International Energy Agency

Demand Controlled Ventilating Systems

Source Book

Energy Conservation in Buildings and Community Systems Program

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Energy Conservation in Buildings and
Community Systems Program
Annex 18
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IEA Energy Conservation

Caution:

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Foreword

This book is a result of the joint effort from all involved in Annex 18, Demand Controlled Ventilating Systems (DCV-systems). One of the main goals with Annex 18 was to write a Source Book with contents which we all could agreed upon. From this Source Book national guidelines were to be developed. We continued the discussion until this goal was fulfilled. The Source Book is a result of a coorperation between all participants. Hence, all individuals in the working group of Annex 18 can be said to be a coauthor of this Source Book.

The participants in the working group have different backgrounds which gave us the opportunity of paying attention to many aspects. Participants in Annex 18 have been researchers and practitioners as well as representatives for manufactureres and property owners.

There have been many people involved in the work of Annex 18 that I would like to give my gratitude to. Some of them I have met at Annex 18 meetings. Some involved in national teams I haven't met. With all their efforts the contents of this Source Book has been made possible.

On behalf of the participants I hereby want to acknowledge the members of the Executive Committee of IEA Energy Conservation in Buildings and Community Systems Programme as well as the funding bodies.

One particular person I would like to address my gratefulness to is Linda Newell, (Porter, Newell & Associates in Canada). She took care of our manuscript and rewrote into proper English. But most important was her work to read it with fresh eyes and rewrite some of the parts so that the contents were more clear and easier to follow.

Finally we ended this work in unified agreement of the contents. We felt a relief to have finished and a sadness to say goodbye to dear friends without knowing when to meet again.

To all involved in Annex 18 I would like to say "Thank you very much for your excellent work"

To all readers "Enjoy the reading, take benefit, and implement properly".

Lars-Göran Månsson
Operating Agent

CONTENTS

Foreword..........3
Preface..........11
Executive Summary..........15

1. Introduction..........17
1.1 IEA Annex 18..........17
1.1.1 *Objectives*..........17
1.1.2 *Scope*..........17
1.1.3 *Organization*..........17
1.1.4 *Reports*..........18
1.2 The Source Book..........18
1.2.1 *Objectives*..........18
1.2.2 *Target Audience*..........19
1.2.3 *Field of Application*..........19

2. The DCV Approach..........21
2.1 Background..........21
2.2 DCV Systems..........21
2.2.1 *Objectives*..........21
2.2.2 *Strategies*..........22
2.3 Pollutants..........22
2.3.1 *Driving Pollutant*..........23
2.3.2 *Key Indicator*..........23
2.4 Benefits and Limitations..........24
2.5 Definitions..........24

3. Pollutants and Indicators..........27
3.1 Purpose..........27
3.1.1 *Definitions*..........27
3.1.2 *Risk Discussion*..........27
3.1.3 *Subjective Perception versus Objective Data*..........28
3.2 Pollutants and their Sources..........28
3.2.1 *Bioeffluents*..........28
3.2.2 *Moisture*..........31
3.2.3 *Tobacco smoke*..........31
3.2.4 *Particle*..........32
3.2.5 *Building Materials and Cleaning Substances*..........33
3.2.6 *The Ventilating System*..........34
3.2.7 *Other sources*..........35
3.3 Usable Indicators and Concentration Limits..........35
3.3.1 *Humidity*..........35
3.3.2 *Carbon Dioxide*..........36
3.3.3 *Presence Indicator*..........37

3.3.4 *Mixed Gases* 37
3.3.5 *Particles* 38
3.4 Conclusions 38
3.4.1 *Pollutant Rating* 38
3.4.2 *Indicator Selection* 38

4. Sensor Types 41
4.1 Purpose 41
4.2 Guidelines 41
4.3 Active Elements 42
4.3.1 *Humidity Sensors* 42
4.3.2 *Carbon Dioxide Sensors* 45
4.3.3 *Mixed Gas Sensors (IAQ sensors)* 45
4.3.4 *Occupancy Sensors* 46
4.4 Connection to Control Systems 47
4.4.1 *Types of Control System* 47
4.4.2 *Sensor Location* 47
4.4.3 *Connection to the Control Device* 48
4.5 Test Laboratories 48
4.6 Testing and Rating 49
4.7 Conclusions 50
4.7.1 *Humidity Sensors* 50
4.7.2 *Carbon Dioxide Sensors* 51
4.7.3 *Mixed Gas Sensors* 52
4.7.4 *Occupancy Sensors* 53
4.7.5 *Future Development* 53

5. Control Principles 55
5.1 Purpose 55
5.1.1 *Definitions* 55
5.1.2 *Airtightness* 56
5.1.3 *Control Strategies* 56
5.2 Base Ventilation Control 58
5.2.1 *Constant 24-hour Base Ventilation* 59
5.2.2 *Constant Part-Time Base Ventilation* 60
5.2.3 *Pre-Ventilation with Higher Ventilation Rate* 60
5.2.4 *Intermittent Forced Ventilation (Flushing)* 61
5.3 Occupancy-Related Ventilation Control 62
5.3.1 *Constant Flow* 62
5.3.2 *Clock Control* 63
5.3.3 *Manual Control* 63
5.3.4 *Presence Sensor Control* 64
5.3.5 *Continuous Monitoring and Control* 64
5.4 Choice of Control Strategy 67
5.5 Sensor Location 69
5.5.1 *General* 69
5.5.2 *Mixing Ventilation Systems* 69

8.2.1 *Carbon Dioxide* 111
8.2.2 *Moisture* 112
8.2.3 *Volatile Organic Compounds* 112
8.2.4 *Thermal Comfort* 113
8.3 Ventilation Principles 113
8.3.1 *Ventilation Strategy* 113
8.3.2 *Ventilation System Operation* 113
8.3.3 *Comparative Flow Rate Demands* 114
8.3.4 *Window Airing* 117
8.3.5 *System Regulating Ability* 118
8.3.6 *System Response Time* 120
8.4 System Design 120
8.4.1 *Ventilation Equipment in the Room* 120
8.4.2 *Central System* 121
8.4.3 *Distributed System* 121
8.4.4 *Combined System* 122
8.4.5 *Quality and Risk* 123
8.5 Sensor Type and Location 123
8.6 Energy savings 123
8.6.1 *Window Airing* 124
8.6.2 *Comparison of Strategies* 125
8.6.3 *Dilution of Pollutants* 127
8.7 Recommendation 128
8.7.1 *General* 128
8.7.2 *Design* 128
8.7.3 *Operation* 129
8.8 Checklist 129

9. Auditoriums 131
9.1 Purpose 131
9.1.1 *Auditorium Ventilation* 131
9.1.2 *Driving Pollutant* 131
9.1.3 *Subjective IAQ Response versus Objective Data* 132
9.1.4 *Other Pollutants* 132
9.1.5 *Comfort* 133
9.2 Control Strategy 134
9.2.1 *System Regulating Ability* 135
9.3 Ventilation Strategy 136
9.3.1 *Air Flow Pattern* 136
9.4 System Description 138
9.4.1 *Variable Air Flow* 138
9.4.2 *Return Air* 139
9.5 Sensor Type and Location 140
9.6 Performance 140
9.6.1 *Energy Savings* 141
9.7 Recommendations 144
9.8 Checklist 144

5.5.3 *Displacement Ventilation Systems* 69
5.5.4 *Regulating Ability of System* 70
5.5.5 *Simulation Techniques* 71
5.6 Summary and Conclusions 71
5.7 Checklist for Control Principle Choice 72

6. Feasibility Analysis 73
6.1 Purpose 73
6.2 Feasibility Factors 73
6.3 Analysis 74
Step 1: Compliance with Regulation 74
Step 2: Pollutant Analysis 74
Step 3: Building Features 77
Step 4: HVAC Systems 78
Step 5: Climate 79
Step 6: Potential Savings 80
6.4 Checklists for DCV System Design 83

7. Dwellings 85
7.1 Purpose 85
7.2 Pollutants and Indicators 86
7.2.1 *Driving Pollutants* 88
7.2.2 *Other pollutants* 90
7.2.3 *Comfort* 91
7.2.4 *Humidity Control Strategy* 91
7.3 Ventilation Principles 92
7.3.1 *Options* 92
7.3.2 *Supply and Exhaust* 92
7.3.3 *Recirculation* 93
7.3.4 *Flow Rate* 94
7.3.5 *Standalone Systems* 95
7.4 Natural Ventilation Systems 95
7.4.1 *System Design* 95
7.4.2 *Sensor Type and Location* 96
7.5 Mechanical Systems 98
7.5.1 *Exhaust Ventilation* 98
7.5.2 *Supply Ventilation* 99
7.5.3 *Supply and Exhaust Ventilation* 99
7.5.4 *Sensor Type and Location* 100
7.6 Energy Savings 101
7.7 Recommendations 104

8. Schools and Day Nurseries 107
8.1 Purpose 107
8.1.1 *Building Types* 108
8.1.2 *Ventilation System Types* 109
8.1.3 *Building Use and Occupant Load* 110
8.2 Driving Pollutant 111

10. Offices and Office Buildings....................................145
10.1 Purpose....................................145
10.2 Driving Pollutant....................................145
10.3 Ventilation Strategy....................................145
10.3.1 *"Free Cooling Cycles"*....................................145
10.3.2 *Air Leakage*....................................146
10.3.3 *Other Pollutants*....................................147
10.4 Subjective Response versus Objective Data....................................147
10.5 Comfort....................................147
10.6 Energy Savings....................................148
10.7 Control Strategies....................................148
10.7.1 *Meeting Rooms and Small Offices*....................................148
10.7.2 *Whole Building Control- Automatic*....................................148
10.7.3 *Whole Building Control- Manual*....................................149
10.8 Sensors and Sensor Location....................................149
10.9 Quality and Risk....................................149
10.10 Conclusions....................................150
10.11 Recommendations....................................150
10.11.1 *Meeting Rooms*....................................150
10.11.2 *Office Buildings*....................................150
10.12 Checklist....................................151

11. Operation and Maintenance....................................153
11.1 Purpose....................................153
11.2 Operation and Maintenance strategies....................................153
11.3 Balancing....................................153
11.4 Quality Assurance....................................154
11.5 Commissioning....................................154
11.6 Operational Routines....................................155
11.7 Inspection Routines....................................155
11.7.1 *Final Inspection and Commissioning*....................................155
11.7.2 *Regular Routine Inspections by the Operator*....................................155
11.7.3 *Periodical Audit of Energy Conservation and Function*....................................155
11.8 Maintenance and Renewal Routines....................................156
11.9 Operator's Manual....................................157
11.10 Regular Staff Training....................................157
11.11 Checklist for the Design of DCV Systems....................................157

12. Conclusions and Recommendations....................................159
12.1 Potential Benefits....................................159
12.2 DCV Strategies....................................159
12.2.1 *Prerequisites*....................................159
12.2.2 *Design Considerations*....................................160
12.2.3 *Cautions*....................................161
12.3 Applications....................................161
12.4 Recommendations....................................163

12.4.1 *DCV Option for Energy Savings* 163
12.4.2 *Systems to Support DCV* 163
12.4.3 *Building Design* 163
12.4.4 *Building Use* 163
12.4.5 *Sensors* 164
12.5 Future Developments 164

Appendixes

Appendix A: Terminology 165
Appendix B: Calculation for Feasibility Analysis 173
Appendix C: Calculation of RH on Surfaces 185
Appendix D: List of References 189
Appendix E: Annex 18 National Representatives 195

Preface

International Energy Agency (IEA)

In order to strengthen co-operation in the vital area of energy policy, an Agreement of an International Energy Program was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Co-operation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities (CEC) participating under special arrangement.

As one element of this program, the IEA Committee on Energy Research and Development (CRD) co-ordinates co-operative activities in energy research, development, and demonstration. A number of new and improved energy technologies with the potential to make significant contributions to our energy needs were identified for collaborative efforts.

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of energy-related areas. In the area of energy conservation in buildings, the IEA is sponsoring various exercises to improve the accuracy of energy consumption forecasts, including:

comparison of existing computer programmes;

* building monitoring;

* comparison of calculation methods;

* ventilation and air quality; and

* occupancy studies.

Sixteen countries and CEC have elected to participate and have designated contracting parties to the Implementing Agreement that covers collaborative research in this area. As participation was not restricted solely to governments, a number of private organizations, universities, and laboratories were selected as contracting parties. This brought a much broader range of expertise to projects in various areas of technology. The IEA, recognizing the importance of associating industry with government-sponsored energy research and development, is making every effort to encourage this trend.

The Executive Committee

Overall control of the R&D program "Energy Conservation in Buildings and Community Systems" is maintained by an Executive Committee.

Its role is to monitor existing projects and identify new areas where collaborative effort may be beneficial.

The Executive Committee ensures that all projects fit into a predetermined strategy without unnecessary overlap or duplication but with effective liaison and communication. To date, the Executive Committee has initiated the following projects, each implemented by a subcommittee or Annex.

Annex Project

1. Load Energy Determination of Buildings *
2. Ekistics & Advanced Community Energy Systems *
3. Energy Conservation in Residential Buildings *
4. Glasgow Commercial Building Monitoring *
5. Air Infiltration and Ventilation Centre
6. Energy Systems & Design of Communities *
7. Local Government Energy Planning *
8. Inhabitant Behaviour with regard to Ventilation *
9. Minimum Ventilation Rates *
10. Building HVAC Systems Simulation *
11. Energy Auditing *
12. Windows and Fenestration *
13. Energy Management in Hospitals *
14. Condensation *
15. Energy Efficiency in Schools *
16. BEMS 1 - User Interfaces & System Integration *
17. BEMS 2 - Evaluation & Emulation Techniques
18. Demand Controlled Ventilating Systems
19. Low Slope Roof Systems
20. Air Flow Patterns
21. Thermal Modelling of Buildings
22. Design of Energy Efficient Communities & Urban Planning
23. Multizone Air Flow Modelling
24. Heat-,Air-, Moisture Transfer in New Retro-fitted Insulated Envelope Parts
25. Real-Time Simulation of HVAC-systems for Building Optimisation, Fault Detection and Diagnosis
26. Energy Efficient Ventilation in Large Enclosures

* Project complete

Annex 18

The objectives of Annex 18 were to develop means, methods and strategies for Demand-Controlled Ventilating Systems and to contribute to the application of knowledge gained during the process.

The Annex 18 National Representatives and experts involved in preparation of the Source Book are listed next. Full addresses, telephone numbers and fax numbers for the national representatives are provided in Appendix E.

Annex 18 Source Book Contributors

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Reference to other Annexes

Throughout the Annex 18 project, work carried out in the Annexes 5,8,9, and 14 (see list above) has been taken into consideration. Annex 18 work was also linked to the Annex 20 project, mostly through personal contacts among the participating members.

Executive Summary

This Source Book contains an outline of an IEA strategy for Demand Controlled Ventilating (DCV) systems, including an analysis of the prerequisites for their use; a description of different types of sensors; and examples of DCV applications for different types of buildings. It provides guidance and checklists to determine whether a DCV system is appropriate for a specific building. Conclusions and key findings are given below.

A DCV system is defined by IEA Annex 18 as a ventilating system where the air flow rate is governed by a sensor detecting humidity or airborne pollutants, in order to keep the concentration level of the detected substance(s) below a preset value. Such a DCV system can utilize manual or automatic controls. The sensor can be a person (based on subjective perception) or an automatic device (based on measured data).

A ventilating system that is intended to exchange air should normally be able to control temperature. A DCV system responds primarily to an air quality indicator. The ventilation strategy must be carefully chosen to maintain thermal control and to avoid inadvertently creating other Indoor Air Quality (IAQ) problems. The intention of a DCV system is to ventilate more efficiently by tailoring the air flow rate to time-dependant needs. Depending on the application, this can lead to better energy efficiency, improved IAQ or both.

Experience has shown that DCV systems are feasible in new or existing buildings and will work in dwellings, schools, offices and auditoriums. These building types account for approximately 85 % of the total energy demand for heating and ventilation of non-industial buildings in industrialised countries.

The life cycle cost of a building with a DCV system is often lower than that of a building with a traditional ventilating system. The building configuration, its use and other local factors may render this approach economically ineffective. Each situation must be analysed separately. DCV systems are still developing rapidly, especially in the field of sensors. Applications that are now marginal may become economically feasible in the near future.

Benefits DCV is aimed to guarantee good air quality at low energy consumption and hence lower life cycle costs for many buildings and applications. They will vary depending on climate, building type, ventilation system and occupancy pattern.

Applications The examples presented are cases with a real background and must be suitably treated when used in an individual situation. Sensor development is foreseen to be rapid. Thus any given recommendation must be checked at the market before decision on its use.

Limitations Local regulations may inflict on implementation proposals in the source book. Sensor imperfections may lead to lower savings and higher life cycle cost than expected from general conclusions.

Cautions The decision on usage of a DCV system must be taken for each type of process and building under the individual auspices that are at hand.

Development Further development is necessary, especially in the sensor field, with respect to both control accuracy and long term operation stability.

1 Introduction

1.1 IEA Annex 18

Annex 18 of the International Energy Agency (IEA) is working on demand controlled ventilating (DCV) systems as part of the IEA's R&D program "Energy Conservation in Buildings and Community Systems". The results of the work are contained in this source book and four associated reports.

1.1.1 Objectives

The objectives of IEA Annex 18 are:

* To develop guidelines for demand controlled ventilating systems based on state-of-the-art analyses and case studies for different users in different types of buildings
* To develop means, methods, and strategies for demand controlled ventilating systems and to demonstrate application of the knowledge accumulated during the work

1.1.2 Scope

The work of Annex 18 focused on ventilation systems in different types of buildings exemplified by:

* Dwellings (single family houses and apartment buildings)
* Schools and day nurseries
* Commercial buildings
* Auditoriums

These types of buildings account for approximately 85 % of the total energy demand for heating and ventilating non-industry buildings in industrialised countries.

1.1.3 Organization

The work was divided into the following subtasks:

1. Review of existing technology
2. Sensor tests and case studies
   a) Long term tests of sensors in the laboratory and in the field
   b) Trials in unoccupied test buildings or test rooms
   c) Full scale tests in buildings in use
3. Compilation of a source book containing general conclusions and recommendations on the design and operation of DCV systems

1.1.4 Reports

The results of Annex 18 work are contained in four reports and this source book:

1. Demand Controlled Ventilating Systems:
   State of the Art Review
   ISBN 91-540-5169-X

2. Demand Controlled Ventilating Systems:
   Sensor Market Survey
   ISBN 91-540-5417-6

3. Demand Controlled Ventilating Systems:
   Sensor tests
   ISBN 91-7848-331-X

4. Demand Controlled Ventilating Systems:
   Case studies
   ISBN 91-540-5511-3

5. Demand Controlled Ventilating Systems:
   Source Book
   ISBN 91-540-5513-X

The reports can be ordered from

Svensk Byggtjänst
Literature Service
S-171 88 SOLNA
SWEDEN
Fax +46-8 734 50 98

These and other IEA Annex reports can also be ordered or borrowed from:

AIVC,
University of Warwick Science Park, Barclays Venture Centre,
Sir William Lyons Road,
Coventry CV4 7EZ,
UK

Fax: +44-203-416306

1.2 The Source Book

1.2.1 Objectives

The objectives of this source book are:

* To provide facility managers, designers and manufacturers with guidelines concerning the use, applications and benefits of DCV systems
* To provide general principles for the design and operation of DCV systems
* to serve as a basis for producing national guidelines
* to serve as a source of inspiration in promoting further development

Every country has its own design solutions based on regional or local regulations as well as national building codes and practice. This book can not be looked upon as a procedural handbook or detailed guideline for designing systems and choosing components. However, the working group of Annex 18 foresees that a country may want to use the source book and associated documents as the basis for a national handbook.

1.2.2 Target Audience

It is assumed that readers of this source book will have a thorough knowledge of the general solutions used in designing, constructing and operating ventilation and air conditioning systems. Typical users might be:

* Mechanical engineers (designers)
* Facility managers (operation and maintenance)
* Writers of national handbooks on DCV systems
* Manufacturers
* Scientists and students
* Authority representatives

1.2.3 Field of Application

Table 1.1 shows the types of non-industrial buildings and rooms for which DCV systems are considered in this volume.

Table 1.1. DCV application

Chapter	Direct applications	Application hints
7. Dwellings	Single-family houses Apartment buildings	Hotels
8. Schools and Day Nurseries	Classrooms	Offices
9. Auditoriums	Assembly halls Theatres Lecture halls	Department stores Athletic halls Churches
10. Offices	Enclosed offices Meeting rooms	Office landscapes Shops

2 The DCV Approach

2.1 Background

The impact of energy conservation measures on indoor air quality (IAQ) has been discussed since the first so-called energy crisis in the early 1970s. As a side-effect of subsequent efforts to make building envelopes almost airtight, ventilation rates were reduced substantially. This led to increased indoor air pollution and damage to the building from mould growth, corrosion, or other problems related to water condensation. More recently, the expression "sick building syndrome" was coined to describe the problem.

Many IEA countries now face an increasing problem with IAQ. Studies have been undertaken concerning odour, threshold limits, and outgassing from building material as well as the effects on IAQ of human activities and habits. The studies show there may be a general rise in demand for increased supply of outdoor air. Demand controlled ventilating (DCV) systems offer an alternative solution. By governing the air change rate according to the actual need as it varies over time, DCV systems can serve the occupants with good indoor air quality without unnecessary waste of energy. Control signals may be taken from a sensing device or may be dependent on a human operator.

2.2 DCV Systems

2.2.1 Objectives

In general, the ventilation system in a building should be designed to achieve the following effects in an energy-efficient way:

* Remove pollutants
* Provide thermal comfort
* Remove moisture

The purpose of a DCV system is to provide more effective ventilation, which in turn could lead to better energy efficiency or improved IAQ or a combination of both.

For the purposes of IEA Annex 18, a DCV system should be specially designed to do one or more of the following:

* Control room air quality in order to limit contamination levels within the occupied zone, while also fulfilling the other roles of a ventilation system;
* Control moisture content in building material and room air, thereby reducing the risk of mould growth and degradation of the building;
* Reduce energy consumption without unacceptable interference with indoor climate.

2.2.2 Strategies

Pollutants can originate in building materials, furnishings and decorations, as well as from activities and processes taking place within the building. Consequently, to achieve a good indoor air quality the two most important strategies are:

* Pollutant source control

* Provision of an adequate supply of outdoor air

The strategy for DCV systems will depend on the type and function of the buildings in which they are installed, and on the type of pollutant(s) present. In non-industrial buildings, the demand for indoor air quality will depend mainly on occupancy load and human activities on the premises. Annex 18, therefore, focuses on odours from occupants and pollutants from building materials, tobacco smoke, carbon dioxide and humidity. Methods to cope with radon, combustion products (except moisture from gas fired household apparatuses), etc, are not covered in this source book. At times it may be necessary to increase the rate of outdoor air supply, thus increasing the energy consumption for heating, cooling and distribution of the ventilation air. If, however, the ventilation system can be operated so as to adjust the flow rate of supply (and exhaust) air to the demand, significant energy savings may result, along with an improved quality of the indoor air.

