to measure the effectiveness of ventilation at supplying air or removing contaminants, which requires using tracer gases to track or mimic outdoor air or contaminants. TN21 (1987) [64] looked at ventilation effectiveness; TN28 (1990) [19] air change efficiency; TN 28.2 (1991) [20] pollutant removal effectiveness; and TN34 (1991) [21] airflow patterns. The last major AIVC technical publication on the topic was TN39 (1993) [28], which reviewed the whole field.

A key concept of ventilation effectiveness is known as “age of air” and has long been a popular concept for evaluating ventilation and/or pollutant removal effectiveness for applications such as displacement ventilation (See LL21). Sherman (2008) evaluated the benefits and limitations of the concept with a particular emphasis on a multi-zone environment.

Most tracer techniques are expensive to do on a large scale and tend to be limited to research activities. For this reason, the passive-tracer method—often called the PFT method for the PerFluorocarbon Tracers (PFT) typically used—became a popular method due to its low cost. Sherman et al. (2014) showed that the technique is much more uncertain than had been previously thought and may not be suitable for many surveys.

Most recently, tracer-gas methods have been developed to measure the capture efficiency of cooker(range) hoods. Evaluating cooker hood performance has been a priority for the AIVC for the last few years. At the 39th AIVC conference, Walker et al. (2017) evaluated a laboratory technique for determining the capture efficiency of cooker hoods using a single tracer gas.

Information in the following sections is condensed from the references discussed above. A reader wishing a more in-depth understanding of the topic is encouraged to consult these references, most of which can be found on the AIVC website. Tracer gas techniques, like all measurements, are subject to a variety of systematic errors that depend on the experimental design and may not be obvious from the data itself. Therefore, quantitative error analysis needs to be performed for tracer gas measurements but these analyses are not described below.

4.2.2. Single zone

A tracer gas is a substance that can be added to air (not changing its properties) and moves along with it. It is used to tag the air, so its movement can be followed. No compound is a perfect tracer, but some are better than others. A tracer should be measurable by some means, but one should avoid tracers that interact with their surroundings either physically or chemically, that are harmful, that decay or that separate from the air they tag. A tracer should not be present in the air at a significant concentration.

After one has selected a suitable tracer gas, one must also have means to inject it into the space and to measure its concentration in air. If we measure the concentration and emission rates of the tracer gas, we can infer the airflow rate by using conservation of mass. Such a derivation leads to what is normally called the *continuity equation*:

$$V\dot{C} + QC = S \qquad 4.1$$

Where the time varying parameters are:

V is the (effective) volume of the space (m^3) [which is often assumed known and fixed]
Q is the airflow rate (m^3/s) at inside density
C is the tracer concentration (-) [The dot over the parameter indicating a time derivative.]
S is the tracer source (emission) rate of the tracer (m^3/s) at inside density

Our objective is to find the airflow rate, *Q*, and it would seem like a trivial bit of algebra to extract that from the continuity equation assuming we know the volume, the concentration time-series and the source term. Unfortunately, that turns out not to work in practice. The uncertainty in the concentration signal is almost always too large to make it work over any small time period. Furthermore, the assumption that concentration in a space can be represented by a single value is always questionable. While the instrumentation involved may contribute to the uncertainty, there is a systematic uncertainty in tracer gas approaches caused by a variety of effects that can be labeled together as poor *mixing.*

There is an assumption in the derivation of the continuity equation that the concentration of tracer gas is the same at every point in the space. Physically we know that cannot be true, but ASTM E741 does require it to vary by no more than 10 %: if there is air infiltration then untagged air is coming in somehow and the concentration will be lower there; if there is injection of tracer the concentration will be higher there.

One might think that using the average concentration in the space would be sufficient to minimize this effect, but a careful review of the derivation of the continuity equation reveals that there is an implicit assumption that the average concentration in the outgoing air is the same as the average zone concentration. The only solution to this is adding extreme mixing to make sure the concentration is in fact uniform Such extreme mixing is almost never done both for practical reasons and because it is highly likely to change the thing one is trying to measure. Thus, the certainty of any tracer-gas measurement is dependent on uniformity of concentration.

Accordingly, real tracer gas experiments should be planned to minimize both the systematic errors (e.g. from nonuniform concentrations) and the concentration measurement error. We can briefly look at the range of approaches that have been and can be used.

The **tracer decay** is the simplest and earliest approach used. In this technique, an amount of tracer is added to the space and is well mixed. The amount of tracer only needs to be sufficient to achieve a tracer gas concentration within the range of the measurement equipment and does not need to be otherwise measured. The space is configured under the desired test conditions, and the decay of the tracer concentration is observed.

If the tracer gas source term is zero, the continuity equation can be solved to express the concentration as a function of time:

$$C(t) = C_o e^{-At} \qquad 4.2$$

where A=Q/V is the nominal air change rate (1/s).

Experimentally, we see that after a period of stabilizing the concentration follows an exponential decay curve as expected. Various fitting or integral approaches can be used to find the two parameters, C_o and *A*, with reasonable precision. Unfortunately, the volume that is appropriate to use in these equations is virtually never the physical volume of the space, V_o, which means that even determining the air change rate well leaves the actual airflow poorly determined.

The reason behind this is that there are going to be parts of the zone that are not at the same tracer gas concentration as other parts of the zone, e.g. a closet or cabinet. The space will act as though it has a smaller effective volume than the physical volume, leading to a measurement bias. Furthermore, the concentration will decay slower in any poorly mixed zones compared to the main zone. If this effect is strong equation 4.2 cannot be used because the actual concentration decay follows a superposition of two or more exponential decay curves with substantially different time constants. On the other hand, if the measured concentration values can be nicely fitted to one single exponential decay curve (such as equation 4.2), this is a clear indication that the problem with poor mixing is small or even negligible.

This effective volume problem can be minimized by allowing the zone to come to steady-state concentration. In such a case, these poorly mixed zones have time to equilibrate with the main zone and as long as the concentration is held steady the bias disappears and one does not need to worry about the coupling.

This is the idea behind the **constant concentration** technique for measuring the airflow. In this approach the source of tracer gas is controlled to keep the concentration of tracer at a constant, target concentration, C_T. This removes the dependence of the answer on the effective volume and on time variation of concentration. The airflow can be derived simply from the continuity equation as:

$$Q = S/C_T \tag{4.3}$$

In practice, this approach is limited by the ability of the controller to keep the concentration at the target. Because of the imperfect mixing and the intrinsic delays between a chance of source emission and the response of the concentration, it is usually necessary to average this equation over some period of time where the average concentration rather than instantaneous one is equal to the target.

Unfortunately, this causes a different kind of bias having to do with the fact that the average of the inverse is not the same as the inverse of the average.

When the concentration cannot be well controlled, the proper solution to find the average airflow is then

$$Q = \overline{S/C} - V \ln\left(C_{final}/C_{Initial}\right) /\Delta t \tag{4.4}$$

where the overbars indicate a time average over period Δt between the initial and final times.

Since the concentration is varying around its target, it is always possible to use the data to select a time period at which the initial and final concentrations are the same. That, however, requires an a-posteriori analysis. If one picks a long enough time period the second term will always become negligible, but the time period for that can be longer than one justifies an assumption of constant airflow. The airflow can be calculated from the average of the emission/concentration ratio, the former varying a lot from the controller and the latter moderately noisy but constant. It is not that difficult, however, to calculate the second term and thus tune the analysis period to the specific experiment.

Given that we are averaging, one does not need to have a highly complex (and expensive) control system. A more robust approach is the **constant emission** technique, in which the source emission is held constant over time. This would result in a constant concentration if the airflow were constant, but given that for most experiments the airflow is likely to change slowly over time, so will the concentration. The slow change in concentration means that the system will be in steady state and this approach is not seriously hampered by effective volume issues.

If one selects the averaging periods appropriately to make the second term negligible, then the constant emission technique yields the following:

$$Q = S\overline{\left(\frac{1}{C}\right)} \tag{4.5}$$

The constant emission approach is generally the most robust as it minimizes the errors induced by imperfect mixing without introducing biases or difficult protocols. This is also the way airflow through a duct can be measured; a constant source is emitted well upstream of a concentration measurement point and the data is analyzed as above.

The **passive tracer** approach is a modified version of a constant emission approach in which passive emitters are used to provide somewhat constant source emission and passive samplers are used to measure a time average concentration. The equation used to analyze the data is as follows:

$$Q = \overline{S}/\overline{C} \qquad 4.6$$

Comparing this equation to the constant concentration expression, we see that the second term is not included and so has the inverse coupling of the concentration. The second term is justified in disappearing because the standard protocol for use of this approach is to have a very long measurement period (days or weeks). The long measurement period means that the airflow, source emission and concentration will be varying and thus inducing substantial bias errors.

4.2.3. Multi-zone

Most buildings are not single, well-mixed zones but rather a collection of interconnected zones, some of which are independent and some of which are coupled. Additionally, a single, poorly-mixed zone might logically be broken up into several well-mixed zones. Either way, it is natural to consider multizone approaches for understanding airflow in such buildings.

The same continuity equation applies, except now the quantities are treated as matrices:

$$\underline{V} \cdot \underline{\dot{C}} + \underline{Q} \cdot \underline{C} = \underline{S} \qquad 4.7$$

where the underbars and dot products indicate matrix notation.

The volume and airflow matrices are matrices of rank two having a row and column for each zone. That means the number of unknowns to derive from the data goes up quadratically with the number of zones creating more demands for the measurements and analyses.

In theory, a multizone decay approach could be used to infer the airflow. It has been shown to work in well-controlled laboratory settings, but it does not work in most field situations such as shown by Persily (2011). Dynamic range of instruments, systematic biases such as imperfect mixing and non-steady flow make such an approach more complex and potentially error prone.

The biggest exception to this statement is if one's interest is estimating the age of air in each zone for e.g. room - clearing purposes. If all of the assumptions associated with multizone age-of-air conditions are met, a simultaneous decay test can produce usable results.

Steady-state approaches are, as in single zone, much more robust. A constant emission approach will work well but requires at least one different injection pattern for each zone. If there is only one tracer gas, that process can take a long time.

Multi-gas systems that inject a unique tracer in each zone have been shown to work acceptably in field. Unfortunately, the skill needed to conduct these experiments and the cost of the instrumentation have limited the use of such approaches to a small number of leading research organizations.

The only multiple tracer approach currently in common usage is the passive technique which uses 2 5 PFTs to estimate flow for a like number of zones. As discussed in the references, one cannot really expect results for the external flows to be much better than a factor of two in typical situations. Such accuracy, however, may be perfectly acceptable for some purposes.

4.2.4. Non-tracer approaches

Although the most important approaches are based on tracer gas measurement, there are other approaches for measuring airflow. These are mentioned in the reviews referenced but are not covered in this chapter. They include the following:

- Pitot tube velocity traverse measurements
- Anemometer velocity traverse measurements
- Envelope Airtightness measurements
- Duct Air Tightness measurements

4.3. Current AIVC activity

As mentioned above, one of the current AIVC projects is looking at the performance of vented cooker hoods. Cooking may be the biggest indoor source of contaminants across the population and methods for controlling those emissions are important for indoor air quality and health.

Being able to measure the performance of cooker hoods (and developing a standard test method to do so) is a critical path element. Like air change in a room, these measurements can only reasonably be done using tracer techniques, which are similar to those used to measure air change.

The test is done by injecting a tracer at a warmed cooker surface to mimic emissions from cooking. To calculate the capture efficiency *(CE),* one needs only to measure the tracer concentration in the exhaust port (C_e), in the room (C_r) and in the ambient space (C_a) where the make-up air comes from (e.g. outside):

$$CE = \frac{C_e - C_r}{C_e - C_a} \qquad 4.8$$

If the mixing in the space and duct were perfect, this expression would be good at all times, but as a practical matter it is best to wait for steady-state to occur to minimize timing issues and the impact of imperfect mixing—as is typical of tracer-gas approaches in general.

A potentially valuable tracer-gas approachto estimate whole-dwelling air change is on the horizon and is being looked at by various researchers. It involves using constituents of outdoor air (e.g., CO_2, particles, ozone, etc.) as a tracer. This approach only works, however, if the outdoor air concentration varies on a short enough time scale, typically a few hours or less.

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5. Infiltration modeling

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5.1. Introduction

The ability to model infiltration using physics-based engineering calculations grew from the desire to know more about the energy associated with heating (and sometimes cooling) loads. This was driven by the first “energy crisis” starting in about 1973 when oil producing countries began to control the market for oil and its derivatives. This led to fuel shortages and price increases, and an increasing awareness of how much energy was wasted in buildings to heat the air coming in through building leaks.

Researchers in Europe, Canada and the US began investigating these air flows. They characterized the leakiness of building envelopes using various techniques, that led to the development of test equipment that combined air flow meters with fans to pressurize or depressurize a building. They also started to measure air exchange – primarily using various tracer gas techniques. These latter experiments soon showed that the air exchange increased with building envelope leakage and with harsher weather – either higher winds or bigger indoor-outdoor temperature differences. Thus began an effort to estimate the infiltration using the measured envelope leakage and weather conditions.

Due to the extremely fast evolution of hardware and software capacities, many of these older AIVC reports are probably outdated concerning the description of specific modelling tools that have since disappeared, but they are still useful to understand the possible approaches for modelling ventilation, air movements, pollutants transport, etc.

5.2. Historical role

At the first AIC conference a couple of papers were presented that summarized many of the key issues and presented simplified models that allowed infiltration rates to be calculated from envelope air leakage measurements and weather. They also introduced concepts that recognized that it was not practical to have knowledge of all leakage sites on a building, so simplifying assumptions would be necessary. At this first conference it was already realized that both wind and temperature differences (stack effects) drove natural infiltration and the models separately calculated infiltration flows due to wind and stack effects, then combined them empirically using measured field data. A paper by Warren and Webb (1980) investigated the impact of envelope air leakage on ventilation rates measured using tracer gases. Warren and Webb made the following modeling assumptions for their simplified model:

1. There is a need to relate the flow through the building envelope to the pressure difference between inside and outside the building. They used a power law and identified a lack of measured data at the low envelope pressures experienced during natural infiltration. Later studies (e.g., Walker et al. (1998)) confirmed that it was OK to extrapolate from high measured pressures to pressures of interest and this was discussed in the AIVC’s Air Infiltration Review – with two opposing voices: one for the power law (Liddament (1987)) and one for a combined laminar/turbulent flow model of building leaks (Etheridge (1987)).
2. Envelope pressures depend on leak locations on the envelope because envelope pressures are not uniform. Warren and Webb presented examples of leak distribution assumptions.
3. A single pressure exponent is assumed for all leaks.
4. Surface pressures averaged over all the walls were assumed for ventilated underfloor spaces.

A paper by Sherman and Grimsrud (1980) followed a similar path to Warren and Webb. They assumed a pressure exponent of one half and the concept of leakage area to describe the envelope leakage. They also introduced the idea of splitting envelope leakage into floor, wall and ceiling leaks to be given different heights for stack effect and pressure coefficients for wind effect, where the building geometry determined the height of the leak for calculating stack effect and wind pressure coefficients. This approach allowed an analytical approach to the model such that algebraic equations could be used to estimate the wind and stack flows. Wind and stack were combined in quadrature – in effect adding the wind and stack pressures. As with Warren and Webb the predictions were compared to tracer gas measurements of infiltration and showed good agreement for 15 tested buildings.

At the third AIVC conference, Handa and Gusten (1982) presented an infiltration model that set up an air flow for each leak and solved a mass balance based on determining the internal pressure shift required to have equal in and out mass flows. This approach eliminated the need to calculate separate wind and stack flows and combine them using an empirical model (such as quadrature used by Sherman and Grimsrud). It also allowed for mechanical airflows to be directly included in the mass balance, eliminating the need for empirical superposition of natural infiltration with mechanical air flows. The Handa and Gusten approach has served as the basis for subsequent detailed infiltration models.

At the 5th AIC conference Yoshino et al (1984) compared air infiltration model predictions to measurements in three test houses.

At the 8th AIC conference, Scartezzini et al. (1987) outlined a methodology for validating infiltration and ventilation models.

At the 10th AIVC conference, Feustel (1989) summarized the state of the art in infiltration modeling. This included summaries of modeling approaches (empirical models, physical models, single and multi-zone models). It also included an introduction to the COMIS multi-zone ventilation model project that included both infiltration and mechanical ventilation and followed on from existing multi-zone approaches AIRNET (Walton (1983)) and MOVECOMP (Herrlin (1985)). Nielsen (1989) summarized progress in air flow simulation techniques.

Some work has also gone into estimating ventilation rates in parts of the building that are not deliberately conditioned, but contribute to building loads and whose moisture performance depends on the air flow through the spaces. For example, at the 16th AIVC conference Walker et al. (1995) presented a simplified model using the same approach as AIM-2 (see above) for attic spaces.

5.3. Infiltration modeling

AIVC Tech Note No. 11 (Liddament and Allen (1983) [8]) was the first comprehensive attempt to compare several single and multi-zone model predictions of infiltration to measured data. Tech note No.11 found that all the models gave reasonable predictions (+/- 25%) compared to measured data and that the biggest source of uncertainty was estimating wind pressure changes due to shielding and different building shapes. Given the limited capacity of computers at this time, the tech note discussed modeling limitations (such as the number of allowed nodes and connection in multi-zone models) and computer memory requirements (and in some cases specific computers – this is the era before the generic “Personal Computer”.

The nature of the relationship between flow through building cracks and the pressure difference across the crack and the crack geometry has been thoroughly debated in AIVC publications (e.g., Liddament (1997) and Etheridge (1997) published on both sides of the discussion in Air Infiltration Review). There are essentially two alternative viewpoints (Walker et al. (1997) give a more detailed summary in the Proceedings of the 17th AIVC Conference). The first assumes that we can combine fully developed laminar flow with entry and exit losses to describe the pressure-flow relationship. The other uses a semi-empirical approach based on measured characteristics and developing flow experiments called the power law. These two governing equations are:

Laminar + entry/exit (usually called a quadratic approach): $\Delta P = AQ + BQ^2$

Power law: $Q = C\Delta P^n$

Over time the power law has been used more and is the basis of most infiltration modeling.

The multi-zone models shared many common characteristics: they almost always used a power law pressure-flow function for each leak, natural infiltration due to stack effects (based on the height of each leak) and wind effects (based on a pressure coefficient for each leak from wind tunnel data) together with fixed mechanical air flows. An air flow network was developed coupling the building envelope leaks and internal air flow paths.

The multi-zone models were:

- Building Services Research and Information Association (LEAKS). This model used measured envelope leakage values or published individual leak values.
- Canadian National Research Council. Like LEAKS. This model was purposely developed for high rise buildings with vertical shafts and open floor plans on each floor. It forms the core of the US National Bureau of standards model for calculating building loads.
- IMG-TNO Instituut voor Milieuhygiene en Gezondheidstechniek NL (ELA4). This model included open windows and the effects of wind pressure fluctuations.

- Oscar Faber Partnership (SWIB). This model included the effects of backpressure on mechanical ventilation components rather than fixing the flows and a method for calculating vertical wind profiles.
- British Gas Model (VENT). This differed from other models by using a semi-empirical pressure-flow relationship. It also included turbulence effects and simplifying assumptions about the density and viscosity of air flows – particularly when estimating stack effects.

Like the multi-zone models, the single zone models shared many common characteristics: they almost always used a power law pressure-flow function for each leak, natural infiltration due to stack effects (based on the height of each leak) and wind effects (based on a pressure coefficient for each leak from wind tunnel data) together with fixed mechanical air flows. The single zone models were:

- Norwegian Building Research Institute (ENCORE). This used a multi-leak approach similar to multi-zone models and solved the resulting set of equations to balance the mass flows in and out of the building. It included default wind pressure coefficient data for eight building shapes.
- Gas Research Institute/Institute of Gas Technology (IGT). This model assumed a pressure exponent[1] of 0.5, split leaks between windward and leeward sides of the building and introduced simple relationships for wind pressures using the angle of incidence to the wind to adjust wind surface pressures, and allowed there to be a heated flue as a separate leak. It does not use measured building leakage.
- Lawrence Berkeley Laboratory (LBL). This model assumed a pressure exponent of 0.5, used algebraic equation to directly calculate stack and wind effects separately, then combine them in quadrature. The stack and wind flows depended on factors describing leak locations split between wall, floor and ceiling leaks, rather than assess individual flow paths.
- Building Research Establishment. Like the LBL model this model calculated the stack and wind effects separately and used pre-calculated functions to determine the magnitude of the stack and wind flows.
- Reed, McBride, Sepsy model. This model assumed a pressure exponent of 0.5 and calculated wind and stack effects separately, combining them in quadrature. Fixed constants rather than leak distributions were used to calculate the stack and wind effects, together with a fixed multiplier of the total air flow empirically determined based on comparisons to measured data.

The research effort behind Tech Note No. 11 included the development of standardized formats for reporting ventilation/infiltration measurements (AIC Tech Note No. 6 (Allen (1981)). Over 300 measurements of infiltration in 14 buildings were used in the model evaluation. The large majority of the model predictions were within the +/-25% acceptability criterion set out by the tech note.

The tech note had several other major conclusions:

- Wind effects (direction and shelter) needed to be well known.
- Measured building leakage was considerably larger than predicted leakage from specified component leakage.
- Model validation data sets need to include as many of the input data required by models as possible. E.g., temperatures, wind speed, shelter and direction, building height, envelope leakage, etc.
- It was not possible to see the benefit of including wind pressure fluctuations.
- The LBL model gave the best overall performance for a single zone model. This was attributed to the model's ability to select different wind shelter factors.

Tech Note No. 13 (Allen (1984) [9] followed on from Tech Note No. 11[8] to improve the estimation of wind pressures on buildings for infiltration purposes. The Tech Note summarized the published information on wind surface pressures on buildings, referring to over 250 references. A comprehensive review of the relevant factors was presented that included: wind surface pressure distributions across building exterior surfaces (including variation with wind direction), building geometry, windspeed and turbulence variations with height (boundary layer structure), the effect of cladding, wind pressure fluctuations, pressures on chimneys and flues, and shelter from other buildings. The Tech Note went on to describe some approaches to determine empirical relationships between wind pressures, building geometry and wind direction. The tech note pointed to further work being required on the impacts of turbulence – particularly at low windspeeds – and the shelter of neighboring buildings.

The AIC held a workshop on Wind Pressures held in Brussels in 1984 and published the proceedings as Tech Note No.13.1[10]. The summary remarks focused on simplifying the wind surface pressure complexities into formats

[1] Note that this is often called a flow exponent in the literature.

suitable for infiltration modeling beyond the research community and on developing simplified models for predicting wind pressures that could be applied to a wide range of building geometries and wind conditions.

The next AIC tech note related to infiltration was Tech Note No. 16 (Allen (1985) [11] on Leakage distribution in buildings. Like with wind-pressures, this was intended to address the key results of Tech Note No. 11 – in this case better ways of estimating the magnitude of and distribution of leaks on the building envelope. The tech note summarized the results of 65 publications (mostly in the AIVC air leakage database). Data were presented showing changes in air leakage with time – with significant increases - particularly in the first year of construction. This tech note discussed methods of deliberately controlling the location of leakage – one example being the use of trickle vents in Swedish homes that could be changed seasonally to reduce winter infiltration. There was also a summary of diagnostic techniques for finding building envelope leaks with the intent of targeted air sealing.

Tech note No. 16 [11] went on to discuss:

- techniques for measuring envelope air leakage for input to models with a focus on low pressure measurements and presented alternatives – such as alternating pressures (that are having a resurgence of interest in recent years).
- the use of a single value in models to represent building leakage – asking the question: can leaks simply be added together (e.g., the 4 Pa (US) or 10 Pa (Canada) leakage areas) to get the total?
- the modeling simplification of evenly distributed leakage that appeared to give the best results when models using this approach were compared to measured infiltration for whole building infiltration rates, however, for infiltration for individual rooms more specific leak locations are required.
- Leakage distribution can be highly variable – even between otherwise identical houses.

In 1986 the AIVC published a guideline on air infiltration calculations (Liddament (1986) [5]. The guideline stated its purpose as follows:

"The intention of this publication is to provide both researchers and designers with detailed background to air infiltration modelling and to give step-by-step guidance on the application of modelling techniques in design. Particular emphasis is devoted to providing specific guidelines on the calculation of steady state air infiltration and on air change rates in industrial, commercial and domestic buildings"

The guide covered both infiltration and mechanical systems. For commercial buildings the focus was on reducing air flows through the envelope to maximize the performance of mechanical systems – particularly heat recovery systems. For dwellings the focus was on optimizing airtightness and ventilation strategies to provide cost-effective performance. The infiltration modeling section recognized the need to go beyond calculating infiltration for a single specific weather condition and to look at how air change rates carried with weather, the need to evaluate wind shelter, accounting for leak distribution on the envelope and thoughts on purpose-provided air inlets and outlets. The guide provided a process by which a user could select the appropriate infiltration calculation technique depending on the application.

The guide discussed simple empirical models: dividing the measured envelope air leakage at 50 Pa by 20 (a rough rule of thumb) and regression models that fitted known air flows to measured temperatures and windspeeds. It showed the theoretical extremes for laminar and fully developed turbulent flow calculations and stated that usually the building leaks are a combination that results in a power law pressure flow relationship.

For wind effects, the guide presented methods of converting a wind speed measured at a meteorological site to a building reference height. It went on to explain that for buildings of 3 story or less wind pressures on faces of the building could be average value over the building face and given for wind directions every 30 or 45 degrees and noted that for taller buildings this simplification would not hold. The guide stated that it was much more useful from a modeling perspective to use reference wind speed at a fixed height for wind pressures rather than the local wind speed at a specific building height/location. Theoretical equations were presented for turbulence effects for single openings and openings in opposite faces of an idealized otherwise sealed building and stated that these effects were uncertain and had not been verified in real buildings.

For stack effects the guide similarly presented the theoretical equations governing the temperature difference induced hydrostatic pressures. This was repeated for both single and multiple indoor temperatures and for the effects of air flow resistance between floors of high-rise buildings. The equations were presented in a form that assumes there are only two openings: one high and one low.