2.3 Pollutants

Pollutants generated within a building are from two main sources:

* the building fabric (structure and furnishings)

* activities of the occupants (work, cleaning)

The most important pollutants affecting the indoor air quality of buildings discussed can be grouped as follows:

* bioeffluents

* moisture or humidity

* volatile organic compounds (VOCs)

Bioeffluents are pollutants in the form of odours from human beings. Bioeffluents only seldom can be measured but their tracer gas CO_2 can. Carbon dioxide in normally existing concentrations is not a pollutant, but its presence can be used to indicate human activities.

Humidity should be addressed in a DCV system because a high humidity concentration level is apt to cause building damage in the form of mould and rot, corrosion, and ice damage. In due course this could lead to expensive repairs, comfort degradation or dangerous airborne pollutants.

Volatile organic compounds (VOCs) stem from three main sources: building material, cleaning material, and activities of human beings. In some cases also the ventilation system can contribute to smell. Some VOCs emanate at a more or less constant level from building materials, while levels of other VOCs fluctuate with occupant activity level.

2.3.1 Driving Pollutant

An analysis must be done to determine which pollutant requires the highest ventilation rate in order to maintain an acceptable level of concentration. This is known as the driving pollutant and is the one whose presence will govern the control of the DCV system. It is generally the least desirable, with potential to do most harm.

A DCV system should be considered when the level of the driving pollutant is:

* High enough to warrant ventilation in addition to that supplied by natural ventilation or by existing mechanical systems
* Variable over time
* Unpredictable in terms of time and concentration

All three factors must apply to the driving pollutant.

2.3.2 Key Indicator

Having identified the driving pollutant, there must be a means of detecting its presence in order to control it with a DCV system. Some pollutants, such as moisture, can be readily detected by sensors. But currently available sensors cannot detect all pollutants directly. So a detectable substance in the makeup of the pollutant is used to indicate the presence and concentration of the pollutant. For instance, the tracer gas carbon dioxide can be used as an indicator of human activity even though it is not a pollutant itself at normal indoor air levels.

The key indicator is the detectable substance whose presence will control the DCV system. It may be the driving pollutant or a component of the driving pollutant. The key indicator for a DCV system will depend on:

* Selection of the driving pollutant according to the individual needs of the occupants and the building or space to be treated
* Available means of detecting the pollutant itself, or a substance that serves to indicate the presence of the pollutant

2.4 Benefits and Limitations

The benefits of a DCV system are that they provide a platform for human well-being, good room climate, acceptable or required concentrations of pollutants in room air, and energy conservation. Although a good room climate can be achieved with conventional ventilating systems, DCV systems offer a more energy-efficient solution. Energy conservation achieved in ventilation systems has been up to 60 % under circumstances favourable for DCV systems.

The greatest total benefits will be achieved when using DCV systems in combination with other energy-saving and air quality control measures. For example, a low concentration of pollutants can be reached at a minimum flow rate by introducing ventilating systems giving high ventilation efficiency. Thus a DCV system can be used more effectively when combined with a system with a good ventilation efficiency.

Savings are only possible under the following circumstances:

* The outdoor air rates must be controllable

* The occupancy or other dominant pollution source must be unpredictably variable

* The building must spend a very significant proportion of the year in a mode where outdoor air is either heated or cooled

* The strength of the controlled pollutant must dominate and emissions from other sources must be low

Savings can be achieved by reducing the outdoor air flow rate (reducing over-ventilation) or by clock presence governed operation. Using currently available technology, DCV systems will require increased maintenance over conventional systems. Otherwise there is the risk that energy consumption will actually increase or air quality will worsen.

In general, the normal ventilation rate for a new or refurbished building should be used only after the outgassing period. All local produced pollutants should be removed by using local extraction facilities.

2.5 Definitions

The following definitions apply with regard to the specific goals of IEA Annex 18 and the ongoing research work.

Demand Controlled Ventilating (DCV) System: a ventilation system in which the air flow rate is governed by a measured or perceived level of airborne pollutants.

Automatic DCV System: a DCV system in which the air flow rate is governed by an automatic control device.

Manual DCV System: a DCV system in which the air flow rate can be governed by the user (a human being acts as an indicator).

A DCV system can therefore consist of a clock control and/or a presence control and/or a sensor control, where the latter is activated by suitable gases such as carbon dioxide, humidity or hydrocarbons to keep air quality at a desired level.

Further definitions are given in Appendix A.

3 Pollutants and Indicators

3.1 Purpose

This Chapter describes the form and origin of various types of airborne pollutants. It addresses levels of acceptability, taking into account health risks and comfort levels of the occupants and potential damage to the building fabric. For each pollutant, key indicators that can be used to detect the presence of the pollutant are described.

3.1.1 Definitions

A pollutant is a substance that makes another substance impure and is either not wanted or is present at a too high concentration. Thus, all sorts of substances that are not a natural part of clean outdoor air should be regarded as pollutants. Many pollutants are often present at the same spot and at the same time. For example, human beings at normal levels of activity produce odours, water vapour and carbon dioxide. In other cases different sources are not related in time and space in a foreseeable way.

Bioeffluents are mixtures of particles and gases originating from the metabolism of human beings.

Indicator is an easily detected substance characterized by its ability to represent one or more annoying substances or pollutants. For example, CO_2 is an indicator of human body odour; relative humidity (RH) is an indicator of moisture from human beings and other sources of water vapour that may lead to mould growth.

3.1.2 Risk Discussion

Airborne pollutants may affect the occupants or the building in different ways:

Health risks to occupants Exposure to airborne pollutants such as tobacco smoke, formaldehyde, combustion products, organic compounds, radon, mould and fungi (caused by too high humidity) may result in an acute short-term health response or more severe long-term health risks.

Irritation or discomfort Body odour, other odours and irritants, although not directly damaging to health, may give rise to minor physical irritation. High sensitivity to irritants may be inherited or acquired, in the latter case physically or mentally.

Damage to building fabric Water and water vapour often lead to severe damage to the building fabric.

3.1.3 Subjective Perception versus Objective Data

The human nose can detect most volatile organic compounds (VOCs). The perceived level can serve as a warning signal but it can seldom alert a person to possible danger. In some cases VOCs might cause a sensation of dryness, possibly the result of a reaction to VOCs by the mucus membrane in the nose. Other VOCs that are dangerous in the short or long term cannot be detected by the human nose. Human receptors cannot therefore be looked upon as relevant indicators on VOCs.

A human being cannot usually detect relative humidity levels lying within normal values of 15-75 %. The same stands for CO_2 levels lower than 2 % (20 000 ppm), at which level a higher breathing activity can be observed. Thus none of these parameters can be used for manual control of air change.

Under normal circumstances it is not relevant to measure the concentration of respirable particles and use it for governing the air flow rate. A relatively high particle concentration often causes a feeling of dryness in the air. In most cases this can be remedied by lowering the room temperature. The usual explanation is that low relative humidity causes a higher rate of particle emission from surfaces in the room.

Body odours are noticeable only for a short period of time, after which the sensitivity of the receptors in the nose is reduced. Thus only a "fresh nose" can perceive the odour level caused by human bioeffluents and it is irrelevant to use the odour level as an indicator for air change rate in a room where people stay for long periods. On the other hand, new visitors can be annoyed by the perceived odour level, in which case a larger air change rate must be considered.

3.2 Pollutants and their Sources

The following pollutants and sources will be discussed:

* Bioeffluents
* Moisture
* Tobacco smoke
* Particles
* VOCs from building materials and cleaning substances
* The ventilation system as a source of pollution
* Other sources

3.2.1 Bioeffluents

A bioeffluent is a mixture of particles and gases originating from human metabolism. In this process food is converted into heat, CO_2, water vapour, and waste products. The waste products give most of the bioeffluents such as sweat and other skin secretions; and respiration, mouth, stomach and intestine. Also included are substances such as perfumes and deodorants used to "cover" the original bioeffluents.

Table 3.1 Metabolism data as a function of activity level

Activity	Lung vent l/(min·p)	CO2 produced l/(h·p)	Water evaporation g/(h·p)			Metabolism W/p
			18°C	20°C	22°C	
Rest	< 7	12	30	35	45	75
Office work (writing)	< 10	18	35	40	50	110
Standing	10 - 15	21	45	50	60	130
Walking (4 km/h)	15 - 25	39	160	180	190	240
Tennis, shovelling	40 - 50	5 - 80	250+	270+	330+	350 - 500
Wrestling	> 50	110 - 150	circa 1000			700 - 900

Notes, Table 3.1:

Note 1: The figures are given for male adults, 18-65 years of age, weight 65 kg. Female persons have 15 % lower values. Metabolism values include latent heat of water evaporation.

Note 2: Higher weight increases the values accordingly: Male 1.20 W/kg, Female 1.13 W/kg.

Note 3: An office with 50 % men 75 kg, 50 % women 60 kg, gives an average of 120 W/person.

Note 4: A higher air temperature at constant RH increases the water vapour pressure, which would reduce evaporation from skin surface, but skin temperature rises as room temperature is increased. Net result is a somewhat higher evaporation.

Human heat production can be found indirectly by measuring the intake of oxygen and the dissipation of carbon dioxide. Experiments on the heat production from different types of nutrients have shown that a person consuming "normal" food will dissipate about 20 kJ per litre of oxygen absorbed.

Moisture dissipation from human beings varies mainly with activity level and only to a small extent with the water vapour pressure of the air (temperature and relative humidity). Vapour pressure at the skin surface is 5-6 kPa, depending on activity level. Approximate levels of carbon dioxide and water vapour produced by adults in relation to metabolic load are shown in Table 3.1.

Table 3.2 shows the heat production from human beings at rest. Production of CO_2 and water vapour can be calculated from the percentage levels given.

Table 3.2 Heat production for resting human beings

Age, years	% of adult heat production
< 1	20
1 - 2	30
2 - 3	40
3 - 10	50
10 - 15	75
Adults	100
Adults >60	80

The values in the table are for persons at rest. In reality, a child has a relatively higher metabolism than an adult under the same working conditions. This can be attributed to growth and to the more active way in which children perform certain work. Measurements carried out in Sweden and Denmark based on CO_2 dissipation led to the conclusion that heat and CO_2 production from active children is practically constant at 110 W/p and 18 l/(h·p), irrespective of age and weight.

The values in Table 3.2 were calculated from the following expressions, deduced from ref. 4, 5.

Water evaporation rate from skin (q_m) as a function of activity level and room temperature can be set to:

$$q_m = a + b \cdot P \cdot T \qquad g/h$$

where

P = Metabolism W
T = Room temperature °C
a, b = Constants

Carbon dioxide production (q_c) as a function of activity level was calculated from ref. 5:

$$q_c = 17 \cdot M = 0.162 \cdot P \qquad h^{-1}$$

where

M = Metabolism met
P = Metabolism W

Table 3.3. Constants for the calculation of water evaporation

P Watt	a	b
100-150	- 50	0.039
200-350	+ 25	0.034

Note: Probable error will be ± 5 % in the higher range.

Table 3.4 Moisture generation in rooms

Type of Room	Moisture Dissipation	
	g/h*	kg/24 h**
CLASSROOM (30 pupils)	1000	6
DWELLING		
Bedroom, one person	40	0.3
Bedroom, two persons	80	0.6
Bathroom	500	1.0
Shower room	3000	3.0
Kitchen, cooking (1 kW)	1500	1.5
Dwelling, four persons	200	2.4
Pot plants/100 m^2	120	3.0
OFFICE (per person)	50	0.4

* for momentary moisture generation for an occupied room
** as an average with respect to occupation pattern

3.2.2 Moisture

Moisture in a building stems from a number of activities, including:

* Metabolism of persons, animals and plants
* Human activities such as dishwashing, laundering, food preparation, bathing and showering
* Deliberate humidifying of the supply air or the indoor air

The water vapour balance in a building is dependent on:

* Outdoor air water vapour content
* Indoor air water vapour content
* Moisture generation in the building
* Ventilation air flow rate

Moisture production momentarily and during a normal 24-hour period in classrooms, dwellings and offices are presented in Table 3.4.

3.2.3 Tobacco Smoke

Smoking tobacco produces pollutants in the form of VOCs, particles and carbon monoxide. Many of the pollutants are carcinogens. In some cases the concentration of a specific pollutant may be higher than the maximum allowable concentration for room air.

One cigarette emits about 75 mg of particles, of which 5 mg is absorbed by the smoker in the form of particles 0.1-0.5 μm where the number of particles is about $350 \cdot 10^9$ per inhalation. The main part of the smoke goes directly to the room air ("side smoke"). The particle concentration caused by smoking is presented in table 3.5.

Table 3.5. Particles from tobacco smoke in a room

Item	Particle concentration*	
	number/m³	mg/m³
One cigarette, side smoke	$40 \cdot 10^9$	1.0
One cigarette, exhaust smoke	$20 \cdot 10^9$	0.5
One cigarette/hour, continuous	$120 \cdot 10^9$	3.0

* Concentration levels are given for a room (50 m^3) with air change rate 0.5 h^{-1}.

The pollutant load is highly variable and not individually foreseeable, which should lead us to the conclusion that DCV systems would be a practical solution. But, air change rates needed to dilute these pollutants to an allowable level are much higher than those achievable at maximum flow rate in normal ventilating systems. As an example, one cigarette calls for a total air volume of 1 400 m^3 in order for the concentration level to become lower than 0.05 mg/m^3. In a normal room of 50 m^3 volume and an air change rate of 0.5 per hour, the time for diluting the smoke to a level of 300 000 particles per litre will be about 10 hours. Thus, tobacco smoking in a room calls for special measures such as special smoking areas, prohibition, and exhaust hoods. Dilution by air changes is illustrated in Figure 3.1.

3.2.4 Particles

Particles are defined as solid or liquid matter in equivalent sizes less than 1 mm in diameter down to fractions of micrometers.

Sources of particles include:

* Smoke from cigarettes and pipes
* Human activities (skin fragments, fragments from clothing)
* Erosion of surface material
* Particle dissipation from paper, etc.
* Vacuum cleaning
* Outdoor air particles (pollen, dust in general)
* The ventilating system

Particles can be removed from supply air or room air using filters (fine or micro filters). Particle concentration in room air is a relevant indicator of room air quality and in many cases is a good indicator of human activity levels. However, the possibility of indicating human activity by sensing particle concentration is more or less destroyed by tobacco smoking. The concentration of particles in room air is shown in Table 3.6.

Smoke from cigarettes and pipes is a form of organic and other particles. This smoke is often absorbed by furniture and textiles and thus also represents a source of mixed gases.

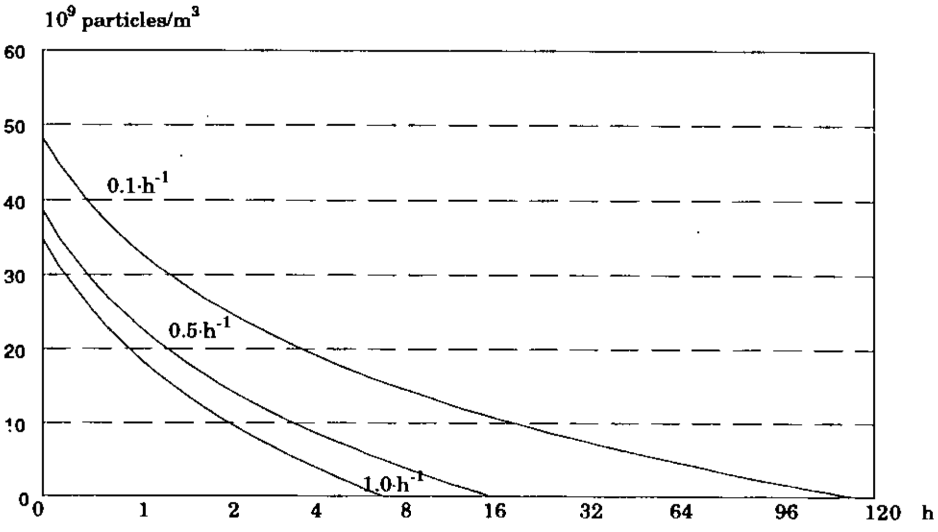


Figure 3.1 Dilution of tobacco smoke by ventilation in a room (50 m^3, 0.5 h^{-1}).

In most cases, with the exception of smoking, the particle concentration of indoor air is not crucial because other factors govern the necessary ventilation rate.

3.2.5 Building Materials and Cleaning Substances

Practically any building material emits more pollutants when it is newly installed than when it has been in use for some time. Although it is possible to predict emissions from building materials, the composition is seldom so exactly described with respect to production methods that the desired precision in a product declaration can be achieved. In general, the new or newly refurbished building calls for a larger basic air change rate than necessary at a later stage of usage. The emission of pollutants mainly consists of VOCs and is normally perceived by the occupants. The emission is practically constant as

Table 3.6. Particle concentration in rooms

Room type and activity	Particle concentration number/m^3	mg/m^3	Relative level
APARTMENT OR OFFICE			
Normal (upper) level		0.05	1.0
Vacuum cleaning		0.15	1.5
Acceptable level		0.25	2.5
LIVING ROOM			
(50 m^3, 0.5 ach)			
One cigarette, start level	$60 \cdot 10^9$	1.5	30
One cig/hour, continuously	$120 \cdot 10^9$	3.0	60

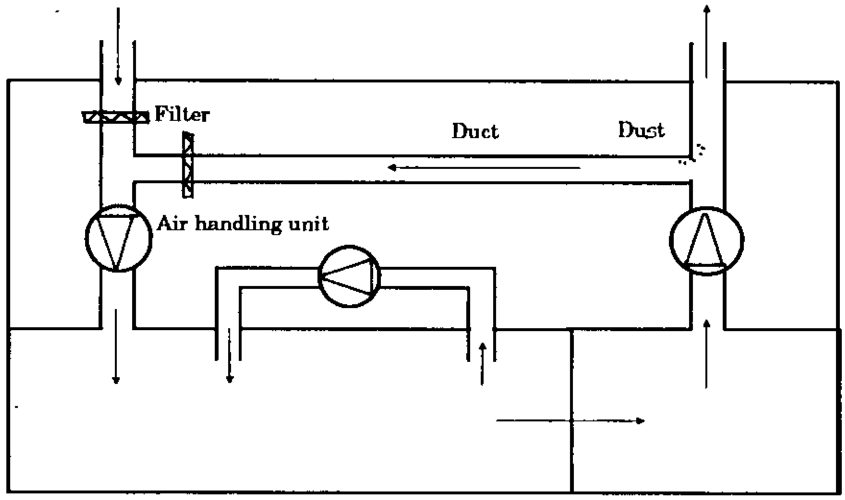


Figure 3.2 Pollutant sources in a ventilating system

long as no wet cleaning is undertaken. A constant basic ventilation rate is therefore logical. When using a cleansing compound the emission of pollutants rises as a function of both the wetting of the surfaces and direct emission from the cleansing compound.

Cleansing compounds often give such a high dissipation of mixed gases that a forced ventilation is needed during the cleaning operation and for some time thereafter. The forced ventilation may be fulfilled by window airing.

Absorption of cleansing compounds in the building surface materials raises the subsequent emission of pollutants for a period of time which is dependant on the type of cleansing compound and that of the surface material and its ruggedness.

3.2.6 The Ventilating System

The ventilating system may contribute to room pollution in one or more of the following ways:

* Outdoor air supply
* Emission from supply air components
* Pollutants from air transferred from an adjacent room
* Pollutants from room air via circulation in the room Pollutants
* Pollutant from room air via return air
* Emission from return air components

Figure 3.2 illustrates some potential pollution sources in a ventilating system.

The emission of pollutants from a ventilating system in continuous operation should normally be low and practically constant. A constant basic ventilation rate to keep the concentration level low is therefore logical.

In order to keep the system as clean as possible, fine filters should be used to filter supply air and return/circulation air (preferably F 85, Eurovent class EU 7). The filters should be changed regularly according to recommended or measured intervals. If not, the filters may emit pollutants and there would be an evident risk for increased pollutant emission from the ventilating system, especially at start up.

The risk for dust spread into the ventilating system calls for sealing of ducts and equipment during construction and a careful cleaning before first start up. A ventilation plant should not be allowed to operate without proper filters installed.

3.2.7 Other Sources

Combustion products such as water vapour, carbon oxides, and nitrogen oxides from stoves should usually be removed by exhaust hoods or by directly connected chimneys. Exhaust equipment should not cause building depressurization to a level that causes spillage of combustion products from appliances connected to chimneys. So treated, these pollutants should be of minor influence to the indoor air quality.

Copiers and laser printers in high-intensity use (several hours of uninterrupted use per day) should be treated as combustion sources, or should be placed in a separate room. In normal-low intensity use, the pollutant emissions from these machines can be looked upon as harmless. Hair sprays and perfumes should usually be treated as human-related bioeffluents.

3.3 Usable Indicators and Concentration Limits

Usable indicators or indication techniques are those substances and techniques that are easily detected and give a clear correlation to the load in the controlled room.

3.3.1 Humidity

Humidity can be a relevant indicator for demand-controlled ventilation, particularly in dwellings. Too high RH may cause mould growth, which is often found to be an active source for allergic or toxic reactions.

Acceptable RH values depend in part on occupancy patterns and tolerances, outdoor climate, and the condition of the building.

Acceptable long-term values RH values for room are:

Lower limit: 10-30 %, dependant on the number of particles generated in the room by the occupants, by the building and furnishings, and by different types of activities. As a rule, the number of particles in the room air rises if the RH is lowered.

Upper limit: 55-75 %. 55 % in order to prevent growth of house dust mites and 75 % in order to prevent building material degradation caused by condensation and/or high moisture content in the material. In a severe cold climate the upper RH limit can be as low as 15 %, depending on thermal bridges and cracks in the building envelope. The house dust mites can hardly survive if the water vapour content is below 7 g/kg corresponding to 50 % RH at 20°C, ref 25.

Short-term RH values often reach 100 %, for instance in kitchens or bathrooms. This can be acceptable if the moisture content in the room air and in affected building materials dries quickly or is otherwise dissipated within reasonable time. A guideline regarding the risk related to condensation and mould growth caused by moisture can be found in IEA Annex 14, Condensation. IEA Annex 24 is conducting further studies on interstitial condensation. Working documents and standards from the CEN/TC 89 deal with risks from cold bridges in the envelope.

3.3.2 Carbon Dioxide

Carbon dioxide, in general, is the main exhaust product from metabolism of human beings and animals. Carbon dioxide is a key indicator of human presence and has been found to follow the emission of bioeffluents from human beings very well.

If the maximum CO_2-concentration caused by human beings is allowed to rise to as much as 2 % (20 000 ppm) the necessary ventilation rate for a person at rest is about 0.25 l/s. The oxygen concentration of the surrounding air is thereby reduced from about 21 % to about 19 %, a drop that is hardly significant when compared with concentrations of about 14 % in a typical pressurized aircraft cabin.

Although a lack of oxygen caused by low ventilation rate is not critical, high CO_2-concentration is. Table 3.7 shows the CO_2 concentra-

Table 3.7. Carbon dioxide concentration and risks

Situation	CO_2 concentration, ppm abs	Remarks
Death risk	50000	
Medical limit	20000	Air raid shelter
Hygienic limit	10000 - 15000	Peak 15 minutes
Hygienic limit	5000	8 hours
Quality level	800 - 1500	From metabolism; CO_2 from open fires not included
Outdoor air	350 - 400	550 ppm has been observed in parts of the Ruhr area of Germany

tion levels for different classes of room air quality, Ref 25, 26..

Where smoking is allowed, the CO_2 concentration cannot be used as an indicator of the odour level. The ventilation rate should be set by the number of people smoking and the tobacco consumption rate.

3.3.3 Presence Indicator

A presence indicator can be designed to indicate movement or radiant heat or both. It can therefore indicate the presence of human beings. Insofar as that presence causes pollution of the room air the presence indicator can be used only to start and stop the ventilating system or to alter the air change rate of the treated space. The quality level must be controlled by other types of sensors, unless the number of occupants and their activity level is predictable and constant.

3.3.4 Mixed Gases

VOCs and some other oxidable gases (such as carbon monoxide) cannot usually be analysed separately. Sensing elements have been designed to detect mixtures of oxidable gases.

Average concentration of mixed gases in room air in new or refurbished buildings has been found to be significantly higher than that in old buildings. Moisture accelerates the dissipation of mixed gases from most building materials, as shown in Table 3.8, ref 27, 28.

Acceptable levels of mixed gases vary with the type of chemical substance. A maximum environmental hydrocarbon concentration, which form the main part of mixed gases, of 0.05 ppm is allowed according to German standard, ref. 25. This corresponds to a VOC concentration of about 0.04-0.10 mg/m^3, depending on molecular weight of the pollutant. Thus, most of the mixed gases have its origin in the building itself or in actions by the user.

Mixed gases usually indicate the presence of persons or animals, or of materials emitting organic com-

Table 3.8 VOC concentration in room air

Building type	Concentration, mg/m^3	
	Dry material	Wetted material
New or refurbished, all	2.9	30
Old:		
Dwellings	0.1-0.4	
Offices	0.5-0.8	
Schools, day nurseries	0.2-0.3	
Outdoor air	0.01-0.04	

pounds. In a normal building the concentration of mixed gases is therefore always higher than outside the building.

The human response to mixed gases is known only for a restricted number of products. The individual concentration of each mixed gases in a building is normally far below the hygienic limit. On the other hand the number of mixed gases is high, and the synergistic effect of mixed gases present at the same spot and at the same time is not known. The influence of synergism could vary from 0 (antidote reaction) to for instance 10 (magnifying reaction). Threshold values for the individual person are widely different.

3.3.5 Particles

The cost of currently available particle sensors prohibits their use in DCV systems.

3.4 Conclusions

3.4.1 Pollutant Rating

In table 3.9 is summarized the comparative potential effects, under various load conditions, of pollutants and indicators discussed in this Chapter.

3.4.2 Indicator Selection

CO_2 is a good indicator of human presence and activity, while water vapour because of absorption in building fabric cannot correctly describe this activity in a short term perspective. "Odour" is a common denominator for bioeffluents, mixed gases and tobacco smoke. Odour cannot be measured in an objective way. It can only be evaluated subjectively, which leads to the conclusion that odour sensing is at present an art of engineering that must be much further developed before coming into commercial use.

Heat and moisture dissipation often follow the emission of carbon dioxide provided that solar heat gain and internal heat gain from non-human heat sources are not dominant.

The use of particle sensors is a possible way of controlling the neces-sary ventilation rate in rooms where smoking is allowed. However, at present the prohibitive cost and need for evidence of long-term stability of particle counters is a hindrance to using them in commercial systems.

Table 3.9. ***Effects of pollutants and indicators on buildings and occupants.***

Pollutant/Indicator	Health	Discomfort	Building damage	Load type
Moisture	None	Small	Large	C + D*
VOCs from building fabrics surface coatings cleaning substances	 Small Small Moderate	 Moderate Moderate Moderate	 - - Small	 C C D
Bioeffluents	None	Small	-	D
Particles	Moderate	Moderate	-	D
Tobacco smoke	Large	Large	Moderate	D**
CO_2 (<20 000 ppm)	None	None	-	D***

C = Constant load, at least over periods of 24 hours
D = Dynamic load, caused by human activities
* Relevant mostly for dwellings
** Absorption to and emission from furnishing
*** Indicator on human activity

4 Sensor Types

4.1 Purpose

Use of the temperature sensor as a controlling device for ventilating systems is well known and understood and so need not be treated here. Only sensors responding to the composition of the indoor air or the occupancy of a building space will be covered.

This Chapter discusses the findings of two recent surveys of available sensors, and presents some recommendations and conclusions. The surveys include sensors for humidity, carbon dioxide and mixed gases such as volatile organic compounds (VOCs). The results of the 1989 IEA Annex 18 survey of sensors are available in the survey report ref. 3. The second survey was undertaken in July 1991, ref. 8. Numerical values used in the Chapter are derived from ref. 1, 5.

4.2 Guidelines

It is important to bear in mind that no sensor measures the "quality" of air. "Quality" is a term that is difficult to quantify and that has a large portion of subjective content. Control systems, on the other hand, respond only to quantitative, measured signals. Furthermore there is not always a direct coupling between the perception of air quality, the concentration levels of various substances and their toxicity or irritability. The perception will depend both on the substance and the individual person exposed to the substance.

Thus it is of primary importance to give careful consideration to the meaning of "air quality" in each application and to identify possible sources of pollution. Before selecting the appropriate type of sensor, or indeed before contemplating a DCV system at all, possible obnoxious substances should be identified and their threshold levels quantified.

Because these substances are not always easy to detect using currently available sensing devices, surrogates can be identified that will serve as indicators of their presence. For instance, carbon dioxide can be used as an objective indicator of human body odour. Suggestions concerning commonly used indicators for different applications are presented in Chapters 7-10.

In control applications the most important measuring characteristics of a sensor are:

* A high sensitivity to the chosen indicator and a low sensitivity to other influence factors (a low cross-sensitivity)
* Measuring and general operating ranges that are relevant to the application;

* Good reproducibility combined with a low level of hysteresis
* A short rise time (a rapid response) compared to the rise time of the indicator of a particular application
* A high degree of stability
* A suitable output signal
* Capacity for periodic calibration
* Immunity to climatic, mechani cal and electro-magnetic interference

Other less important measuring characteristics, such as accuracy and linearity, may be compensated for by suitable signal processing intelligence. Consideration should also be given to the installation, operation, and maintenance features of a sensor. These may include:

* Ease and durability of installa tion
* Type of mounting (wall or duct mounting)
* Type of filter (if required)
* Type of casing and its protection class
* Size and weight
* Type of power supply
* Level and frequency of mainte nance and calibration
* Expected lifetime

Last but not least, the purchasing characteristics of a sensor should be contemplated. Possible items of consideration are:

* Availability (alternative suppli ers)
* Price and delivery time
* Documentation

4.3 Active Elements

Within a sensor is an active element that is sensitive to the target pollutant or substance. Sensors now used in DCV applications include types for monitoring indicators such as:

* Humidity (relative humidity, wet bulb temperature, dew point temperature)
* Carbon dioxide
* Mixed gases (volatile organic compounds, VOCs)
* Occupancy
* Particles

In the following paragraphs the active elements of commonly used sensors of the first four types are briefly described. Particle sensors are not discussed since they are not a realistic option for DCV purposes, being prohibitively expensive and needing frequent calibration.

4.3.1 Humidity Sensors

Humidity sensors respond to either relative humidity or absolute humidity. Of the numerous principles employed to sense either of these, the most common types now in use are presented below.

Dimensional Change Hygrometers (human hair, plastic strips, wood fibres)

A large class of relatively inexpensive hygrometers utilizes the dimensional change of a sorbing substance (i.e. one capable of absorption or desorption). Many types of organic fibres such as human hair and wood fibres, as well as various plastic materials, are sufficiently sensitive to changes in relative humidity to act as sensing elements. The dimensional change of human hair due to a change in relative humidity by 100 % is approximately 2 %. Nylon fibres have a corresponding change of about 3 %.

Dimensional change sensors may act directly on a simple switch for the on/off control of a fan. In other cases the dimensional change may operate on a variable resistor to produce an analogue control signal.

Advantages: Simple and inexpensive. Large operating humidity range.

Disadvantages: Requires frequent reconditioning and recalibration. Substantial hysteresis (up to 15 % RH). Inaccuracy below 5 % requires daily single-point calibration. Response is relatively slow and temperature-dependent.

Electrical Impedance Hygrometers

Certain hygroscopic substances change their dielectric and/or their conductive properties in relation to changes in relative humidity. These changes can be measured as changes in capacitance and/or changes in resistance of the sensing element.

Dunmore Cells commonly use lithium chloride and/or polyvinyl alcohol on a plastic support as the sensing element. The operating resistance change may cover 2-4 decades in response to a change in relative humidity of 30 %.

Advantages: Low inaccuracy (< 1.5 %) and low hysteresis (< 0.5 %). Good stability (drift < 0.5 % per year).

Disadvantages: Limited operating range and high electric impedance. Sensitive to certain vapours (e.g. sulphur dioxide, some acids, alcohols), salts and high humidity or free water. Temperature-dependent rise time and drift in calibration.

Aluminium oxide hygrometers use an anodized material sandwiched between electrodes consisting of a metal base and a porous metallic film. Changes in relative humidity cause changes in the capacitance and/or the resistance between the electrodes.

Advantages: A fairly large operating range and very quick response times (< 1 s).

Disadvantages: A fair amount of hysteresis (several percent). Sensitivity to high humidity levels or free water.

Other impedance-type hygrometers use a plastic foil as the humidity-dependent dielectric material. The change in capacitance is used to provide an electric output. This type of sensor seems to be less sensitive to high humidity and has a very low level of hysteresis.

Weight Change Hygrometers

The mass of water accumulated in an absorbent material can be made to change the resonant frequency of a piezoelectric crystal. The quantity absorbed depends on relative humidity and the selected material.

Advantages: Immunity to interference and easy Analogue/Digital (A/D) conversion (the sensor is inherently digital).

Disadvantages: Expensive and not commonly used in control applications outside industries.

Dew Point Hygrometers

The dew point of water vapour is a temperature uniquely related to the absolute humidity. This temperature is normally detected by chilling a metal surface until water just begins to condense on this surface. Condensation changes the reflection of light from a light-emitting diode and this change is detected by a photo transistor.

Advantages: Direct, simple relationship between the measurand and the output signal. Low inaccuracy (< 0.2°C dew point temperature) and low hysteresis. Good stability under conditions of clean air. Low output impedance (e. g. 100 ohm platinum resistance transducer).

Disadvantages: Expensive. Relatively slow response. Requires an air pump or a minimum air velocity in a duct.

Wet and Dry Bulb Psychrometer

The latent heat exchange caused by the evaporation of water results in a well defined reduction of temperature in an adiabatic system, thus relating the absolute humidity to a set of temperatures. This temperature change can be measured by comparing the temperatures of one thermometer that measures the normal air temperature (dry bulb) and one that measures the temperature of a wick soaked in water (wet bulb). Equations relating the dry- and wet-bulb temperatures to the absolute (or relative) humidity assume heat exchange to be entirely convective.

Advantages: Direct thermodynamic relationship between the humidity and the output signal. Low electrical output impedance. Well proven and reasonably accurate method.

Disadvantages: Requires a supply of distilled water and a specified air flow rate. Slow response. Sensitive to impurities and heat exchange by radiation.

Saturated Salt Solutions

The vapour pressure of a saturated salt varies with temperature. A hygrometer using this concept is made by fitting a pair of electrodes to a substrate covered in salt, commonly lithium chloride. Water vapour is absorbed by the salt until a balance is reached between the pressure in the salt and the absolute vapour pressure in the air. If the sensing element is heated, the vapour pressure will rise until it exceeds the vapour pressure in the air. At this point the salt will be saturated, water will start to evaporate, and the electrical resistance will change abruptly. The temperature of the sensing element at this point serves as a measure of the absolute humidity.

Advantages: Reasonable measuring range (-29 to +71°C dew point temperature) and fairly low inaccuracy (< 1°C dew point temperature). Reasonably quick response (a few minutes).

Disadvantages: Salts may become polluted. Requires regular reconditioning of the sensor.

4.3.2 Carbon Dioxide Sensors

Sensors designed to measure the carbon dioxide content of air use absorption of infrared light (NDIR, Non Dispersive Infra Red). A light source transmits light through a selective infrared filter into a measuring cell. The room air is passed through this cell and absorption of the infrared light excites vibrational energy bands of the carbon dioxide molecules. The filter ensures that only wavelengths typical of carbon dioxide are transmitted into the cell. There appears to be a requirement concerning a minimum amount of water vapour in the air to stimulate the vibrational action of the carbon dioxide molecule. Two methods of detecting the absorption are commonly used: the photoacoustic method and the photometric method.

Photoacoustic Infrared Detection

The increase of molecular vibration caused by absorption of light leads to an increase in temperature of the absorbing gas. With a closed cell this change in temperature also leads to a change in pressure. Modulation of the light source creates a pressure change with the modulating frequency and an amplitude dependent on the concentration of the absorbing gas. The pressure changes are detected by a sensitive microphone.

Advantages: Low cross-sensitivity, low hysteresis, reasonable inaccuracy (10-100 ppm) and linearity.

Disadvantages: Discontinuous measuring principle (cell has to be closed off between samples), slow response (rise times may be in excess of 10 minutes), little long-term experience.

Photometric Infrared Detection

Absorption of light in a cell results in less light coming out at the end of the cell. The emerging light is measured by a photodetector and converted to an electric output signal. To achieve sufficient absorption at low concentrations the light path is increased by multiple reflections in mirrors.

Advantages: Low cross-sensitivity, low hysteresis, reasonable inaccuracy (10-100 ppm) and linearity.

Disadvantages: Inverted response (low gas concentration gives high transmission), fairly slow response (rise times of up to 10 minutes).

4.3.3 Mixed Gas Sensors

There are three types of solid state sensors used to monitor the presence of certain gases in air: homogeneous metal oxide sensors, MOSFET sensors and catalytic gas sensors. MOS means Metal-Oxide

Semiconductor and FET acronym for Field-Effect Transistor. These sensors are commonly called "air quality sensors" and provide an output signal scaled as 0-100% air quality.

Homogenous Metal Oxide Sensors (Taguchi sensors)
The most commonly used homogeneous metal oxide sensors use n-type polycrystalline semi-conductors such as SnO_2 or ZnO. The sensor is heated and combustible gases can react with oxygen on the heated surface. The reactions excite electrons into the conduction band of the semi-conductor, thus changing the resistance of the sensor.

Advantages: Sensitive to a broad range of human-generated odours, cigarette smoke and emissions from building materials. Inexpensive.

Disadvantages: Sensitivity varies widely with the type of gas and not necessarily in relation to toxicity or irritability. Greatly affected by variations in temperature and humidity. Slow gas/temperature dependent response. Difficult to know what to calibrate against.

Use of thin-layer technology can reduce response times and increase the sensitivity to simple gases such as H_2S, CO, NO_2, CH_4, and C_2H_5OH.

MOS-FET Sensors (Field Effect Transistors)
In contrast to the Taguchi sensor, which is a surface effect device, MOS-FET sensors are volume effect devices. Gas molecules diffuse into the sensor and react at the gate of the transistor thereby changing the current through the device. By choosing different metals as the gate material, the sensor can be made highly selective in its sensitivity to specific types of gases.

Advantages: Rapid and specific response. Possible to integrate the sensor in an amplifier circuit.

Disadvantages: Pollutants must be known in advance. At present sensors are expensive and experience is limited.

Catalytic Gas Sensors
The heat of exothermic reactions at the surface of a sintered body will increase its temperature and thus also increase its resistivity. To enhance the reaction rate of the non-oxidized gases the sensor is heated by an embedded heating wire and the surface is covered by a thin catalytic layer.

4.3.4 Occupancy Sensors

Various methods of detecting occupancy changes have been devised for military purposes or for burglar alarms. Detection may be accomplished by sensing infrared radiation emitted from people (passive IR-sensors); by interruption or reflection of infrared beams (active IR-sensors); by sensing a change in impedance for microwave radiation, vibration or noise.

In the case of DCV applications it is not only the change in occupancy that is important but the occupancy itself. A sensor must detect the presence of people even if no movements occur for a considerable time. Therefore the passive IR-sensor technique seems to be most suited for use in DCV systems.

4.4 Connection to Control Systems

The control device on a DCV system should provide quick and correct reactions to changes in the concentration of the selected indicator or pollutant. The reaction should not be influenced by the presence of other substances in the form of gas, vapour or particles (cross-sensitivity). Nor should the reaction be affected by environmental factors such as temperature, vibration and electromagnetic fields. The correct connection of sensors to the control system is thus of the utmost importance, as is the design and construction of all devices comprising the control system.

4.4.1 Types of Control System

Sensors are normally used to control the rate of exhaust air flow and the supply of outdoor air by operating the speed of fans and/or the position of dampers. Control may be exerted by means of either on-off control or continuous control.

On-off control
This is a simple and inexpensive type of control that is used frequently to limit humidity levels in dwellings. In the case of hygrostats the sensing element is often directly acting on an electric switch which operates the fan or damper. In other cases the magnitude of the current to be switched may require an intermediate relay.

Continuous control
Controllers operating with continuous control can be classified as Local Controllers (LC) or Direct Digital Controllers (DDC). Local controllers may be of the traditional analogue type or may operate digitally with an analogue output. Modern control systems often operate a number of local controllers, so-called Programmable Local Controllers (PLC), from a central computer. Whatever the type of controller a variety of different control strategies may be used (see Chapter 5).

4.4.2 Sensor Location

The sensor must be located in a representative position if is to respond correctly. The position will depend on the application and the type of sensor. This is discussed in the chapters on specific applications (chapters 7-10). Sensors should not be mounted where they are liable to be exposed to excessive amounts of dust, grease, vibration or electromagnetic fields.

4.4.3 Connection to the Control Device

To facilitate connection to systems employing continuous control, the sensor should have a standardized current or voltage output. Input to controllers is usually 0-20 mA, 4-20 mA, 0-5 V or 0-10 V. Digital communication may be of a series or parallel type. In this case standardized and well specified transmission protocols and baud rates should always be used.

Standard precautions concerning shielding and electric separation of low voltage signals and high voltage/current power conductors should be taken to avoid electromagnetic interference. Immunity to electromagnetic interference should be part of an evaluation of sensors (see for instance the proposed test program in refs. 4 and 5). It goes without saying that all requirements concerning electrical or other safety aspects should be complied with.

The service life of a DCV control system will depend on various aspects of individual components such as component lifetime, installation, manner of operation, and the requirements and possibilities of service. It will also depend on the overall configuration of the system. The installation must be made in such a way that subsequent service, calibration and adjustment to sensors are easy to perform. The cost of different types of sensors may vary considerably but in general the cost of on-site service or calibration will be close to or even exceed the cost of a new sensor. Therefore long-term stability and reliability are important features. A target value for the service life of a sensor should be at least 10 years.

4.5 Test Laboratories

The following official testing laboratories were directly involved in the IEA Annex 18 evaluation of sensors and control systems:

SIB (National Swedish Institute of Building Research)
Box 785, S-801 29, Gävle, Sweden

SINTEF
N-7034, Trondheim-NTH, Norway

SP (Swedish National Testing and Research Institute)
Box 857, S-501 15 Borås, Sweden

A number of institutions around the world perform accurate calibration of humidity sensors, for example:

CETIAT (Centre Technique des Industries Aérauliques et Thermiques) B.P. 6084, F-69604 Villeurbanne Cedex, France

NIST (National Institute for Standards and Technology)
Gaithersburg, Maryland, USA

NPL (National Physical Laboratory)
Teddington, Middlesex, TW11 O1W, England

NRC (National Research Council)
Ottawa, Ontario, K1A OR6, Canada

Carbon dioxide and VOC gases can usually be analysed by well equipped chemical laboratories. Sensors for these substances can probably also be tested by such institutions. The Swedish National Testing and Research Institute has carried out initial investigations according to the test program, ref. 4 and 5.

4.6 Testing and Rating

Sensors and other components for the operation of DCV systems should be tested according to standardized methods. Results of such tests must be presented in a form that is comprehensible and that makes meaningful comparisons possible. In the report on Sensor Tests, a proposal for such a test program is presented and the required test equipment is described.

Regular functional tests and, if necessary, calibration should be carried out on site. Some sensors have inherent control facilities such as test signals or warning lights. Other sensors may be checked by special service and test instruments. Calibration is normally carried out using either of the following two methods:

* Comparison with a calibrated re ference instrument exposed to the same atmosphere.
* Exposing the sensor to a well known reference atmosphere.

Many humidity sensors can be checked by using saturated salt solutions of different types, ref. 1. If the salt solutions are regenerated regularly this is a method that is sufficiently accurate for control applications. Suitable salts are for instance potassium acetate (21-23 % RH), sodium iodide (37-41 % RH), sodium bromide (57-60 % RH) and potassium chloride 84-86 % RH). ● *Caution:* Some sensor types are adversely affected by certain salts. This should always be checked with the manufacturer before exposing the sensor.

Carbon dioxide sensors can be calibrated by the use of bottles with reference gas of a known composition. Such gas may be obtained from some of the suppliers of sensors or from major suppliers of liquified gas. A suitable concentration of a calibration gas is in the range of 1000-1500 ppm. ● Caution: IR sensors for carbon dioxide rely on the presence of a minimum humidity level of 10-20 % RH. Therefore it is not possible to apply carbon dioxide out of a bottle directly to the sensor without first adding some humidity. The sensor output will also depend on the pressure and therefore care must be exercised to avoid exposing the sensor to the pressure of the bottle.

Mixed gas sensors can be checked in much the same way as sensors for carbon dioxide by means of certified reference gases. Selective sensors, such as some of the experimental FET-devices, should obviously be checked with the gas they were optimized to detect. Broad band devices, such as the

Table 4.1. Gases for calibration of mixed gas sensors

Application (source of pollutant)	Type of gas	Concentration
Occupancy (body odour)	Acetone (C_3H_6O)	1-100 ppm
Smoke (tobacco 1-2 ppm, car exhaust 10-100 ppm)	Carbon monoxide (CO)	1-100 ppm
VOCs (building materials, photocopiers, printed documents etc)	Nonane (C_9H_2O)	1-10 mg/m^3

Taguchi-type semi conductor sensor, will require careful consideration before one or several calibration gases are chosen. Manufacturers of the sensing elements will normally provide data concerning the relative sensitivity of the sensor to various gases.
➤ Caution: This type of sensing element is also sensitive to water vapour and it is highly influenced by the operating temperature.