The guide stated that stack and wind flows could not be added directly. The quadrature model was presented – that is loosely based on adding pressures. Also, equations for mechanical fixed flow and variable flows (i.e., influenced by wind and stack pressures) were presented. In subsequent years, other approaches for combining natural and mechanical air flows have been a topic at AIVC conferences. For example, at the 12th AIVC conference Palmiter and Bond (1991) presented and algebraic approach for stack dominated homes. Recently, more detailed approaches to combining natural infiltration and mechanical ventilation have been presented at AIVC conferences, e.g., the method currently used in the US national ventilation standard, ASHRAE Standard 62.2 (2016) was presented at the 2015 AIVC Conference (Hurel et al. (2015)) that used a massive number of simulations of residential buildings to find optimum simplified combination methods.

Single zone multi-leak calculation methods were given that used a mass balance to determine an internal pressure that is common to all leaks in the building. This was expanded to include multi-zone models and their associated calculations to find the internal pressure for each zone. Details of the BRE and LBL simplified models were given as examples of ways to minimize calculation effort and the input data requirements for modeling. The guide also included example calculations for several models to provide more information and insight for potential users.

To complete the guide as a single document that included all necessary information, a chapter was dedicated to providing example climate, wind pressure and air leakage data, as well as a glossary of terms.

Publication of this guide by the AIVC marked a point at which infiltration calculations could become standardized and much more widespread and provided the guidance necessary for the building industry.

Tech Note No. 27 (Bassett (1990) [18] investigated the accuracy of multi-zone infiltration modeling comparing the US National Bureau of Standards model (Walton (1981)) to a dataset of 300 tracer gas measurements in five New Zealand homes. While results were deemed acceptable, the tech note reported that the main sources of uncertainty were wind direction effects and leak location on the building envelope.

Tech Note No. 29 (Feustel and Raynor-Hoosen (1990)) [21] described the model developed by the COMIS (Conjunction of Multizone Infiltration Specialists) workshop. COMIS was the result of analyzing all the existing multi-zone approaches and creating the best possible model. It included relatively sophisticated approaches for creating wind pressure coefficients (wind pressures being recognized as one of the most difficult aspects of infiltration modeling). The tech note included a detailed theoretical description of wind and stack effects, hydrodynamics of building leaks, duct system air flow modeling, and the introduction of an inter-zonal pollutant transport model. Several numerical approaches were investigated for solving the multi-zone flow network, with the “skyline-Cholesky” method chosen as the optimum method.

Tech Note No. 40 (Kendrick (1993) [29] was focused on heat transfer modeling and building loads but included commentary on envelope leakage and wind pressures when calculating air flow rates. It referred to the AIVC Technical Guide to air exchange and air tightness measurements (Charlesworth (1988)) [3] for further information on envelope leakage and the AIVC numerical database (that was published by the AIVC as Orme et al (1998)) as a source of wind pressure coefficient data.

The AIVC then published a couple of data resources for infiltration modelers. The first was Tech Note No. 41 – Infiltration Data from the Alberta Home Heating Research Facility (Wilson and Walker (1993)) [30], followed by Tech Note No. 44 Numerical Data for Air Infiltration and Natural Ventilation Calculations (Orme et al. (1998)) [36]. The intent of Tech Note No. 41 was to provide information for infiltration modelers as a resource for further model development. It provided over 6000 hours of hourly averaged tracer gas measurements with matching onsite weather conditions. It also provided a wealth of detail on the home together with a detailed description of the test house surroundings. Tech Note No. 41 also included some data summaries for weather and measured infiltration rates. Tech Note No. 44 summarized the content of the AIVC’s Numerical Database that was developed in response to the need for a core of data suitable for design purposes and model validation. This was presented in three sections: Component Leakage Data, Whole Building Leakage Data and Wind Pressure Evaluation. Some key data summaries included geographical and temporal trends in envelope leakage (houses are tighter in harsher climates and in newer construction), distributions of air leakage and pressure exponent, and surface wind pressure coefficients as a function of wind directions and shelter. Additional information on wind shelter pressure coefficients was published in Air Infiltration Review (Walker (1992)) and by Wilson and Walker (1991) at the 12th AIVC Conference.

The most recent AIVC publication on infiltration modeling is Tech Note No. 51: Applicable Models for Air Infiltration and Ventilation Calculations Orme ((1999)) [38]. After about 10 years of modeling development since the first AIC/AIVC Tech Note on infiltration modeling, Tech Note No. 51 summarized the new state of the art. The following models were included in the tech note:

– Simplified[2] single zone:

[2] Simplified models do not require a computer to calculate infiltration. They use closed-form analytical solutions.

    - AIM-2. This is an adaptation of the LBL model that uses the measured flow coefficient and pressure exponent and includes a separate furnace flue with its own separate wind shelter. The technical details on having a separate flue were discussed in an article in Air Infiltration review (Walker and Wilson (1990)). The combination of stack and wind flows used a power law rather than orifice approach together with an empirical wind-stack interaction factor. Like the LBNL model it can be hand-computed.
    - CEN-Explicit. This is a simplified version of the CEN-Implicit model with some simplifying assumptions.
    - LBL. This is one of the oldest models and used analytical procedures to develop functions to calculate infiltration flows based on assumptions about building geometry and wind pressures, and was discussed in previous Tech Notes.
    - VENT. Combines distributed leaks with large openings.
- Simplified thermal + ventilation:
    - NatVent. Developed for naturally ventilated buildings.
    - NiteCool. Developed to assess night time ventilation cooling of offices.
    - SUMMER-Build. Includes a simplified design tool for night ventilation cooling.
- Single zone ventilation:
    - AIDA. This was developed by the AIVC and requires user input of leak location and wind pressure coefficient for each individual leak.
    - CEN-Implicit. Performs calculations based on input of individual leaks using an iterative computer technique.
- Multi-Zone Ventilation:
    - AIOLOS. This multizone model allows time series analysis and sensitivity analyses for some input data.
    - BREEZE. Uses a graphical sketchpad input screen to enter individual leak characteristics.
    - COMIS. Has a graphical user interface and includes a detailed duct model.
    - CONTAM96. Has a graphical user interface to enter individual leak information and has been specifically developed to track contaminant transport.
- Thermal + ventilation
    - Passport Plus. Principally a thermal model it also includes air flows.
    - SUMMER-Tech. More complex than SUMMER-Build it includes natural ventilation.

By this time infiltration modeling had become widespread, with certain models achieving widespread adoption – either as design tools or into building codes and standards. The models were categorized as being single or multi-zone, multi-leak or simplified, together with two models that combined thermal and infiltration calculations. The model descriptions/applications were further broken down by: including air handling systems, input format for airtightness, including large openings with two-way flow, wind pressure modeling, pollutant tracking, occupancy schedules, inclusion of weather data, type of user interface and output format, and weather it was in the public domain or was a commercial piece of software. Example calculations were performed to help guide a user through the process for three multizone models: COMIS, BREEZE and CONTAM93 that showed good model agreement.

In 2002 the AIVC published Guideline 5: Ventilation Modeling Data Guide (Orme and Leksmono (2002)) [6]. With ventilation and infiltration modeling maturing it was realized that the core physics of the models was fine, and refinements to improve accuracy and useability should focus on the data input to the models. To reflect this, Guideline 5 built on the contents of Tech Note 51 [38] (Guideline 5 still contained a summary of the same ventilation models as Tech Note 51) to include more information for users on model input data and the appendixes of Guideline 5 contain a wealth of information on data input for ventilation and infiltration modeling. Three characteristic air flow equations were discussed: the power law (used in almost all models), orifice and two-way flow for large openings and the quadratic formulation (used in the VENT model). The guideline discussed sources of data for component and whole building leaks that could be used by modelers. For wind pressures the guideline built on the default values for simple building shapes in Tech Note 51 and added information on new studies that had developed calculation techniques to account for building geometry and local shielding. Furthermore, wind pressures were modelled as continuous functions of wind direction, as had been presented at AIVC conferences (Knoll et al. (1995) and Walker and Wilson (1994)) and other venues (Grosso et al. (1994). This significantly improved wind effects modeling.

Guideline 5 provided direction to publicly available weather data. Recognizing that many modelers wished to model an entire year of infiltration and ventilation rather than specific/design conditions, the guideline discussed the availability of hourly weather data. Examples were provided of the urban heat island effect so that modelers could account for temperature differences between meteorological stations and the local sites being studied if local data were not available. Wind corrections were presented that considered the different boundary layer wind profiles between measurement stations (often on flat unobstructed ground at airports) and the local site (often in an urban area).

Example occupancy profiles were given based on work from IEA Annexes 20 and 27 (and others), with attention particularly paid to window opening behavior as this has a large impact on infiltration, e.g., data were given for percentage of window opening as a function of outdoor temperature from AIVC Tech Note 23 (Dubrul (1988)) [15]. More model evaluation data was available, and the Guideline referred to ten different data sets that covered a wide range of building types. Other input data were discussed in less detail such as: properties of moist air, duct fitting losses for duct system modeling, and pollutant sources.

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6. Ventilation and health

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6.1. Introduction

Ventilation has developed faster and faster in recent years, after a centuries-long relatively slow start. In the Middle Ages, homes were heated with open fires in fireplaces, and smoke often spilled into the room. In 1631 King Charles 1 decreed that ceilings must have a certain minimum height and that windows had to be higher than they were wide, for smoke removal. In the 17th Century Mayow placed mice in a glass dome with a burning candle that was extinguished. He concluded that igneo-arial particles had killed the mouse. Laverois concluded in 1771 that the igneo-arial particles was CO_2. Pettenkofer (1862) concluded that it was not a lack of oxygen or too much CO_2, but that poor indoor air was due to human effluents and that CO_2 was an indicator.

6.2. Historic role of AIVC

At the start of the IEA Annex V, the focus was on airtightness and the effects of airtightness on ventilation. However, more and more emphasis was placed on ventilation. This changed the name in 1983 to the Air Infiltration and Ventilation Centre, AIVC. In ventilation, the emphasis was placed on odor nuisance and CO_2 as a marker for indoor air quality. When it came to the health effects of indoor air, in the period from 1983 to 2000 it limited itself to naming the harmful contaminants. In the period between 2000 and 2010, the emphasis was on protection against the harmful effects of these pollutants. From 2011 until 2020 ventilation and health became important, and the pollutants are prioritized according to health effect. There is a growing belief that it is possible to make an assessment method based on exposure of contaminants. Ventilation is more and more seen as the dilutions of contaminants, but a reduction in exposure of contaminants requires source control measures.

6.3. Pollutants in indoor air

Exposure in homes is the most important contributor to exposure of airborne pollution during a lifetime. This can contribute to 60 to 95 percent of exposure during a lifetime, with approximately 30% exposure during sleep. Exposure to homes has various sources, these can be indoors but also outside. Contamination from outside enters the home through infiltration and through windows and ventilation systems. Indoor exposure can also come from sources inside, they can be tied to human activities, but also furniture and products and internal combustion.

In Technote 55 “Review of ventilation criteria” from 2001 [42] an overview is given from required ventilation flow per country as well as the criteria for contaminants expressed in terms of long and short term exposure and in terms of Maximum Allowable concentration (MAC) and Acceptable indoor Concentration (AIC) per country. Criteria that are included are for example CO_2, Ozon, formaldehyde but Particulate Matter is missing. In TN 58 “Reducing indoor exposures to outdoor pollutants” from 2003 [45] an overview is given of relevant outdoor pollutants including particulate matter. Per contaminant the indoor versus outdoor ration is given based on literature. Different strategies are given to reduce the indoor exposure due to outdoor pollutants. VIP 02 “Indoor Pollutants” from 2003 [57] provides an elementary overview of the health effects and concentration of interest of indoor pollutants including CO and Particulate matter. CO_2 is mentioned as a “surrogate” for human odors (odorous bio-effluents), but not as a pollutant.

In TN 62 “Energy and environmental quality of low income households” (2007) [49] describes the problem that half the population of the world uses unprocessed solid fuels that have high emission factors for a range of health damaging air pollutants for cooking and associated space heating. These solid fuels produce 10-100 times more particulate matter per meal. Most of the houses have no adequate ventilation. 30-40% respiratory diseases worldwide are caused by particulate air pollutions alone. Thermal stress due to low temperatures during the winter causes many excess winter deaths, as well of heat waves causing excess deaths. 13 % of all European households contain damp patches, the most in southern Europe, with almost 33,4 % of households in Portugal, associated to respiratory and cardiovascular diseases.

In 2011, Logue (Logue et al. 2011) made an overview of contaminants that are ubiquitous, and those with the highest average and peak values. Two indicators were used to describe the chronic and acute exposure. Ventilation is seen as a good strategy to improve ventilation. But to go to effective solutions to improve indoor air quality it is important to know which contaminants are most important. In the same year, Logue set priorities based on the impact of chronic residential exposure. This study used the DALY metric. It turned out that particulate matter was the most important health risk. The results of this have been presented at the AIVC Conference in Brussels 2011 and Copenhagen 2012, and are also described in Technology 68 "Residential Ventilation and Health" (2016) [55]. This technote describes the potential health risks for acute and chronic exposure. The different sources of pollutants are appointed, as cooking as an important indoor source for particulate matter. At AIVC conferences much attention is given in papers towards cooking as a source for particulate matter and range hoods as a solution for source control. In the study" A Method to Measure Emission Rates of PM2.5s from Cooking" (O'Leary et al. 2017) presented at the AIVC Conference in Nottingham, a study was presented to estimate typical source strength of particulate matter due to cooking.

6.4. Control strategies

The primary purposes of ventilation in buildings are to provide a sufficient oxygen supply for the occupants and to remove any hazardous substances or noxious odours in the indoor air. For thousands of years societies have realized the need for ventilation for specific indoor tasks. The first efforts to provide intentional ventilation of residences is unknown, but was likely used to remove combustion gases from indoor heating and cooking such as introducing vents for fires. Ventilation is provided to bring outdoor air indoors and to move indoor air, and its associated pollutant load, outdoors reducing indoor concentrations and occupant exposures.

TechNote 23 from 1988 [15] investigated the relationship between user behavior and ventilation behavior. The main focus was on window use. A distinction was made between type of room and the effect of cooking on window use was recognized. Behavioral influence was mainly viewed from the perspective of energy saving and not from health. IEA Annex IX from 1989 gives an overview of contaminants including the damage to the health of the occupants and cause of annoyance. It also gives per contaminant a ventilation strategy and a difference is made between (1) dilution, (2) source removal, alteration or substitution, (3) direct extract ventilation or air cleaning. In case of particles only smoking and internal combustion are identified. In Technote 28.2 "A guide to contaminant removal effectiveness" from 1991[47] the effect of different ventilation strategies on contaminant removal is identified including the use of multizone models to analyze this over time.

Technote 46 "1994 Survey of Current Research into Air Infiltration and Related Air Quality Problems in Buildings" [33] shows an increase in projects' focus on indoor quality and the energy impact of ventilation. However, there are less studies reported on tracer gas and air flow modelling studies. AIVC publication "A guide to energy efficient ventilation" form 1996 [5] is a very complete description of the different aspects of ventilation from rationale and background to ventilation, towards indoor air quality and comfort, ventilation strategies, air cleaning and ventilation efficiency. Different contaminants are described including pollutants from outside.

VIP 04 "Night ventilation Strategies" from 2004 [59] describes strategies to reduce the cooling load by night ventilation. It also describes the effects of night-ventilation; in humid areas moisture and condensation control is necessary (for example to prevent mold grow) but also pollution, acoustic and privacy play a role. It is estimated that in 70-80% of cities above 500.000 inhabitants the level of one of the pollutants is above WHO standards at least once a year. Only with the use of flow controlled natural ventilation components or mechanical ventilation systems air cleaning or filtration is possible. Noise can also be a serious limitation when natural ventilation is used.

In VIP 07: "Indoor Air Pollutants Part 2: Description of sources and control/mitigation" from 2004 [62] an overview of different pollutants is given including sources and examples of control and mitigation. There is no prioritizing in pollutants yet and no emphases on cooking as a source of particulate matter. There is a paragraph about ventilation but source control and compartmentation and filtering as strategies to reduce exposure are not included.

In TN60 "Efficacy of Intermitted Ventilation for providing Acceptable Indoor Air Quality" from 2006 [47] describes a model that allows to calculate how much intermittent ventilation is needed to get the same indoor air quality as a continuous value specified. An assumption in this method is that dose (i.e. average concentration) is the defining risk criterion. It ignores the impact of peak and/or threshold and assumes constant pollutant production.

In CR 08 "Occupant behavior and attitudes with respect to ventilation of dwellings" from 2007 [101] the use of provisions is influenced by temperature but also due to outside noise and odour from outside pollutants. In more than 90% of the dwellings occupants vent more to get rid of specific odours (e.g. from cooking). In a Danish study no direct relation was found between the amount of air change and humidity. Older dwellings are associated with an increased of Sick Building symptoms to be caused at least partly by the introduction of new plastic material. In general health problems are not directly related to the type of ventilation system, but perceived health problems of perceived indoor air and climate problems are often especially related to balanced ventilation systems. Insufficient information to the occupants about the ventilation system in their dwelling may promote health problems.

6.5. Ventilation and Health

Technote 68" Residential ventilation and health" (2016) [55] describes the impact of ventilation on indoor air quality and the different types of residential ventilation: whole house ventilation, task ventilation, including other measures to improve indoor air quality as source control, air cleaning and enclosure. Different ventilation control strategies are described depending on the source and the type of contaminant.

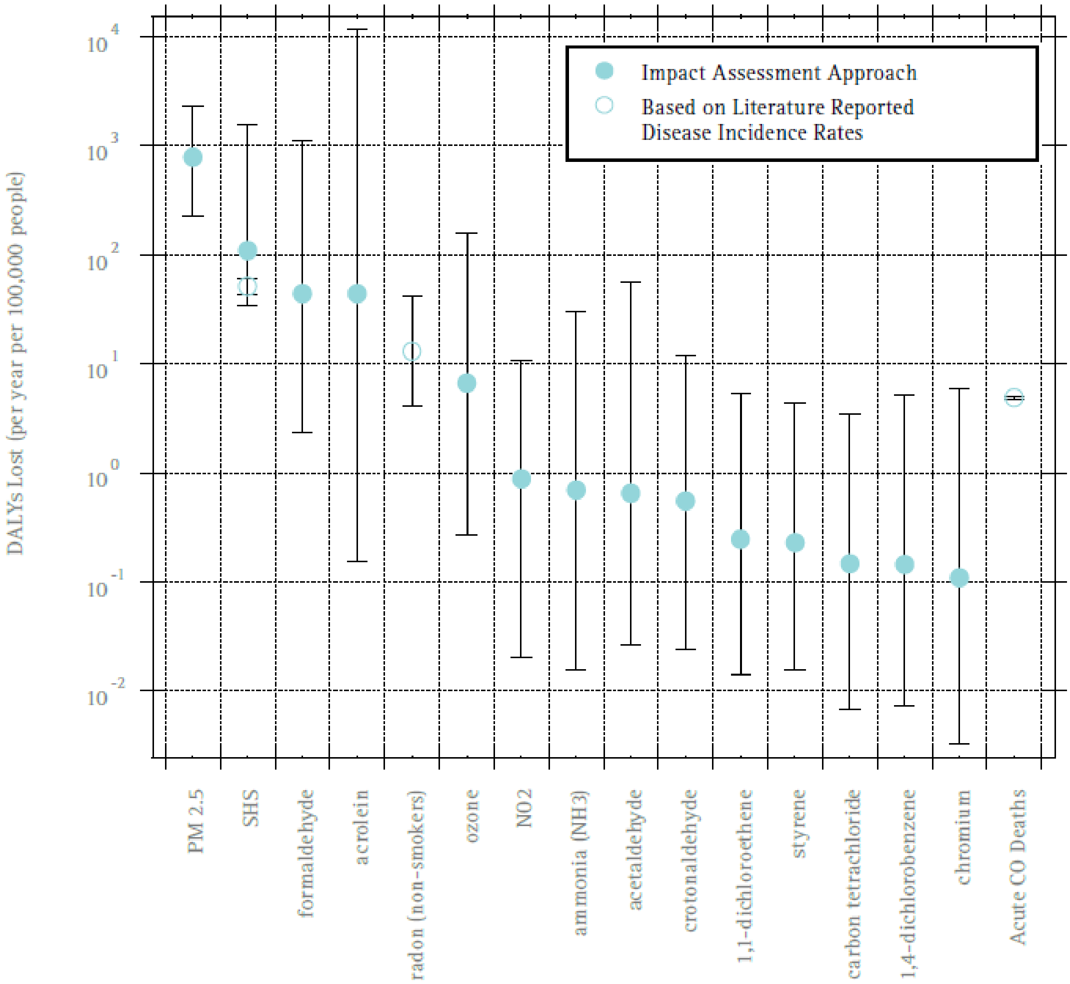

Figure 4: Estimated population averaged annual cost, in DALYs, of chronic air contaminant inhalation in U.S. residences (Logue et al., 2011; Borsboom et al., 2016).

Health adjusted life years (HALY) are measures of health over time and give weighted years a person or cohort lives with a disease or disability. Disability is weighted by its effect on a person's life in general, and so can account for mental illness. There are two key HALY metrics. The first is the disability adjusted life year (DALY), which is a measure the disease burden in a population, expressed as the sum of the number of years lost due to morbidity and mortality, where a value of 0 represents no loss. In the case of IAQ, the disease burden is a measurement of the difference between the current health status of a population of building occupants and an ideal situation where they all live into old age, free of disease and disability (WHO, 2009). The second is the quality-adjusted life year (QALY), which reflects the quality of life of a person or cohort but is the approximate inverse of a DALY because it considers the health gained from an intervention where a value of 1 represents a year lived in perfect health and 0 is death.

Both the QALY and DALY can be used to assess the financial values of exposures to poor IAQ and interventions designed to minimize it.

Measured and modelled pollutant concentrations can be used to estimate chronic health impacts in HALYs lost or gained. Here, temporal measurements made in-situ and source emission rates are required. AIVC TN 68 (Borsboom et al., 2016) [55] uses DALYs to rank and prioritize household pollutants for mitigation, see figure 4. It predicts that PM2.5 are more hazardous than any other pollutant by an order of magnitude. It should be noted that current approaches assume that the toxicity of individual pollutants remains unchanged when they are combined with other pollutants. Furthermore, the toxicity of indoor sources of some pollutants, such as PM2.5, is assumed to be the same as those from outdoor sources, which is unlikely to be true.

Table 1: Rooms and the state of the art ventilation measures in residential buildings (Borsboom, 2016).

ROOMS	POLLUTANT	VENTILATION MEASURES (STATE OF THE ART)	DEMAND CONTROL DETECTION OPTIONS
Toilet	Odour of feces, urine, moisture	Exhaust ventilation, a minimal level is needed to have dominant airflow underneath the door of the toilet.	Presence (light switch), CO_2, humidity, SMO (Semiconducting Metal Oxide), timer
Kitchen, stove	Cooking, gas burner	Exhaust ventilation, cooker hood (no specific efficiency), operable windows	CO_2, humidity, SMO, timer
Shower	Moisture (mould)	Exhaust ventilation	Presence (light switch), CO_2, humidity, SMO, timer
Bed rooms, living room	Odour of persons	Extract ventilation, supply of ventilation	CO_2, humidity, SMO, timer

6.6. References

All AIVC references are in the AIVC general reference list (chapter16) which is added as a separate chapter at the end of this Technote

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7. Moistur e

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7.1. Introduction

Traditionally, buildings were primarily constructed to provide adequate protection against wind and rain. Now, buildings aim at providing good thermal comfort, indoor air with low levels of pollutants and resource efficiency, for example with respect to energy use. Moisture in the air is one of the reasons for ventilating a building, as is removing contaminants and odours, and maintaining desired temperature and air movement (Parfitt, 1985) [12]. Liddament (1996) [5] describes that moisture often is a dominant pollutant in dwellings, generated by occupants and their activities, such as cooking and washing. Since there are major health issues related to high moisture levels in buildings, moisture is an important aspect to consider. Fungal spores and dust mites proliferate under high levels of moisture and have been identified as aggravating conditions such as allergy, asthma and other bronchial problems (Concannon, 2002) [44]. Furthermore, water vapour in contact with cold surfaces leads to high surface humidities or condensation, where it can cause considerable damage through mould growth and fabric decay.

A valuable source of information with regards to ventilation and humidity is the guidebook by Liddament (1996) [5], and with regards to health and humidity, Technical note 68 by Borsboom et al. (2016) [55], is recommended.

7.2. Historic role of AIVC

7.2.1. Contributions over the last 40 years

When looking at the AIVC publications and conference papers of the past, moisture was discussed in combination with other pollutants that influence the need for ventilation. In the 1980's moisture problems appeared in relation to the effects of weather stripping actions and inadequate energy saving measures (thermal bridges, air gaps,…), resulting in increased humidity indoors and various types of moisture damage.

These problems have been discussed in a number of AIVC conference publications. Elmroth et al. (1981) considered moisture problems arising in retrofitted houses, and the effectiveness of different types of weatherstrips in energy conservation. Finbow (1982) showed that the principal problem resulting from lack of thermal insulation and inappropriate methods of heating and ventilation was condensation and mould growth. Wouters et al. (1988) illustrated the relation between the occurrence of mould problems and the airtightness of Belgian houses. In general recommendations of these publications were for dedicated ventilation systems, with optimized flow rates, minimizing moisture problems and ventilation heat loss.

Technical Note 26 (1989) [17] summarized the findings of Annex IX about sources, effects and control of indoor pollutants, in order to define ventilation rates which meet the requirements of energy conservation as well as the demands of an adequate indoor environment. One of the seven pollutants discussed in the publication was indoor humidity, in relation to condensation problems and mould growth. Apart from the presence and activities of occupants as the main source of water vapour production, three other sources were mentioned: construction moisture, ground water and seasonal storage of water vapour. The incidence of mould growth was related to the relative humidity in a room, with 70% as a limiting value below which the incidence was found to be small. Ventilation was defined a necessary but not a sufficient condition to maintain relative humidities below this value, the level of heating and thermal insulation being equally important.