Unless the exact indicator(s) is (are) known the following gases could be used to calibrate mixed gas sensors:

Laboratory tests of five mixed gas sensors were conducted using nonane, toluene and octanal as reference gases, ref. 5. The sensors displayed roughly the same sensitivity to a specific gas concentration irrespective of the type of gas used as a single component or mixed in equal parts.

4.7 Conclusions

Experience from a great number of research projects and practical applications of DCV control systems has been summarized in ref. 3. Further experience was gained concerning different types of sensors during the course of the IEA Annex 18 activities. Conclusions concerning the state of the art of sensors for humidity, carbon dioxide and mixed gases (volatile organic compounds) are summarized below.

4.7.1 Humidity Sensors

Application: The main field of application for humidity sensors is in dwellings to control the humidity levels in bedrooms, bathrooms, laundry rooms and kitchens. The principle objectives are to avoid deterioration of the building structure and to minimize the risk of mould growth. Mould growth is augmented by a high relative humidity and will therefore generally commence on room surfaces with the lowest temperatures. Surface temperatures will change due to changing outdoor temperatures as well as changing room temperatures. Thus it is beneficial to use an advanced humidity controller, which adjusts the set point in accordance with the prevailing room conditions, ref. 6 and 7.

It is generally much easier to control specific activity-related emissions than occupancy-related emissions by means of humidity sensors. Unless the basic ventilation is extremely poor, the occupancy-related humidity variations will be smaller than those caused by climatic variations and some sort of advanced controller will be required to distinguish between occupancy-related and natural humidity changes.

Availability: There is an abundance of humidity sensors of different makes and types in all price ranges. Most electronic sensors come with a choice of standardized output signals. Thus availability should not be a problem.

Price: From US$ 1-2 (0.8-1.6 ECU) for simple sensing elements up to US$ 10 000 (8 000 ECU) for sophisticated dew point hygrometers. Typical good quality, capacitive sensors cost in the range of US$ 100-600 (80-480 ECU) including the necessary electronics.

Performance: Electrical impedance change sensors, e g capacitive sensors, in general have excellent performance characteristics with good linearity, low hysteresis and quick response. ● Caution: Some sensors will not tolerate condensation of water on the sensor element. Sintered filters may slow the sensor time response considerably.

Dimensional change sensors (e.g. hair or plastic strip hygrometers) are generally less accurate than impedance change hygrometers. For control purposes the relatively slow response and large amount of hysteresis may prove to be important disadvantages.

Service life: The service life of most humidity sensors is expected to exceed 10 years. Calibration or functional control intervals should be approximately 1-2 years depending on the type of sensor and its application.

4.7.2 Carbon Dioxide Sensors

Application: Since carbon dioxide is at present the best documented indicator of occupancy, carbon dioxide sensors are frequently used to control occupancy-related emissions. However, they show hardly any response to tobacco smoke. Therefore other measures must be taken to avoid problems in premises where smoking may occur.

Availability: Carbon dioxide has previously been measured using costly and bulky laboratory equipment. In recent years smaller sensors have come onto the market with prices that are still high but not exuberant. Size and type of output signal are fairly similar for different makes and therefore availability should not be a problem.

Price: Price range is US$ 500-2 000 (400-1 600 ECU).

Performance: The error of measurement is normally well within ±50 ppm at a measured level of 1 000 ppm, which should be sufficient for control purposes (this corresponds to an uncertainty in the controlled flow rate of ± 8 %). Some sensors are fairly slow which may be a disadvantage in control applications.

Service life: Long-term experience is still limited but continuous operation over a period of one year seems to cause no problems. Possible sources of maintenance are the IR-lamp, the air pump (if any) and cleaning of the optical filter. Calibration check-ups should be performed annually

4.7.3 Mixed Gas Sensors

Application: Mixed gas sensors are used in very diverse applications such as warning devices for gas leaks, detection of occupancy-related problems (including tobacco smoke) for DCV systems, and ventilation control of garages and tunnels. The sensor's broad-range sensitivity is both its strength and its weakness.

Availability: Although there are a number of suppliers of mixed gas sensors, nearly all of these suppliers use sensing elements from the same manufacturer. At present, there-fore, there are few alternatives on the market.

Price: US$ 20-400 (16-320 ECU) depending on whether the price pertains to the sensing element or to a complete sensor including the controller.

Performance: Mixed gas sensors are difficult to assess in terms of ordinary performance criteria since these sensors react on such a large variety of substances. Furthermore there is no direct relationship between the sensitivity of the sensor to a certain gas and the effect of this gas on the indoor air quality. In most cases the user of the sensor does not know the cause of a change in output signal. Experiments have shown that sensors using the same sensing element but different electronics may react quite differently. The output is very sensitive to the temperature of the sensing element and therefore also to the supply voltage of the sensor heating element. The electronics may contain compensation circuitry, e g for the influence of temperature and humidity.

Service life: Long-term experience of mixed gas sensors in DCV applications is scarce. The effect on the sensing element of extended exposure to for instance dirt and grime has yet to be documented.

4.7.4 Occupancy Sensors

Application: Occupancy sensors are commonly used in burglar alarms to detect the presence of people. A few applications in DCV systems (e.g. in schools) have also been reported. ➤ Caution: The actual positioning of the sensor is crucial if the entire space is to be covered. Also when a room is entirely filled with people there is a risk that the sensor will detect this as an elevated back-ground temperature.

Availability: Readily available from several suppliers.

Price: US$ 100-200 (80-160 ECU) for the sensing element including some signal processing intelligence such as time delay functions and sensitivity adjustments.

Performance: The operating principle is often based on IR-sensing elements that detect the heat radiation from human beings. They seem to work well in burglar alarm systems and there is also some positive feedback from DCV systems although experience is still limited. One negative aspect is the inability to detect the effect of occupancy on indoor air quality. This means that occupancy sensors will generally operate only in on-off control systems.

Service life: Long-term experience of occupancy sensors in burglar alarms is abundant. The effect on the sensing element of extended exposure to for instance dirt and grime has yet to be documented.

4.7.4 Future Developments

If DCV systems are to attain widespread application, sensors must be inexpensive, easy to check and calibrate, and offer both stability and a long service life. Humidity sensors and carbon dioxide sensors are already sufficiently accurate, but could still be improved concerning the other aspects mentioned above. Mixed gas sensors, on the other hand, need improvements regarding ability to control the response to various substances. For all types of sensors the low cost of intelligent electronics makes extensive use of self-checking features feasible.

The rapid progress in hybrid electronic circuitry using thin-film and thick-layer technology in combination with micromechanics may in the future provide us with integrated multi-sensor devices. Such a device could for instance include a temperature sensor to control cooling requirements, a humidity sensor in case humidification or dehumidification is needed, a CO-sensitive solid state sensor responding to tobacco smoke and sensitive solid state devices reacting to some specific human related emissions. Even sensing elements for specific emissions related to building materials could be included.

5 Control Principles

5.1 Purpose

This Chapter discusses selection of a control strategy for a DCV system. It examines factors related to the building and its occupancy that influence pollutant levels and hence drive the ventilation requirements.

The control principles that are discussed are based on a distinction that is drawn between the load profile over time and the ventilation profile over time. There is no exact correlation between the two. For instance, certain pollutants are generated continuously from building materials but continuous operation of the ventilation system is not necessarily required to remove them. The purpose of the control system is to remove the pollutants in the most energy-efficient manner and still maintain acceptable IAQ levels for the periods of occupancy.

A control strategy is strongly dependent on the ventilation principle (mixing or displacement), and the resulting air flows. This in turn will affect placement of the sensor(s) that act as control devices.

Since acceptable indoor air quality and thermal comfort must be sustained at the same time a combination of air quality control and temperature control is necessary. Priority must then be given to the criterion that demands the higher ventilation rate. Building cooling using outdoor air during cold periods (free cooling) is recommended in order to achieve simultaneous ventilation and cooling. This is not discussed in the scope of this document.

The removal of pollutants from local areas of specific activities where exhaust hoods or other local exhaust methods could be applied is not included in this discussion.

5.1.1 Definitions

Pollutant sources described in Chapter 3 can be divided into two main categories:

Continuous pollutant sources are not directly related to the presence of people and their activities. Emissions from these sources are always present although their strength can vary over time. Examples are emissions from building materials, furniture, and the ventilating system.

Non-continuous pollutant sources are related to the presence and the activity of persons. This kind of pollution can only occur during the service periods of the building. It is variable in intensity and often unpredictable with respect to fluctuations in time. Examples are emissions from persons in the form of odour and cigarette smoke; and emissions from cleaning substances.

Following the same principles, operation of the ventilation system can be classified at two levels:

Base ventilation rate which is sufficient to remove pollutants from continuous sources; or

Occupancy ventilation rate (in cludes presence-related and activity-related) which removes non-continuous emissions from the occupants and any equipment they use.

A ventilation system should combine both types of ventilation. DCV strategies, which by definition aim to control ventilation according to time-dependent demand, are most concerned with occupancy ventilation but must accommodate base ventilation requirements.

5.1.2 Airtightness

Any discussion of ventilation system control must address the level of airtightness of the building. In buildings with a moderate or poor airtightness, base ventilation can be supplied in whole or in part by uncontrolled air infiltration. However, there is no guarantee that this kind of air renewal is sufficient and the adoption of a DCV system may result in significant energy savings even when considerable air infiltration takes place in the building. When a ventilation system is designed for a leaky building, it is usually designed to handle all ventilation requirements, as if there were no natural infiltration.

When balanced (i.e. supply and exhaust) and, to a lesser extent, extraction (exhaust only) ventilation systems are adopted in a leaky building, significant infiltration may take place which adds to the mechanical ventilation rate and helps reduce the level of pollutant. As a result, the DCV will operate and consequently reduce the overall ventilation rates.

A more appropriate solution in terms of energy conservation would be to increase airtightness and to supply the required ventilation in a controlled way. The airtightness at dampers and ventilation induced by mandatory exhaust fans (e.g. toilets, kitchens, laboratories) must be assessed to ensure that control is possible. Often, even with the system on its minimum setting, the building may be overventilated.

The airtightness of dampers and ventilation induced by mandatory exhaust fans (e.g. washroom kitchen, or laboratory) must be assessed to ensure that control is possible. Often, even with the building on its minimum setting, the building may be overventilated.

5.1.3 Control Strategies

When considering control strategies for a DCV system, the designer must consider the options for both base ventilation control and occupancy ventilation control. For every ventilating system the designer

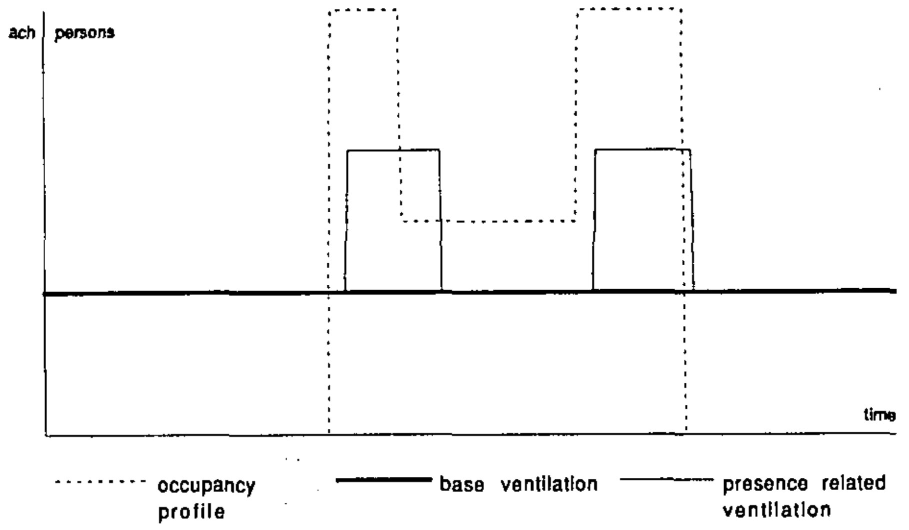


Figure 5.1. Combination of base ventilation rate and occupancy ventilation rate

must select one control strategy for each of these categories. This chapter presents the strategies and provides some selection guidelines.

Design of a ventilation control system based on fluctuations in demand is feasible only if the occupancy ventilation rate is significantly greater than the base ventilation rate. This can be achieved only if:

* continuous pollutant sources are reduced to a minimum for base ventilation purposes

* the dominant or driving pollutant is identified as the controlling factor for occupancy ventilation

Any pollution of the treated space that may be caused by the ventilating system itself must be reduced to a minimum by careful system maintenance. Residual pollution from this source will not influence the control strategy, but would remain a factor when defining the required flow rates for outdoor air.

The rate and duration of base ventilation and occupancy ventilation will vary according to the occu pancy profile and other load factors. A simple example is shown in figure 5.1, where the system is operating continuously at the base ventilation rate and is increased to the occupancy ventilation rate in response to periods of occupancy.

Table 5.1. Average pollutant load (olf/m^2) caused by building and occupants, ref 4

Building Type	Building			Occupants	Total
	Material	Ventilation System	Total Building		
Offices	0.12	0.25	0.37	0.07 *	0.44
Auditoriums	0.32	0.28	0.60	1.50 *	2.10
Schools	0.11	0.20	0.31	0.50 *	0.81
Day nurseries	0.07	0.32	0.39	0.38	0.77

* Assuming occupancy is according to ASHRAE 62-1989 with 1 olf/person.

Control of both types of ventilation is based on:

* Timing (on/off) control

* Control of the ventilation rate (fan speed, damper position and so on)

In the following sections, the control strategies will be presented diagrammatically showing variations of the model presented in figure 5.1.

5.2 Base Ventilation Control

Emissions from the building fabric and other continuous sources must be removed by base ventilation. The choice of the control strategy for base ventilation will depend on the intensity of the pollutant, the occupancy profile and ability of the system to adapt the air flow rate (continuously or in steps) to the actual demand.

Several studies by P.O. Fanger and others show that indoor air pollution from continuous sources can easily be as or more significant as pollution caused by the occupants. Table 5.1 shows the total olfactory (olf) load (as defined by Fanger, 1988) for different building types.

In order to allow the application of a demand control strategy the pollu-

Table 5.2. Range of pollutant load caused by the building, ref 4

Building Type	Range (olf/m^2)
Offices	0.02-0.95
Auditoriums	0.09-1.32
Schools	0.12-0.54
Day nurseries	0.02-0.74

tants from building materials and from the ventilating system must be reduced to a minimum. Table 5.1 may be used to indicate the occupants' load versus the building load and provide a first indication as to whether the building type might be suitable. The average pollutant load cannot be used in the individual case, as table 5.2 shows that the pollutant caused by the building can vary widely. The lower level can be compared to the maximum levels for occupants shown in table 5.1, from which it will be seen that the variation is from 3 to 20 times as high from the occupants as from the buildings.

The wide range of values shows that DCV systems will only be feasible in some buildings. The source of odour will be related to occupancy almost always in auditoriums, usually is schools, often in day nurseries and seldom in offices. The same may be said for the applicability of DCV systems.

Figures 5.2 to 5.5 show four possible strategies for control of base ventilation. All of them can easily be handled by a clock relay. Occupancy ventilation is not shown in the diagrams; in practice, it must always be added to the base ventilation rate.

5.2.1 Constant 24-hour Base Ventilation

Pollutants that are continuously emitted call for constant base ventilation if accumulation is to be avoided. This kind of base ventilation rate is appropriate in buildings with continuous round-the-clock occupancy such as hospitals or homes for the elderly, see figure 5.2.

Figure 5.2. Constant 24-hour base ventilation

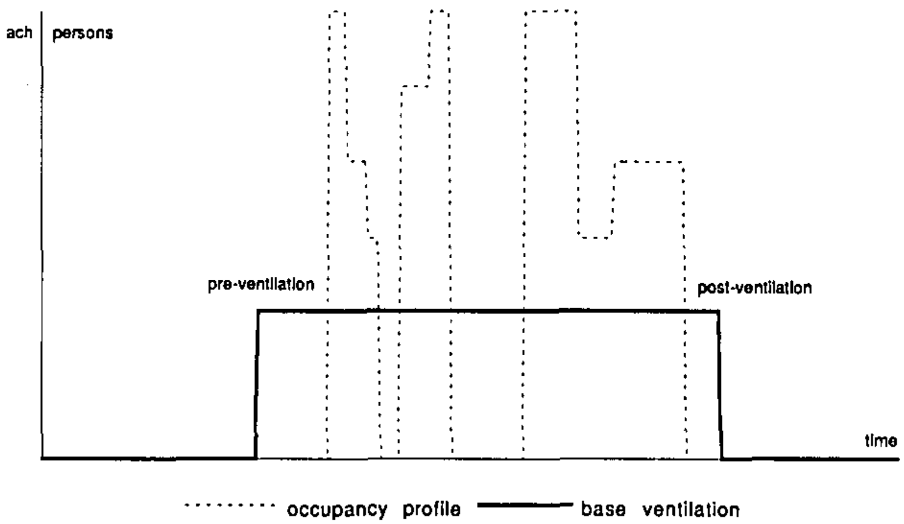


Figure 5.3. Constant base ventilation rate during part-time with pre- and post-ventilation periods

5.2.2 Constant Part-Time Base Ventilation

In many cases the emission of pollutants, although continuous, is low enough that part-time operation of the base ventilation may be sufficient. There is no change in the base ventilation rate over the period. Accumulation of pollutants during times of no occupancy can be dealt with by a pre-ventilation period. A post-ventilation period can also be added in order to promote a fast reduction of the pollutant level after the occupancy period.

The length of the pre- and post-ventilation periods should be calculated according to the emission rate and air change rate. If these periods are too short, the base ventilation rate may be higher than would normally be required during occupancy periods.

Note: If the emission rate of the building materials is high, (for instance in a new building) a continuous base ventilation rate is recommended, see figure 5.3.

5.2.3 Pre-Ventilation with Higher Ventilation Rate

This strategy employs a change in base ventilation rate. The pre-ventilation period can be reduced by increasing the air change rate during that time. During the rest of the service period of the building the base ventilation rate is lower and thus the occupancy ventilation rate and its control become more important. This can be favourable in terms of energy savings, see figure 5.4.

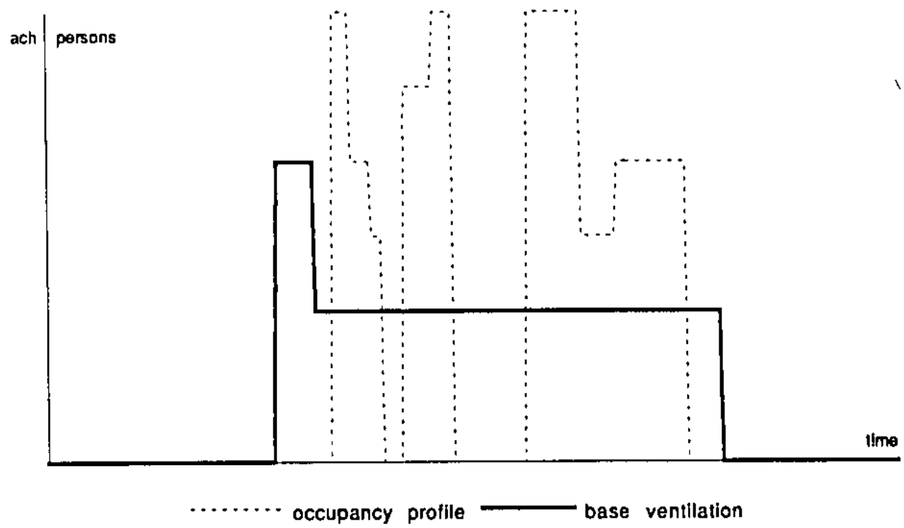


Figure 5.4. Pre-ventilation with higher ventilation rate

5.2.4 Intermittent Forced Ventilation ("Flushing")

If the occupancy of the room is not continuous or the continuous pollutant generation rate is low, intermittent forced ventilation or "flushing" of the room can be a valuable solution to remove the continuous-

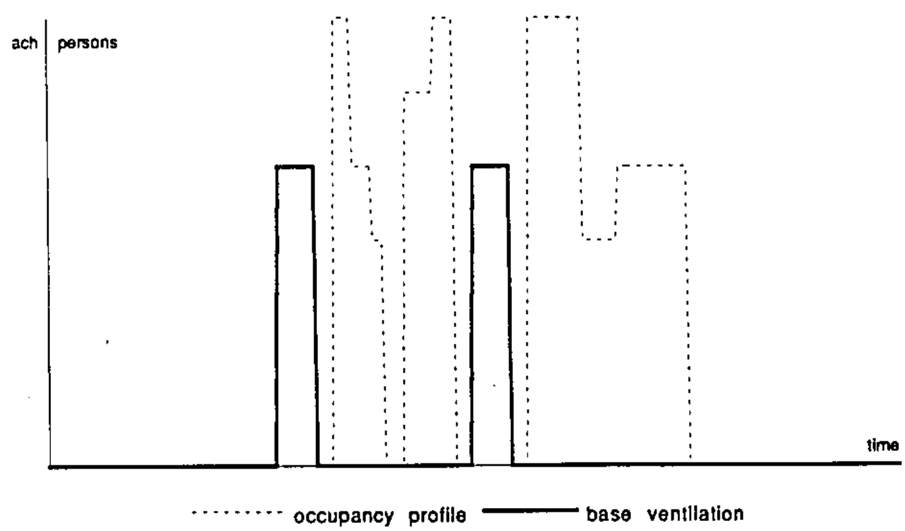


Figure 5.5. Intermittent forced ventilation

source pollutants. The duration of the rinsing periods and the interval between them is set according to pollutant source strength, air change rate and load profile, see figure 5.5.

5.3 Occupancy Ventilation Control

Occupancy ventilation should be used in addition to base ventilation and must account for changes in ventilation demand caused by the occupancy of the treated space. Data presented in Chapter 3 on occupancy and activity-related pollutants can be used for the assessment of demand for occupancy ventilation.

The following paragraphs describe strategies for the setting the occupancy ventilation rate. The strategies are presented in order of availability of information about the fluctuations in pollutant load.

5.3.1 Constant Flow

A constant ventilation rate requiring neither timing control nor rate control throughout the service time of the building can be regarded as an appropriate demand control strategy when the strength of the pollutant source is known and constant throughout the occupancy period. A constant air change rate can be calculated to keep the pollutant concentration below a chosen level. If the time of operation is around

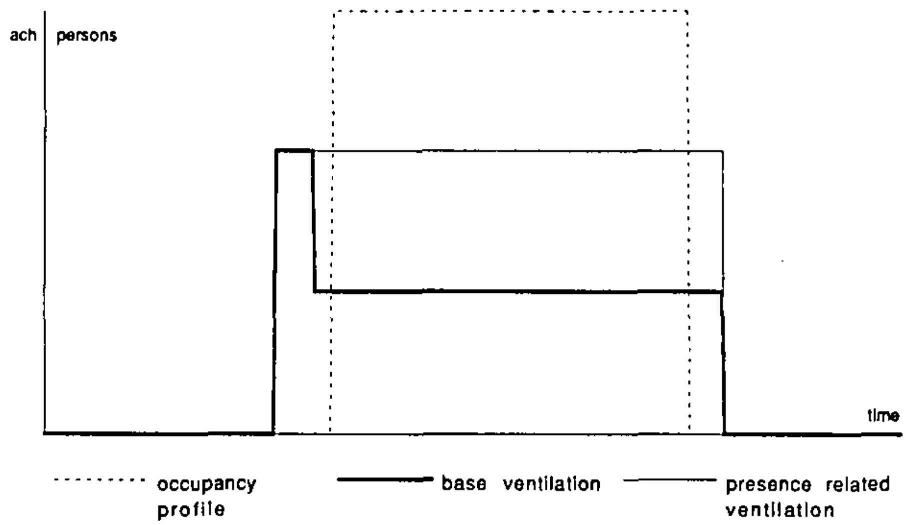


Figure 5.6. Constant and known pollutant source strength with constant system operation during the service time of the building

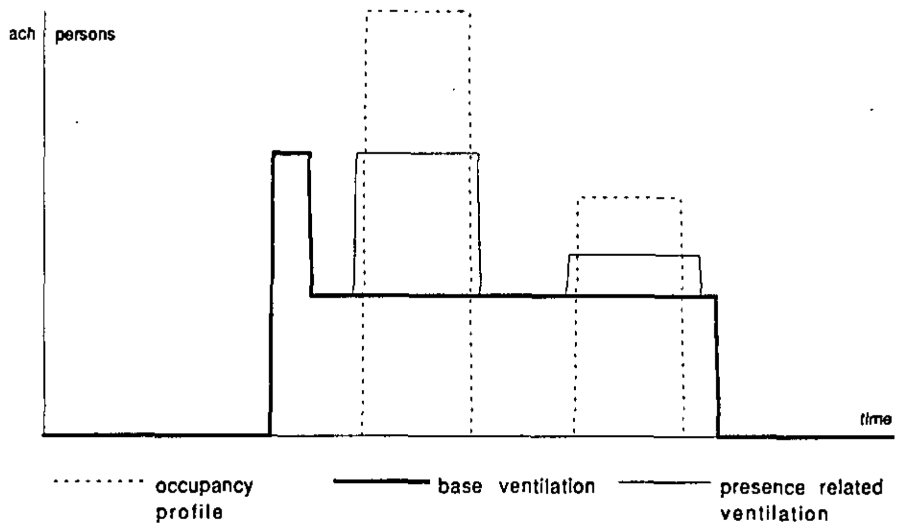


Figure 5.7. Predictable occupancy with clock-controlled ventilation rate

the clock (as in a hospital) no control devices are needed but system performance should be monitored and regular inspections must be made.

5.3.2 Clock Control

System operation can be controlled by a simple clock when both the occupancy period and the pollutant source strength are always predictable. In order to guarantee an appropriate ventilation rate, information must be transmitted to operating personnel in advance and a continuous adaptation of the programming is required. Unpredicted changes in occupancy cannot be dealt with and can lead to occupancy periods with unnecessarily high or unacceptably low ventilation rates. Examples are shown in figures 5.6 and 5.7.

5.3.3 Manual Control

Manual control of the system leaves the responsibility of assessing the actual ventilation demand to the occupants or service staff. Complicated information flow for unforeseen occupancy periods can thus be eliminated. In this case the occupants (such as teachers) or service staff must be trained on the appropriate use of the system.

Occupants will tend to leave the system in operation when leaving the room or the building. To avoid unnecessary operating time the manual switch can be combined with a clock relay which limits the operation time as appropriate.

5.3.4 Presence Sensor Control

Very often the occupancy profile is not predictable in time although the pollutant source strength is constant over periods of occupancy. In these cases an infrared sensor can be used to detect the presence of people. As soon as somebody enters the room, the occupancy ventilation system is switched on. A short post-ventilation can be adopted after people have left.

An example is shown in figure 5.8, where the ventilation rate accommodates the maximum load (period 1). During the period of lower load (period 2) the ventilation rate is too high for the load situation.

5.3.5 Continuous Monitoring and Control

When neither the time nor the level of occupancy and pollutant are predictable, a continuous monitoring and control system is desirable.

Chapters 3 and 4 showed that the following pollutants or indicators can be used to assess indoor air quality and control the operation of the ventilating system: CO_2, humidity, VOC. Which one of the mentioned indicators should be chosen to control the system depends strongly on the occupancy profile and the activities in the treated space.

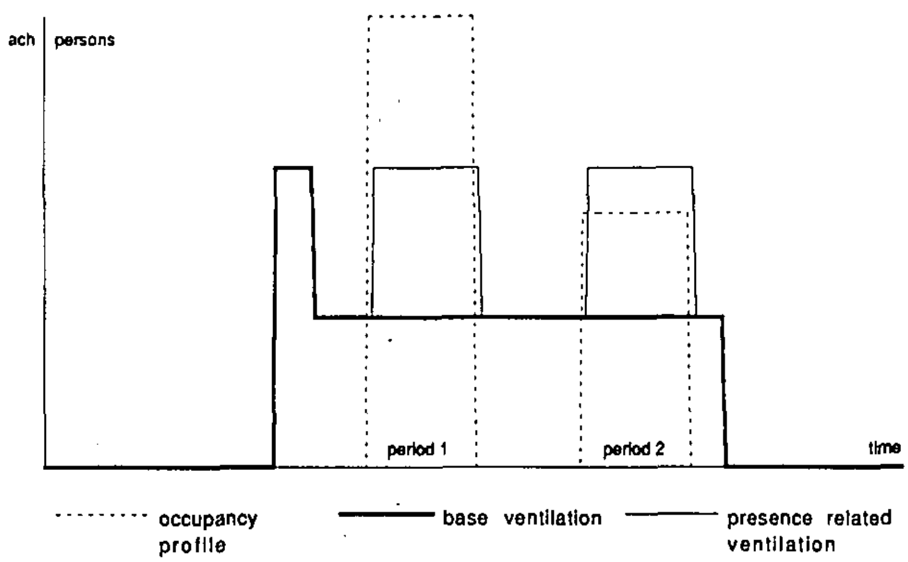


Figure 5.8. Adaptation of ventilation rate according to the presence

Table 5.3. Possible applications for different driving pollutants / indicators

Driving pollutants/indicators	Suitable applications
Carbon dioxide	Non-smoking areas; schools, auditoriums, theatres, cinemas; offices; meeting rooms; dwellings (bedrooms)
Humidity	Dwellings
Volatile Organic Compounds	*Smoking areas; restaurants; kitchens*

Table 5.3 gives a general recommendation about the choice of the driving pollutant for different building types. More specific information about this choice is given in the chapters about the different building types (see Chapters 7-11).

Once the key indicator is chosen there are two basically different ways of adapting the ventilation rate:

Multi-speed fans For every fan speed a threshold for the key indicator must be chosen. A dead band or time delay guarantees a minimum operation time of the system. When the measured concentration of the key indicator rises above the threshold value the according fan speed is activated. When the concentration falls below the dead band the speed of the fan is reduced.

Continuous modulation When a system with continuous modulation of the outdoor air rate (variable flow rate) is adopted only a single threshold for the key indicator must be chosen. As long as the threshold is not exceeded the ventilation rate is equal to the base ventilation rate. When the threshold is reached, the ventilation rate will automatically be modulated to keep the pollutant concentration at the chosen level.

Threshold values must be chosen in accordance with the perception of the occupants. Information about acceptable levels for the different driving pollutants, see ref. 5.

Example to compare two-speed fans with variable flow rate: A sample room was selected, with operational data as shown in table 5.4 and an occupancy profile as shown in

Table 5.4. Operational data for sample room

General description	Key indicator: Room volume: Occupancy profile:	CO_2 300 m^3 See figure 5.9
Two-speed fans	*Base ventilation:* Occupancy ventilation: Threshold value for speed 2: Dead band:	Speed 1: $n = 3\ h^{-1}$ Speed 2: $n = 6\ h^{-1}$ 1000 ppm 300 ppm
Variable flow rate	Base ventilation: Occupancy ventilation: Threshold:	$n = 1\ h^{-1}$ $n =$ 1-6 h^{-1} 1000 ppm

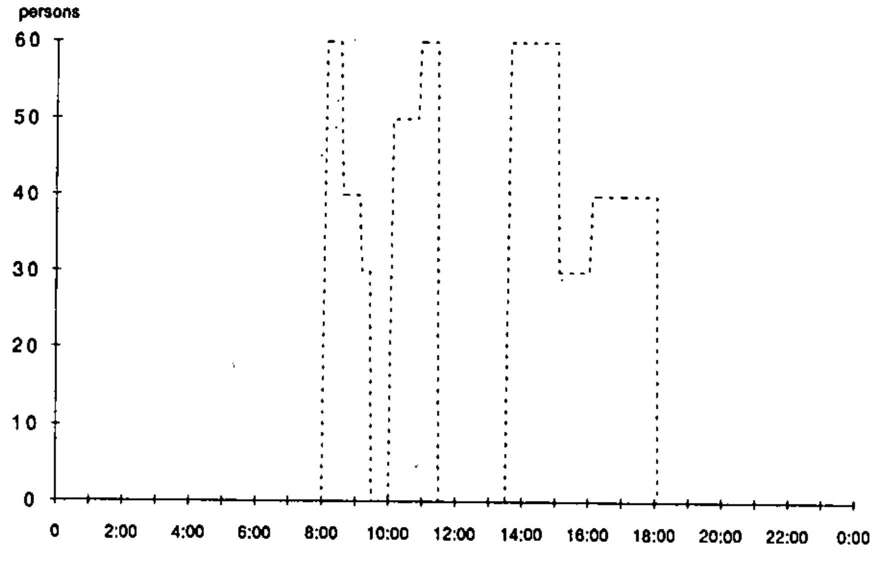


Figure 5.9. Occupancy profile for sample room

figure 5.9. Figures 5.10 and 5.11 show the system operation characteristics for the same room but with different control strategies: two-speed fans or variable flow rate.

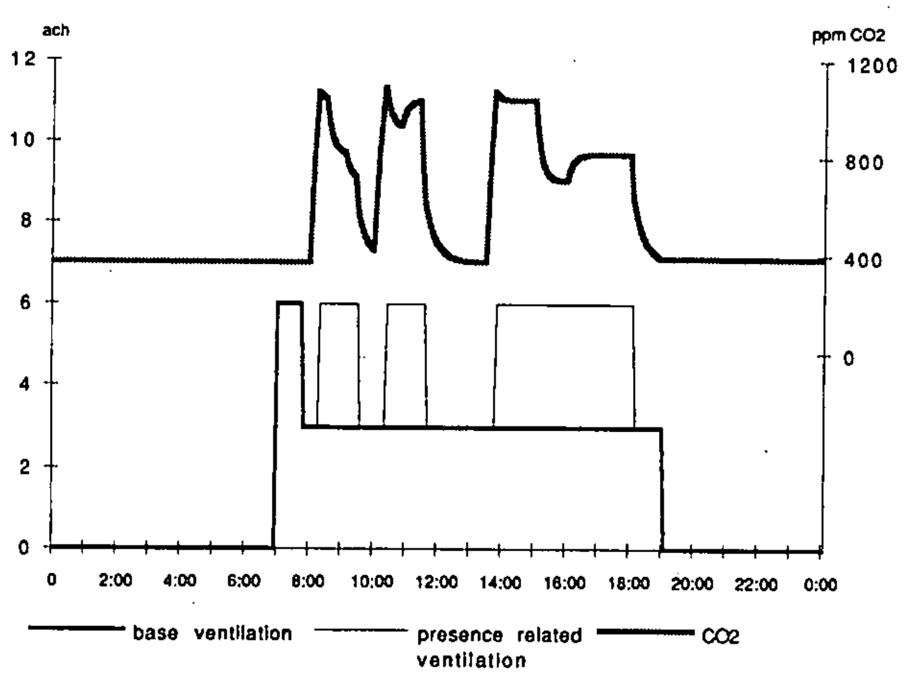


Figure 5.10. Ventilation operation with two-speed fan

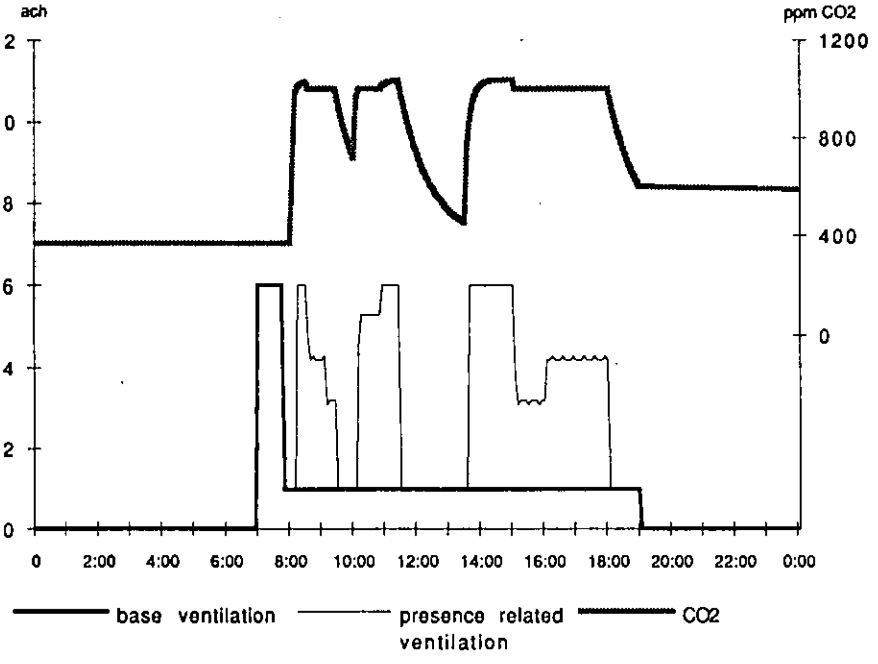


Figure 5.11. Ventilation operation with variable air flow

A comparison of figures 5.10 and 5.11 shows the area under the curve for the ventilation rate in figure 5.11 is smaller. Thus the system with variable air flow is more energy efficient. Whether the increase in energy savings is sufficient to pay for the higher system costs will depend on chosen threshold values, air flow rates, occupancy profile, and the cost of conditioning the air.

5.4 Choice of Control Strategy

The more information that is available about the source of pollutant, the simpler the control strategy that can be adopted. Pollutant characteristics and the amount of available information will vary not only for different building types but also from room to room. Every case must be studied carefully before choosing a control strategy. Tables 5.5 and 5.6 show recommended control strategies for different characteristics of pollution.

Table 5.5. *Choice of strategy for base ventilation rate*

Characteristics	Control Strategy	Possible Applications	Remarks
* Continuous 24-hour occupancy	Constant 24-hour base ventilation	Hospitals, dwellings	
* Considerable emissions from building materials * Continuous occupancy during known periods	Constant part-time base ventilation	Offices, schools, cinemas, theatres, dwellings	* does not solve "sick building" problem * might improve controllability of system
* Low emissions from building materials * Continuous occupancy during known periods	Pre-ventilation with higher ventilation rate	Offices, schools, cinemas, theatres	* gives more emphasis to occupancy ventilation
* Low emissions from building materials * Discontinuous occupancy	Intermittent forced ventilation	Meeting rooms, department stores, schools, auditoriums	Forced ventilation periods in accordance with source strength, air change rate and occupancy profile

Note: New or refurhished buildings will have higher emissions from building materials during the first period of operation. During this period, the choice of a higher base ventilation rate or even the disconnection of the demand control to achieve a constant ventilation rate should be considered.

Table 5.6. *Choice of strategy for occupancy ventilation rate*

Characteristics	Control strategy	Possible applications	Remarks
* Known source strength * No fluctuations of pollutant load	Constant ventilation rate	Storehouses, archives, offices with constant occupancy load	
• Known source strength • Predictable fluctuations of pollutant load	Clock control	Classrooms	• Information flow crucial * System cannot handle unforeseen changes in occupancy
• Known source strength • Unpredictable occupancy * User willing to take responsibility	Manual control	Classrooms, meeting rooms	* Simple installation * User must be trained * Does not guarantee acceptable indoor climate
• Constant load during occupancy periods * Unpredictable occupancy periods	Presence sensor control	one-person offices; classrooms	* Cannot handle load fluctuations • Pre-ventilation not possible
* One dominant pollutant * Unpredictable fluctuations of pollutant load	Continuous monitoring and control (indicaters are CO_2, RH or VOC)	Auditoriums, dwellings, offices, meeting rooms	* Sophisticated solution • Crucial to recognize dominant pollutant • Only strategy for true control of IAQ

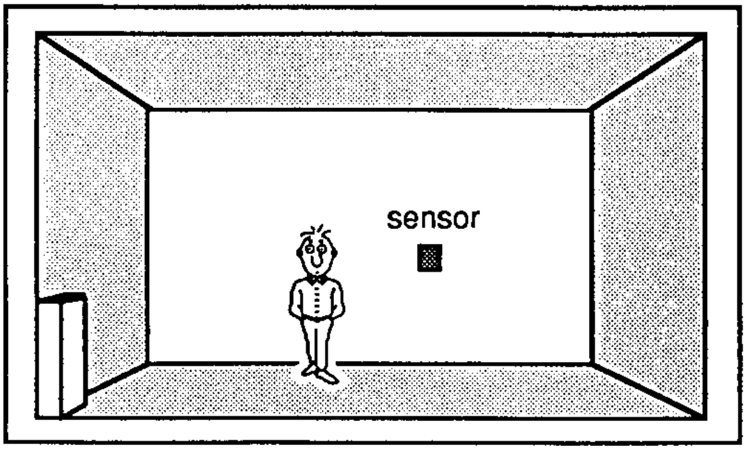


Figure 5.12. Location of sensor in the occupied zone

5.5 Sensor Location

5.5.1 General

In order to control the air quality in an occupied zone, sensors should be placed as near as possible to an occupied zone but be outside the breathing zone (direct influence) of occupants. Sensors should not be placed in poorly ventilated zones such as corners.

5.5.2 Mixing Ventilating Systems

Sensor location is not crucial for a mixing ventilation system as long as a good mixing is achieved. Since the concentration of pollutants will be approximately the same all over the room, the sensor could also be placed in the exhaust duct. In this case the ventilating system must extract air from the room throughout the operating period. However, if the flow rate of the ventilating system is allowed to be reduced to zero the sensor in the exhaust duct cannot detect what is happening inside the room. This means that a strategy of intermittent flushing cannot be applied if the controlling sensor is placed in the exhaust duct.

5.5.3 Displacement Ventilation

The ideal location for the controlling sensor is in the occupied zone at about head height. The height of the sensor can then be used to control the height of the interface between the lower comfort zone and the upper convection zone, see ref. 6.

When the floor is not horizontal (e.g. in assembly halls) the convective airflow will not only be vertical but will also have a horizontal component toward the back of the room. In this case the air flow patterns also depend on the occupancy distribution in the room, so that it would be hard or even impossible to define an appropriate location for the sensor in the room. In these cases the exhaust duct is recommended as a sensor location. A continuous exhaust from the room must then be applied and the setpoint must be adjusted because only an average value is registered by the sensor.

5.5.4 Regulating Ability of the System

Frequency and amplitude of changes in ventilating demand have an important influence on the behaviour of the system. When a few people continuously enter or leave a room which is already heavily occupied, the pollutant load will vary only insignificantly around an average value. When a large group of people enters or leaves a room (e.g. theatre, auditorium) the system will react with something like a step response.

The reaction of a system to a given change in pollutant load will depend upon two factors:

* Dead time until the sensor realizes the change
* Characteristics of the controller loop

Locating the controlling sensor within the occupied zone reduces the dead time. In cases where the sensor is placed in the exhaust duct the dead time will be longer and problems with the regulating ability might occur. If a quick response is essential the dead time can be reduced by increasing the base ventilation rate, although this will of course result in higher energy consumption.

Rooms with displacement ventilation generally have higher dead times than rooms with mixing ventilation, ref. 3.

The characteristics of the controller loop must be adapted to the needs in response velocity. On the other hand the controller loop must be designed to achieve consistent reactions to the most frequent changes in pollutant load.

In systems without return air, the air flow through the heating and cooling coils might change very rapidly. If these changes are significant they will also influence the dynamic behaviour of the thermal control. This fact must be considered when designing a DCV system especially in cases of retrofits with existing thermal control.

Since the situation will be different for every application the problem of regulating ability must be studied carefully for each case. The solution will depend upon building type and system complexity.

5.5.5 *Simulation Techniques*

To improve the design of DCV installations, simulation techniques may in principle be used as a tool, for example to determine the correct position of sensors, and terminal devices. This can be accomplished by using rather sophisticated Computational Fluid Dynamics (CFD) codes, based on the simultaneous numerical solution of the three-dimensional equations of continuity, momentum, and energy (if temperature gradients are present) in a discretized space domain. A review of CFD codes which may be used to analyse air flow patterns and pollutant dispersion in rooms is presented in ref. 7. Examples of commercially available CFD codes are shown in table 5.7.

Table 5.7. Sample CFD codes

Name	Producer
ARIA	Abacus, UK
FIDAP	FDI, USA
FLOTRN	Compuflow, UK
FLOVENT	Flomerics, UK
FLOW-3D	Harwell, UK
FLUENT	Creare, UK
PHOENIC	CHAM, UK

5.6 Summary and Conclusions

In buildings which are leaky, DCV systems may offer larger savings. A more energy efficient solution, however, is to seal the building. In some buildings with leaky dampers or with a significant number of exhaust fans, the induced leakage will be such that DCV is not possible.

All control strategies must account for the need for base ventilation as well as occupancy related ventilation.

For DCV to be cost-effective, the occupancy ventilation must be large compared to the base ventilation. From an odour perspective, this is most likely to occur in auditoriums, less likely to occur in schools and day nurseries and least likely to occur in office buildings. No data is available for dwellings.

Depending on the characteristics of the pollutant sources, several strategies area available for control of base ventilation and occupancy ventilation. The most advantageous choice will be situation-dependent and will often not include DCV with continuous monitoring and control. Cheaper, simpler and more robust choices will often be available. Sensor location will depend on the characteristics of the ventilating system.