Technical note 20 (1987) [13] reports on a workshop in New Zealand addressing the specific problem of moisture accumulation in the building envelope as a result of air leakage. The publication showed that moisture control in light weight building envelopes is predominantly related to air movements, often in small amounts, and not to water vapour diffusion controlled by vapour barriers as was the general understanding in construction practice at the time. Some of the papers in the publication present computation methods to calculate airborne moisture transfer in building components based on hydraulic network analysis, methods that have later been applied in more comprehensive numerical models for heat, air and moisture transfer (Hens, 1996).

The understanding of the consequences of airborn moisture transfer led to recommendations to design ventilation systems to create a slight under-pressure in dwellings in cold climates to prevent indoor water vapour from penetrating and condensing in the building fabric (Liddament, 1996).

7.3. State of the art

7.3.1. Moisture sources

Moisture usually origins from humans and their activities in the building but can also origin from the outdoor environment. Moisture from the ground construction (rising damp) is a possible source, as is rain leakage, built in moisture and water leakages from building services. Indoor activities that produce moisture are for example cooking, bathing and clothes washing. Liddament (2001) provides statistics on moisture production from Annex 27.

Water consumption: Water consumption contributes, through washing, showering, clothes drying etc. to potential moisture related problems such as condensation and mould growth. Water consumption is estimated at approximately between 140-250 litres/day.

Clothes washing and drying: Clothes washing is undertaken several times a week in family dwellings, reducing to less frequently among older people. Air drying was most common at approximately 70% with 30% using drying machines or cupboards.

Bathing and showering: Approximately 70-85% of people take regular showers while the remainder use baths. The typical shower time is 10 minutes and the water vapour production is approximately half a litre of water per shower.

Cooking: Water vapour is produced by cooking and, if gas is used, by combustion. Cooking time varies between about 1-2 hours each day. Mechanically extracted cooker hoods are estimated to capture and remove up to 70% of the moisture generated.

Currently, the moisture itself should not be considered a pollutant, but too high exposure to moisture can initiate processes that can lead to elevated exposure levels (Borsboom et al., 2016). Increased levels of moisture can lead to high levels of relative humidity on surfaces (including surface condensation) and high relative humidity or condensation inside the building envelope. Surface condensation occurs when the dew point on a surface is reached, which usually occurs at thermal bridges or during peaks in indoor air relative humidity. If the surface is hygroscopic, the moisture will be absorbed, if not the water will form drops and runoff can occur. The latter is more common in humid climates and in connection with cooling. Moisture can penetrate into the building components from the inside by either diffusion (slower process) or moisture convection (faster process). Moisture convection occurs when the air pressure inside is higher than the pressure outside and there are air leakage paths. An early description of air leakage paths resulting in exfiltration is found in Elmroth (1983) [1] as shown in Figure 5.

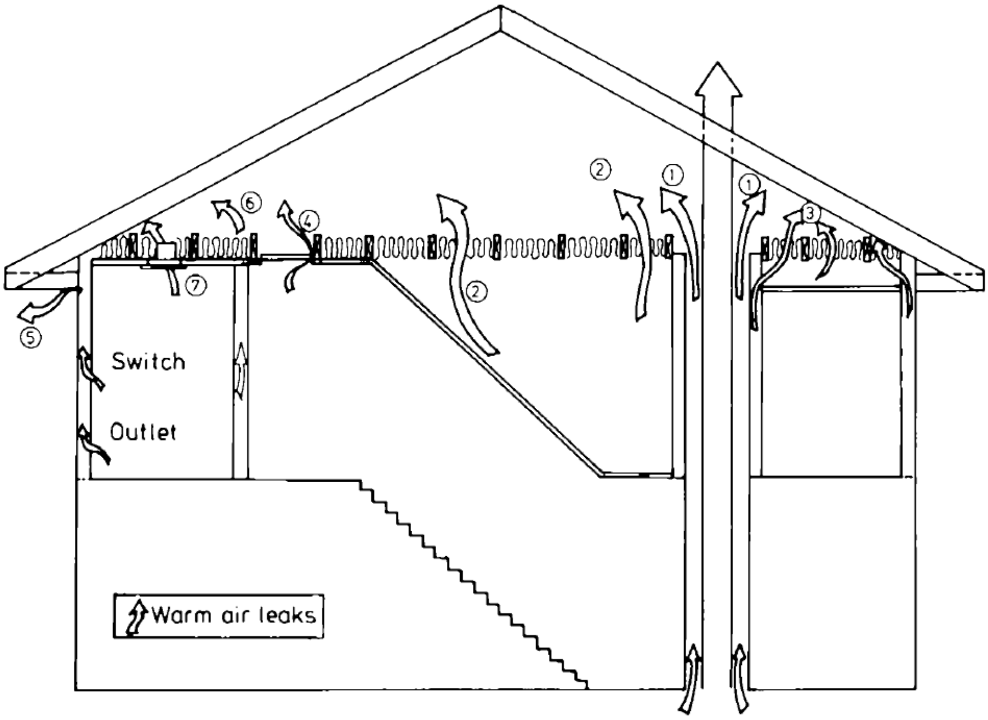

Figure 5: Common air exfiltration paths from the living space at the upper portions of the house: (1) around flue and plumbing stack, (2) through the insulation, (3) above dropped ceilings, (4) around entries, (5) penetrations in outer walls and eaves, (6) leakage up through interior walls and electrical systems and (7) recessed lights.

7.3.2. Moisture consequences on the building

When building materials are subjected to high moisture levels, most materials are affected. In case of wood based materials, there is risk of mould growth, fungal growth, hydrolysis of resin in particle boards and plywood. This, in combination with the air leakages in Figure 5 has resulted in a large amount of moisture damaged attics. Metals corrode and stone materials can get, for example, algae or moss growth (Mumovic, 2009). There can also be an increase in emissions from materials with higher moisture levels, for example increased VOC emission from plasticized glue due to hydration, from PVC flooring with di-2-ethylhexyl phthalate (DEHP) hydrolyzing on moist concrete (Borsboom et al., 2016) and from particle boards (Hens, 2011). Moisture can also result in dimension changes in wood and, consequently, changes in airtightness of buildings .

7.4. Impact on indoor air and health

In addition to the above consequences, high moisture levels are also favorable for some bacteria and viruses, and for mites. It should also be mentioned that low moisture levels also have drawbacks. These include growth of some other bacteria and viruses, of respiratory infections, and ozone production (Alsmo, 2014). Borsboom et al. (2016) describe some biological pollutants measured in homes associated with fungal proliferation and bacteria activity as well as release of allergens and mycotoxins. Examples include *Candida*, *Aspergillus*, *Pennicillum*, ergosterol, endotoxins, 1-3β–$_D$ glucans. Typical indoor concentrations of fungi in homes in US, UK and Australia have been seen to range from 10^2 to 10^3 colony forming units (CFU) per m^3 and as high as 10^3 to 10^5 CFU/m^3 in particularly moisture damaged environments (McLaughlin, 2013).

Germination of moulds depend on the surface type (which need to provide sufficient substrate), availability of nutrients, temperature and moisture. When germination is occurring, mould spores that enter the air can cause allergic reactions in form of bronchial asthma, runny nose or other symptoms. Mould spores and particles containing moulds, even when dead, can still emit toxic chemical compounds so called mycotoxins. Moulds can also emit metabolic volatile organic compounds (mVOCs), which are secondary metabolites producing musty odor typical for houses where moulds are suspected. Biological exposures due to bed dander and dust mites have been associated with allergy outcomes (Borsboom et al., 2016).

The World Health Organization, WHO, has guideline values for several pollutants regarding indoor air quality. Many of them, such as formaldehyde, are affected by moisture levels. However, for dampness and mould their recommendations are qualitative instead of quantitative. Mould growth always signals inadequate building features and a potential health risk to be remediated, and there is no exposure value for mould growth that can be considered safe for health. The same applies to mould spores which are practically omnipresent in residential indoor environments. The following is stated in WHO Housing and health guidelines (2018):

- Persistent dampness and microbial growth on interior surfaces and in building structures should be avoided or minimized, as they may lead to adverse health effects.
- Indicators of dampness and microbial growth include the presence of condensation on surfaces or in structures, visible mould, perceived mouldy odour and a history of water damage, leakage or penetration. Thorough inspection and, if necessary, appropriate measurements can be used to confirm indoor moisture and microbial growth.
- As the relationships between dampness, microbial exposure and health effects cannot be quantified precisely, no quantitative health-based guideline values or thresholds can be recommended for acceptable levels of contamination with micro-organisms. Instead, it is recommended that dampness and mould-related problems are prevented. When they occur, they should be remediated because they increase the risk of hazardous exposure to microbes and chemicals.
- Well-designed, well-constructed, well-maintained building envelopes are critical to the prevention and control of excess moisture and microbial growth, as they prevent thermal bridges and the entry of liquid or vapour-phase water. Management of moisture requires proper control of temperatures and ventilation to avoid excess humidity, condensation on surfaces and excess moisture in materials. Ventilation should be distributed effectively throughout spaces, and stagnant air zones should be avoided.
- Building owners are responsible for providing a healthy workplace or living environment free of excess moisture and mould, by ensuring proper building construction and maintenance. The occupants are responsible for managing the use of water, heating, ventilation and appliances in a manner that does not lead to dampness and mould growth.
- Local recommendations for different climatic regions should be updated to control dampness-mediated microbial growth in buildings and to ensure desirable indoor air quality.
- Dampness and mould may be particularly prevalent in poorly maintained housing for low-income people. Remediation of the conditions that lead to adverse exposure should be given priority to prevent an additional contribution to poor health in populations who are already living with an increased burden of disease.

7.5. Ventilation strategies and impact on moisture

The ventilation of a building is designed to remove pollutants in indoor air. Table 2 presents priority pollutants in the indoor residential environment for consideration in making ventilation standards. Several of these pollutants are affected by moisture levels.

Table 2: Priority pollutants in the indoor residential environment for consideration in making ventilation standards (Borsboom et al., 2016)

Priority Pollutants for Chronic Exposure (ranked by population impact)	**Potential Acute Exposure Concerns**
Particulate matter	Acrolein
Mould/ moisture	Chloroform
Formaldehyde	Carbon Monoxide
Acrolein	Formaldehyde
Mould/moisture	NO_2
	PM2.5

When humans control the ventilation by window opening, the following reasons are described in Dubrul (1998) [15]: get fresh air, remove smells, remove stale air or condensation, air the dwelling during domestic activities. Thus, air humidity is an important aspect in ventilation performance.

The strategies and techniques for ventilation is summarized in Liddament, 1996 [5], in terms of natural and mechanical ventilation systems, methods to achieve displacement air flow and approaches to demand control ventilation. With respect to removing moisture, there are performance differences between strategies, but for all strategies, the ventilation openings should be intended and controlled for best performance. The main disadvantage of natural ventilation with respect to moisture control is that there is inadequate control over the ventilation rate, since the driving forces are stack effect (temperature dependent) and wind. Furthermore, in cold weather or climate, there is an overpressure in the upper part of the building. This can result in exfiltration of moist indoor air into the upper walls and the roof construction, resulting in high relative humidity in the construction and possibly moisture/mould problems.

As opposed to natural ventilation, mechanical ventilation is more easily controlled. Mechanical supply, mechanical exhaust and balanced ventilation mix the pollutants in the room that are being produced, and after mixing and dilution they are extracted in the toilet, bathroom and kitchen.

The mechanical extract ventilation aims at creating an underpressure in the whole building at most weather induced pressures. Consequently, the risk of moisture exfiltration is decreased in comparison with natural ventilation. However, in cases where the ground construction is damaged, for example crawl spaces with mould growth, the mechanical extract ventilation can result in odour or mould spores transport into the building from the ground (Airaksinen et al. 2004). The mechanical supply ventilation is usually not recommended for dwellings since the indoor moisture can be pushed into the building components, resulting in high relative humidity or condensation. (Borsboom et al., 2016). Mechanical balanced ventilation is designed to maintain a low underpressure in the building. However, this is sometimes overruled by climatic conditions and can for example result in an overpressure in the upper parts at large temperature differences inside/outside or insufficient ventilation rates in some rooms at high wind speeds.

Task ventilation refers to ventilation that is associated with a specific activity. The two most common forms of task ventilation are bathroom or WC ventilation and cooker/range hoods. Bathroom fans remove bio-effluents, moisture and pollutants generated in bathroom activities such as showering. Bath fans tend to be run for occupant comfort or moisture control rather than indoor air quality. Controlling mould and moisture reduces the likelihood that there will be a resulting health issue (Borsboom et al., 2016) [46]. Demand controlled ventilation is essentially restricted to carbon dioxide and humidity control. Savin (2009) describes humidity controlled exhaust ventilation more in detail.

Borsboom et al. (2016) [46] summarizes the main indoor processes, resulting pollutants and preferred control measure for several processes in dwellings. Table 3 shows the processes relating to moisture.

Table 3: Main indoor processes and measures to be preferred

Main indoor processes	Pollutant	Preferred control measure	Demand Control detection Sensor	Alternative
Construction failures and faults	Moisture (mould)	Insulated cold bridges, use of moisture barriers, built in moisture/dry construction phase (especially in bathrooms)	Humidity	Local dehumidification, extra heating

7.6. References

All AIVC references are in the AIVC general reference list (chapter 16) which is added as a separate chapter at the end of this Technote

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8. Ventilative Cooling and Thermal Comfort

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8.1. Introduction: Importance of Ventilative cooling

Traditionally, ventilation is provided to buildings to provide fresh air for occupants (maintaining life) to dilute and exhaust pollutants (maintaining indoor air quality for health) and to protect the building against moisture (maintaining building structure). This is reflected in the building regulations in most countries in which minimum ventilation rates are prescribed based on internal and external pollution sources. Thermal comfort needs were not part of ventilation provision.

However, overheating in buildings is emerging as a challenge both at the design stage and during operation. This is due to a number of reasons:

- high performance standards to reduce heating demand by high insulation levels;
- restriction of infiltration in heating dominated climatic regions;
- development in glazing and window technologies have led to an increase in the glazed areas; the most efficient windows provide a positive energy balance during the heating seasons and the area is no longer strongly limited by the heat loss.
- the occurrence of higher external temperatures during the cooling season due to changing climate and urban climate not usually considered at design stage;
- changes in internal heat gains during operation not factored in the design.

Such factors have resulted in significant deviations in energy use during operation which is usually termed the energy 'performance gap'. In most energy performance comparative studies, energy use is higher than predictions and post-occupancy studies frequently report overheating problems.

Ventilative cooling can be a solution. IEA EBC Annex 62[3] defines ventilative cooling as 'the use of natural or mechanical ventilation strategies to cool indoor spaces'. This use of outside air can reduce the energy consumption of cooling systems and potentially maintain thermal comfort. Each function of ventilation (for IAQ or comfort) requires different air flow rates, air flow distribution and control.

In parallel, thermal comfort models have been developed, namely (a) the heat balance model based on laboratory experiments at steady state usually applied to mechanically cooled buildings and (b) the adaptive model based on statistical data in operational buildings usually applied to free-floating buildings (EN 15251).

This section reviews the AIVC contribution to Ventilative cooling research and application, presents its state-of-the art related to work enabled by AIVC and outlines the next steps.

8.2. Historic role of AIVC: Contributions over the last 40 years

Participants to early AIVC conferences presented papers addressing the role of ventilation to reduce cooling demand. The rising importance of the topic was acknowledged in the 18th AIVC conference in 1997 which was entitled 'Ventilation and Cooling'. In parallel, AIVC publications started to emerge such as TN48[35] which discussed the need for cooling for thermal comfort and the role of ventilation in meeting cooling requirements; TN49 [36] exploring (based on data from 13 countries) why infiltration and ventilation account for a significant proportion of energy use in

3 http://venticool.eu/

buildings and investigating the role of controls; and TN47 [34] focusing on energy requirements for conditioning ventilating air. During the same time, IEA EBC Annex 28 completed in 1997 operated in which elements of Ventilative cooling such as night cooling, slab and ground cooling using air as a medium, and evaporative cooling were included.

A number of AIVC publications focus on the cooling role of ventilation during the decade of 2000. These focus on Ventilative cooling strategies VIP 03 [58] and VIP 04 [59], the relationship of ventilation and adaptive thermal comfort criteria as well as the use ceiling fans to enhance thermal comfort VIP12 [67] and VIP 13 [68] and ventilation for urban buildings with emphasis on natural and hybrid ventilation VIP 03 [58] and TN61 [48]. During the same time, IEA EBC Annex 44 completed in 2011 operated in which the integration of ventilation for cooling was addressed as one of the environmentally responsive elements in buildings through advanced integrated facades, thermal mass activation, earth coupling and phase change materials.

Since the 34th AIVC Conference (held in Athens in 2013), a new strand has been added on Ventilative Cooling. It continues to-date; the 6th Venticool conference was part of the 40th AIVC Conference held in Gent in 2019.

In 2008, AIVC initiated a new IEA EBC Annex on Ventilative Cooling supported by the Platform venticool which started in 2012 and was completed in 2018. AIVC published VIP 35 [14] on the state-of-the-art. The results of Annex 62 are presented in the next section.

8.3. State of the Art: Where is Ventilative cooling and thermal comfort now

The SOTAR carried out as part of Annex 62 in 2014 highlighted the following:

- Potential: The ventilative cooling potential is favourable in most European countries, especially during night. The possible cooling energy savings is at a level of 30-50% in office buildings and lower in the residential sector.
- Available Tools: Design and analysis of ventilative cooling requires combined modelling of air flow and building thermal performance and at different level of detail in each design phase. Designers need clearer guidance regarding the uncertainty in ventilative cooling performance predictions and ways to improve the reliability and robustness.
- Regulations: It is complex to include ventilative cooling requirements in regulations as it includes aspects related both to ventilation, energy, building construction and comfort. Energy performance calculations in many countries do not explicitly consider ventilative cooling and most available tools used for energy performance calculations are not well suited to model the impact.

Regarding the potential, Key Performance Indicators for Ventilative Cooling were formulated for thermal comfort, energy and components' efficiency to enable assessment at the design stage and a tool was developed suitable for feasibility design stage. These are described in chapters 3 and 5 of Design Guide.

- The thermal comfort indicator is based on EN 15251:2007 for long-term evaluation of general thermal comfort conditions, where the combination of the "Percentage Outside the Range Index" (method A) and the "Degree-hours Criterion" (method B) enable the evaluation of both frequency and severity of overheating and overcooling occurrences. The reference comfort temperature can be derived from the Fanger model, the adaptive comfort model or briefed by the building owner/occupants.
- For energy, two new indicators were developed; (a) the Specific Primary Energy Consumption of a ventilative cooling system, to express the primary energy consumed by the ventilative cooling system per heated floor area and (b) the Cooling Requirements Reduction (CRR), to express the percentage of reduction of the cooling demand of a scenario in respect to the cooling demand of the reference scenario.
- For components efficiency two indicators were developed; (a) Ventilative Cooling Seasonal Energy Efficiency Ratio (SEERvc) of the ventilative cooling system expresses the energy efficiency of the whole system. The SEER rating of a system is the reduction in cooling demand during a typical cooling season divided by the electrical consumption of the ventilative cooling system, in case ventilation rates are provided mechanically and (b) the ventilative cooling advantage [-] (ADVVC) indicator defines the benefit of the ventilative cooling in case ventilation rates are provided mechanically, i.e. the difference cooling energy use divided by the energy use for ventilation.

A ventilative cooling potential tool (VC Tool) was developed with the aim to assess the potential effectiveness of Ventilative cooling strategies by taking into account building envelope thermal properties, occupancy patterns, internal gains and ventilation needs. Figure 6 reports the tool GUI with input and outputs visualization. It has to be considered only as a preliminary analysis on the assumption that the thermal capacity of the building mass is sufficiently high and therefore does not limit the heat storage process.

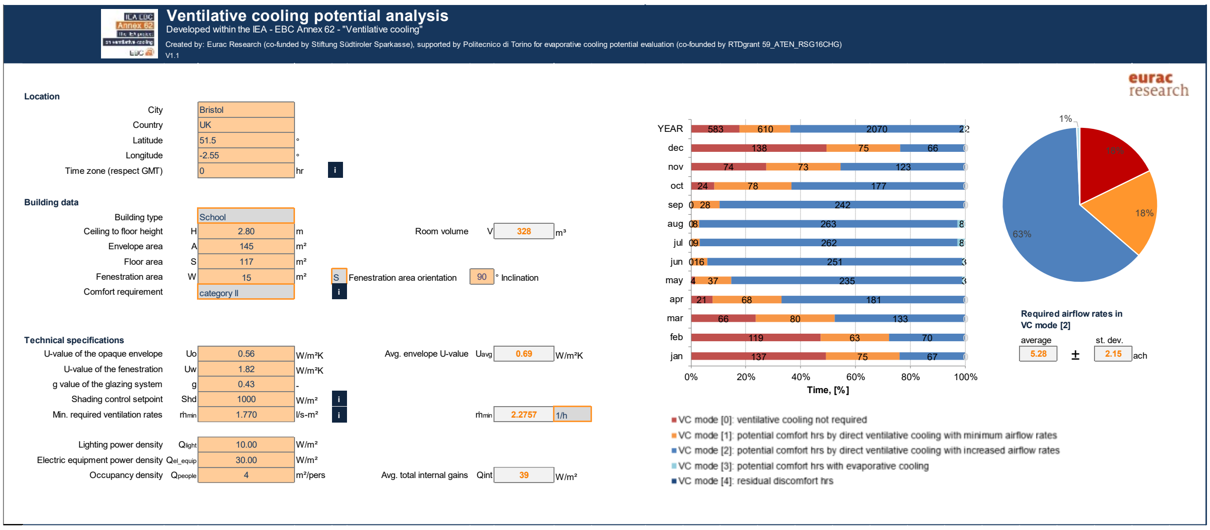

Figure 6: Tool GUI with input data and output visualization.

Regarding available tools for buildings with a ventilative cooling strategy, the natural choice should be to use design and simulation tools that combine thermal and airflow models. Only tools with such combination of modelling options allow accurate insight into energy performance versus thermal comfort. Bulk airflow models seem to offer a reasonable compromise for evaluation of naturally driven ventilative cooling configurations and control rules in a quick and inexpensive way. A step-by-step method is described suitable for the detailed design and design evaluation phase while existing controls in the studied case-study have shown that are essential for the success of the strategy, Figure 7 (O'Donnavan A. et al., 2018).

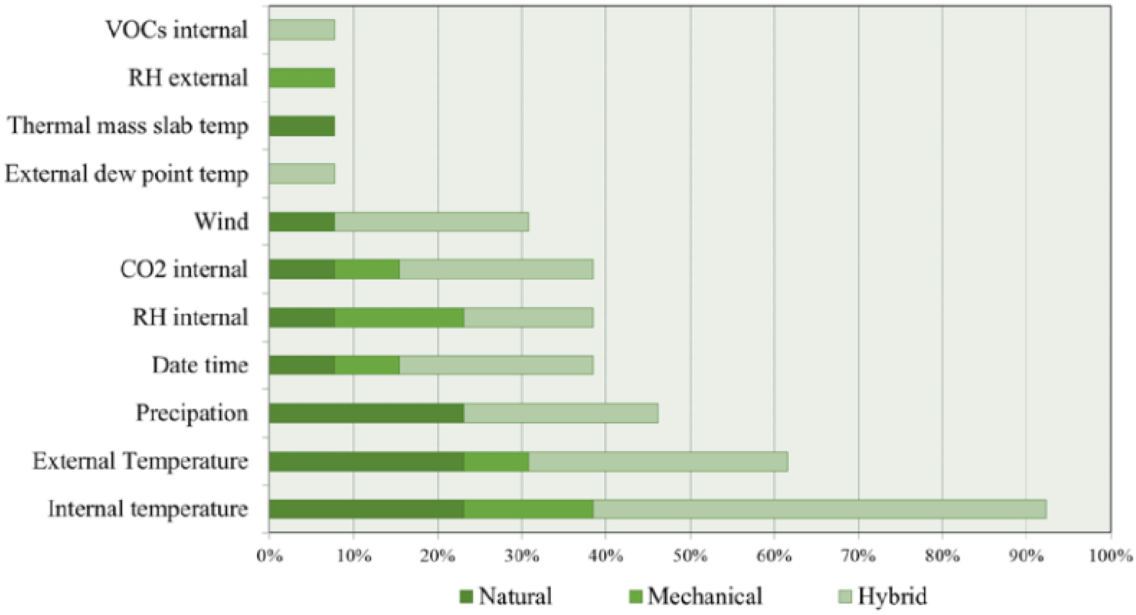

Figure 7: Summary of parameters used in Annex 62 studied case-studies (Annex 62 Design Guide)

Analysis of operational case-studies (O'Donnavan A. et al., 2018) has shown that during design and construction an important consideration is the use of detailed building simulation tools with customization of strategies and components for the specific building and systems. Then ventilation cooling becomes cost effective. During operation, analysis has shown that achieving the high standard of IAQ, thermal comfort and energy efficiency is difficult. To be achieved, engagement with the building owners or operators (even during the design stage) is important. Fifteen successful buildings using Ventilative cooling have been studied and presented.

Regarding regulations and standards, work carried out by Annex 62 revealed that ventilative cooling is in most cases not sufficiently integrated in standards, legislation and compliance tools. However, it also revealed that there is a broad field of evaluation methods for ventilative cooling, ranging from very simple to detailed that can support a stronger integration of Ventilative cooling in the near future.

The report recommends that when revising standards with respect to the prediction of the expected thermal comfort and cooling requirements by using ventilative cooling, it is recommended to use a method that is based on the static Fanger model (PMV evaluation) (using mechanical ventilative cooling) or the Adaptive comfort model (using natural ventilative cooling). It also recommends using Key Performance Indicators for "thermal comfort" that are used in the IEA EBC Annex 62 "Ventilative cooling design guide". To allow for Ventilative cooling to be treated better, it is important to consider the following points:

- Standards: The support of calculation methods that fairly treat natural Ventilative cooling for the determination of air flow rates including e.g., the dynamics of varying ventilation and the effects of location, area and control of openings.
- Legislation: Include assessment of overheating, e.g. (a) Requirements to thermal comfort, including adaptive temperature sensation and (b) Requirements to energy performance including cooling.
- Compliance Tools: They should allow for assessment of increased air flows when efficient ventilative cooling systems are used; Differentiation should be made i.e. for cross- or stack ventilation vs. single-sided ventilation, automated systems vs. manual control, large vs. small opening areas and Associated airflows should preferably be based on building physics for e.g. dynamic tools (using pressure equations) or - as a simpler solution - on “coefficients” which increase air flows based on the chosen system. Also, it is important to evaluate if the current methodology for the evaluation of ventilative cooling in compliance tools is sufficient to assess overheating.

8.4. Looking forward: Is topic complete? What are next steps? Future needs.

8.4.1. Current Work for Standards

As reported in the Build-up platform, the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) approved new standardization projects on ventilative cooling and natural and hybrid ventilation systems in 2017. The projects started in 2018 under CEN/TC 156 (Ventilation for buildings) and ISO/TC 205 (Building environment design) and focus mainly on design aspects of natural and hybrid ventilation and ventilative cooling tackling both overheating and indoor air quality issues. More specifically, working group 21 is dealing with a technical specification on “Ventilative cooling systems” which focuses on overheating prevention. Beside the revision of EN 16798 part 3 and 4 on performance requirements for ventilation in non-residential buildings, working group 20 is dealing with a technical specification on “Natural and hybrid ventilation systems in non-residential buildings” which focuses on indoor air quality aspects. ISO standard on “Design process of natural ventilation for reducing cooling demand in energy-efficient non-residential buildings” is under development within working group 2 in ISO/TC 205.

8.4.2. New Work on Resilient Cooling

Work supported by AIVC on Ventilative Cooling to-date has not considered in detail issues of:

- urbanization and densification;
- climate change;
- extreme climates; and
- elevated comfort expectations.

There is international current work on these issues; for example a conference organized in Dubai in April 2019 included Ventilative cooling discussions and how ventilation can be incorporated in the design and operation in climates where traditionally buildings are air-conditioned.

The above open issues will be researched in the near future by the work of IEA EBC Annex 80 which started in June 2018 and will be completed in 2023. On-going work will be presented at the Venticool strand of the AIVC conferences.

8.5. References

All AIVC references are in the AIVC general reference list (chapter 16) which is added as a separate chapter at the end of this Technote

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9. Ventilation Standards

Willem de Gids, VentGuide Netherlands

9.1. Introduction

At the creation of AIC in 1979 the air infiltration and airtightness of buildings was the most important focus of the work. AIVC was mainly formed because the infiltration part of the energy balance of the predicting modelling was completely unclear. Nevertheless, soon thereafter ventilation seemed also not quite well modeled. Ventilation and infiltration are of course unbreakably coupled. Their interaction cannot be neglected in any way.

The work of AIVC on standards was not a leading one. Over the 40 years AIVC has published a number of publications on the subject of standards but in most cases the role of AIVC was an observational one.

9.2. Overview of standard related work over 40 years of AIVC

IEA ECBCS annex IX: Minimum Ventilation Rates started in 1980 and published their work in 1987 and finally in 1989 also as AIVC TN 26: Minimum Ventilation Rates [17]. The work is a summing up all kinds of constituents polluting inside air. It was a review of existing knowledge and did not really focus on existing ventilation standards. Nevertheless, TN 26 was used as a reference for many ventilation standards.

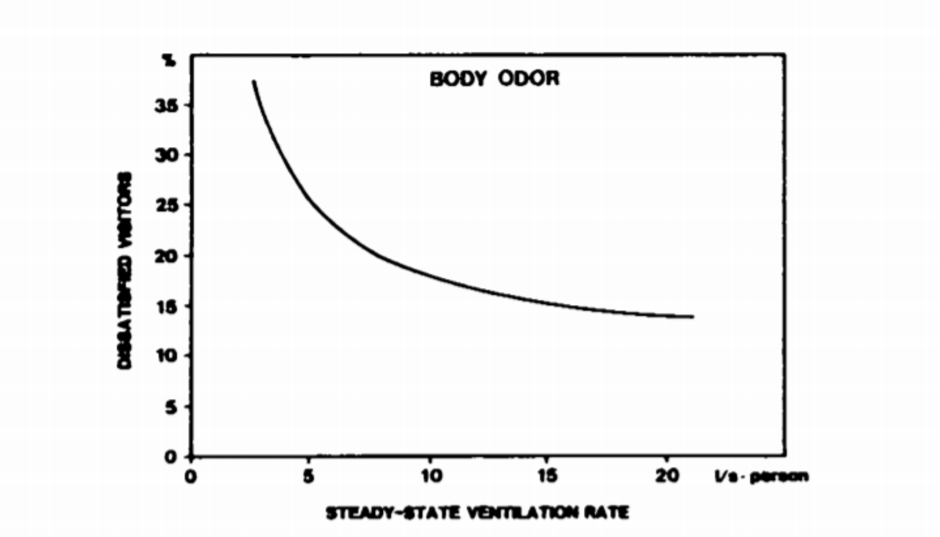


Figure 8: Percentage of dissatisfied visitors as a function of calculated steady-state ventilation rate

In 1994, TN 43: Ventilation and building airtightness: an international comparison of standards, codes of practice and regulation*s* was published, and later in 2001 replaced by TN 55 [42]. The purpose of this comparison of specified airtightness and ventilation rates is to provide a reference document for all those involved in ventilation and building research. It summarizes available airtightness and minimum ventilation rate requirements in the AIVC's Member Countries. It also examines a number of indoor air quality standards. Certain analyses have also been included, whenever uniformity of standards permits.

Table 4: A comparison of flow coefficients and air change rates from minimum air tightness standards for whole buildings

Country	ACH (max) at specified pressure difference (Pa)	Calculated flow coefficient k, (m^3/s) at specified air change rate and Pressure Difference (Pa)	Normalised air change rate to 50Pa
Italy (schools)	5.0 ach at 98Pa	0.243	3.2 ach at 50Pa
Netherlands (NL)(Cl1-Min)	2.24 ach at 10Pa	0.49	6.5 ach at 50Pa
Netherlands (NL)(Cl2 Min)	1.15 ach at 10Pa	0.252	3.3 ach at 50Pa
United States of America	1.6 ach at 4Pa	0.64	8.5 ach at 50Pa

In 2001, TN 52: Acoustics and Ventilation [39] was published. An overview of all aspects concerning acoustics and ventilation is given in this TN which is very worth reading. It gives a description of acoustics aspects of all kinds of ventilation systems. It includes references to many international standards for determining the noise level as well as criteria for all kinds of rooms.

Table 5: Maximum Sound Insulation (Brick façade, room volume $80m^3$, façade surface $10\ m^2$)

Cross-section of the ventilation opening (cm^2)	Maximum noise reduction (dB(A))
10	40
50	34
100	31
200	28
300	26
400	25
500	24

In 2002 TN 57: Residential Ventilation [44] was published. An overview of the requirements in 15 countries are summarized and analyzed.

Table 6: Distribution of Ventilation Systems in the Existing Dwelling Stock

	Single Family Houses					Multi Family Houses				
	Natural			Mechanical		Natural		Mechanical		
	Adv.	Stack	S+Fan	Ext.	Bal	Adv.	Stack	S+Fan	Ext.	Bal
Belgium	100					95	5			
Canada		15	85							
Denmark		50*		48	2		50*		50	
Finland										
France	40	15	20	22	3	40	20	10	30	
Germany										
Italy	80		10	10		75			25	
Japan										
Netherlands		62*		38			37*		63	
Norway			80	15	5		60		30	10
Sweden		12	63	14	11		40		44	16
Switzerland	70		30			40		60		
UK		95*	5				100*			
USA	60			40						

VIP 02: Indoor Air Pollutants Part 1 [57]: General description of pollutants, levels and standards, was published in 2003; it is also available in french. The work is focusing on pollutants.

In 2005, TN 59 [46]: Parameters for the design of demand-controlled hybrid ventilation systems for residential buildings was published. This work was part of the European Project *Reshyvent*. It gives guidelines to all aspects of ventilation design parameters. In relation to standards the European components test standards in the series EN 13141 part 1 to 10 are in some cases mentioned as important. Particularly the test method for roof outlets and cowls EN 13141 part 5 is described.

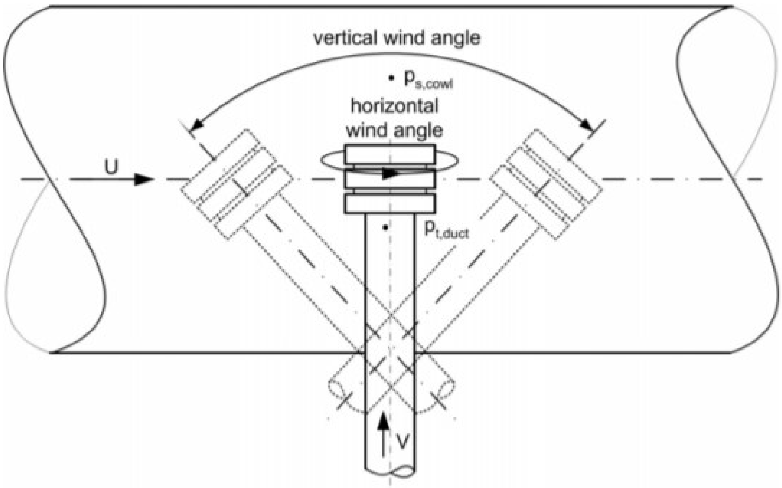


Figure 9: Experimental measurement of Cp-value of a cowl (CEN EN 13141-5)

In 2006, TN 60: Efficacy of Intermittent Ventilation for Providing Acceptable Indoor Air Quality [47] was released.

Ventilation standards and guidelines typically treat ventilation as a constant and specify its value. In many circumstances a designer wishes to use intermittent ventilation, rather than constant ventilation, but there are no easy equivalencies available. This report develops a model of efficacy that allows one to calculate how much intermittent ventilation one needs to get the same indoor air quality as the continuous value specified.

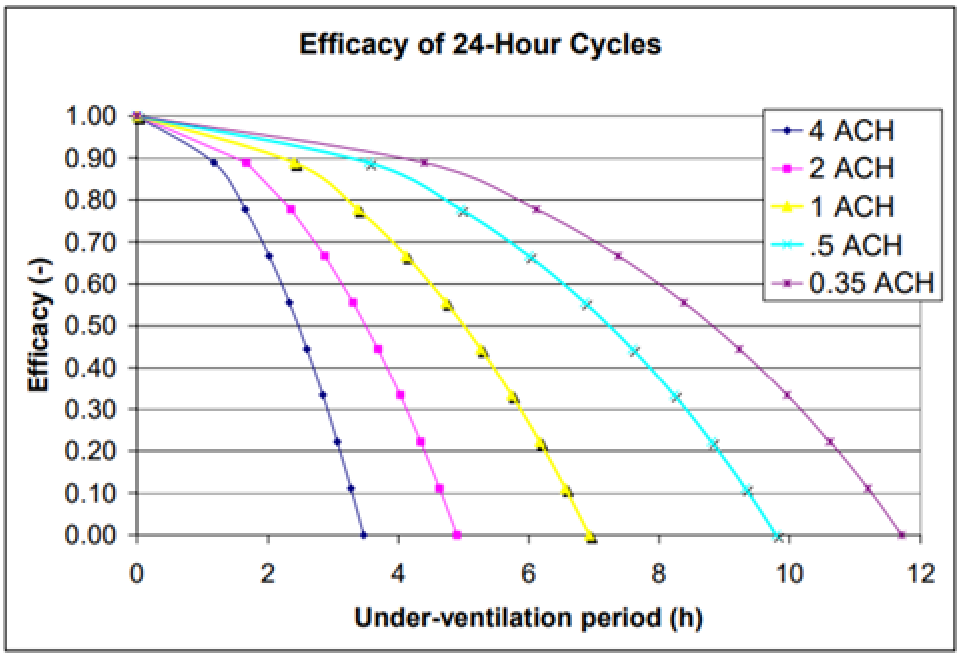


Figure 10: Efficacy of 24-hour cycles as a function of under-ventilation fraction for different air change rates

VIP 14: European ventilation standards supporting the Energy Performance Buildings Directive of the European Union [69] was released in 2007. A number of European ventilation standards are summarized.

In 2012, TN 67: Building airtightness: a critical review of testing, reporting and quality schemes in 10 countries [54] was published. Under Reliability issues it refers to ISO9972 and EN13829 the test method for determining airtightness of buildings. About the reliability and accuracy issues it also refers to AFNOR GA P 50-784 (2001) and to DIN 4108-7 (2011). In the last conferences, workshops and seminars there was a lot of information on reliability and accuracy.

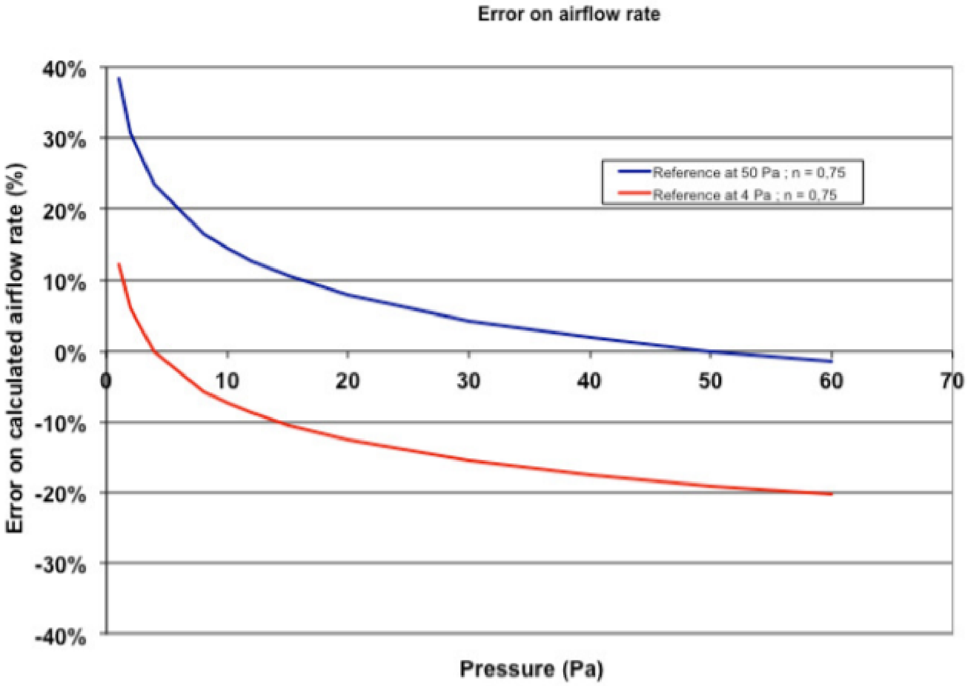


Figure 11: Error calculated air flow as a function of pressure inside the building for an actual flow exponent of 0,75 , assuming a flow exponent of 2/3 in the calculation

Since 2011 airtightness got a more international focus. TightVent Europe was formed. More attention was also given to duct airtightness.

Table 7: Airtightness classification as defined in pr EN 13779 and additional class D (.10^{-3} $m^3/s.m^2.Pa^{0,65}$)

Class K	K_K=	0.081
Class A	K_A=	0.027
Class B	K_B=	0.009
Class C	K_C=	0.003
Class D	K_D=	0.001

In 2016, TN 68: Residential Ventilation and Health [55] was published. A review of existing residential ventilation standards including the basis for existing ventilation standards is described and analysed. It also gives guidelines for future ventilation standards.

In 2017, VIP 36: Metrics of Health Risks from Indoor Air [91] was published. It refers mainly to US standards but is a very good description of the problem including the history.

9.3. Ongoing work

In 2017 the AIVC project: Rationale behind ventilation Requirements and Regulations started. Information of all AIVC countries plus another 14 countries was studied and analyzed. As of 2022, a VIP will be published and probably also a more detailed TN.

The differences are big while most countries declare that ventilation is based on nuisance from body odours.

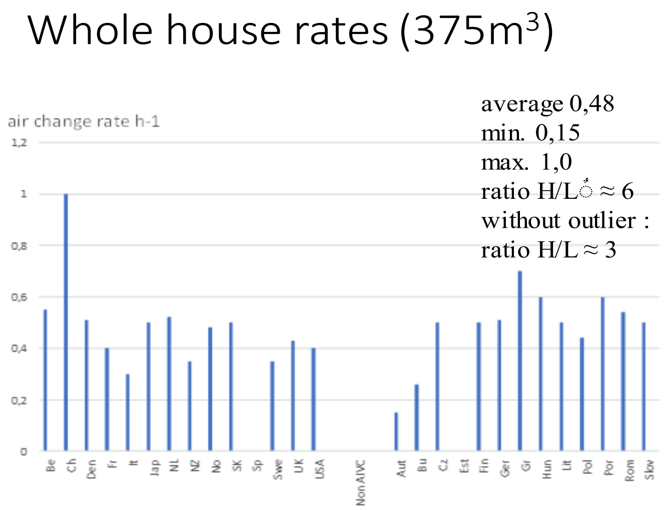


Figure 12: Calculated whole house ventilation rate for different countries

The rationale behind the requirements is also different. The following elements are mentioned:

- Human occupation, bio-effluents
- Human activities (bio-effluents, washing, showering, dishes, cooking)
- Dilutions of pollutants/contaminants
- Formaldehyde concentration and time
- Cooking fumes, combustion products
- Bacteria, viruses
- Solve sick house
- Radon (radioactive gasses)

It seems that experts studied literature and made best guesses for the ventilation levels. No solid scientific reports are found as background for the requirements. In most cases the requirements are based on a philosophy made by the experts.

9.4. References

All AIVC references are in the AIVC general reference list (chapter 16) which is added as a separate chapter at the end of this Technote

10. Occupant roles

Sonia García Ortega, CSIC, Spain

10.1. Introduction

The role of occupants is one of the most important factors that influence Indoor Air Quality (IAQ). Occupants are at the same time, the objects to be protected, they have an active role in the operation of ventilation systems and are also a source of pollutants. Occupants also have an effect on ventilation by using their ventilation provisions.

Humans spend a great amount of their lives inside buildings. Exposures in homes constitute the major part of exposures to airborne pollutants experienced through the human lifetime. They can constitute from 60 to 95% of our total lifetime exposures, of which 30% occurs when we sleep.

Ventilation needs to provide air for metabolism, as well as dilute and remove pollutants. Knowledge on the role of occupants allows to adapt ventilation based on the generation of contaminants and needs for fresh air.

10.2. Occupants as contaminant source

Metabolic carbon dioxide (CO_2) and moisture from baths are the most significant contaminants, among others, when thinking about occupants as a contaminant source. An incomplete list includes:

- CO_2 and moisture from breathing, depending on the metabolic activity;
- volatile organic compounds (VOCs) and moisture from cooking, bathing, cleaning;
- moisture, CO_2, nitrogen dioxide (NO_2), depending on the case of hob; e.g unvented indoor combustion of natural gas is a significant source of NO_2, carbon monoxide (CO) and other pollutants.
- odours;
- CO_2, VOCs and others from cigarette smoke;
- etc.

Some of the reasons why ventilation refers frequently to CO_2 and moisture are:

- CO_2 is a good maker for bio-effluents. CO_2 is harmless at regular indoor levels but is related to occupants' number and metabolic activity. It is easy to measure, and ventilation standards could be developed (VIP 33 [88]).
- Moisture may condense on surfaces, can grow mould and damage the building. It is the main contaminant in bathrooms, and one of the contaminants in kitchens, associated with the role of occupants.

Other major sources of pollution, not related to occupants, are emissions from building materials, furniture and outdoor environment (traffic, industry, radon and other pollutants).

Figure 13 summarizes approximate ventilation rates needed to reduce these concentrations to acceptable threshold levels.

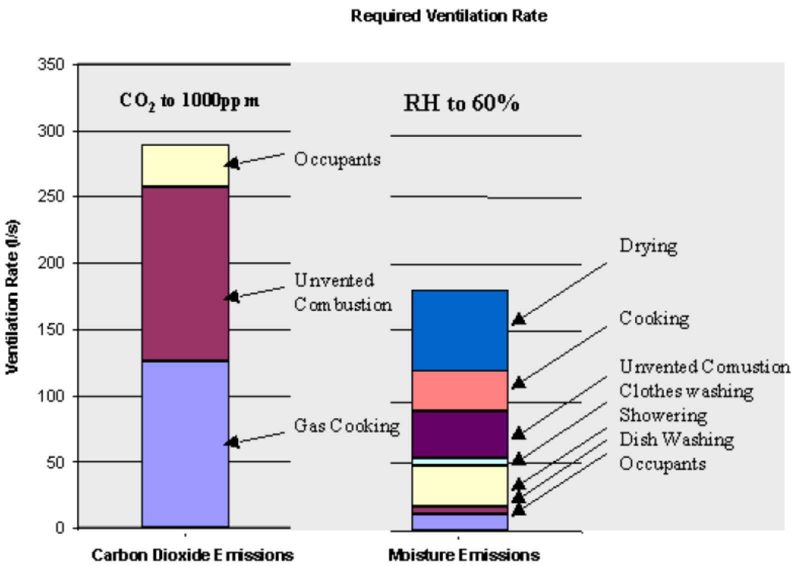


Figure 13: Typical ventilation rates needed to deal with various household activities (Figure 4.1 of AIVC Technical Note 53 Occupant Impact on ventilation [68].

10.3. Occupants as control devices

People usually intervene with ventilation devices or systems. Occupant patterns, such as open-closed windows, operated exhaust fans such us range hoods, etc. have undoubtly an influence on the ventilation effectiveness. E.g. open windows could be effective for pollutant control, but occupant behaviour could be influenced by climate, season of year, and other subjective reasons.

Table 8 shows the use of vent lights during a moderate winter in Dutch dwellings. Figure 14 shows the cumulative distribution function of high (H) or high plus medium (H+M) ventilation for each season in new California houses. When analysing the figures, an idea of the great variability of behaviors occupants have can be formed.

Table 8: The use of vent lights during a moderate winter in Dutch dwellings (Table 2 of AIVC Contributed Report 08. Occupant behaviour and attitudes with respect to ventilation of dwellings [101].

	living room		kitchen		main bedroom		second bedroom	
width of opening	fully	half	fully	half	fully	half	fully	half
hours open (24h):								
0	33	43	22	41	30	46	30	37
0 – 1	18	21	15	13	7	6	12	11
1 – 4	18	12	26	16	11	15	17	16
4 – 8	10	9	14	8	9	6	9	8
8 – 16	5	3	7	4	7	5	5	6
nearly always (22h)	16	11	17	16	36	23	26	22
mean hours open	5.2	3.7	6.1	4.7	9.6	6.4	7.3	7.0

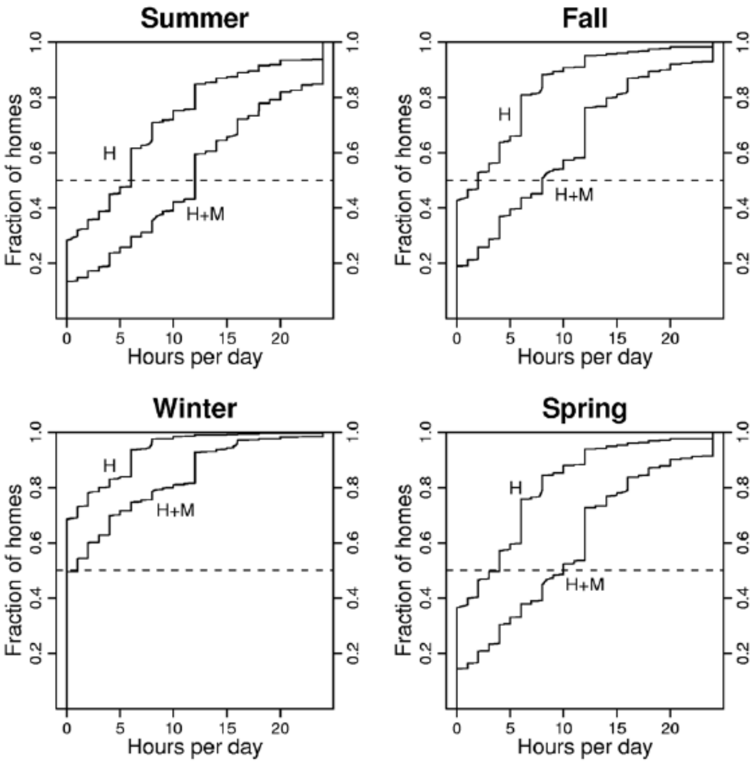


Figure 14: Cumulative distribution function of reported hours of ventilation per day, by season (Figure 1 of Contributed Report 10. Ventilation behaviour and household characteristics in new California houses [103]).

The main reasons why occupants ventilate are related to the effects of their behaviour such as the number of persons in a dwelling, visits, presence of pets and plants etc. [van Dongen][109]. By this it can be concluded that occupants are not “average people” and ventilation provisions need to be very flexible. The prediction or analysis of ventilation patterns is complex. According to the author, sharp features at 6 and 12 hours is an indication of the reflection of peoples’ choices when filing out the questionnaire rather than an indication that people actually open their windows for this exact number of hours.