5.7 Checklist for Control Principle Choice

The following steps should be taken when selecting a control principle for designing a DCV-system:

1. Assess the characteristics of the base ventilation requirements;

2. Choose the corresponding energy-efficient base ventilation strategy from table 5.5;

3. Assess the characteristics of the occupancy ventilation requirements;

4. If the occupancy ventilation requirement is significantly larger than the base ventilation requirement, choose an appropriate ventilation strategy from table 5.6;

5. Assess the characteristics of the building envelope and ventilation system to determine whether control is possible, or whether the control strategy should be adapted to account f or leakage; and

6. If a DCV system is still considered appropriate, choose a sensor according to the driving pollutant/key indicator and choose a sensor location according to the characteristics of the ventilation system to be controlled.

6 Feasibility Analysis

6.1 Purpose

This Chapter describes factors governing the feasibility of a centralized DCV system that will maintain acceptable indoor air quality (IAQ) in an energy-efficient way. The analysis is presented as a decision tree, with supporting text providing details of each step. The analysis is based on accepted engineering principles, as documented in Appendix B. Any calculations or assumptions specific to DCV design are included in the Chapter.

In this way a step-by-step guideline is provided that can be applied to any non-industrial building for which a DCV system is being considered. The user should be familiar with the DCV design principles outlined in previous chapters before embarking upon a feasibility analysis.

Use of the decision tree and six-step analysis will point out where DCV systems are practical and may result in real advantages. Although their use in other applications is sometimes possible, it will not likely be profitable. A first-attempt evaluation of potential energy savings may be made according to the procedure outlined in Step 6. Each situation, however, must be analysed on the basis of its own merits, and sometimes requires the use of more sophisticated simulation techniques.

6.2 Feasibility Factors

Factors governing DCV feasibility are:

1. Building regulations
2. Pollutant emissions within the building
3. Building related factors
4. Existing or designed ventilation systems
5. Climate
6. Potential benefits

Each of these factors must be weighed carefully in the DCV feasibility analysis for the project under consideration. The decision tree in figure 6.1 is based on consideration of the feasibility factors in the order given. The approach moves from the broad considerations such as regulatory factors through the rational and technical aspects of each potential application.

Step 1 Compliance with Regulations. National and local codes and regulations must be examined to ensure that DCV features would comply with requirements.

Step 2 Pollutant Analysis . An analysis of the pollutant sources and characteristics is the most important factor in the decision as to whether the installation of DCV systems may lead to consistent benefits.

Step 3 Building Features. Analysis of the technical feasibility of DCV systems related to their compatibility with building features.

Step 4 Ventilation Systems. The ventilation systems must allow outdoor air ventilation rates to be varied in the space(s) to be controlled, while still maintaining acceptable thermal control.

Step 5 Local climate. Local climatic conditions and their effect upon the indoor air and upon potential savings must be considered.

Step 6 Potential benefits. Analysis of benefits such as user comfort and building life; and potential savings related to life cycle costs, and energy savings compared to other competing technical solutions.

6.3 Analysis

A qualitative analysis of the most important aspects of system design is provided. The steps of the analysis follow the feasibility factors, as presented in the decision tree in figure 6.1.

Step 1: Compliance with Regulations

A preliminary question to be solved is whether the DCV system to be adopted will comply with existing regulations. For instance, when regulations require fixed (non-closeable) openings in rooms where individual gas heaters are placed, it will not be possible to adopt humidity-controlled devices. In other cases regulations not only do not prohibit DCV systems, but actually encourage their use, whenever, for instance, they ask for a certain amount of ventilation per person.

Step 2: Pollutant Analysis

Step 2.1: Pollutant production within the building

Among the pollutants and the indicators generated into the building, there is one which will require the highest average ventilation rates in order to maintain its concentration below the required acceptable limit. This can be defined as the driving pollutant.

The main prerequisite for installing a DCV system in a building is that the driving pollutant emission rate should meet the following criteria:

* High level: high enough to require the installation of additional natural or mechanically assisted) ventilation in combination with that provided by natural infiltration

* Variable: the level varies significantly over time

* Unpredictable: the time and location of the pollutant source cannot be scheduled

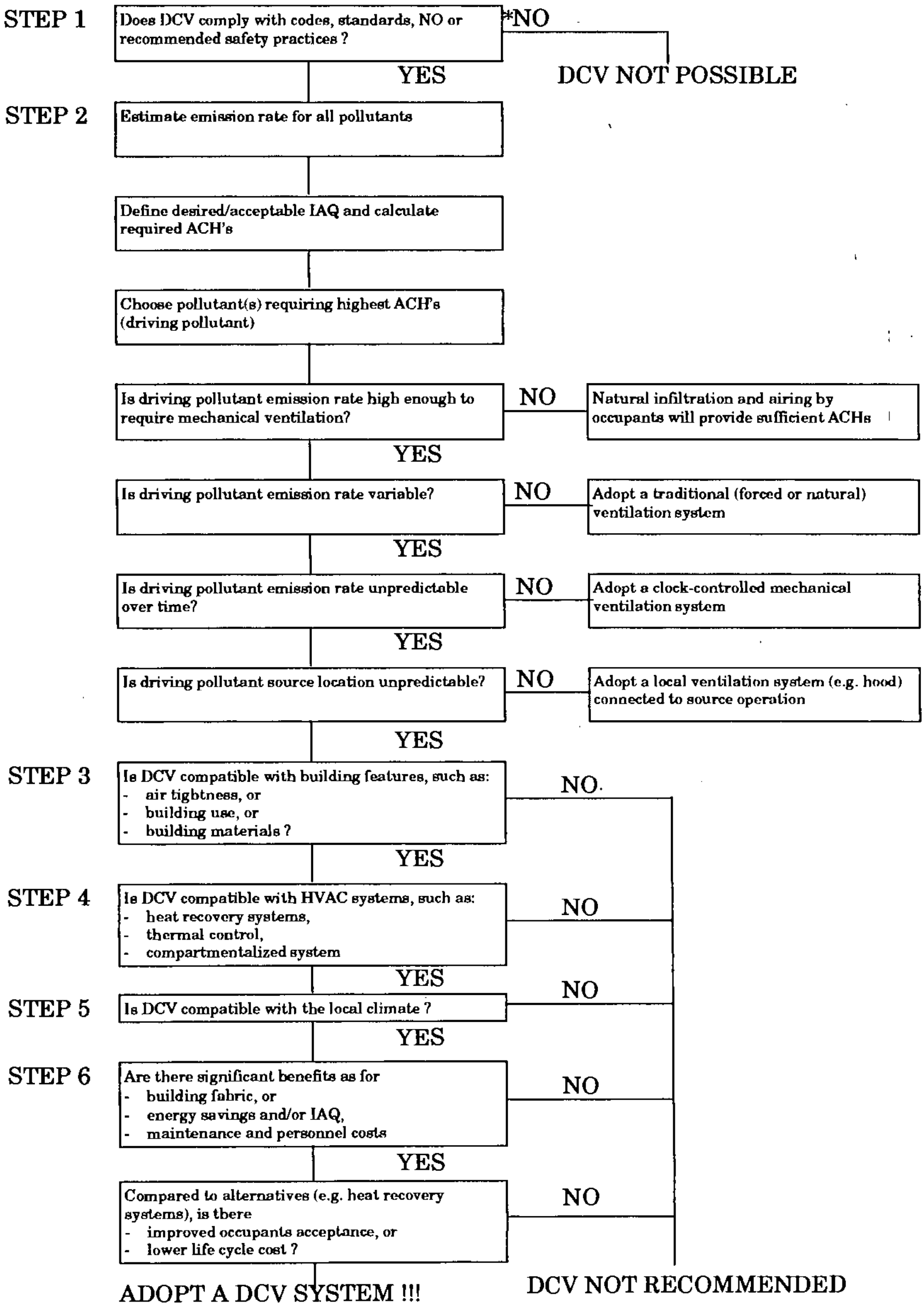


Figure 6.1. DCV feasibility analysis

As there are many pollutants produced within the building, it should be stressed that all three criteria must apply simultaneously to the driving pollutant.

The three criteria are described in more detail next.

Step 2.2: Level of pollutant emission

The level of pollutant emission should be "high enough" so as to make a DCV ventilation system relevant, useful and effective. This means that maximum acceptable levels of pollutants as established by standards, ref 4, or by the system operator, would actually be often exceeded if a suitable ventilation system were not available.

A simple relation between pollutant emission rate, air flow rate and pollutant concentration can be derived from the equation of continuity (see Appendix B) under the following hypotheses:

* Perfect mixing
* Steady state
* No background concentration of pollutant
* No absorption or desorption by building materials

$c = P/(n \cdot V)$ with
$n = q/V$ where

c =	pollutant concentration	kg/m^3
P =	pollutant emission rate	kg/h
n =	nominal air change rate	h^{-1}
V =	volume of the room or building	m^3
q =	nominal air flow rate	m^3/h

Low values of pollutant emission (or comparatively high values of acceptable pollutant concentration) lead to low air flow rates. The lower the air flow rate, the less interesting is the installation of a relatively complicated automatic system (as a DCV system usually is). In fact, adoption of such a system is justified only if it leads to consistent energy savings.

Step 2.3: Variability of Pollutant Emission Rate

Only large enough emission variations (in some cases above 100 % respect to average emission rates) make a DCV system suitable. If the variations are small a constant ventilation system may be adopted, since it will produce acceptable without requiring much higher average ventilation rates.

In order to take into account the presence of other pollutants (such as building emissions), requiring less, but constant ventilation, a base flow rate must always be provided.

Frequency of variation is also an important factor: if pollutant emission frequency of variation is expected to be too high (e.g. if emission rates are likely to vary every 5 minutes or less), the DCV system will not be able to track these variations. In fact, the time response of the installation (sensor + regulator + actuator chain) and of the phenomenon itself (i e the time required by the pollutant to spread across the ventilated space) is far from being instantaneous.

Step 2.4: Unpredictability of Pollutant Emission Rate

The emission rate should be unpredictable with respect to time and location or both. If the time when a strong increase of pollutant emission will take place is known in advance, a simple clock-control system may be adopted. If, on the other hand, the location of pollutant emission is well known and localized in a small area within the conditioned space, it may be preferable to adopt different strategies (such as hoods). In fact, local exhaust systems are much more efficient in the removal of pollutants than are even well designed central systems.

In principle, a local exhaust system can be "demand controlled", but in the case of a localized source of pollution, it will usually be preferable to operate the system automatically in connection with the operation of the source itself, for example connecting the switch of an electrical kitchen to the switch of the exhaust fan.

Step 3: Building Features

The main building-related factors which may be relevant for adoption of a DCV system are:

* the air tightness of the envelope of the building
* the building use
* emission/adsorption of pollutants by building materials

It should also be considered that there is an obvious intersection between IAQ and indoor thermal comfort, in that natural or forced ventilation may be used, both in the cooling and in the heating season, to control room temperature, thus influencing also IAQ. In this sense, the ability of the building to maintain an acceptable indoor climate (e.g. factors as thermal inertia, window area) will be influential to IAQ.

Step 3.1: Airtightness

If a building is so leaky that natural infiltration gives sufficient ventilation or even more than required, there will be no real possibility to control the ventilation rates completely using a DCV system. However, the adoption of a DCV system may result in significant energy savings even when considerable air infiltration takes place in the building.

In fact, where a ventilation system is used in a leaky building, it will usually be designed to handle all ventilation requirements, as if no natural infiltration would be at hand. When balanced supply/exhaust (and, to a lesser extent, exhaust) ventilation systems are adopted, significant infiltration may take place, adding to the mechanical ventilation rate.

The level of pollutant, which is in its turn influenced by both natural and mechanical ventilation, will therefore decrease and the DCV will operate, consequently reducing the mechanical ventilation rates and perhaps turning these off when not needed.

Step 3.2: Building use

The characteristics of pollutant emission listed in step 2 (intensity of sources, variability and unpredictability) are mostly determined by the use of the building. Buildings generally offering these requisites are:

* Residential buildings
* School buildings (provided the organization of activities requires a flexible, time dependent use of spaces)
* Auditoriums (such as lecture halls, cinemas, courtrooms and theatres)
* Office buildings (or enclosed areas such as offices and meeting rooms within office buildings)
* Other buildings (such as commercial buildings or stores)

Step 3.3: Building materials

If building materials are strong sources of noxious pollutants, such as formaldehyde, a high base rate or even a constant flow mechanical ventilation system should be used to permanently keep their concentration at an acceptable level. Such a situation is often found at the beginning of use of a building, new or refurbished. Later on, the decay of emission may call for a more energy saving way of operation, and a DCV system may become suitable and profitable.

Step 4: HVAC Systems

Step 4.1: Ventilation systems

Once the sources of noxious pollutants have been removed as far as possible, energy costs can be reduced by a careful design of the ventilation system, for example

* Adopting heat recovery systems
* Improving the efficiency of ventilation
* Adopting DCV systems

In some cases these three options may be conflicting. For example, a DCV system as a complement to a system with a highly efficient heat recovery installation might be found not profitable. Conversely, when a DCV system has been already installed a proposed later installed heat recovery system may turn out to be unprofitable. Thus it is necessary from case to case to make a correct profitability analysis before steps are taken for a choice of system components both for a new building and when retrofitting an existing ventilation plant.

There are cases when a DCV system turns out to be unsuitable: for example, when the ventilation system is strongly undersized, if the ventilation rate is not variable or, as is often the case, the system induces more air than is necessary, even on its minimum setting.

Step 4.2: Heating/cooling systems

Heating and cooling are often achieved using ventilation air. In this case, the system must be carefully designed so that thermal control is not lost. In some case, this will not be practical.

In some buildings, outdoor air is used to provide "free" cooling. In moderate climates or in the case of very large buildings, this may exclude the possibility of reducing outdoor air rates for a large portion of the year since to do so would result in increased energy consumption.

Step 5: Climate

Step 5.1: Outdoor climate

There are a number of climatic factors which may affect the choice of a DCV system because they influence one or more of the following:

* indoor climate
* natural infiltration
* humidity controlled ventilation systems

Step 5.2: Indoor climate

Outdoor temperature, solar radiation, wind velocity, etc., are all factors that influence indoor microclimate, eventually inducing a need for airing or ventilation, when this may be used to control room air temperature. For example, in mild climates airing by occupants during mid-seasons may outdo the performance of the ventilation system, either controlled or not. For a discussion about the consequences of natural infiltration (or airing) on DCV systems performance, see step 3.1.

Step 5.3: Natural infiltration

Natural climatic factors such as wind and temperature difference, together with envelope characteristics, contribute to the air infiltration. The higher the wind speed and temperature difference across the building envelope, the higher the infiltration rate will be. For a discussion about the influence of natural infiltration over the adoption of DCV systems, see step 3.1.

Step 5.4: Climatic factors influencing hygrocontrolled ventilation systems

Outdoor climate will exert a primary influence on the behaviour of ventilation systems designed to maintain indoor relative humidity below a certain level (a rather frequent case for residential buildings). In this case its importance will be second only to that of indoor vapour production indoors.

Because there is always a certain amount of water vapour in outdoor air, the amount of air required to keep indoor air relative humidity (RH) constantly below limit values (e.g. 55 % at 20°C) will vary according to outdoor air moisture content, usually decreasing with decreasing temperature of outdoor air. In this case (Fantozzi et al, 1990) the amount of outdoor air needed to control indoor RH diminishes with decreasing outdoor temperature, thus tending to compensate for the tendency of increasing ventilation losses with decreasing outdoor temperature.

On the other hand, if the aim is to maintain the dew point temperature of the air below the surface temperature of the coldest spot on the walls surfaces, the maximum allowable moisture content indoors will also decrease with decreasing outdoor temperature, partially counterbalancing the above effect. For a more detailed discussion on this topic, see ref. 3.

Hygrocontrolled supply devices are unsuitable in severe climates, where strong winds occur, and may cause cold draughts, or inversion of air flow with consequent freezing of moisture on the outer side of the devices. This kind of system appears most suitable in those regions where humid and mild winters are frequent.

Step 6: Potential Savings

Step 6.1: Evaluation of potential energy savings

Evaluation of potential energy savings is a necessary step to assess the viability of a DCV system. Unfortunately, only a few experimental data are known about existing DCV systems performance; these data do not allow generalization, because the resulting energy consumption and IAQ is always specific to the climate, the building and the installed ventilation system. Therefore, to evaluate the potential energy savings and/or the improvement of IAQ, simulation techniques should be used.

The installation of a demand control on a new ventilation system may lead to a consistent reduction of both energy used for heating (or cooling) the air, and electric energy for driving the fans compared to a traditional mechanical system providing the same maximum pollutant level inside the building. When, on the other hand, a DCV system is applied in an existing building where the IAQ was poor or there were moisture problems its installation may not lead to energy savings, but will rather lead to an improvement of air quality or to the solution of moisture problems.

Although electricity has a higher thermodynamic and economic value than thermal energy, its consumption is usually at least one order of magnitude smaller than energy used for thermal treatment of the air, and its savings may be usually neglected in a cost-benefit analysis. The following input data are needed to predict the operation of the system:

* Typical meteorological data
* Pollutant emission rates
* Features of the mechanical ventilation system
* Geometrical and physical characteristics of the building
* Absorption and desorption features of building walls and furniture

Zero-dimension models based on single-zone or multizone network analysis techniques, such as AIRNET, may be used to study the phenomena. These models are based on the equation of continuity written for each room (see Appendix B). The equation will contain a "source" term for each room, including absorption/desorption terms, a "convective" term for each air flow from or to the room and a term expressing the variation over time of the amount of pollutant contained in the room. In order to investigate the feasibility of a DCV system the simulation model should provide, as a function of time:

* The resulting IAQ level, in terms of pollutant concentration(s)
* The air flow rates
* The ventilation heat loss

In order to establish a cost/benefit analysis the total ventilation energy losses should be calculated and compared to ventilation energy losses induced by competing systems (e.g constant flow rate ventilation systems). The energy savings and the extra costs for DCV will lead to the evaluation of the return on investment, profitability or Life Cycle Cost of this installation.

Step 6.2: Calculation of energy savings

A simplified approach for the evaluation of energy savings in DCV systems is provided in Appendix B, which provides:

* Guidelines for calculation of ventilation heat loss;
* Guidelines for calculation of energy savings;

Table 6.1 Energy savings in DCV school application

Ratio base/maximum ventilation rates	Potential energy savings
Base rate 25 % of maximum	25 %
No base ventilation	33 %

* An example of a DCV application in a school.

The calculation method was applied to the example of a DCV application in a school. The results are shown in table 6.1. Calculations were made assuming base rate of 25 % of the maximum ventilation rate, and assuming no base ventilation.

Step 6.3 Cost/Benefit Analysis

One essential part of the DCV energy conservation strategy is to use the ventilation system only when there is a need for it. In most cases it is quite possible to present values on energy savings achievable by using a DCV system. Large savings (up to 60%) can be shown for some ventilation systems where the energy consumption has been high due to continuous operation. Increased demands for improved air quality can result in little or no savings for other systems.

The required ventilation rate is affected by building materials, the surface treatment and the activities taking place in the building. The following table may serve as a guidance for discussing the profitability of using different types of DCV systems in buildings for different purposes. Data relate to DCV systems only. The cost of energy is supposed to be 0.1 ECU/kWh (0.125 US$/kWh).

The relative energy savings (%) achieved by DCV is calculated from the ratio of the energy demand for the DCV system studied and the energy demand for a conventional system, both at a yearly basis. Once the total energy losses are calculated these will be compared to ventilation energy losses induced by competing systems (e.g constant flow rate ventilation systems).

The calculated energy savings must be weighed against the extra costs for a DCV system in order to evaluate the return on investment, the profitability or the life cycle cost of the installation. In practice, the savings actually achieved have been found to lie in the region of 0-80 % of those theoretically calculated. The zero level is usually a result of lack of proper operation and maintenance.

In order to investigate the feasibility of a DCV system a simulation model could be used to make a cost-benefit analysis. The system performance will have to be analysed under typical and not design climatic conditions.

Table 6.2. Estimation of energy saving and payback time with DCV systems

Building type	DCV system type	Savings range %	ECU*/(m^2y)	Investment ECU*/m^2	Payback time, years
Dwellings	Manual or humidity sensitive	5 - 15	1 - 3	3 - 5	1 - 5
Office					
Sales (40 % present, 50% heat recovery)	CO_2	20 - 30	1 - 2	10 - 20	5 - 10
Admin (90 % present, 50% heat recovery)	CO_2	3 - 5	0.3	10 - 20	>30
School					
Heat exchanger	CO_2	5 - 10	3 - 6	5 - 10	0.5 - 3.0
No exchanger	CO_2	20 - 40	15 - 25	20 - 60	1.5 - 2.5
Auditoriums	CO_2	20 - 50	20 - 40	10 - 70	0.5 - 3.0
Day nurseries	CO_2	20 - 30	3 - 5	5 - 10	0.5 - 3.0
Department store	VOCs	50 - 70	15 - 20	<0.1	<0.1
Athletic hall	VOCs	40 - 60	20 - 30	5 - 10	0.2 - 0.5

* 1 ECU is approximately US$ 1.25.

6.4 Checklists for DCV System Design

Checklists for describing prerequisites and reviewing the performance of DCV systems have been set up for the different types of buildings in Chapters 7-10. These lists are meant to be utilized by designers and consulting engineers when choosing systems and components. They are also intended for use during the commissioning process made before taking a plant into regular use.

7 Dwellings

7.1 Purpose

The goal of ventilation for dwellings is to provide a healthy indoor environment. This is achieved by diluting indoor pollutants, and preventing indirect pollution and building damage caused by condensation of moisture and mould growth.

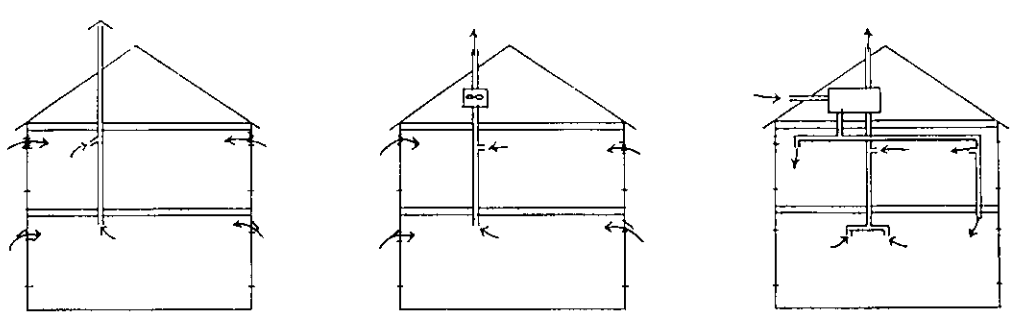
For purposes of this discussion, a dwelling is taken to mean a room, a single-family house, or a multi-family building. It does not include institutions such as nursing homes or student residences.