10.4. Historic Role over the last 40 years

The role of occupants has been investigated throughout the 40 years AIVC’s existence. For example, in 1988, the *Technical Note 23 Inhabitant Behaviour with Respect to Ventilation* [15] was published as a part of the work of the Energy Conservation in Buildings & Community Systems Programme of the International Energy Agency (IEA). This TN summarized the work of IEA Annex VIII “Inhabitants’ Behaviour with respect to Ventilation” with contributions from Belgium, Germany, Switzerland, the Netherlands and United Kingdom. The results of these investigations provided findings about ventilation and occupant behaviour and its consequences from an energy point of view and laid the groundwork for future studies. In figures 15 and 16 examples of results of different projects can be seen. Figure 15 shows the linear correlation found between window use and temperature (range -10ºC to +25ºC) reported by the Schiedam project (from the Netherlands). Figure 16 illustrates the inverse linear correlation between wind velocity and window opening obtained in the Duisburg project (from Germany).

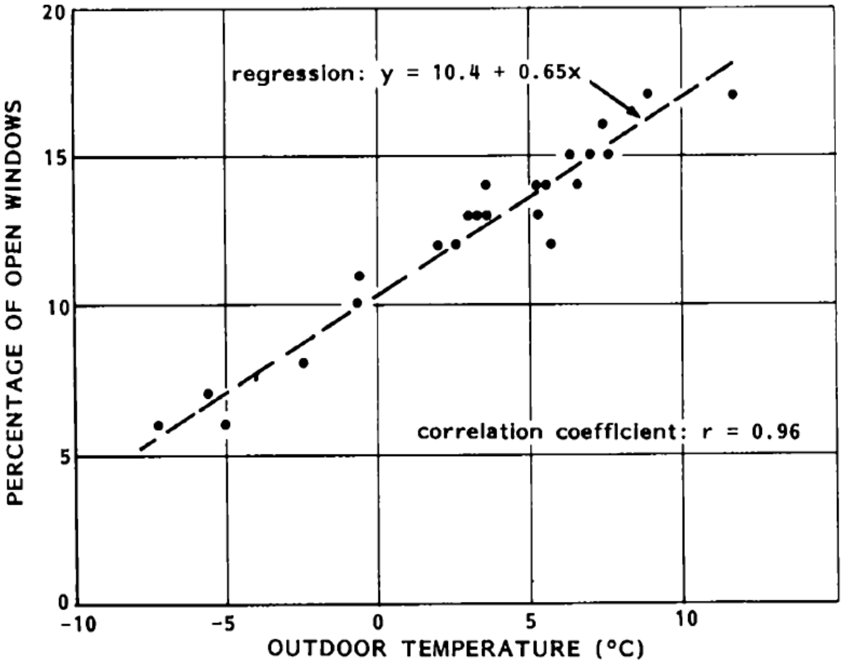


Figure 15: Relationship between the average use of windows and doors and the average outdoor temperature (Figure 2.1 of Technical Note 23 Inhabitant Behaviour with Respect to Ventilation [55]).

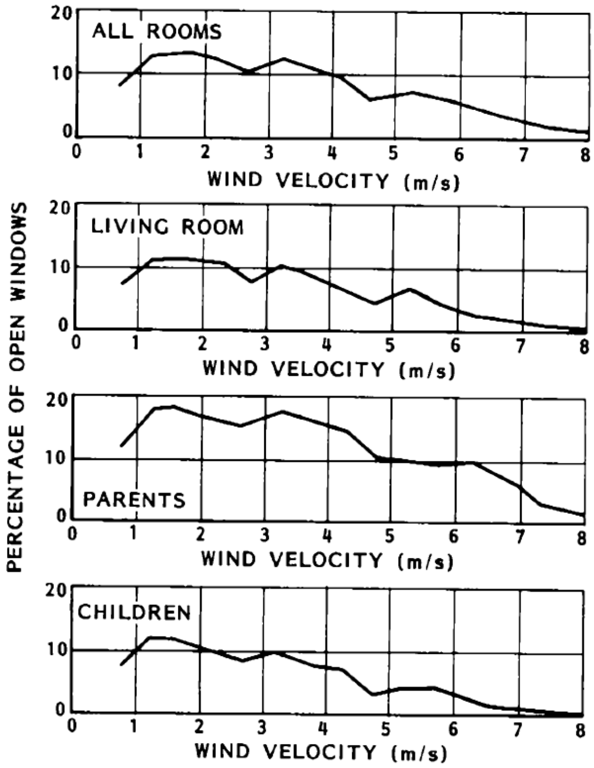


Figure 16: Percentage of open windows as a function of wind speed (Figure 2.2 of Technical Note 23 Inhabitant Behaviour with Respect to Ventilation [15]).

In recent times, the publications listed below could stand out, as a compendium on related subjects:

- Technical Note AIVC 53. Occupant Impact on Ventilation. AIVC Document AIC-53-2001 [40].

- Contributed Report 08. Occupant behaviour and attitudes with respect to ventilation of dwellings. AIVC-CR08. 2007 [101].
- Technical Note AIVC 68. Residential Ventilation and Health. INIVE EEIG 2016 [55].

The last AIVC annual congresses, at the forefront of the state of the art, discussed topics like:

- **Smart ventilation**: Smart ventilation systems could adapt the ventilation to the occupant ratio and to contaminant generation. Smart ventilation could be defined as a process to continually adjust the ventilation system in time, and optionally by location, to provide the desired IAQ benefits while minimizing energy consumption, utility bills and other non-IAQ costs (such as thermal discomfort or noise). In 2018 the 39th AIVC - 7th TightVent & 5th Venticool Conference took place in France with the topic "Smart ventilation for buildings".
- **Pollutants from domestic kitchens**: Exposure from pollutants during cooking depends not only on capture efficency but also on the disturbances from the cooks themselves (Ortega & Alemparte, 2017).
- **Relation between occupant behavior** (related to ventilation) and energy consumption, also in low energy buildings (TN 53 [40]).
- **Simulation of occupant roles**: estimations of CO_2 produced by occupants and indoor particle concentration as function of occupant behavior (CR 08 [101]).
- **Ventilation requirements based on exposure**: occupant exposure with current regulations, additional key factors beyond capture efficiency that influence occupant exposure using hoods (Borsboom et al., 2018)
- **Special populations: such as students at schools** (figure 17), with long holidays and breaks between lessons (Gil-Báez et al., 2017).

Figure 17: Schools are an example of occupants who may need special protection and who have very marked and characteristic schedules. Typical school building windows of the south of Spain. Inlet rounded in red. (Figure 2 of Natural ventilation systems in Mediterranean schools)

10.5. Towards occupant-centric ventilation

In order to better take account of the needs of occupants in the future, ventilation regulations and standards need to be based on the occupant's exposure rather than on the concentration of pollutants in rooms. This would require a better knowledge of the behaviour of occupants, and the development and use of smart ventilation that adjusts the actual ventilation in time and place.

10.6. References

All AIVC references are in the AIVC general reference list (chapter 16) which is added as a separate chapter at the end of this Technote

Ortega, S-G., Alemparte, P.L. (2017). *Pollutant exposure of the occupants of dwellings that complies with the Spanish indoor air quality regulations*. Proceedings of the 38th AIVC Conference "Ventilating healthy low-energy buildings". 13-14 September 2017. Nottingham, UK. p709-p715. AIVC.

Borsboom, W., de Gids, W., Walker, I., Jacobs, P. (2018). *Assessment of Range Hoods based on Exposure*. Proceedings of the 38th AIVC Conference "Ventilating healthy low-energy buildings". 13-14 September 2017. Nottingham, UK. p.1091-p1099. AIVC.

Gil-Báez, M., Barrios-Padura, A., Roldán-Vendrell C., Molina-Huelva, M. (2017). Natural ventilation systems in Mediterranean schools. A prototype experience in Andalusia as an alternative to mechanical ventilation. Proceedings of the 38th AIVC Conference "Ventilating healthy low-energy buildings". 13-14 September 2017. Nottingham, UK. p503-p512. AIVC.

11. Carbon Dioxide in Ventilation and IAQ Evaluation

Andrew Persily, National Institute of Standards and Technology, USA

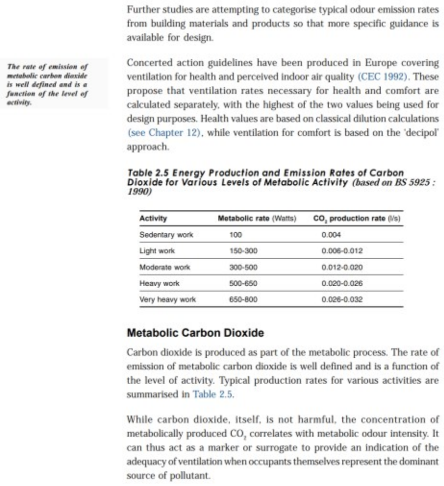
11.1. Introduction

The role of carbon dioxide (CO_2) to control the indoor air quality in buildings is based on the fact that CO_2 developed by people breathing may be used as a marker for the bio-effluents produced by people. CO_2 itself can't be seen in the same way as other constituents in the air. Nevertheless, the use of CO_2 as marker for the indoor air quality is widely used.

The Air Infiltration and Ventilation Centre has published many articles and pursued many activities related to indoor carbon dioxide over the 40 years that have transpired since its creation. These publications and activities, like most applications of indoor CO_2 to the fields of ventilation and indoor air quality, have focused on the following: control of outdoor ventilation rates, i.e., demand control ventilation; use as a tracer gas to measure outdoor air change rates; the role of CO_2 an indicator or metric of IAQ; and direct impacts of CO_2 on human health, comfort and performance. More recently, AIVC publications have featured work on CO_2 generation rates from building occupants and CO_2 concentrations in standards and building regulations is also covered. This chapter was generated by searching on Air Infiltration and Ventilation Centre publications, though the findings also reflect the evolving application and understanding of indoor CO_2 in the broader literature.

11.2. Historic role of AIVC

One of the earliest Air Infiltration and Ventilation Centre (AIVC) publications on the application of indoor CO_2 is a short article covering a range of topics, including tracer gas applications, indoor air quality (IAQ) evaluation, and CO_2 as an indicator of occupancy (Liddament, 1996). Another short paper was published more recently, which focused on CO_2 as an IAQ indicator and for ventilation control (de Gids and Wouters, 2010) [88].



The rate of emission of metabolic carbon dioxide is well defined and is a function of the level of activity.

Further studies are attempting to categorise typical odour emission rates from building materials and products so that more specific guidance is available for design.

Concerted action guidelines have been produced in Europe covering ventilation for health and perceived indoor air quality (CEC 1992). These propose that ventilation rates necessary for health and comfort are calculated separately, with the highest of the two values being used for design purposes. Health values are based on classical dilution calculations (see Chapter 12), while ventilation for comfort is based on the 'decipol' approach.

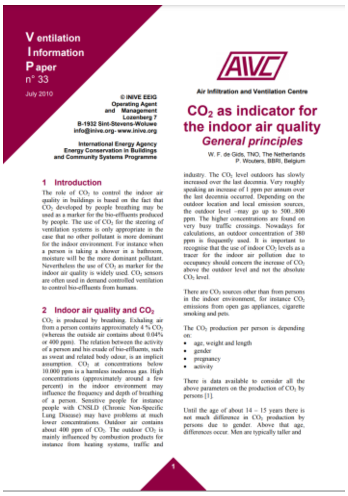
Table 2.5 Energy Production and Emission Rates of Carbon Dioxide for Various Levels of Metabolic Activity (based on BS 5925 : 1990)

Activity	Metabolic rate (Watts)	CO_2 production rate (l/s)
Sedentary work	100	0.004
Light work	150-300	0.006-0.012
Moderate work	300-500	0.012-0.020
Heavy work	500-650	0.020-0.026
Very heavy work	650-800	0.026-0.032

Metabolic Carbon Dioxide

Carbon dioxide is produced as part of the metabolic process. The rate of emission of metabolic carbon dioxide is well defined and is a function of the level of activity. Typical production rates for various activities are summarised in Table 2.5.

While carbon dioxide, itself, is not harmful, the concentration of metabolically produced CO_2 correlates with metabolic odour intensity. It can thus act as a marker or surrogate to provide an indication of the adequacy of ventilation when occupants themselves represent the dominant source of pollutant.



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International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

Air Infiltration and Ventilation Centre

CO_2 as indicator for the indoor air quality
General principles

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P. Wouters, BBRI, Belgium

1 Introduction

The role of CO_2 to control the indoor air quality in buildings is based on the fact that CO_2 developed by people breathing may be used as a marker for the bio-effluents produced by people. The use of CO_2 for the steering of ventilation systems is only appropriate in the case that no other pollutant is more dominant for the indoor environment. For instance when a person is taking a shower in a bathroom, moisture will be the more dominant pollutant. Nevertheless the use of CO_2 as marker for the indoor air quality is widely used. CO_2 sensors are often used in demand controlled ventilation to control bio-effluents from humans.

2 Indoor air quality and CO_2

CO_2 is produced by breathing. Exhaling air from a person contains approximately 4 % CO_2 (whereas the outside air contains about 0.04% or 400 ppm). The relation between the activity of a person and his exude of bio-effluents, such as sweat and related body odour, is an implicit assumption. CO_2 at concentrations below 10.000 ppm is a harmless inodorous gas. High concentrations (approximately around a few percent) in the indoor environment may influence the frequency and depth of breathing of a person. Sensitive people for instance people with CNSLD (Chronic Non-Specific Lung Disease) may have problems at much lower concentrations. Outdoor air contains about 400 ppm of CO_2. The outdoor CO_2 is mainly influenced by combustion products for instance from heating systems, traffic and industry. The CO_2 level outdoors has slowly increased over the last decennia. Very roughly speaking an increase of 1 ppm per annum over the last decennia occurred. Depending on the outdoor location and local emission sources, the outdoor level –may go up to 500..800 ppm. The higher concentrations are found on very busy traffic crossings. Nowadays for calculations, an outdoor concentration of 380 ppm is frequently used. It is important to recognise that the use of indoor CO_2 levels as a tracer for the indoor air pollution due to occupancy should concern the increase of CO_2 above the outdoor level and not the absolute CO_2 level.

There are CO_2 sources other than from persons in the indoor environment, for instance CO_2 emissions from open gas appliances, cigarette smoking and pets.

The CO_2 production per person is depending on:

- age, weight and length
- gender
- pregnancy
- activity

There is data available to consider all the above parameters on the production of CO_2 by persons [1].

Until the age of about 14 – 15 years there is not much difference in CO_2 production by persons due to gender. Above that age, differences occur. Men are typically taller and

1

Figure 18: Some information about CO_2

No other general reports or publications on CO_2 have been issued by the AIVC over its 40 years. The application of CO_2 has been covered mostly by individual conference papers on the topics covered below.

11.3. State of the art

11.3.1. Introduction

The application of CO_2 has been covered mostly by individual conference papers on the topics covered below. For each of the topics, one can find references in the AIVC General Literature List at the end of this publication. Most items even have their own chapter in this technote.

11.3.2. Demand Control Ventilation

Indoor CO_2 has been discussed as a control parameter for outdoor air ventilation for decades, with the goal being to provide sufficient ventilation for the occupants in a space.

Proceedings 21st AIVC Annual Conference, "Innovations in Ventilation Technology, 26-29 September 2000, paper 6

Demand Controlled Ventilation in Schools
– Energetic and Hygienic Aspects

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Keywords
Demand Controlled Ventilation, Indoor Air Quality, Mould Problems, Bacteria Concentration, CO_2 Concentration

SIMULATIONS OF INDOOR AIR QUALITY AND VENTILATION IMPACTS OF DEMAND CONTROLLED VENTILATION IN COMMERCIAL AND INSTITUTIONAL BUILDINGS

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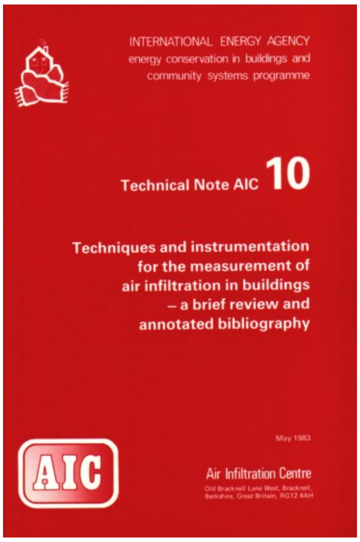
Ventilating for the actual occupancy rather than a maximum design value provides an opportunity to reduce energy used for space heating and cooling, as well as assuring that the ventilation is sufficient to meet the needs of the occupants. In 2001 the AIVC generated a literature list (LL) that identified about 50 publications on the topic of CO_2 demand control ventilation, many of them not published by the AIVC itself. Additional work on the topic has continued in subsequent publications on sensor performance, energy and IAQ impacts, case studies in a variety of building types.

11.3.3. CO_2 as a Tracer Gas

Carbon dioxide has long been recognized as a useful tracer gas for studying building ventilation and airflow given its low reactivity and toxicity, relative ease of measurement and, in some applications, building occupants serving as a convenient tracer gas source. CO_2 was identified as a potential tracer gas in an early AIC publication (Liddament and Thompson, 1983)[7]. Since 1983, CO_2 has been used as a tracer gas in many studies.



ON INVESTIGATING INSTANTANEOUS WIND-DRIVEN INFILTRATION RATES USING CO_2 DECAY METHOD

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11.3.4. IAQ Assessment

Indoor CO_2 concentrations have long been used as part of IAQ assessments with the oldest reference listed in the table below dating back to 1985. Some of these assessments measure CO_2 concentrations as one of many pollutants monitored, though many assessments do not explain the significance of the measured concentrations or compare them to a reference or guideline value.

Such measurements are still common as part of IAQ investigations; the explicit consideration of CO_2 concentration metrics is a more recent development and is discussed next.

11.3.5. IAQ Metric

The AIVC has focused on IAQ metrics in recent years, with the topic being a major theme of its 2016 conference held in conjunction with the ASHRAE IAQ conference series. Only two papers on the topic of CO_2 as an IAQ metric are listed in the table below, but the issue has been discussed in recent AIVC workshops and conference sessions without any papers being published and those discussions are likely to continue.

11.3.6. CO_2 generation rates

The use of CO_2 as a tracer gas for quantifying building and space ventilation rates requires a value of the rate of CO_2 generation by the building occupants. For many years, default values from ASHRAE and other sources have been used without evaluating their accuracy or the sources on which they were based. Recent publications have developed more well-documented and robust methods for estimating these generations rates, with three AIVC conference papers included in the table below.

CO_2 Generation Rates
M. Tajima, T. Yorimitsu, Y. Shimada. 2018. Accuracy Improvement for Estimating Indoor Carbon Dioxide Concentration Produced by Occupants. 39th AIVC Conference.
A. Persily, L. de Jonge, 2017. A New Approach to Estimating Carbon Dioxide Generation Rates from Building Occupants. 38th AIVC Conference.
M. Tajima, T. Inoue, Y. Ohnishi. 2014. Derivation of equation for personal carbon dioxide in exhaled breath intended to estimation of building ventilation. 35th AIVC Conference.

11.3.7. Standards and Regulations

While indoor CO_2 has been considered in ventilation and IAQ studies for decades, most standard or guideline values were only for industrial environments. More recently a number of standards and building regulations have been promulgated with specific indoor CO_2 concentration limits. Several of these are covered by the publications listed in the table below, though other countries and localities appear to also be setting such limits.

Standards and Regulations
S. Caillou, J. Laverge, P. Wouters. 2018. IAQ in working environments in Belgium: alternative approaches to CO2 requirement. 39th AIVC Conference.
A. Persily. 2015.Indoor Carbon Dioxide Concentrations in Ventilation and Indoor Air Quality Standards. 36th AIVC Conference.
P. Paulino. 2015. Impact of the new rite 2013 (regulation on thermal installation) on indoor air quality. 36th AIVC Conference.

11.3.8. CO_2 Impacts on Building Occupants

Finally, a number of recent studies have taken a new look at how CO_2 impacts building occupants both physically and mentally. Many of these studies have been looking at concentrations that are typical of indoor spaces. However, the studies in the broader literature are not consistent as to the human effects observed. The three studies listed in the table below are just an example of such work that has been presented in recent AIVC conferences.

CO_2 Impacts on Building Occupants
L. Yoshimoto, T. Yamanaka, A. Takemura, K. Ikeda. 2018. Subjective Evaluation for Perceived Air Pollution Caused by Human Bioeffluents. 39th AIVC Conference.
P. Wargocki, J.A. Porras-Salazar, W.P. Bahnfleth, 2017. Quantitative relationships between classroom CO2 concentration and learning in elementary schools. 38th AIVC Conference.
X. Zhang, P. Wargocki, Z. Lian, 2015. Effects of Carbon Dioxide With and Without Bioeffluents on humans. 36th AIVC Conference.

11.4. References

All AIVC references are in the AIVC general reference list (chapter 16) which is added as a separate chapter at the end of this Technote

12. The impact of outdoor air (pollution and humidity)

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Maria Kolokotroni, Brunel University London, UK
Max Sherman, LBNL, USA

12.1. Introduction: The importance of outdoor air

Ventilation has multiple functions that relate to maintaining the ‘health’ of both the building (e.g. protecting the structure against moisture) and the occupant (e.g. diluting and exhausting indoor pollutants, replacing ‘stale’ air with ‘fresh’ air, and contributing to thermal comfort through air movement).

Outdoor air is mixed with indoor air to achieve these purposes. Outdoor air is defined as ‘air taken from the external surrounds and therefore not previously circulated through the system’ (TN 26 [17]).

One of the challenges associated with introducing outdoor air to indoor environments relates to contaminants that may be in the outdoor air. Two key pollutants that are of particular concern at the present moment are PM2.5 (which penetrate deep into the lungs and therefore becomes a chronic health hazard) and tropospheric ozone (caused by VOCs and NOx interacting with heat and light). Ozone can affect the lungs, respiratory system and immune system.

The second challenge associated with outdoor air relates to moisture. In hot or warm humid climates condensation and mould inside the building can present a threat to both the building and the occupants unless it is managed.

Ventilation systems, regardless of whether natural, mechanical or hybrid, need to take into account the relevant characteristics of the outdoor air that directly impinge on achieving its functions. This means that attention must be paid to outdoor air, in particular the pollutant concentration, moisture content, temperature and movement of the outside air. Strategies that are responsive to these characteristics need to be implemented to ensure that the introduction of outdoor air does not make indoor environmental conditions worse. This chapter examines the work of the AIVC in relation to outdoor air, over the past 40 years.

12.2. Historic role of AIVC: Contributions over the last 40 years

The role of the AIVC in examining the impact of outdoor air on ventilation systems and effectiveness can be viewed in two distinct historical periods.

12.2.1. Approximately 1980 – 2000

Prior to the new millennium, the focus of ventilation research was on indoor air. Despite the external environment being acknowledged as one of the three factors contributing to indoor pollutants (the other two were indoor contaminants and occupancy / occupant behaviour), the design intent of ventilation systems was to maximise the ventilation rate without causing discomfort and ensuring that all building zones met minimum ventilation levels. The four major design strategies were (i) extracting contaminants at the source; (ii) ventilating for the worst pollutant; (iii) avoiding by-passing of the supply and extract air; and (iv) controlling the flow rate [14]. Controlling air flow rate, by addressing infiltration, was the focus of the 1983 Handbook [1].

The quality of the outdoor air, in terms of pollution and relative humidity, was generally not considered in this period of history, exemplified by the interchangeable descriptions of supply air as ‘outdoor’, ‘outside’, ‘fresh’, ‘clean’ or ‘ambient’, and indoor air as ‘polluted’ or ‘stale’. It is also exemplified in a range of publications in this period, such as:

- Technical Note 21 (1987) [14] that reviewed definitions and measurements of ventilation effectiveness (focused on ventilation efficiency and effectiveness in relation to the mixing of ‘fresh’ and ’polluted’ air) with an objective to contribute to the development of Standards;
- Technical Note 23 (1989) [15] that reviewed the impact of occupants in opening doors and windows to manage air quality. This report communicated a distinction between infiltration, airing, natural ventilation and

mechanical ventilation. Only a passing mention was made to mechanical ventilation systems that may combine with air treatment facilities (such as heating, heat recover and filtration);

- Technical Note 26 (1989) [17] that acknowledged that outdoor air could be a source of contamination, but in developing ventilation rates for effective control of indoor air quality it focused strongly on indoor contaminants such as tobacco smoke, and indoor sources of humidity relating to the presence and activities of occupants;
- Technical Notes 28 [19] (1990) and 28b [20] (1991) that examined air change efficiency and contaminant removal effectiveness, but used definitions based on net concentrations of pollutants in reference to outside air pollutant concentrations;
- Technical Note 35 (1992) [25], a state of the art review (SOTAR) of advanced ventilation systems that focused on systems for removing human generated pollutants in well constructed, airtight and insulated buildings and discussed humidity controlled ventilation that responds to indoor vapour loads and a control system that assumes a lower absolute humidity outdoors than indoors; and
- Technical Notes 39 (1993) [28] and TN 42 (1994) [31] that reviewed ventilation efficiency and strategies, yet focused on the flow rate of supply air, not its quality. There is an unstated assumption that indoor air is of porter quality than outside air.

The 1992 SOTAR (TN35) [25] noted the divergence of ventilation system development in different countries (Table 9), attributed to an interaction of climatic conditions, building techniques, ventilation philosophy, accepted indoor air quality limits, comfort expectations and the cost effectiveness of energy conservation measures. While not directly referring to outdoor air pollution or humidity, it is nevertheless significant in acknowledging the role of external climate conditions in influencing the type of ventilation system and technology trends. The report suggested that it may be necessary for ventilation classification systems to be differentiated to the type of outside climate.

Table 9: Climate influences on ventilation system types and developments

Climate	Dominant ventilation system	Technology trends
Severe (cold)	Mechanical	Improved mechanical systems
Moderate	Natural + some mechanical	Advanced natural ventilation systems
Mild	Natural	

TN49 [36], in evaluating the energy impact of ventilation, further pointed out the impact of climate variations, in particular climates where dehumidification was required. The well-accepted concept of heating degree days (HDD) was used to evaluate annual energy loads of ventilation systems, however it was acknowledged that the related concept of cooling degree days (CDD) was not as widely accepted, because of the need to account for humidity (p34). An example was given for a very cold climate, where the latent heating load was almost 1/3 of the sensible heating load (p32). This demonstrated the not-inconsequential energy impact relating to outdoor air humidity and the need for further research in this area.

It should be noted that the need for controlling moisture from the perspective of protecting the building fabric was examined in various reports during this period. Some countries were looking for relationships between outside conditions (wind, temperature and humidity) and inside conditions (ventilation rates and moisture levels), whilst others were focusing solely on indoor conditions (TN 20 [13]).

12.2.2. From 2000

The new millennium saw a shift in research to a better understanding of pollutants – both indoor and outdoor. The 2003 VIP03 [58] identified sources of outdoor air pollutants (motor vehicles, commercial and manufacturing activities, building exhaust), pollutant transport driving forces (wind, stack effect, HVAC/fans, flues, exhaust and elevators) and major outdoor-to-indoor pathways (indoor air intake, windows/doors, cracks and crevices).

TN55 [42] (2001) was one significant publication during this period, providing a reference document for “all those involved in building ventilation and air leakage research and practice”. While it focused on airtightness, indoor air quality pollutants and minimum ventilation rates, it nevertheless included existing standards for outdoor air pollutants (Table 10) and in some cases reported typical indoor/outdoor ratios of specific pollutants. Despite the report stating that outside air may contribute to internal pollutant loads (p25), the USA was the only country in this report to recommend providing some form of air supply treatment (in this case, particulate filtration) (p167). No other countries specifically referenced managing outdoor pollutants (as part of the outdoor air supply rate) and the widely accepted national standards (ANSI and ASHRAE) remained focused on air flow rates. The USA also recommended control of internal latent heat (30-60% RH) as a general goal for buildings with mechanical HVAC systems.

Table 10: Outdoor air pollutant standards as recorded in TN55 [42]

Outdoor Air Pollutant	USA National Ambient Air Quality Primary Standard		WHO Air Quality Guidelines	
	Guideline	Averaging Time	Guideline	Averaging Time
Ozone (O_3)	235 µg/m^3	Hr	120 µg/m^3	8 hr
Carbon monoxide (CO)	10 mg/m3 40 mg/m3	8 hr 1 hr	100 µg/m^3 60 µg/m^3 30 µg/m^3	15 min 30 min 1 hr
Nitrogen Dioxide (NO_2)			200 µg/m^3 40 µg/m^3	1 hr Annual
Sulphur Dioxide (SO_2)	365 µg/m^3 80 µg/m^3	24 hr Annual	500 µg/m^3 125 µg/m^3 50 µg/m^3	10 min 24 hr Annual
Particulate Matter	75 µg/m^3 260 µg/m^3	Annual 1 Hr	Effect response	
Benzene			6 x 10^{-5} (µg/m^3)-1	Lifetime
Lead (Pb)			0.5 µg/m^3	Annual

Outdoor air humidity and pollutants were both addressed in 2002 in TN57 [44]. External air pollutants were classified by source (Table 11) and, importantly, mechanisms for controlling outdoor air pollutant were suggested (Table 12).

Table 11: Classification of external pollutants and their sources

External pollutant source	Specific pollutants (examples)
Rural	Natural – fungal spores, pollen, dust (seasonal) Man-made – fertilizers, weedkillers, insecticides (seasonal)
Industrial	Nitrogen oxide, sulphure oxide, ozone, heavy metals, VOCs, hydrocarbons, smoke, particulates, fibres
Traffic	Carbon monoxide, carbon dust, lead, oxides of nitrogen, fuel additives, unburnt fuel
Ground	Radon, methane, moisture

The impact of outdoor humidity on the energy consumption of ventilation systems was communicated through the work of Colliver [34], who estimated the energy required to condition each kg/h of incoming air to the same conditions (heating set point 18ºC; cooling set point 25.6ºC; RH 40%) for 43 sites throughout Europe and the United States. Figure 4 in the report of Colliver demonstrates the impact that dehumidification has on energy consumption. Cooling Degree Days (CDD) was considered a useful concept, however it was noted that different countries used different base temperatures.

Table 12: General mechanisms for outdoor air pollutant control

Control method	Details
Legislation	For example: Clean Air Act or traffic planning controls
Careful siting of air inlets	Inlets should be sited as far away from pollutant sources as possible: • Upwind of ventilation exhaust outlets (prevailing wind) • Lower than ventilation exhaust outlets (variable wind direction) • As far away from static / slow moving traffic as possible, and at a high level • Way from other pollutant sources (e.g. plumbing and oil vents, boiler flues, stagnant water, roosting ledges, areas of vegetation and areas where litter can accumulate)
Occupant intervention	Reduce ventilation during times of high pollution production (easier implementation with mechanical systems)
Filtration	Particulate filters on air intake systems Possible future use of active carbon filters for gaseous pollutants

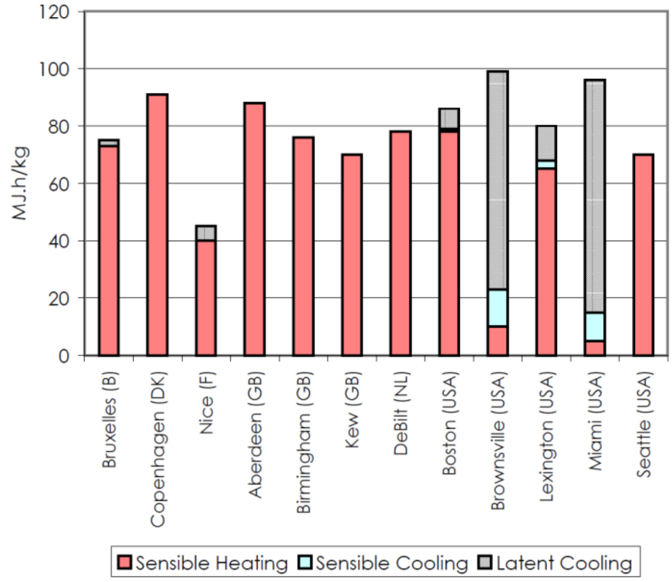

Figure 19: Comparison of energy demands of managing sensible and latent heat (TN55, derived from TN47)

TN61 [48], in examining natural and hybrid ventilation in urban environments, reiterated some of the control mechanisms of the previous report, in particular to design the position of air inlets near the building facades which are less exposed to outdoor pollution in order to enhance the possibility of using outdoor air without filtering; and controlling ventilation intakes in order to avoid ingress of polluted air during periods of peak traffic load.

TN58 [45] went a step further by examining the protective capacity of buildings to provide protection against potentially hazardous outdoor pollutants, including widespread pollutants, accidental events and potential attacks. The key strategies are summarised in Table 13 and were further re-iterated in VIP10 [65].

Both polluted outdoor air and high humidity were identified as limitations to the potential utilisation of night ventilation strategies to address the growth in air conditioning for cooling and the associated problems with peak demand.

Table 13: Strategies for reducing indoor exposures to outdoor pollutants

	Shelter in Place	Building Air Tightening & Pressure Balancing	Ventilation (if insufficient infiltration)	Filtration	Contaminant Removal
Allergens	Yes	Yes	Supply ventilation with filtration (better) Or Exhaust ventilation	MERV 6-8 (minimum) MERV 9-12 (better) Or Stand-alone high efficiency particle filtration system	Cleaning and vacuuming (high efficiency particle filtered)
Soot and Other Particulate Matter	Yes	Yes	Supply ventilation with filtration (better) Or Exhaust ventilation	MERV 9-12 or higher efficiency filter if soot includes ultrafine particles	Cleaning and vacuuming (high efficiency particle filtered)
Gaseous Contaminants	Yes	Yes	Supply ventilation with filtration	Gas phase filtration (charcoal absorption)*	Reduce outdoor emissions
Toxic Air Pollutants	Yes	Yes	Shelter in Place and turn off central distribution system to minimize toxin circulation into safe haven – at-risk individuals may need to create a safe haven with high-efficiency particle filtration and gas phase filtration	Gas phase filtration (charcoal absorption) if the contaminant to be removed is known	Reduce outdoor emissions

*If no gas phase filtration in place, circulate air within the house to lower ozone concentration by decomposition and shelter in place during high ozone periods.

12.3. State of the Art

The increased interest in specific pollutants and the role of ventilation in managing those pollutants has continued and is now evidenced by the focus on indoor air quality and health. TN68 (2016), for example, provides an overview and prioritisation of pollutants, identification of potential health effects and control strategies to reduce health effects. In highlighting the need to have better insight into outdoor sources of pollutants and pollutant behaviour indoors, it details specific polluting compounds that can have an outdoor source, including Acetaldehyde, Acrolein, Alpha-Pinene, Benzene, CO, CO_2, Ethylbenzene, Formaldehyde, NOx, Ozone, Phthalates, PM2.5 / PM10, Polycyclic aromatic hydrocarbons (PAHs), SO_2, Toluene and Ultra fine particles (UFPs). This report was important in highlighting the lack of a universal approach to addressing the potential hazards posed by a diverse range of compounds from a diverse set of sources nor a method for quantifying the benefits of reducing concentrations to non-hazardous levels. The current state of the art, regarding outdoor air pollutants, can be seen in Figure 19, demonstrating the increasing attention being paid to the link between pollutants (indoor and outdoor) and occupant health. Better understanding of pollutant exposure is required, including emission rates, dispersion processes, and loss mechanisms such as chemical losses or deposition. This report eloquently elaborates the role of ventilation in managing health risks, and the need for the development of methods to quantify the benefits and limitations of ventilation for this purpose.

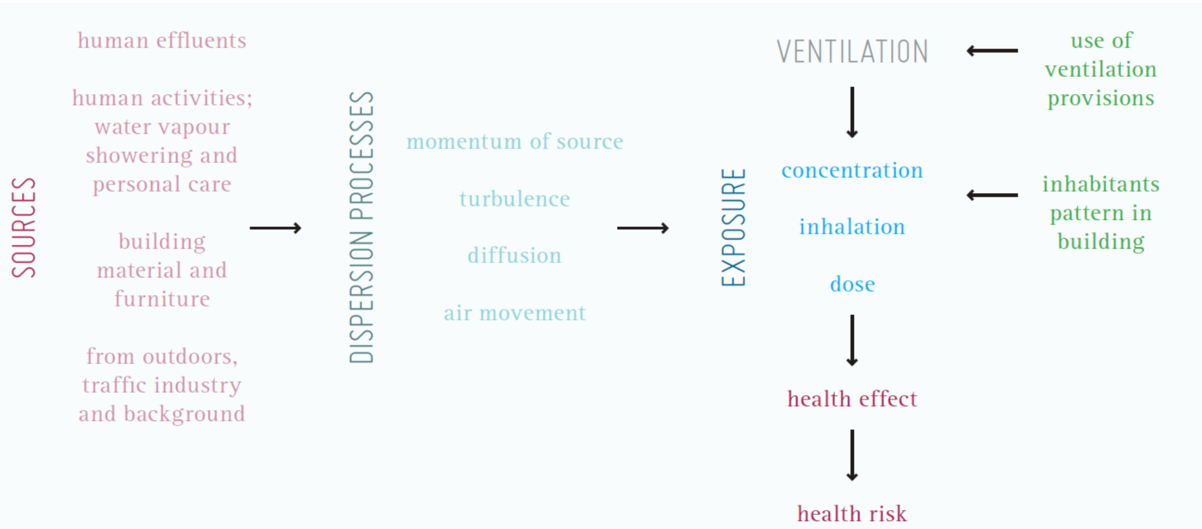

Figure 20: Path from pollutant to health risk (TN68 [55], from de Gids 2012)

12.4. Looking forward

The work examining the link between ventilation, pollutant control and health is likely to continue. Addressing moisture issues in low energy cooling technologies also needs much more work. Some questions that could be addressed in the coming decade include:

- Will the nature and distribution of outdoor air pollutants change as our stationary energy and transport systems are increasingly electrified? In particular, how will electrification of these systems impact on the prevalence of PM2.5 and tropospheric ozone? How could this impact on ventilation options?
- Can the world afford mechanical systems to be installed in all buildings globally (arguably the systems providing greatest control of outdoor pollution), or should we be proactively examining hybrid ventilation options that can make greatest use of ambient conditions when the outdoor air is of high quality (in terms of pollution, temperature and humidity)?
- Have we adequately defined indoor environment conditions that protect the health and wellbeing of occupants, are low energy, and yet account for different climates, cultures, building types, and occupant demographics?
- Ventilation and heating and cooling technologies to date have focused on average weather conditions. What new technologies and design strategies are needed for managing extreme events? How do extreme weather conditions impact on outdoor air pollutants and humidity?

Some of these questions will be addressed by the new Annex 80 Resilient Cooling.

12.5. References

All AIVC references are in the AIVC general reference list (chapter 16) which is added as a separate chapter at the end of this Technote

13. Smart Ventilation and IAQ metrics

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13.1. Introduction

In order to address energy demand and indoor air quality issues better, ventilation systems need to become smarter. To be smarter they must be able to shift ventilation in time, changing airflow rates, detecting occupancy, responding to measured contaminants, knowing when other air moving systems are operating (such as kitchen extract ventilation), and responding to signals from the electric grid or energy management systems. This is an important change from the current state-of-the-art of fixed airflow rate continuously operating systems. For example, a smart ventilation system should provide more air at times when there is an energy and/or an indoor air quality (IAQ) advantage, and less when there is a disadvantage. Ventilation systems that have smart elements can achieve energy savings of up to 60% without compromising IAQ, but those that are poorly executed can increase their energy demand by up to 26% (Guyot et al., 2018). Accordingly, future ventilation systems need to sense their environment to make decisions over extended periods so that they moderate their performance proactively, rather than reactively, and they must do this using performance metrics that go beyond a simple specified airflow rate. They need to be smart.

Smart Ventilation is a relatively new concept and so the information discussed herein can be considered state of the art.

13.2. Historic Role of AIVC

Because Smart Ventilation is a development from just the last five years, AIVC's role was to be a platform for papers and presentations during the yearly conferences. Several years ago papers were presented at the AIVC conference that included smart ventilation concepts, such as improved humidity control (Ticci et al., 2015) and use of outdoor temperature controls (Lubliner et al., 2016). As more applications for smart ventilation were investigated it became clear that a definition was needed, particularly as the term was beginning to be used to describe systems that we would not consider to be "smart" – usually because they saved energy while compromising IAQ+.

AIVC VIP 38 (2018) [93] smart ventilation as "a process to continually adjust a ventilation system in time, and optionally by location, to provide desired IAQ benefits while minimizing energy demand, utility bills, and other non-IAQ costs, such as thermal discomfort or noise".

13.3. What is Smart Ventilation?

Commercial buildings have controlled their ventilation systems by monitoring outdoor conditions and occupancy to help reduce energy demand use for many years. Until recently, there was no equivalent for residential ventilation systems. The concept of smart ventilation for homes was initially developed at the Lawrence Berkeley National Laboratory and was based on ventilating less when outdoor temperatures are extreme and more at other times combined with sensing the operation of kitchen/bathroom exhausts and clothes dryers (Walker et al., 2012). Of key importance was the concept of ventilation equivalence that ensures occupant exposures are not increased by smart ventilation strategies (Sherman et al., 2010; Sherman et al., 2012). The basic principle of equivalent ventilation is that any two ventilation patterns are equivalent if they provide the same average exposure to a generic contaminant or over the long term. The concept is now established and contained within the US National Ventilation Standard (ASHRAE 62.2) as a compliance option.

A smart ventilation system adjusts ventilation rates in time or by location in a building in response to a range of factors. It can also interact with utilities to respond to local electricity grid control strategies. The information required to control the system can be shared with a building's owners, occupants, and managers giving an indication of its operational energy demand and indoor air quality. The sensors required to detect airflow, system pressures, or fan energy can also be used to show when the system needs maintenance or repair.

13.4. Benefits

13.4.1. Time Shifting

Smart ventilation systems are able to time shift ventilation to minimize heating and cooling loads. For example, ventilation can be increased when the difference between the indoor and outdoor temperatures are at their lowest to minimize heating and cooling loads, or increased when the outdoor temperature is significantly lower than the indoor temperature to take advantage of free-cooling (see Chapter 8 on Ventilative Cooling). Reducing the ventilation rate when the outdoor temperature is significantly higher than the indoor temperature can save energy but requires more ventilation at other times to maintain IAQ. The ventilation can also be varied according to the quality of outdoor air, which may vary periodically.

The time shift period may be a matter of hours but could also be over a number of months to account for seasonal changes. Seasonal time shifting has the greatest potential for energy savings, but the potential increase in occupant exposure to indoor pollutants during extended periods of under-ventilation is unknown and remains a topic of debate.

13.4.2. Occupancy sensing

The concept of equivalent exposure means that a smart ventilation system needs to account for contaminants emitted when people are not in a space. This has serious implications for occupancy-based controls due to the build-up of contaminants during unoccupied times (Walker & Less, 2018). However, a smart ventilation system can pre-ventilate for a period of time before occupancy depending on the IAQ, allowing it to both provide acceptable IAQ and optimize performance.

13.4.3. Fan sensing

The fans of a smart ventilation system can be continuously monitored to determine their performance. A deviation in fan working speed or energy demand could indicate an increase in the probability of system failure. An increase in the system pressure can be used to show when a filter needs to be replaced or a blockage, perhaps in a diffuser.

13.5. Metric for Indoor Air Quality

A new metric for indoor air was discussed in recent years at AIVC workshops and conferences. Currently CO_2 is used as a marker for indoor air quality. As described in VIP 33 [88]: "CO_2 as indicator for the indoor air quality - General principles" (2010): "The role of CO_2 to control the indoor air quality in buildings is based on the fact that CO_2 developed by people breathing may be used as a maker for the bio-effluents produced by people. The use of CO_2 for the steering of ventilation systems is only appropriate in the case that no other pollutant is more dominant for the indoor environment. For instance, when a person is taking a shower in a bathroom, moisture will be the most dominant pollutant. Nevertheless, the use of CO_2 as a marker for indoor air quality is widely used.

Because of studies of Logue and other studies on assessing the impacts of pollutants, several initiatives were taken for a metric for indoor air as within IEA Annex 68 reported in CR 17: "Indoor Air Quality Design and Control in Low-energy Residential Buildings- Annex 68 | Subtask 1: Defining the metrics | In the search of indices to evaluate the Indoor Air Quality of low-energy residential buildings" (2017). In this study indices are described based on ELVs, DALY approach and also taken into account long-term exposure, short-time exposure and indoor air and Energy. Also studies were conducted for instance at Lawrence Berkeley National Laboratory to develop a new Metric for Indoor Air. Results were discussed at several workshops for example at the AIVC conference in Alexandria (2016), in 2016 at the AIVC-REHVA conference in Aalborg, the workshop on IAQ Metrics in 2017 Brussels, and the AIVC workshops in Melbourne and Wellington 2018. The 2017 Brussels workshop is described in VIP 36 [91]: Metrics of Health Risks from Indoor Air (2017). It summarized the discussions and identified the type of contaminants found in many buildings today, the mechanisms of exposure to them and methods of mitigating their effect. And metrics are explored that could be used to quantify the quality of indoor air.

Many current metrics of IAQ are olfactorily based using ventilation rates to dissipate bio-effluents in the first instance and increased to mitigate against other indoor pollution sources, such as moisture and NO_2. Respiratory CO_2 has been used as an indicator of ventilation rates for over 100 years, albeit with significant uncertainty (Persily, 2015; Persily, 2017; Persily, 2018; Persily & Polidoro, 2019).

More recently, the definition of the quality of air has evolved to identify when it is acceptable to the majority of occupants based on odour, moisture, and human health, acknowledging that health effects can be both short (acute) and long term (chronic) and so may not be immediate. However, there are so many contaminants found in indoor environments that it is time and cost prohibitive to measure them all. Pollution sources also vary by room type and so different ventilation measures and controls are required. Smart ventilation is based on the concept of a generic contaminant, but in reality there are several contaminants of concern, which is a topic of on-going research. To do this metrics are used to identify those that are most prevalent and harmful to human health. Then, they can be controlled to minimize occupant exposure. AIVC CR17 (Abadie & Wargocki, 2017) [95] considers two metrics of IAQ determined from indoor contaminants distilled into marker pollutants; see Figure 21.

Exposure limit values (ELV) are used in occupational environments to prevent or reduce risks to health from hazards by setting a maximum quantity a person is exposed to per day. This principle could be applied by a smart ventilation system by measuring the concentrations of target pollutants over time in a building. The ratio of each measurement of a pollutant would be compared to their respective ELV concentrations to give a quick indication of risk where a ratio $\ll 1$ might be acceptable, but one approaching, or exceeding, unity may be problematic. Here, an indication of the relationship between exposure and health consequences is required. ELVs are particularly useful when short term (acute) exposures to pollutants, such as carbon monoxide, pose a significant risk.

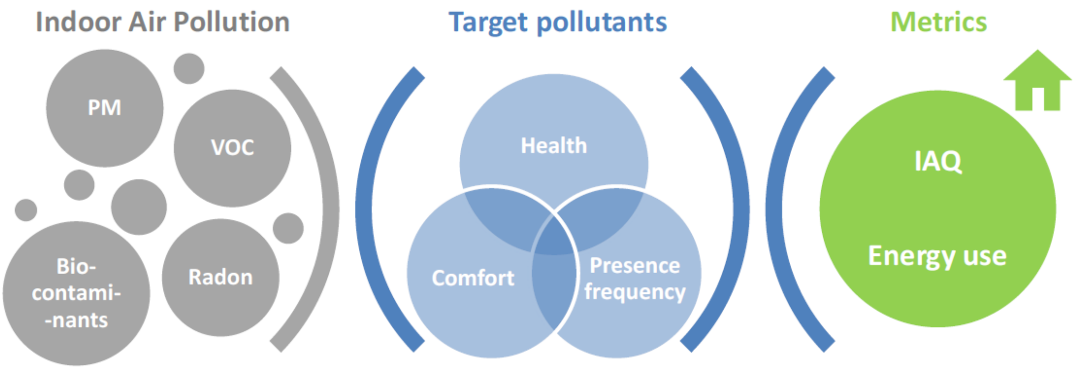


Figure 21: Determining metrics of air quality from indoor contaminants using target pollutants (Abadie & Wargocki, 2017).

Economics and IAQ are normally linked by optimizing the costs of providing ventilation, such as the costs of designing, purchasing, installing, operating the system. Generally, the operating costs exceed the capital costs, which encourages the implementation of technologies such as heat recovery to optimize the life-cycle costs. Smart Ventilation systems make this type of optimization more complex and valuable because it can provide other services while still meeting IAQ criteria. Time shifting ventilation and reducing over-ventilation can save energy costs or peak utility charges. Exploiting ventilative cooling or exogenous local exhausts can also increase energy savings.

However, not all of the benefits of Smart Ventilation can be monetized easily. For example, it is clearly a benefit to reduce exposure by shifting ventilation away from times where the outdoor air quality is bad, but it is not easy to put a value on that benefit and thus determine what mitigation is worth. However, the more IAQ can be monetized, the easier it will be to incorporate it into everyday decision making. HALY IAQ metrics, such as a DALY, can be monetized. However, their value is strongly dependent on the culture and socio-economic status of the person whose DALY is considered. Here, a DALY in a developed western society is likely to be worth more than in a poor country based simply on standards of living. This monetization, however, does not include loss of productivity or costs of health care; it only includes the value of the lost health to the individual and therefore represents a lower limit of the economic cost.

The DALY approach can monetize the health aspects of the IAQ. Nascent efforts are underway to similarly quantify the comfort aspects of the indoor environment. In the future, both the health and perceived aspects of IAQ could be fully monetized.

The advantage of being able to put a monetary value on indoor pollutant exposure is that it facilitates a more efficient means of providing economic value:

A designer can trade-off source control, ventilation, and air cleaning options to meet performance requirements.

A standards-writer will be able to create standards by looking at the monetize value that its protections provide and allow performance-based rather than prescriptive approaches.

A policy maker can determine the relative costs and benefits of specific policy options such as those intended to protect occupant health.

Future IAQ systems can be based more on the control of contaminants and their impact rather than on providing ventilation.

13.6. References

All AIVC references are in the AIVC general reference list (chapter16) which is added as a separate chapter at the end of this Technote

14. Mechanical Ventilation

François Durier, Cetiat, France

14.1. Introduction

In the AIVC Glossary (Limb, TN36,1992)[26], the following definition of ventilation is given:

– *"Ventilation: The process of supplying or removing air, by natural or mechanical means to and from a space".*

The same publication includes also a definition of mechanical ventilation:

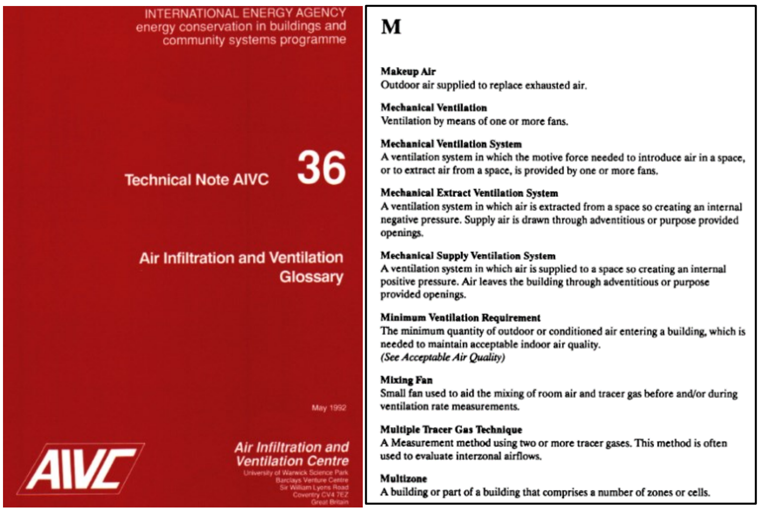
– *"Mechanical ventilation: Ventilation by means of one or more fans".*

As a consequence, a mechanical ventilation system is then defined as:

– *"Mechanical ventilation system: A ventilation system in which the motive force needed to introduce air in a space, or to extract air from a space, is provided by one or more fans".*

These definitions are still fully valid. The AIVC Glossary has supplemented them with other interesting definitions that describe different types of mechanical ventilation systems:

– *"Mechanical extract ventilation: A ventilation system in which air is extracted from a space so creating an internal negative pressure. Supply air is drawn through adventitious or purpose provided openings"*
– *"Mechanical supply ventilation: A ventilation system in which air is supplied to a space so creating an internal positive pressure. Air leaves the building through adventitious or purpose provided openings"*
– *"Balanced supply/extract ventilation system: A ventilation system in which fans both supply and extract air from an enclosed space at equal rates" (Limb, 1992).*



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Makeup Air
Outdoor air supplied to replace exhausted air.