The design of a ventilating system for a dwelling or residence is based on one of the following principles:

* Natural supply and exhaust
* Natural supply and mechanical exhaust
* Mechanical supply and natural exhaust
* Mechanical supply and exhaust (balanced ventilation)

In practice, ventilating system design differs from country to country depending on national standards and building practices. The difference may concern for example the type and position of supply and exhaust devices, or the flow rates. In the Netherlands for example regulations stipulate that a natural supply of outdoor air shall be made via specially installed regulable and closable supply devices, although in France such closable supply devices are forbidden.

There are still many countries in which the majority of dwellings are not equipped with special ventilation devices. Air renewal depends in such cases completely on intentional and unintentional leakages, use of windows and doors by the occupants, and the climatological



a Natural ventilation

b Natural supply system and mechanical exhaust

c Mechanical ventilation
The ventilation often includes heat recovery

Figure 7.1. Ventilation systems frequently used for dwellings

conditions. Such a situation is undesirable in terms of indoor air quality (IAQ), building protection (mould growth and condensation), and energy conservation.

Designs for mechanical balanced ventilation systems do not vary a great deal. A supply of outdoor air is usually required in the bedrooms, while the exhaust normally takes place in the kitchen, the bathroom, and the toilet. Some frequently used ventilation systems for dwellings and flats can be seen in figure 7.1, namely:

* A natural ventilation system
* A natural supply system with mechanical exhaust
  A balanced ventilation system

Residential ventilation systems are not usually controlled automatically. For example, a system with natural supply and exhaust via leaks in the building envelope cannot be controlled at all except by the occupants in response to subjective criteria such as smell or to other indicators such as condensation on windows.

If a ventilating system does not have automatic controls, it may cause ventilation rates higher than what is required for pollution control, resulting in excessive energy consumption. On the other hand, such systems can also cause air flow rates that are too low, resulting in a low level of IAQ.

Both centralized and decentralized residential ventilation units usually run on a constant flow rate, which often result in periods of a too-high or a too-low ventilation rate with respect to the pollution source strengths. An appropriate control strategy can address such risks.

7.2 Pollutants and Indicators

Airborne pollutants in dwellings can be categorized according to their source, as follows:

* Occupancy/activity-related pollutants
* Building and soil-related pollutants
* Outdoor air pollutants

Occupancy/activity-related pollutants
These include pollutants that are directly related to people (H_2O, CO_2) and to their activities in the dwelling (H_2O, CO, NO_2). Production of these pollutants cannot usually be avoided.

Some occupancy habits result in extremely high pollution levels and can be defined as a non-appropriate occupancy behaviour:

* Clothes dryers without internal condensation, where the exhaust duct is not connected to the outside (often found in rental units)
* Clothes hung to dry on or around stoves
* Very large numbers of tropical plants
* Tobacco smoking

Building and soil-related pollutants
These include pollutants that are not directly related to the activities of the occupants such as:

* Pollutants emitted by building materials (formaldehyde)
* Combustion products from heating system
* Water infiltration due to a bad design and/or execution of walls, roofs, foundations
* Paint and other wood protectors (VOCs)
* Radon from building materials and from the soil

For these pollutants, source control is the most appropriate strategy. This means in practice the use of appropriate building materials, appropriate heating systems, and good building design. The emission of these pollutants is often fairly constant over a long time and re quire a base ventilation rate.

Emission rates are usually not available from manufacturers. For DCV, the base ventilation rate (see Chapter 6), must be kept low (10-20 %) in relation to the maximum flow rate of the system by selecting low-emission building materials and furnishings.

Care must be taken that open windows in the upper storey of dwellings or exhaust fans do not cause backdraught of combustion products into the house instead of up the chimney.

Radon reduction needs specific strategies and is not included in this discussion of demand control. The most important radon source is the soil, from which radon enters the dwelling through leaks in the floor. Radon protection methods are very specific and vary according to ground and building type.

Outdoor air pollutants
These include pollutants in the outdoor air generated by industries, traffic and so on. Only air purification or filtering can reduce the concentration of these pollutants. Air supply devices for ventilation systems must be located to minimize pollutant intake.

Indoor air pollutants
Table 7.1 gives an overview of the concentrations of the most important pollutants occurring in dwellings. Notice that the concentration levels can vary widely. For example the concentration of NO_2 in a dwelling supplied with gas will be strongly dependant on heating, cooking methods and domestic water heating devices; and on the

Table 7.1. Pollutant concentrations in indoor air, ref 8.

Pollutant	Concentration	
	Average	High
CO_2 (ppm)	500 - 1000	3000 - 5000
CO (ppm)	2 - 5	10 - 20
NO_2, kitchen with gas (g/m^3)	40 - 80	300 - 3000
NO_2, room without gas (g/m^3)	50 - 100	50- 100
Particles (g/m^3)	20 - 80	100- 1000

use of local exhaust devices. Higher and lower values can be found in some cases.

A DCV strategy is feasible only if pollutant production varies in time and place, resulting in a varying demand for outdoor air. Pollutants caused by the inhabitants and their activities meet these variation requirements.

The strategy for a DCV system combines a base rate ventilation to control the continuous-source pollutants with an increase in ventilation rate to control non-continuous pollutants produced by the inhabitants (see Chapter 6).

The airtightness of the house will govern how base ventilation is achieved. For a tight house the mechanical ventilating system must be run at a low rate, whereas in a less tight house base ventilation is achieved by infiltration. A tracer gas test,ref 6, or a blower door test can be used to determine the airtightness of the house.

7.2.1 Driving Pollutants

For DCV purposes, occupancy-related pollutants that are directly related to human presence and activities can be considered as the driving pollutant. However some of these are not suitable because detection of either the pollution or associated indicator is too difficult and too expensive. Such pollutants are NO_x, formaldehyde, and dust. It is also preferable to control these pollutants by way of source elimination such as the use of vented domestic hot water heaters, and low-emission building materials, often enforced by codes and standards. As discussed in Chapter 3, the following can be considered driving pollutants:

* Moisture
* CO_2
* VOCs (mixed gases)

Moisture
Moisture production in a dwelling varies widely during the day. Figure 7.2 shows daily moisture production calculated for a 4 person-family. It can be seen that around 08:00 and 12:00, and from 16:00 to 22:00, increased ventilation is desirable to remove moisture and control the RH.

The primary purpose of using RH as the indicator for a DCV system is to protect the building envelope against surface condensation and mould growth rather than to maintain good IAQ.

Carbon Dioxide
An increase of the CO_2 concentration is nearly always related to the presence of people. The only other cause of high CO_2 concentrations would be an unvented combustion appliance for cooking, domestic hot water or heating. Measured CO_2 concentrations in sleeping rooms in a Swiss building are dependent on airing behaviour and time of room occupation, ref. 1.

The CO_2 concentration can exceed 1500 ppm only in bedrooms. Table 7.2 gives results from measu-

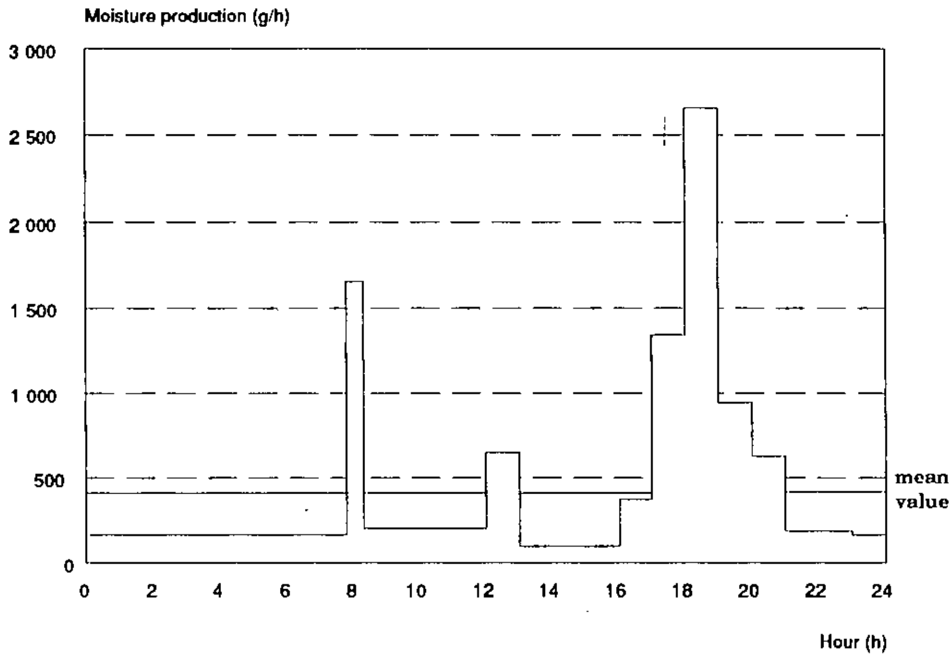


Figure 7.2. Moisture production in a dwelling with 4 persons as a function of time

rements of the CO_2 concentration in bedrooms as a function of the ventilation principle, according to airing principle and time of ventilation. In some cases even the Maximum Allowable Concentration of 5000 ppm for 8 hours has been exceeded; this is due to the very low ventilation rates (close to 0 h^{-1}) which can occur in bedrooms with closed ventilation facilities.

The CO_2 concentration is a good indicator for human presence and for body odour. The proposed CO_2 hygienic limit in rooms is 1000 to 1500 ppm. To keep CO_2 concentrations below these limits a ventilation rate between 12-15 m^3/h·pers (for 1500 ppm) and 20-30 m^3/h·pers (for 1000 ppm) is necessary. In many cases a lower ventilation rate and a higher CO_2 concentration can be accepted temporarily. If there are no persons in a room then the ventilation rate can be reduced considerably.

Table 7.2. Measured CO_2 concentrations in sleeping rooms, ref 1.

window	door	number of persons	CO_2 Median ppm	CO_2 Maximum	CO_2 Increase ppm	Time of room occ. h:min	CO_2 Increase ppm/min
closed	closed	2	999-2934	1182-4286	789-3364	7:20-11:40	1.47-7.64
closed	closed	1	740-1352	828-2084	196-1399	9:45-13:00	0.25-2.39
closed	open	2	986	1318	413	9:00	0.76
ajar	closed	2	760	1210	835	9:30	1.46
ajar	closed	1	820	909	543	11:10	0.80
open	closed	2	519	615-718	219-331	8:00	0.45-0.69
open	closed	1	419-542	515-644	128-272	7:30-9:30	0.24-0.47

Table 7.3. Pollutant indicators for different room types

Room	Indicator		
	RH	CO_2	Mixed gas
Living room		✓	✓
Kitchen	✓		
Bedroom		✓	
Bathroom	✓		
Toilet			✓

Volatile Organic Compounds (VOCs)

VOCs are produced by human activities such as cleaning activities, cooking, personal care, and smoking. They can be detected by mixed gas sensors, which do not react to one specific pollutant but to a broad range of non-oxidized gases in the air. Unfortunately mixed gas sensors are also sensitive to RH (see Chapter 5, 5.6.3).

It is not always necessary to use the concentration of a pollutant as an indicator for the ventilation rate. A time-based or an activity-controlled management of the ventilation system are also considered to be DCV principles. For dwellings, however, it is an acceptable way of controlling the IAQ.

For a single room a DCV principle can be a ventilation system that operates only when the room is in use. This can be controlled manually, by connection to the lighting system, or by a presence sensor.

Table 7.3 shows the usefulness of various indicators for controlling the ventilation in different room types.

Instead of a pollutant indicator, presence-related ventilation can be used, especially for a decentralized ventilation system (see Chapter 6.)

Table 7.4 shows the options for different room types.

7.2.2 Other Pollutants

For dwellings RH and CO_2 can be useful driving pollutants, but the correlation between RH and CO_2 is poor. This means that two sensors

Table 7.4. Control methods for different room types

Room	Control based on			
	Manual	Light use	Presence sensor	Clock
Living room	✓		✓	✓
Kitchen	✓			
Bedroom	✓			✓
Bathroom		✓		
Toilet		✓		

must be used for accurate detection, one for RH and one for CO_2.

Specific emissions from infrequent activities such as painting should not be covered by DCV but by measures undertaken by the occupants such as opening the windows.

As already mentioned, all combustion appliances such as water boilers and stoves should be effectively vented.

7.2.3 Comfort

An interaction between the DCV system and the heating or cooling system must be acknowledged and accommodated in the DCV system design to prevent discomfort in terms of temperature or draughts. If the DCV system does not react to air temperature, the inhabitants must prevent high indoor temperatures (due to heating systems or solar gain) by controlling the ventilation system manually. A pre-heating of the supply air can be necessary to avoid draughts during winter.

With warm-air (forced air) heating systems it is not unusual to integrate the ventilation system with the heating system. This means that a DCV strategy must be subordinated to the temperature control strategy.

7.2.4 Humidity Control Strategy

Humidity is a useful indicator for controlling a DCV system. The reasons for humidity control are:

* To prevent mould growth
* To prevent house dust mites
* To prevent interstitial condensation

Table 7.5. Humidity control strategies

Control strategy	Comments
1 setpoint = $f\{T_e, T_i\}$ or setpoint - $f\{T_{si}, T_i\}$	This is the most advanced on/off control strategy. It requires the use of a microprocessor and the measurement of indoor and outdoor or surface temperature.
2 setpoint = $f\{T_e\}$	Such a simplification is possible, especially in applications where the indoor temperature varies less than 4°C.
3 setpoint = fixed relative humidity	A further simplification is to fix the relative humidity. This simplification clearly reduces the system performance.

where
T_{si} = surface temperature in °C
T_e = exterior temperature in °C
T_i = indoor temperature in °C

* To keep the humidity within the comfort zone

The human tolerance band for room air RH is very wide, in most cases from 20 % to 90 %. A more restricted range with regard to comfort, static electricity and to risk of mould growth, is 30 % to 75 %.

Distinction must be made between the criteria for surface condensation and for mould growth. Surface condensation occurs when the saturation pressure (Pa) at the surface is lower than the water vapour pressure of air, which in practice means that the RH of the air close to the surface must be 100 %. Mould growth can occur at lower RH levels. Depending on the type of material, the temperature levels and the duration of high RH periods, mould growth can start at 75 to 80 % RH (at the surface).

The driving criterion is therefore the avoidance of mould growth. Maintaining an RH level that is low enough to prevent mould growth will also avoid surface condensation. The growth of house dust mites can be avoided if the RH is kept well below 55 % as an average monthly level.

Guidelines for calculating RH on surfaces, based on CEN/TC89, are provided in Appendix C. From such calculations, table 7.5 gives a summary of humidity control strategies.

The setpoint can be used for off/on control or better for a step-by-step control of the flow rate. It is better to maintain a minimum ventilation rate rather than switching off the ventilation entirely. If the setpoint is chosen as 50 % RH, which is a normal value for winter conditions, then the indoor RH value is often exceeded if the outdoor temperature exceeds 9°C and the outdoor air RH is 100 %. The temperature variation from day to night, however, offers a possibility to reduce the indoor air RH.

7.3 Ventilation Principles

7.3.1 Options

A DCV system for a dwelling can be designed in many different ways. Natural or mechanical ventilation principles may be used, or a combination of both, for either centralized or decentralized system designs. Figure 7.3 illustrates the possible options.

7.3.2 Supply and Exhaust

For practical purposes, the rooms in a dwelling can be classified as:

* rooms where an exhaust of ventilation air is required.
* rooms where a supply of ventilation air is required;

Rooms where exhaust of ventilation air is emphasized are those where moisture and odour-producing activities take place such as cooking and personal care in kitchens and bathrooms. The exhaust zones are

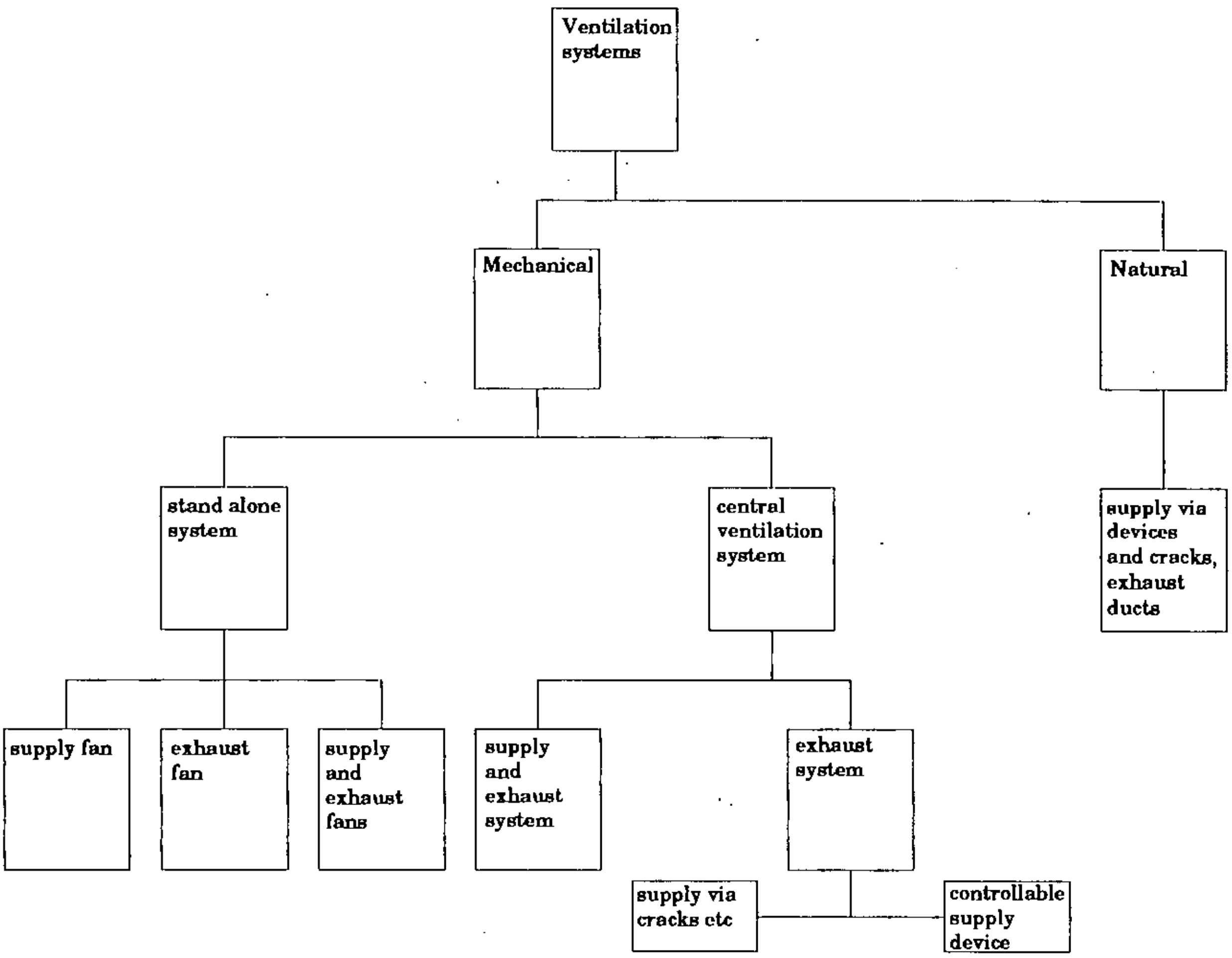


Figure 7.3. Ventilation systems in dwellings, possible options.

bathroom, toilet, and kitchen, see figure 7.4. In most cases humidity is the indicator of ventilation demand.

Rooms with the emphasis on supply of ventilation air, supply zones, are those where the ventilation rate will be determined by the occpants, such as in bedrooms and living rooms see, figure 7.4. These are in fact rooms wherein specially CO_2 and/or mixed gases are the pollutants and thus the indicators for DCV. In poorly insulated and therefore often heated bedrooms a humidity control strategy can be useful to avoid mould growth.

7.3.3 Recirculation

Dilution of polluted air by internal recirculation can be used to control the concentration of a pollutant in a room. This can be applied for example in bedrooms to lower the CO_2 concentrations by recirculation of air from the living room to the bedroom. See also table 7.2 where the "window closed and door open"

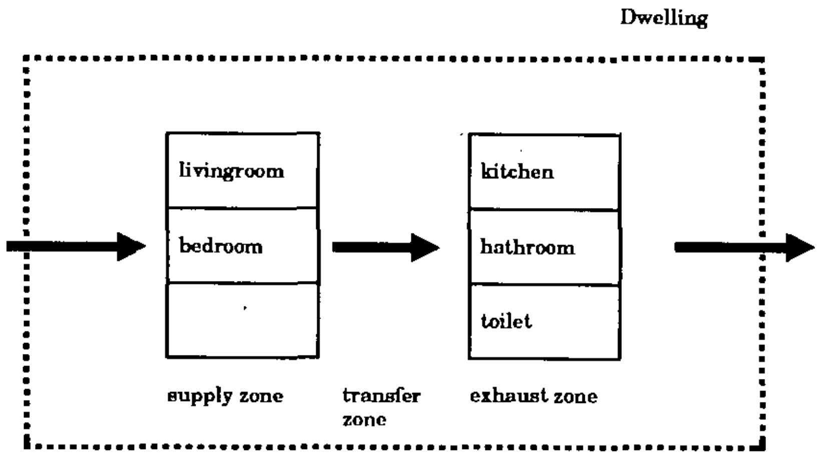


Figure 7.4. Room categories in a dwelling.

option represents ventilation by recirculation.

This type of system is only possible in homes where the air heating system can be controlled separately from the ventilating system. Using a CO_2 sensor in the sleeping room as a control device, the fan of the air heater can be used for recirculation without reference to the heating (or cooling) demand. It may become evident in practice that the heating or cooling demand is more important than ventilation needs.

If such a system is contemplated, the designer must be sure that the quality of the recirculated air will not be laden with other pollutants such as cigarette smoke and body odour. For this reason, recirculation of internal "fresh" air for sleeping rooms is forbidden in some countries.

7.3.4 Flow Rate

The air flow rate of the ventilating system can be adjusted by:
* increasing or decreasing the net section of the devices
* changing the speed of the fans
* installing or turning on additional fans

The net section, or total effective area of an air terminal device, can be increased and decreased by opening or closing dampers. Regulating the net section of the devices allows a more precise adjustment of the air flow rate, but changing the fan speed usually requires only one sensor and can therefore in principle be cheaper.

Flow rate can be controlled in several ways. It is usually done manually by the occupant according to ventilation needs. In single-family homes the fan speed is changed manually, or natural ventilating devices are opened or closed. Time switches for reducing fan speed during the night are often used in central exhaust systems for multi-family houses.

7.3.5 Standalone Systems

Standalone systems usually comprise exhaust fans in bathrooms and toilets, where the fan is activated by the electric light switch.

These ways of controlling the ventilation are in fact also DCV systems but they are not sensor controlled and will not be discussed further.