Mechanical Ventilation
Ventilation by means of one or more fans.

Mechanical Ventilation System
A ventilation system in which the motive force needed to introduce air in a space, or to extract air from a space, is provided by one or more fans.

Mechanical Extract Ventilation System
A ventilation system in which air is extracted from a space so creating an internal negative pressure. Supply air is drawn through adventitious or purpose provided openings.

Mechanical Supply Ventilation System
A ventilation system in which air is supplied to a space so creating an internal positive pressure. Air leaves the building through adventitious or purpose provided openings.

Minimum Ventilation Requirement
The minimum quantity of outdoor or conditioned air entering a building, which is needed to maintain acceptable indoor air quality.
(See Acceptable Air Quality)

Mixing Fan
Small fan used to aid the mixing of room air and tracer gas before and/or during ventilation rate measurements.

Multiple Tracer Gas Technique
A Measurement method using two or more tracer gases. This method is often used to evaluate interzonal airflows.

Multizone
A building or part of a building that comprises a number of zones or cells.

Figure 22: Cover page and inside page of the AIVC Glossary (Limb, 1992)

One interesting aspect of a mechanical ventilation system is that the presence of a fan allows to easily insert into the system a heat exchanger, in order to recover heat from the exhaust air. The additional pressure loss generated by the heat exchanger is overcome thanks to the fan. The AIVC glossary includes a definition of such a heat recovery device:

– *"Heat exchanger (air-to-air): A device designed to transfer heat from two physically separated fluid streams. In buildings, it is generally used to transfer heat from exhaust warm air to incoming cooler outdoor air".*

Nowadays, heat recovery on exhaust air can not only be used for heating incoming outdoor air thanks to a heat exchanger, but also rely on an air-to-air heat pump, or use an air-to-water heat pump for providing space heating and/or domestic hot water.

Another strength of mechanical ventilation systems is the ability to modulate/adjust the ventilation rate according to various parameters that reflect the ventilation needs. The AIVC Glossary (Limb, 1992) provides a definition of such demand-controlled ventilation:

- *"Demand-controlled ventilation: A ventilation strategy where the airflow rate is governed by a chosen pollutant concentration level. This level is measured by air quality sensors located within the room or zone. When the pollutant concentration level rises above a preset level, the sensors activate the ventilation system. As the occupants leave the room the pollutant concentration levels are reduced and ventilation is also reduced. Common pollutants are usually occupant dependent, such as, carbon dioxide, humidity or temperature."*

The length of this definition probably reflects that the concept was rather new at the time when it was written (1992), requiring several explanations. It is common today that demand-controlled ventilation not only relies on sensing a chosen pollutant concentration level. The airflow rate can be for example also governed by a timer, or a sensor to detect room or building occupancy.

It is notable that this definition only includes contaminants (or surrogates such as CO_2) that are directly generated by occupants. It does not include important contaminants from a health perspective, such as formaldehyde and other VOCs from construction materials and building contents. This addition of health concerns to IAQ and ventilation is a key change since this definition was written. Other drawbacks with this definition are that temperature is not really an air contaminant and is mainly not occupant dependent[4]. It would be better to say that demand-controlled ventilation may contribute to comfort and energy use by controlling based on temperature.

Mechanical ventilation also enables air filtration and air cleaning. The fan can be designed to provide an air pressure that overcomes the additional pressure loss due to air filters and air cleaners into the ventilation system (Liddament, [5] 1996; Borsboom & al., TN 68 [55] 2016).

An important consideration of mechanical ventilation systems is the electricity consumption of the fan motors, particularly when ventilation is combined with heat recovery or integrated into distribution systems, both of which significantly increase fan power requirements. This is particularly true for residential ventilation where fan power of a heat recovery ventilation system or a fully ducted forced air system can be 10 to 100 times higher than the power of an exhaust fan. Low power and high efficiency motors can overcome this issue, together with a relevant ventilation strategy.

14.2. Historic role of AIVC

14.2.1. Concepts for rating mechanical ventilation systems

Several AIVC publications (from 1987 to 1993) dealt with the concepts of ventilation efficiency, with the aim to quantify the performance of a ventilation system, on one hand by providing fresh air to occupants, on the other hand by diluting and removing pollutants derived from indoor sources.

Bigger ventilation efficiency reduces ventilation needs, and thus decreases the associated energy load.

The concept of ventilation efficiency can be explained as follows:

- *"Ventilation efficiency may be regarded as a series of indices or parameters which characterize the mixing behavior of air and the distribution of pollutants within an enclosure. These two aspects may be subdivided into indices of air change efficiency and contaminant removal effectiveness respectively" (Liddament TN 39 [28] 1993).*

The air change efficiency indicates how quickly the air is replaced in the room (Limb TN 36 [26] 1992; Liddament TNM39 [28] 1993). An air change efficiency of 100% relates to an enclosure where the actual time to completely replace air is equal to the minimum possible time to exchange all the air with fresh air in this specific enclosure.

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[4] *Note: Indoor temperature mainly depends on outdoor climate, building characteristics, heating and/or air conditioning system operation, and to a lesser extent on some occupant activities.*

The contaminant removal effectiveness is defined as "*the ratio between the steady state concentration of contaminant at the exhaust duct and the steady state mean concentration in the room*" (Brouns & al. TN 28.2 [20] 1991). It depends on the room, on the ventilation air flow rate, on the mixing between fresh air and room air, and on the location of contaminant emission.

Contaminant removal effectiveness will for example be equal to 1 in a room with perfect mixing of incoming air with room air, and equal to 2 in the ideal case of a room in which ventilation creates a piston-flow and contaminant is injected at a constant rate at all points throughout the space (uniform injection in the room) (Brouns & al. TN 28.2 [20] 1991).

Contaminant removal effectiveness has also been called in some AIVC publications "*Pollutant removal effectiveness", defined as "a measure of how effectively pollutant from an internal contaminant source is diluted and removed from an enclosure*" or "Ventilation effectiveness", defined as "*an expression describing the ability of a mechanical (or natural) ventilation system to remove pollution originating in a space, either of a steady state or transient nature*" (Limb, 1992).

Even if all these indicators are not commonly used nowadays, the fact that they have been built on an international consensus is of interest. They allowed to better understand the role of ventilation and the assessment of its performance on providing indoor air quality. They continue to be used in research projects and are mentioned in standards.

In addition to their definition, AIVC also explained how to measure or to calculate these indicators. For example, the diagrams of Figure 23 show how ventilation effectiveness can be measured or calculated using computational fluid dynamics (CFD) (Liddament, 1993).

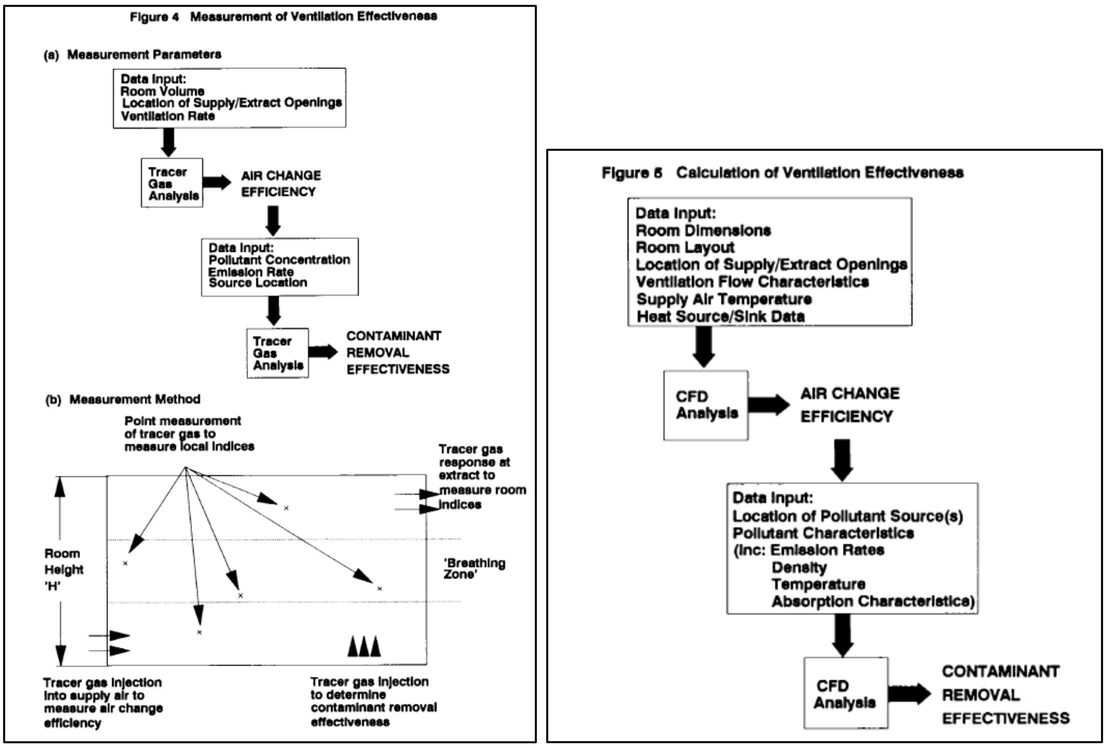

Figure 23: Measurement and calculation of ventilation effectiveness (from Liddament TN39 [28] 1993)

14.2.2. Design of energy efficient mechanical ventilation systems

In the AIVC "Guide to Energy Efficient Ventilation" (Liddament, 1996), whose objective is to review ventilation in the context of both energy efficiency and achieving good indoor air quality, it is estimated that *"approximately 30% of the energy delivered to buildings is dissipated in the departing ventilation and exfiltration air streams. In buildings constructed to very high standards of thermal insulation, the proportion of airborne energy loss can be much higher […] The amount of energy consumed is dependent on the flow rate of ventilation and the amount of conditioning of* *the air that is necessary to achieve thermal comfort […]. Additional energy is needed to drive mechanical ventilation systems […]".*

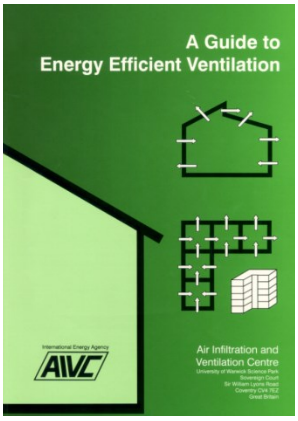

Figure 24: Cover page of the Guide to energy efficient ventilation (Liddament [5] 1996)

The guide points out that ventilation energy demand can be reduced by, for example, minimizing the need for ventilation, avoiding uncontrolled air infiltration losses, using demand-controlled ventilation and implementing heat recovery.

An AIVC document provides recommendations on fan energy efficiency (Schild TN 65 [52] 2009). It emphasizes that energy use for fan operation can be significantly reduced by:

- prudent sizing of ventilation rates by minimizing the ventilation needs, efficient ductwork, and careful choice of room airflow principles;
- minimizing flow resistance, and hence fan pressure;
- optimizing efficiency of the fan system, including the fan, drive, motor, and variable speed drive, and avoiding oversizing.

The energy impact of ventilation of residential and of non-industrial buildings has also been explored by AIVC (Concannon TN 57 [44] 2002; Orme TN 49 [36] 1998).

14.2.3. Characteristics and performance of different mechanical ventilation systems

The AIVC "Guide to Energy Efficient Ventilation" (Liddament, 1996) [5] states that many systems operate:

- to provide 'mixing' or 'dilution' ventilation, in order to dilute pollutants, or
- to 'displace' air in the space to get 'displacement' or 'piston flow' ventilation, in order to remove pollutants without mixing.

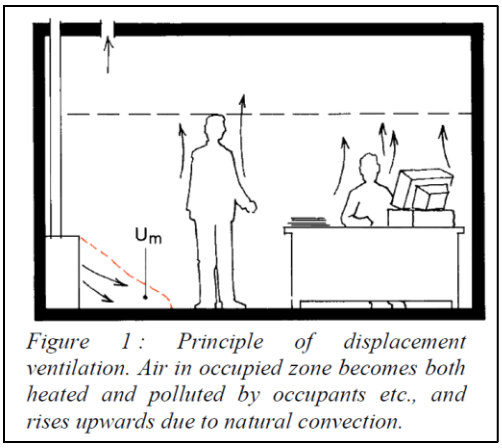

Figure 25: Principle of displacement ventilation (from Schild, 2004)

This guide also explains that mechanical ventilation systems "are capable of providing a controlled rate of air change and respond to the varying needs of occupants and pollutant loads, irrespective of the vagaries of climate. Some systems enable incoming supply air to be filtered while others have provision for heat recovery from the exhaust air stream".

As already mentioned, several configurations of mechanical ventilation are possible:

– extract ventilation;
– supply ventilation;
– balanced supply/extract.

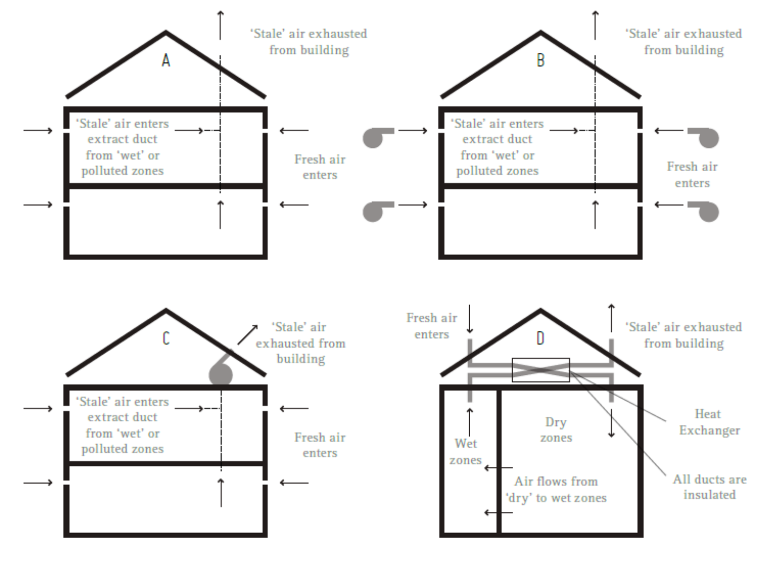

Figure 10: Four principles of ventilation system: A)Passive and natural ventilation, B)Mechanical supply and natural exhaust ventilation, C)Mechanical exhaust and natural supply, and D)Balanced ventilation system.

Figure 26: Different ventilation systems – the upper left system is not mechanical (from Borsboom & al.TN68 [55] 2016)

The guide mentions advantages and disadvantages of each of these configurations. This is summarized in Table 14.

Table 14: Advantages and disadvantages of different mechanical ventilation systems (from Liddament [5] 1996).

	Mechanical extract ventilation system	Mechanical supply ventilation system	Balanced mechanical supply/extract ventilation system
Advantages	• Allows controlled ventilation rates • Makes possible the extraction of pollutants at source • Reduces risk of moisture entering walls • Makes heat recovery from the exhaust air possible	• Outdoor air can be filtered and conditioned • Good air control possible • Entry of radon inhibited. • Flue back-draughting risk reduced	• Allows heat recovery and pre-heating of supply air • Supply air targeted to occupied zones • Absence of high suction pressures reduces risk of back-draughting and entry of radon • Filtration of incoming air possible
Disadvantages	• Energy consumption of the fan • Risk of noise • Risk of back-draughting from flues • Under-pressure can increase presence of radon, if any • Weather conditions can influence air inlets • Adjustment of individual air inlets can affect flow patterns	• Problems if air intake dampers blocked or closed, or if air intakes close to pollutant sources • Indoor moisture may be driven into the building fabric • Heat recovery not possible • Removal of pollutants at source not possible	• Two systems are present, thus doubling installation and costs. • Requires regular long term maintenance • Needs to be installed in airtight enclosures. This reduces safety margins if system fails to operate correctly or if the occupant unwittingly introduces high polluting sources into the building

The different systems are compared in other AIVC publications, from the bibliography (Parfitt, 1985), for residential buildings (Concannon TN57 [44] 2002), for large non-domestic buildings (Dickson TN 50 [37] 1998) and from a health point of view (Borsboom & al.TN 68 [55], 2016).

Specific systems are also analysed in AIVC documents such as: intermittent ventilation (Knoll TN 35 [25] 1992; Sherman TN 60 [47] 2006), humidity-controlled exhaust ventilation (Savin & al., 2009), local demand-controlled ventilation system in each room (Knoll, 1992).

14.2.4. Focus on heat recovery

Air-to-air heat recovery in ventilation systems is documented in several AIVC publications (Irving, 1994; Schild, 2004). They show the different types of heat exchangers that can be used to recover heat (and in some cases also moisture) from exhaust air in order to transfer it to supply air, "*thus reducing the heat loss due to ventilation, and reducing the need to condition the cold supply air*" (Schild VIP 05 [60] 2004).

These publications also define the parameters that can be used to assess the heat recovery performance (heat exchanger efficiency, heat recovery efficiency, seasonal mean heat recovery efficiency), provide information about energy savings and profitability according to building type, and insist on the need for commissioning and maintenance of these systems.

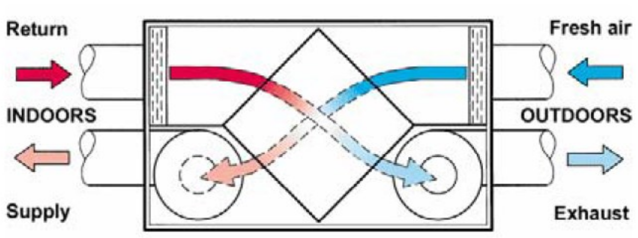

Figure 27: Principle of an air-to-air heat recovery device (from Schild, 2004)

In the heating season, earth-to-air heat exchangers (Santamouris VIP 11 [66] 2006) allow preheating of the supply air, reducing thus the heating load of the buildings, thanks to the higher temperature of the soil than the ambient outside temperature. They are therefore limited to certain climates and soil characteristics (thermal capacity, thermal conductivity, absence of radon, etc.). Design rules must be carefully followed and precautions must be taken to avoid undesirable phenomena, such as stagnation of condensed water and fouling inside buried duct.

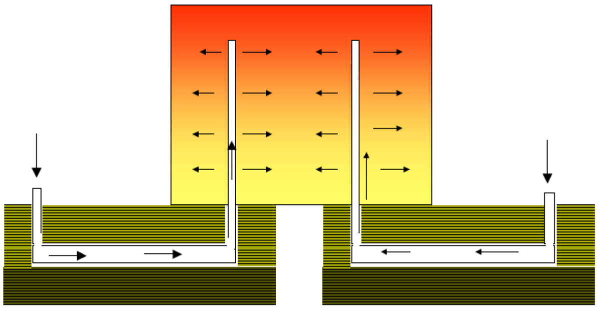

Figure 28: Principle of an earth-to-air heat exchanger (from Santamouris VIP 11 [66] 2006)

14.2.5. Focus on air filtration and air cleaning

Filtration can be used with mechanical supply or balanced ventilation systems to reduce the transfer of contaminants from outside to inside (Concannon TN 57 [44] 2002).

The AIVC report "Reducing indoor residential exposures to outdoor pollutants" (Sherman TN 58 [45] 2003) discusses to what extent air filtration can be used together with the different types of mechanical ventilation systems, in order to remove outdoor contaminants from the incoming air stream. The report provides information on the filtration of particulates as well as the filtration of gaseous contaminants (gas-phase filtration).

The AIVC report " Residential Ventilation and Health " (Borsboom & al. TN68 [55] 2016) states that: "*Without proper maintenance however, filters can become clogged and may reduce the flow or cease the flow of supply systems*".

The same report mentions that air cleaning is a method to capture indoor contaminants by passing the contaminated air through a filter or other medium. Air cleaning is most effective at controlling pollutants associated with specific indoor air quality problems. It is not a substitute for ventilation (introduction of fresh air), which remains necessary "*to meet the metabolic needs of occupants, since air cleaning does not replenish oxygen or normally remove metabolic carbon dioxide from the indoor air*".

In addition, precautions must be taken that the air cleaning of gaseous contaminants does not generate other contaminants resulting from uncontrolled chemical reactions.

In summary, "*various filtration and air cleaning technologies are available, but the energy and health impacts of these technologies vary widely*" (Borsboom & al., 2016).

14.2.6. Focus on ductwork (airtightness, cleaning)

Ductwork is used for transport of air used for ventilation or air conditioning in buildings, as well as extract and exhaust air. A small amount of energy must be used for the air transportation and the indoor air quality must not be deteriorated by ductwork.

One AIVC report (Malstrom TN56 [43] 2002) provides an overview of the issues linked to ductwork: importance of lay out and sizing, interest of duct insulation, safety in case of a fire (avoiding fire and smoke spread), acoustical issues, mechanical strength, flow rate balancing and control, air tightness, and air hygiene.

Other AIVC publications deal with ductwork airtightness (Carrié & al., 1999; Delmotte VIP 01 [56] 2003), showing the importance of this issue to avoid a lack of ventilation and save energy.

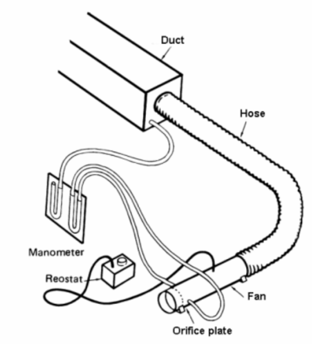

Figure 29: Example of ductwork airtightness measuring equipment (from Delmotte VIP 01 [56] 2003)

Air tightness is a growing concern in several countries (Carrié & al. VIP 29 [84] 2008), where measurement campaigns have been organized and various schemes implemented to stimulate good airtightness: regulations, inspections, training of installers, etc.

Needs and methods for ductwork cleaning are also presented (Barbat & al. VIP 34 [89] 2010) from the French experience.

14.2.7. Noise issues

Acoustics of ventilation systems is not an issue directly investigated in detail by AIVC. Nevertheless, some reports deal with acoustics and ventilation (Ling, 2001), aerodynamic noise of fans (Guédel CR 01 [94] 2005) and noise generated by air flows in ventilation systems (Guédel CR 0[95] 2005).

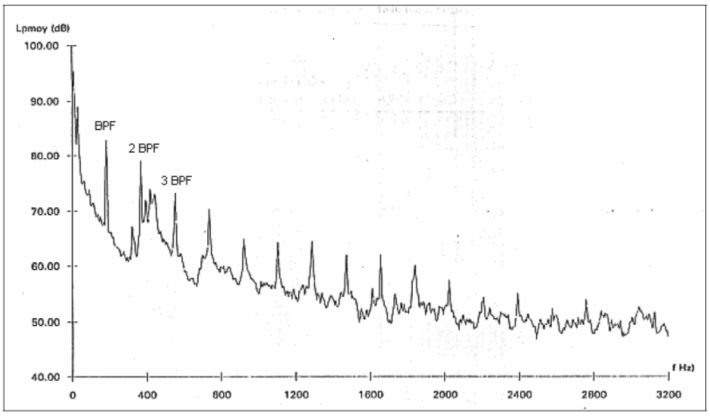

Figure 30: Example of sound pressure spectrum of an axial fan (from Guédel CR 02 [95] 2005)

14.2.8. Standards, regulations, policies and quality improvement of installed mechanical ventilation systems

In Europe, a directive about the energy performance of buildings, implemented in the national regulations of all countries of the European Union, has been presented in several AIVC publications, as well as its impacts on ventilation systems and on European standards (Wouters VIP 09 [64] 2004; de Gids VIP 14 [69] 2007).

In 2008, AIVC dedicated a specific workshop to national trends in AIVC countries about national building ventilation markets and drivers for change. Information was exchanged about policies, regulations and standards.

Among the various documents prepared on the occasion of this workshop, one is especially describing the national trends related to innovative ventilation systems (Heijmans & al.VIP 30 [85] 2008) and the way by which they are taken into account, for example to prove, according to the requirements of the regulations or standards, that they provide ventilation that is equivalent to the one provided by classical ventilation systems.

AIVC publications also describe test methods of systems. One report (Ginestet CR 15 [108] 2012) describes the development and evaluation of a new test method for portable air cleaners.

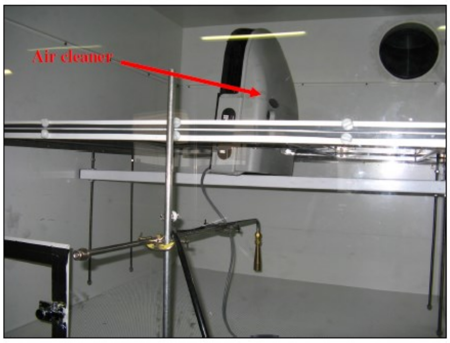

Figure 31: Air cleaner under test installed within the test chamber

The quality of installed ventilation systems is still an issue in a lot of countries. One report (Carrié & al., 2017) describes some results of the European project QUALICHeCK, that show how some countries have implemented measures to improve the quality of the installed mechanical ventilation systems. The measure can be for example: to provide easily accessible technical data about the ventilation system on the market; to operate system inspections; to train and certify installers and maintenance workers.

14.2.9. Models

Several AIVC publications dealt with models allowing to simulate and to predict the whole building airflow, allowing thus to assess the operation and efficiency of the mechanical ventilation system.

These publications describe the possible use of computational fluid dynamics (CFD) to calculate air movements and pollutant transport (Liddament TN 33 [23] 1991), the combined modelling of heat transport and air movement

(Kendrick TN 40 [29] 1993), the interest of 'network' models in which the building is represented by a collection of zones interconnected by air flow paths (Orme TN 51 [38] 1999).

This information is summarized in the AIVC Ventilation modelling data guide (Orme et al. [6] 2002), that provides a description and evaluation of several models and the data to be used to operate them.

Due to the extremely fast evolution of hardware and software capacities, these reports are probably outdated concerning the description of specific modelling tools that have since disappeared, but they are still useful to understand the possible approaches for modelling ventilation, air movements, pollutants transport, etc.

14.3. State of the art

Mechanical ventilation is widely used throughout the world in residential and non-residential buildings. Requirements, available products and design and installation rules exist, but the quality of installed ventilation systems remains poor in many places.

Mechanical ventilation systems have national specificities, due to climates, national construction traditions, national requirements, different sensitivities of occupants to the indoor air quality, etc.

In the last 40 years, a crucial role of AIVC was to reach and disseminate a consensus view at international level on topics such as:

– the different types of mechanical ventilation systems;
– the characterization of their performance regarding IAQ and energy;
– the improvement of their energy, IAQ and noise performance, through relevant components and controls;
– the improvement of their quality of installation and maintenance;
– the way to design and operate models to predict and analyze air movements and pollutant transport.

AIVC is also a place to exchange information about policies, regulations, standards, markets linked to mechanical ventilation systems, especially to improve the quality of installed ventilation systems.

14.4. Looking forward

The topics of ongoing EBC Annexes and AIVC projects reflect some of the research needs about mechanical ventilation at the international level.

Ongoing projects of International Energy Agency's Energy in Buildings and Communities Programme that relate to mechanical ventilation include:

– Annex 78: Supplementing ventilation with gas-phase air cleaning, implementation and energy implications (2018-2023)
– Annex 68: Design and Operational Strategies for High IAQ in Low Energy Buildings (2014-2019)

Ongoing AIVC projects, whose objective is to collect and distribute information on identified interesting topics, in relation to mechanical ventilation include:

– Smart ventilation: this project led in particular to a publication (Durier & al., 2018) that proposes and explains an AIVC definition for smart ventilation
– Utilization of heat recovery on the methods used to assess the influence of heat recovery ventilation on the energy use of buildings
– Cooker hoods in residential buildings, especially looking at possible conflicts between operation of balanced ventilation systems and cooker hoods
– Rationale behind ventilation requirements and regulations, to collect information on this topic in different countries and to analyze differences and similarities
– IAQ metrics: the topic was especially discussed in an AIVC Workshop in Brussels in March 2017
– What can the market uptake of BIM mean for ventilation and airtightness?

In 1992, an AIVC report (Liddament TN 37 [27] 1992) proposed a strategy for future ventilation research and application. As far as mechanical ventilation is concerned, most of the research tasks identified as needed at that time remain valid, for example:

- Evaluate the energy impact of ventilation heating and cooling losses in the present building stock
- Identify the role of ventilation in controlling indoor air quality and comfort conditions
- Evaluate optimum ventilation needs
- Assess the energy benefit of optimum ventilation
- Assess the potential for ventilation heat recovery
- Ventilation system problems
- System specification, design considerations, design tools.

In 2016, another AIVC report (Borsboom & al. TN68 [55] 2016) identified research needs for achieving good indoor air quality in buildings. The items related to mechanical ventilation include:

- Evaluate new advanced ventilation strategies based on health and comfort criteria
- Identify barriers that block innovation having the goal of achieving good indoor air quality
- Identify methods that will encourage the active involvement of building occupants (habits, activities) in creation of indoor air quality
- Compare the indoor air quality performance of different types of ventilation systems (including mechanical) in highly energy efficient buildings.

Nowadays, additional challenges for mechanical ventilation could also be listed:

- Increase the quality of installation and operation of mechanical ventilation systems
- Being able to implement efficient and cost-effective mechanical ventilation systems in existing and renovated buildings
- Move towards smart control strategies: this can be based on the use of low-cost air contaminant sensors that could lead to more advanced mechanical ventilation controls (Walker, 2018; Mouradian, 2018)
- Improve the efficacy of kitchen exhaust systems in homes, and provide make-up air for such local exhausts in very tight homes
- Move towards more air cleaning, for example through IEA/EBC Annex 78: “Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications".

14.5. References

All AIVC references are in the AIVC general reference list which is added as a separate chapter (chapter 16) at the end of this Technote

15. Natural and Hybrid Ventilation

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Per Heiselberg, Aalborg University, Denmark
Carsten Rode, Technical University of Denmark, Denmark
Christoffer Plesner, VELUX, Denmark

15.1. Introduction

A core Raison d'être of the AIVC is to contribute to avoiding leaky buildings, since such infiltration may be uncontrollable, costly on energy, and in some situations even harmful to the building enclosure. However, while the AIVC works for an airtight enclosure, it is equally important to ensure proper mechanisms for fresh air exchange in our buildings. By tradition, this has been by natural ventilation, and later by mechanical ventilation.

Traditionally, ventilation needs have been met by natural ventilation in which the flow process is driven by in wind and differences in temperature. Hence, natural ventilation is the oldest form of ventilation strategy. A fresco in the tomb of Nebamun in Egypt from about 1375 B.C. depict a building with a "malqaf" (traditional windcatcher) used to help ventilate and cool the interior. One of the two wedge shaped bodies was facing windward to provide passive/natural ventilation while the other extracted the warm air from the inside of the building by convection. Many years later, the term "natural ventilation" was used in 1899 (might have been before as well), when Robert Boyle & Son, Limited reprinted a pamphlet called Natural Ventilation, based on an article from "The Building News", dated May 26th, 1899 and published a compendium of the prevailing arguments of the day entitled "Natural and Artificial Methods of Ventilation" (Robert Boyle and Son, Ltd., 1899).

Hybrid ventilation was introduced much later at the end of the 20th century and was described as systems using both natural ventilation and mechanical ventilation systems.

Both natural- and hybrid ventilation systems have the possibilities to enable energy savings, high indoor environmental performance, high user satisfaction etc. These are described further in the chapter "Why do we talk about natural and hybrid approaches". Generally, hybrid ventilation is designed to meet the needs of the building, while maximizing the potential for free cooling by saving fan/cooling energy by utilizing natural ventilation forces during the cooling period, especially efficient during night where temperature differences are often higher.

15.2. Principles

15.2.1. Introduction

This chapter explains in brief the principles of natural ventilation and hybrid ventilation. The definition of the two ventilation principles are (taken from the aligned definitions of CEN/TC 156 and the task group of WG/2, 20 and 21 dealing with natural-, hybrid- and mechanical ventilation):

Natural ventilation "Ventilation whose operation is based solely on the effect of wind and the stack effect"

Hybrid ventilation "Ventilation whose operation is based on the combination or alternation of natural ventilation and mechanical ventilation"

15.2.2. Natural ventilation

The effectiveness of natural ventilation is determined by the prevailing outdoor conditions: microclimate (wind speed, temperature, humidity and surrounding topography) and the building itself (orientation, number of windows or openings, size and location). In addition to the use of windows and other openings for natural ventilation, there are some additional means of enhancing the air movement such as wind towers and solar chimneys. Driving forces for natural ventilation are stack effect (also called thermal buoyancy), wind pressures or a combination of the two.

Basically, the ventilation principle used in the building to exploit the natural driving forces can be divided into three different principles:

- Single-sided ventilation

- Cross ventilation
- Buoyancy driven ventilation

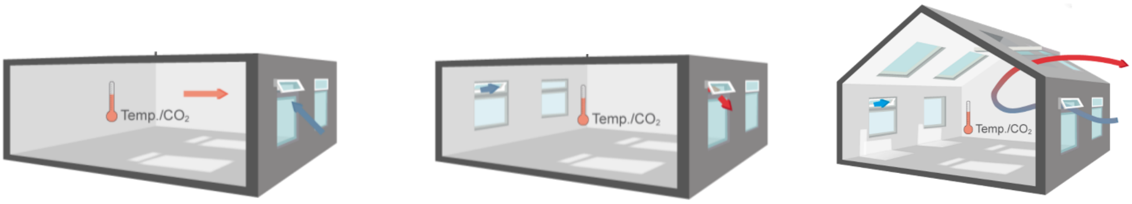
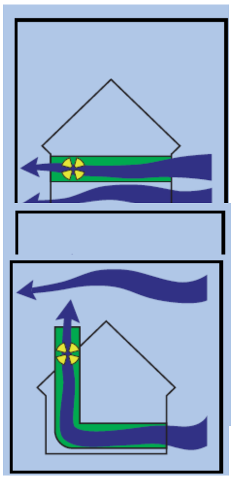


Figure 32: Illustration of ventilation principles (singles sided-, cross- and buoyancy driven ventilation)

15.2.3. Hybrid ventilation

Hybrid ventilation combines the mechanical forces of mechanical ventilation with natural forces of natural ventilation and combines them to optimize the energy consumption and efficiency of the used ventilation principle/system in buildings. IEA ECBCS-Annex 35 (Heiselberg, 2002) described three main hybrid ventilation concepts:



Natural and mechanical ventilation. This principle is based on two fully autonomous systems where the control strategy either switches between the two systems, or uses one system for some tasks and the other system for other tasks. It covers, for example, systems with natural ventilation in intermediate seasons and mechanical ventilation during midsummer and/or midwinter; or systems with mechanical ventilation during occupied hours and natural ventilation for night cooling.

Fan-assisted natural ventilation. This principle is based on a natural ventilation system combined with an extract or supply fan. It covers natural ventilation systems that, during periods of weak natural driving forces or periods of increased demands, can enhance pressure differences by mechanical (low-pressure) fan assistance.

Stack and wind assisted mechanical ventilation. This principle is based on a mechanical ventilation system that makes optimal use of natural driving forces. It covers mechanical ventilation systems with very small pressure losses, where natural driving forces can account for a considerable part of the necessary pressure.

Hybrid ventilation always requires an intelligent control system. With hybrid ventilation, less investment in mechanical equipment is traded with more extensive investment in some elements of the building enclosure.

15.3. What about Natural and Hybrid ventilation approaches?

There are multiple motivations for the interest in natural and hybrid ventilation. The most obvious are higher indoor environmental quality, user satisfaction, lower energy use and environmental impact. Further, it is often stated that passive techniques should be used prior to active techniques (The London Plan) thereby supporting the need to further increase the usage of natural driving forces to reduce or eliminate the energy demand for ventilation and to save cooling energy in buildings, having to cope with the increasing global warming. Night cooling should be evaluated early on when designing your natural and hybrid ventilation systems.

The art and science of using the beneficial elements of nature – sun, wind, earth and air temperatures, plants and moisture – to create comfortable, energy-efficient and environmentally wise buildings is called climatic design. The desirable procedure is to work with, not against, the forces of nature and to make use of their potentialities to create better living conditions. The principles of climatic design derive from the requirement for creating human comfort in buildings using the elements of the natural climate. Perfect balance between natural resources and comfort requirements can scarcely be achieved except under exceptional environmental circumstances and the climatic design will vary throughout the year depending upon whether the prevailing climatic condition is “underheated” compared to what is required for comfort.

Building energy use and the sizes of mechanical equipment are reduced without the use of sophisticated technologies, but only through an effective integration of the architectural design and the design of mechanical systems. Buildings with natural ventilation often include other sustainable technologies such as e.g., daylight, passive and natural ventilative cooling, passive solar heating etc., and an energy optimization requires an integrated approach in the design of the building and its mechanical systems (Heiselberg, 2000 and Tjelflaat, 2001). The integrated design approach achieves this due to the close relationships that exist between the building, its surroundings, the architecture and the mechanical systems.

Natural ventilation is a sustainable, energy-efficient and clean technology, and is well accepted by occupants (if controlled optimally). Hence, it should therefore be encouraged wherever possible. Buildings with natural ventilation are associated with less SBS-symptoms, than buildings with traditional ventilation systems (Seppänen and Fisk, 2002). Natural ventilation is well accepted by occupants and the natural ventilation mode should therefore be used when the climatic conditions allow it. In addition, a building with openable windows and passive cooling techniques may be contributing to a greater degree of user control and therefore a better perceived productivity.

Many studies have pointed out the importance for us as humans to be connected to nature. A theoretical basis for the notion that contact with nature is beneficial comes from E.O. Wilson, who introduced the term Biophilia almost 20 years ago, defined as the "innately emotional affiliation of human beings to other living organisms". The human connection to nature and the idea that this might be a component of good health has a long and fascinating history in philosophy, art, and popular culture.

Figure 33 shows the effect on the percentage reduction in SBS symptoms in relation to “Window View”, “Natural Ventilation”, “Indoor Plants” and “Daylight” found for each study (Loftness, 2007).

The 10 studies dealing with natural ventilation indicates that the use of natural ventilation can reduce the SBS symptoms by 15-70%.

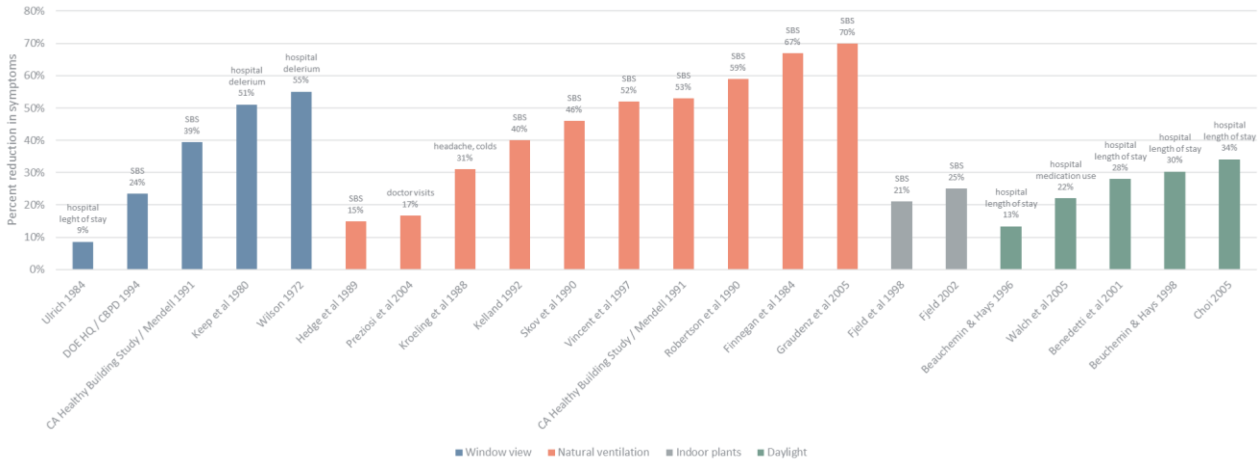


Figure 33: Percentage reduction in SBS symptoms regarding “Window View”, “Natural Ventilation”, “Indoor Plants” and “Daylight”.

Both natural and mechanical ventilation have advantages and disadvantages. Hybrid ventilation provides opportunities for innovative solutions to the problems of mechanically or naturally ventilated buildings - solutions that simultaneously improve the indoor environment and reduce energy demand. Natural and mechanical ventilation have developed separately over many years and the potential for further improvements is limited. But the combination of natural and mechanical ventilation opens a new world of opportunities. There are multiple motivations for the interest in hybrid ventilation: the likelihood of a positive response by occupants and a positive impact on productivity, reduced environmental impact and an increased robustness and/or increased flexibility and adaptability, and financial motivations (the prospect of lower investment costs and/or operation costs).

Available data from the case studies provided in the IEA EBC Annex 35 (Heiselberg, 2002) shows that substantial energy savings have been achieved in a number of buildings, mainly because of a very substantial reduction in energy use for fans and cooling.

Another aspect is that hybrid ventilation implies less noise (provided that there are no outdoor sources of heavy noise), which may also improve the perceived quality. In IEA EBC Annex 35 the high degree of user control in the investigated buildings was greatly appreciated by the occupants.

15.4. Historic role of AIVC

15.4.1. AIVC work

AIVC has been one of the main drivers to enlighten the potential and benefits of natural and hybrid ventilation. Ranging from the ventilation principles, the design process and considerations, control strategies, performance predictions, quality control including commissioning and exemplary case studies. Natural ventilation has developed from being considered only as a largely uncontrolled system using air infiltration through cracks and airing through windows, to a demand-controlled ventilation system with cooling capabilities. While hybrid ventilation was going from a non-existent ventilation approach to a well established and acknowledged ventilation strategy throughout the various task within AIVC.

AIVC has done efficient dissemination work through its annual conferences, workshops and webinars and through its own publications starting with the topic of “natural ventilation” and later “hybrid ventilation”.

TN13 [9] (Allen, 1984) gathered, disseminated and analyzed the wind data (e.g., pressure difference and external pressure coefficients (Cp)) later used to predict air flows though intentional openings in the building envelope. Subtask 2 of the *IEA EBC Annex 20* (Van der Maas, 1992) focused on air flow through large openings in buildings including “New measurements of single-sided ventilation in the presence of wind and/or stack effect” which was completed in 1991. This task showed the needs of experimental work to improve the modeling of both airflow through doors and windows. Hence, new studies of interzonal airflow and single sided ventilation were carried out to improve the existing models.

In 1994 the TN44 [31] (Orme M., Liddament M., Wilson A., 1994) looked at the wind pressure evaluation to provide the user with an indication of the range of pressure coefficient values which might be anticipated for various building orientations and degrees of shielding.

IEA EBC Annex 23 (Warren, 1996) looked at the multizone air flow modelling (COMIS) and found that one of the weakest elements of simulation has been the ability to take into account the natural movement of air into and through a building. Hence, a task of the design of COMIS allowed the algorithms to be improved and extended, for instance to deal with single-sided ventilation through large openings.

The purpose of the *AIVC “A Guide to Energy Efficient Ventilation”* [5] which was published in 1996 (Liddament M.W., 1996) was to review ventilation in the context of achieving energy efficiency and adequate indoor air quality. The natural ventilation strategies are explained from the natural ventilation mechanism (driving forces), Natural Ventilation Techniques (ventilation principles), typical components as well as the robustness of the system.

15.4.2. Relations with other annexes of EBC

The *subtask 2 report of the IEA EBC ANNEX 26* - Energy Efficient Ventilation of Large Enclosures (Heiselberg, 1998) from 1998 gives an overview and an evaluation of the techniques to analyse, measure and model air flows and ventilation in large enclosures as well as working examples of methods. All in all, it summarizes improved and new methods for design and analysis of ventilation in large enclosures including the use of natural ventilation.

One of the most important, if not the most important, project about hybrid ventilation is still the *IEA EBC ANNEX 35 “Control Strategies for Hybrid Ventilation in New and Retrofitted Office Buildings (HybVent)* which was completed in 2002 and lead by Professor Per Heiselberg (Heiselberg, 2002). One task that AIVC played a significant role in was the state of the art towards demand-controlled hybrid ventilation including *IEA EBC ANNEX 35* which was followed up by the EU project RESHYVENT (Reshyvent, 2004), focusing on hybrid ventilation in residential buildings. These efforts are looking to provide sustainable ventilation; not only is transport energy minimized but the delivered air flow is controlled on demand by several sensor and control strategies. Integration is the word for future developments. It is no longer possible to think separately of infiltration or ventilation, neither is it possible to separate the ventilation system from the buildings (Sherman, 2005).

A substantial number of AIVC publications focusing on hybrid ventilation was published the following years. Publications which are to be mentioned are the AIVC Technical Notes: TN 59 [46] (Dorer V., Pfeiffer A., Weber A., 2005) and TN 61 [48] (Niachou K., Santamouris M., Georgakis C., 2007), the Contributed Reports: CR 07 [100] (Schild P.G., 2007) and CR 09 (De Gids W.F. [102] 2007), and the AIVC Ventilation Information Paper: VIP 32 [87](de Gids W.F., Jicha M., 2010) all dealing with hybrid ventilation.

The focus on natural ventilation was also dealt with in the hybrid ventilation publication, but two separate AIVC Ventilation Information Papers: VIP 03 [58] (Santamouris M., 2004) and VIP 12 [67] (Santamouris M., 2006) looked at the adaptive thermal comfort and natural ventilation in urban areas, respectively.

15.4.3. Final remarks

Beside all the above mentioned AIVC publications, natural ventilation and hybrid ventilation has also been addressed in relation to the thermal comfort needs which was not a part of the ventilation provision described in this chapter. The AIVC publications addressing thermal comfort issue is described in the chapter 8 “Ventilative Cooling and Thermal Comfort”.

AIVC has done efficient dissemination of other relevant publications through AIRBASE, which contains abstracts of articles and publications related to energy efficient ventilation. A key word search in the AIRBASE on *natural ventilation* and *hybrid ventilation* leads to 1144 and 79 matches, respectively.

During the 40 years of its existence, the AIVC has been the portal as well as the stimulus for a wide variety of air related annexes. The AIVC has been a main driver of disseminating the potential of natural and hybrid ventilation strategies and served to coordinate some of these important activities as well as disseminate much of their results through knowledge-based publications.

15.5. Looking forward: Is the topic complete? What are next steps? Future needs.

15.5.1. General

While the concepts for natural and hybrid ventilation were developed, researched and well explained around halfway through AIVC’s 40-year history, and were demonstrated in many of notable real life projects, it may be realized that the solutions are not even today recognized as default choices in current new buildings – despite of all the documented benefits. In a recent article in www.eco-business.com it was stated:

"Of all the emissions reductions possible by 2030, buildings are by far the cheapest, research finds. The International Energy Agency (IEA) recently found that by 2050, we can cut 87% of greenhouse gas emissions from buildings by pairing energy efficiency with clean electricity technologies that are already available. Rocky Mountain Institute’s research found that investments in building efficiency like increasing natural daylight and ventilation have been widely undervalued, even by the climate science".

Natural ventilation has in the past years developed from being largely uncontrolled systems using air infiltration through cracks and airing through windows, to a demand-controlled ventilation system with cooling capabilities. Hence, the mindset of the people designing these systems also must reflect on this journey. The building industry has a conservative tradition, despite the fact the natural ventilation was the oldest form of ventilation strategy it still seems like the “old-way” has been forgotten. This might be due to a rapid growth in the mechanical ventilation area as well as a strong focus on the technology and not on the combined effect (of natural- and mechanical ventilation).

15.5.2. Obstacles

Some of the notable obstacles found in the literature (Allard, 1998) and AIVC publication (Heiselberg, 2002) are:

- Uncertainty due to lack of information, knowledge and experience about hybrid ventilation and lack of examples of documented hybrid ventilated buildings
- Absence of regulations, i.e. lack of support for natural ventilation, can be an important barrier as well
- Uncertainty due to lack of suitable standards and regulations
- Uncertainty due to fluctuations in indoor environmental conditions (high peak temperatures, temperature variations during the day, temperature differences between floor and ceiling, etc.)
- Risk of draught from ventilation openings in the façade
- Technical solutions to meet the requirements of regulations exist, but implementation requires special effort by designers

The summary report “Status and recommendations for better implementation of ventilative cooling in standards, legislation and compliance tools” of the *IEA EBC ANNEX 62* (Plesner, C., Pomianowski, M., 2018) concluded that especially in the field of natural ventilation a major gap was found in most of the investigated countries regarding standards, legislation and compliance tools.

CEN and ISO projects are well underway and have the scope of making technical documents focusing on setting criteria and giving guidance to design and dimensioning of ventilation systems (natural and hybrid) as well as ventilative cooling systems. These technical documents will describe how to design natural and hybrid ventilation, as well as ventilative cooling -systems and what to be aware of. The documents will likely include a better way of estimating the thermal comfort and potential of ventilative cooling systems early on, by including both the local climate and the building itself.

However, these initiated projects are foreseen to be released around year 2023.

15.5.3. Other concepts

Other contemporary concepts that also should be coupled to natural and hybrid ventilation are “smart” sensor and control technologies as well as the growing awareness of the importance of users and operators on the performance of the systems. It is expected that the future will see an increased coupling within the triangle:

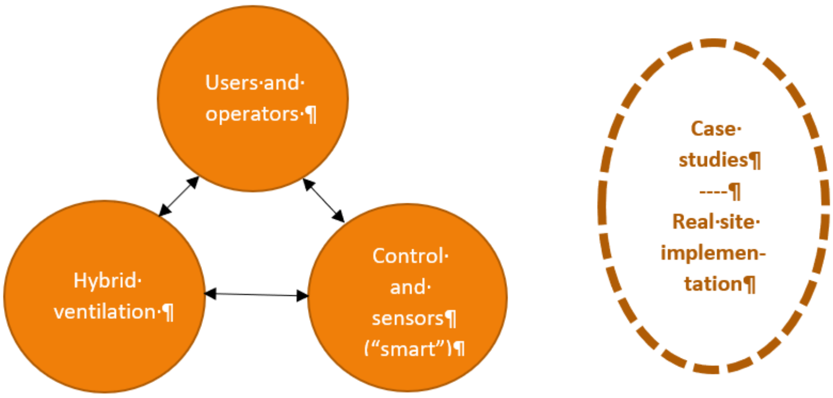


Figure 34 Schematic view on a new concept

Hybrid ventilation is characterized by an anticipated smaller need for technical equipment, but possibly some increased investments in building enclosure elements. Overall, the initial investment costs for hybrid ventilation *may* be larger, depending on climate conditions etc., compared to buildings with conventional systems. However, this should be balanced by smaller running costs.

Business models should be developed for better advancement of hybrid ventilation systems. For instance:

- Consultant honorariums, which are proportional to the cost of mechanical equipment are not conducive for advising the smaller systems that are appropriate in hybrid ventilation. Such honorarium systems, when they still exist, should be replaced.
- Hybrid ventilation has a different balance between initial and operational costs of new buildings than what is the case for buildings with conventional ventilation systems – particularly in comparison with natural ventilation. Business models to cater for this situation should be developed.

Despite the many barriers to the implementation of natural ventilation systems, the vast majority of the existing building stock is actually naturally ventilated. The barriers identified do have solutions – "the skill and technical knowledge of good designers is usually adequate to get around them and find solutions that will work" (Allard, 1998). With the right design and control of the building and natural/hybrid ventilation system, most barriers should be possible to overcome.

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ANNEX 5

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