7.4 Natural Ventilation Systems

7.4.1 System Design

A natural ventilation system consists of different supply and exhaust provisions without a mechanical driving force to support the air flows. Integrating DCV in such a system means that the net section of these ventilation devices must vary (according to internatinal standards) as a function of the concentration of the indicator. Such ventilation devices are on the market today using RH as the indicator. A description is given in 7.4.2.

A natural ventilation system can be applied to single-family and multi-family buildings. In either case the building envelope should be tight, otherwise the moisture-controlled ventilation devices will be short-circuited by leaks. Therefore the leakage, in the form aof air changes per hour at 50 Pa pressure difference as tested in accordance with ISO, should be no higher than 3.

Supply devices such as hygrocontrolled or humidity-controlled are

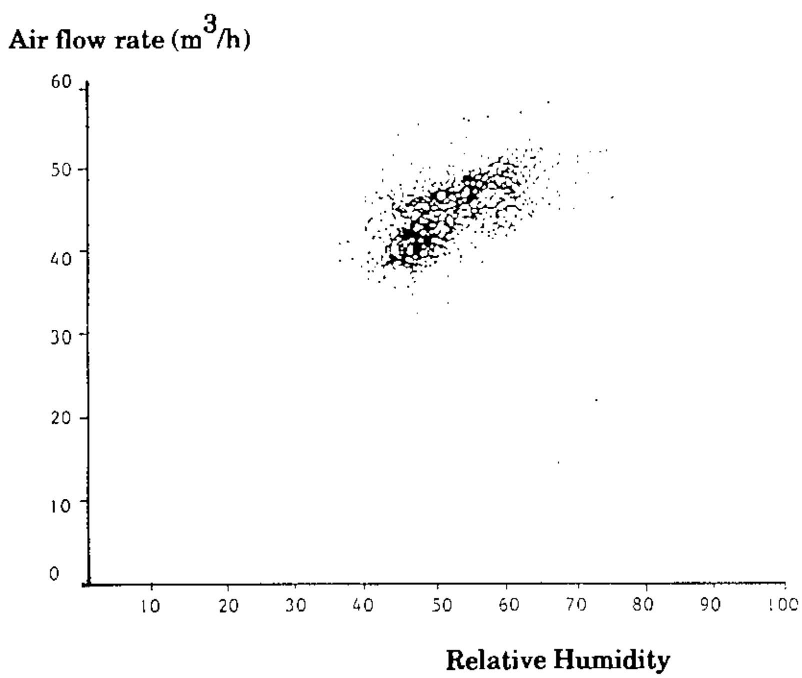


Figure 7.5. The air flow rate for a system governed by a RH-sensor, demonstration project Orsay, France.

usually located in the facade of the bedrooms and the living room, and exhaust devices are usually in the bathroom, the kitchen and in the toilet. The exhaust devices can be combined with a time or manually controlled section which bypasses the RH-controlled section when the pollutant concentration becomes high.

Application of RH-controlled ventilation devices to fully natural systems in apartment buildings will reduce the influence of the stack effect on air flows. The stack effect will initially cause a higher ventilation rate on the lower floors, which will reduce the RH level and hence lead to a lower flow rate, resulting in a decrease of the net section of the exhaust devices.

A system with RH as the indicator provides good control of moisture in a room, as shown by the results of the CEC-Aereco demonstration project, provided in figure 7.5. Control of the CO_2 concentration is poor as a result of a slow response time of the sensor and the bad relation between RH and CO_2 concentration in dwellings.

Despite RH-controlled ventilation provisions, the outdoor air climate has a considerable influence on the air flow rate. This is because RH levels influence only one element (the net section of the ventilation devices) that is responsible for the resulting air flow.

7.4.2 Sensor Type and Location

When an RH sensor is used in a DCV system it causes a mechanical increase or decrease in the net section of the air terminal device. The

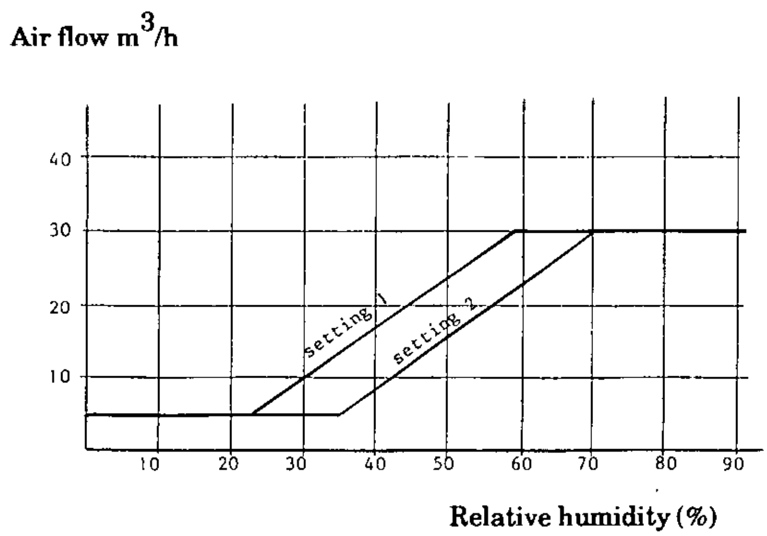


Figure 7.6 Flow rate through an air supply device furnished with humidity sensing control

sensor is integrated in the ventilation device. It is important that the RH at the sensor location equals the RH of the indoor air. Experience shows that the difference between the RH of the room air and the RH at the sensor location can be limited to less than 5 % in a well designed system.

Figure 7.6 gives an example of the relation between the air flow through a RH-controlled supply device and the RH.

Results of various studies in France show that if a system is subjected to an accelerated ageing process before leaving the factory, and if it is calibrated properly, it is technically possible to achieve good durability and no drift of the operation mode.

In very cold climates it is possible that reverse flows at certain times lead to freezing problems at the outside of the air supply devices. The location of heating elements can influence the system performance if the warm air hits the sensor.

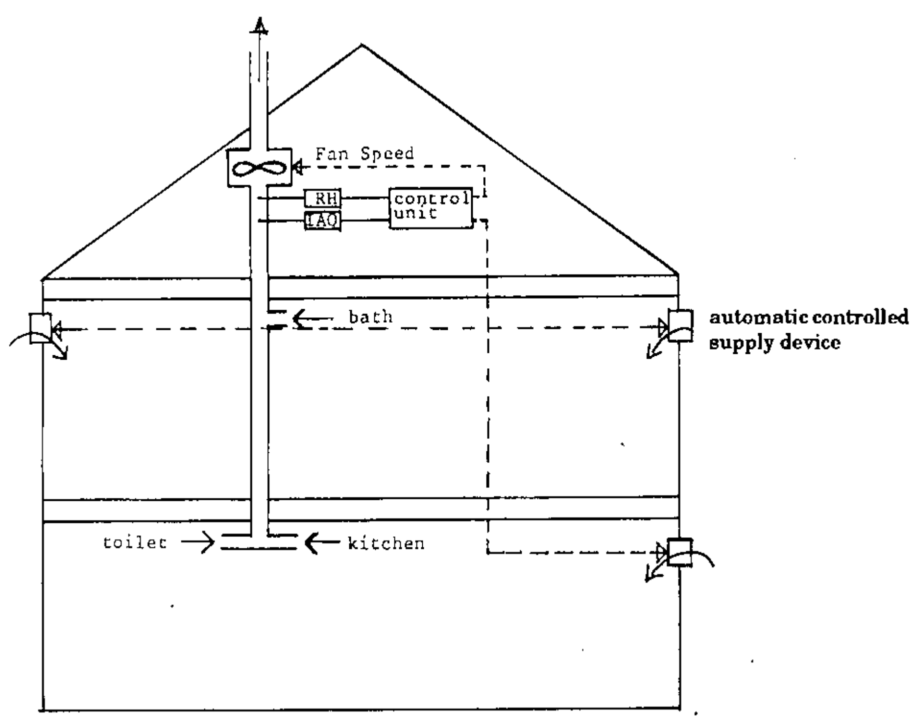


Figure 7.7. A building furnished with a mechanical exhaust system. Fan speed and air supply devices are automatically controlled by relative humidity and / or air quality sensors.

7.5.1 Exhaust Ventilation

A mechanical exhaust system uses a fan for the discharge of polluted air from the kitchen, the bathroom and the toilet. It usually employs one fan that is connected by ductwork to the treated rooms.

The natural RH-controlled ventilation system as described in 7.4.1 can be modified by installing an exhaust fan. The adjustment of the exhaust flow rate is achieved in the same way as described in 7.4.1, by varying the net section of the exhaust devices as the RH changes. It is however necessary that the fan has a flat flow-to-pressure curve and that the ductwork envlope is sealed very well.

For most mechanical exhaust systems, DCV means that the fan has different fan speeds to produce different air flows. The highest fan speed meets at least the requirements of the building code; the lowest fan speed maintains a desired minimum ventilation rate, which is often a ventilation rate of about 0.3 h^{-1}. The DCV system uses one or more fan speeds controlled by a sensor, or uses a continuous variation to control the concentration of the indicator(s) beneath the setpoint. As already mentioned in table 7.3 the useable indicators are the RH sensor and CO_2 sensor.

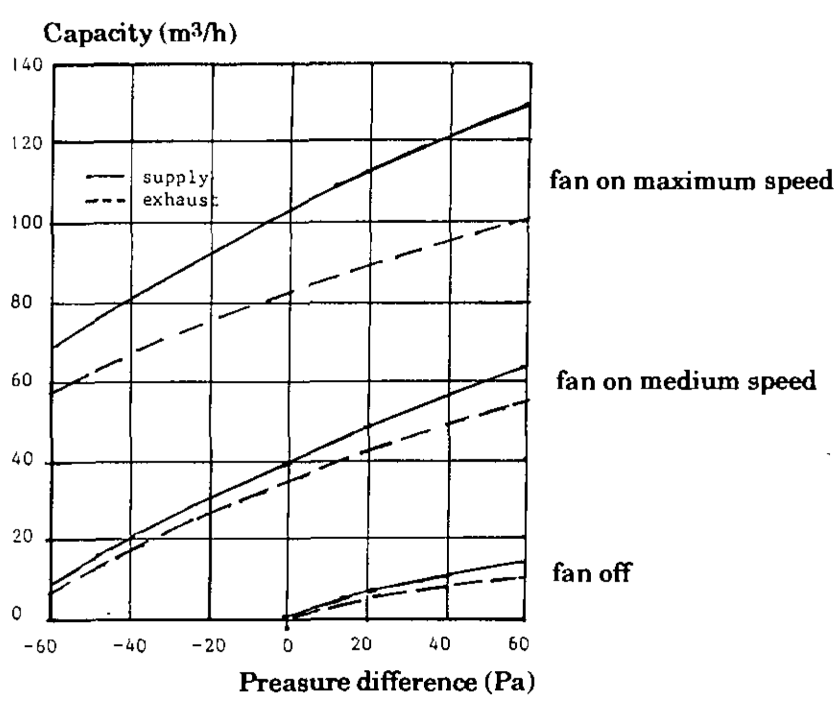


Figure 7.8. Influence of pressure difference on flow rate from wall mounted fans

The supply of outside ventilation air can be achieved naturally through supply devices, chinks and cracks in the building envelope. If the building envelope is too air-tight, provision must be made for supply of ventilation air, for example by automatically controlled supply devices. An example of such a system is given in figure 7.7 where the supply device is opened and closed by an electric motor. The supply devices in the upper levels of a building provide good air distribution during extended periods in winter when the stack effect cancels the pressure caused by the exhaust fan. These rooms should either be open to the rest of the house, or mechanical exhaust should be provided to assure ventilation.

Instead of combining the exhaust air flows of the different rooms into one exhaust airflow, standalone exhaust fans can be used. These systems are readily available and easy to install. They can be equipped with a RH sensor and/or a CO_2 sensor; the setpoint is usually manually adjustable. The fan used in a standalone system is often a axial fan, so that the air flow transported through the fan may be strongly influenced by wind, as shown in figure 7.8. A DCV system compensates more or less for this wind effect, because a larger air flow as a result of the wind pressure gives a faster decrease of the concentration of the indicator resulting in a shorter running time.

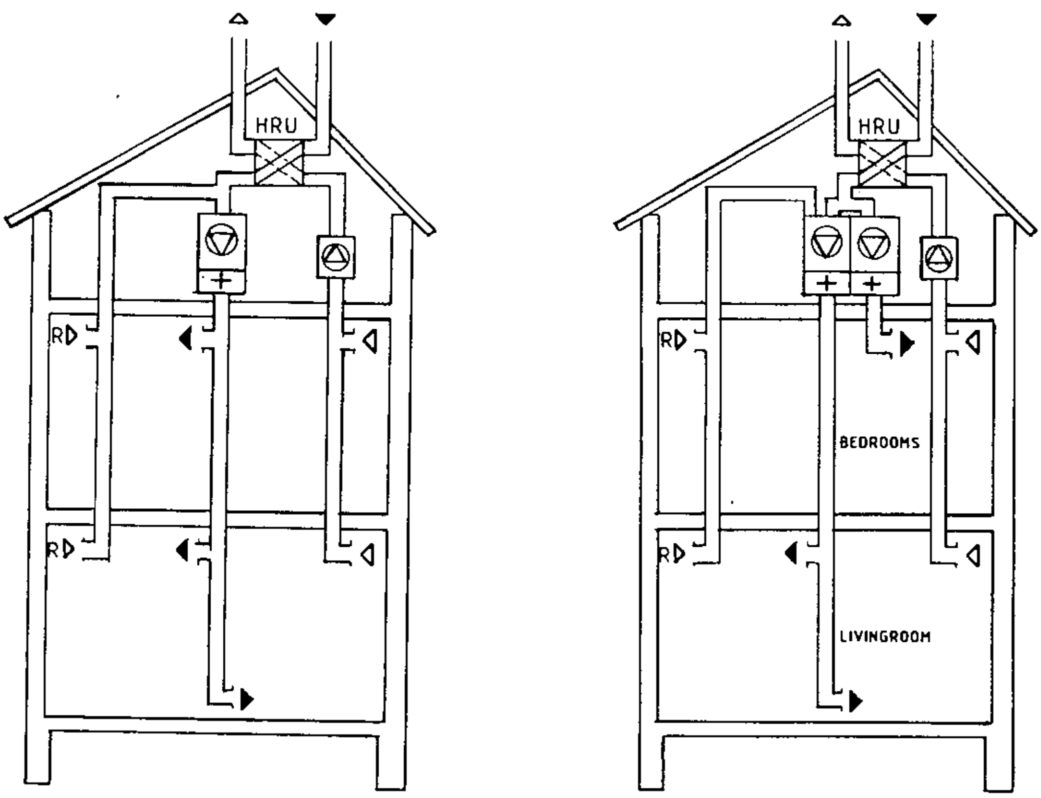
7.5.2 Supply Ventilation

Mechanical supply ventilation in combination with natural exhaust is generally used only as a decentralized ventilating system for one room, not as a central ventilating system. The design and application agrees in the main with a decentralized exhaust ventilation system as already described in 7.5.1.

7.5.3 Supply and Exhaust Ventilation

A ventilation system with mechanical supply and exhaust ventilation for a dwelling is also called a balanced ventilation system. With reference to figure 7.4, outdoor air is supplied mainly to the bedrooms and the living room and if necessary is supplemented in the hall (overflow-zone). The exhaust of the polluted air is in the kitchen, the bathroom and the toilet. The balanced ventilation unit has two fans, an exhaust fan and a supply fan. These are often three-speed fans operating at roughly (system-bound) high (100 %), medium (70 %), and low (40 %). Balanced ventilation systems usually include a heat recovery unit. About 70 % of the heat energy in the exhaust air can be recovered by the heat recovery unit, so the energy-saving potential of DCV is strongly reduced.

The balanced ventilation system can be integrated in an air heating installation. Various system



a One zone air heating system

HRU = Heat Recovery Unit
R = Recirculation

b Two zone air heating system with outdoor air to the bedrooms and recirculation air to the livingroom

Figure 7.9. Mechanical ventilation combined with air heating.

designs are possible as shown in figure 7.9. Heating (or cooling) demands have priority over DCV control. If a heat recovery unit is installed the application of DCV is then particularly focused on IAQ control and the consumption of electric power by fans.

The need for energy saving has also led to decentralized balanced ventilation units for one room. These units are especially designed for renovation purposes.

7.5.4 Sensor Type and Location

Compared to the features indicated in 4.2, sensors used for DCV in dwellings must meet special requirements such as low cost and easy maintenance. In the case of RH sensors, these requirements are met by use of hair or polyethylene-strip hygrometers and capacitive hygrometers, both of which are also used in HVAC systems.

The location of the sensor must ensure that the measured value of the indicator agrees with the control strategy. If the control strategy is based on the concentration of the indicator in the living area, then a sensor must be located in this. In practice this means a position against the wall; the sensor must not be situated on a place which is directly hit by the supply air.

Production of pollutants varies as a function of room and time. This means that an ideal DCV system must have several sensors, as shown in table 7.3. This is at present not realistic based on current costs. The following solutions are often applied:

* An RH sensor in the kitchen and an RH sensor in the bathroom, both connected in parallel to the controller. Each sensor can have its own setpoint strategy which can for example be tuned to the specific properties of building fabrics in according with 7.2.4.

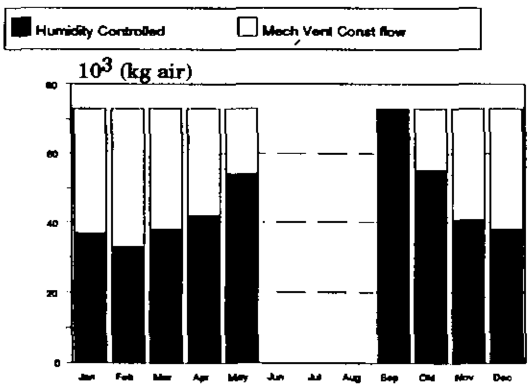
* An RH sensor and/or a mixed gas sensor in the exhaust air flow. This is a simpler solution with no sensors in the room itself. It is only applicable if there is always an airflow in the exhaust duct. The disadvantage is that the measured value at the indicator is a mean value of the concentrations in the different rooms. A case study showed that the use of a mixed gas sensor as a sensor to control the ventilation of the kitchen or living room was more appreciated by the occupants than an RH sensor, due to the fast reaction time.

For decentralized systems, the sensor is usually integrated in the ventilation unit. RH sensors and CO_2 sensors are commonly used.

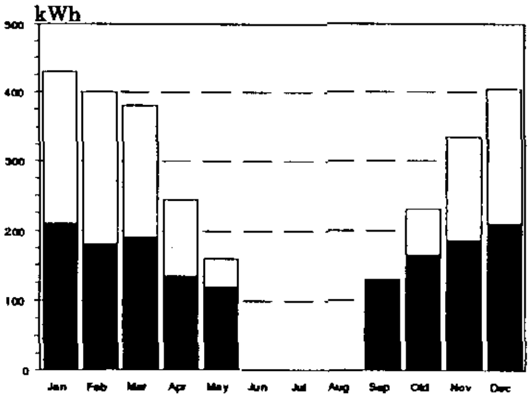
7.6 Energy Savings

Ref. 2 gives an indication of the energy savings that can be realized by installation of an RH-controlled DVC system for a well insulated house, assuming a basic situation where a mechanical ventilation system operates on a constant flow rate throughout the heating season. This constant flow rate meets the requirements of no mould growth during the critical month of September. With a DCV system where the RH is maintained at a maximum value, see 7.2.4, the air flow rate during the heating season and the energy saving are both reduced by about 40 %. Figure 7.10 shows a comparison of the supply air mass per month for these two ventilation strategies. Because the example above did not take into account the flow rate necessary to control the other indoor air parameters, the actual energy saving will be less.

Experiments in Canada with DCV systems, ref. 5, have shown a reduction in air flow rates of about 5 % to about 20 %, where activity level was the indicator and CO_2 was controlled with a setpoint of 650 ppm. In Figure 7.11, air flow rates and



Comparison of supply air mass 'W' with different ventilation strategies



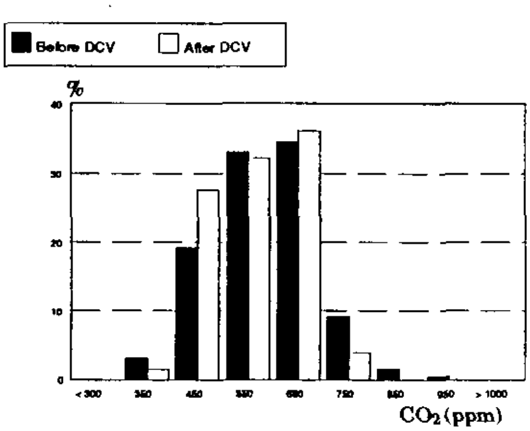
Comparison of energy consumption with different ventilation strategies

Figure 7.10. Comparison of two mechanical ventilation systems, one with constant flow rate and one with RH-control. (Stuttgart - Holzkirchen)

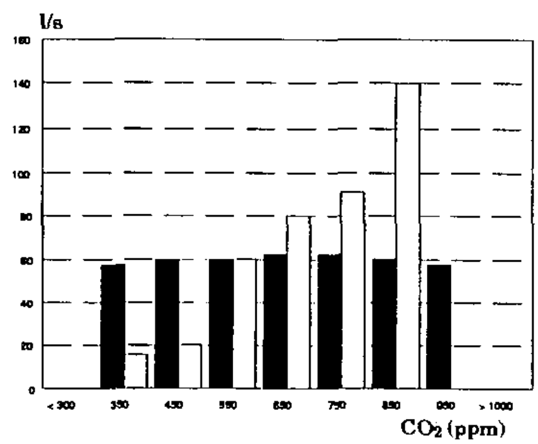
percentages of operating times are shown for different CO_2 values for systems in an existing house before and after introducing DCV. It can be seen that the savings are realized during the time that the CO_2 concentration is low. In this case there was also a reduction of 24 % in electrical energy required to run the fan.

From "hour-by-hour" computer simulations done in a Canadian study, it was estimated that for a base flow rate of 0.1 h^{-1} and a 3-person family, about 30 % savings should be possible with CO_2-controlled ventilation in a recirculation system.

In a Dutch experiment, a strategy was adopted using both a mixed gas



Percentage of time for given CO_2 concentration.
Average after DCV 558 ppm.
Average before DCV 584 ppm.



Flow rate as a function of CO_2 concentration.
Average after DCV 49 l/s.
Average before DCV 62 l/s.

Figure 7.11 Ventilation performance with and without DCV. CO_2 control with the set point 650 ppm.

Table 7.6. Distribution of the fan speed time as function of the controller type

Controller	% of the time with the fan speed:		
	High	Medium	Low
Manual	24	3	73
RH, with variable set point	-	-	100
Combined mixed gas/RH*	55	16	29

Setpoints:

RH-sensor:	low-medium speed:	55 % RH
	medium-high speed:	65 % RH
IAQ-sensor:	low-medium speed:	65 % of full scale
	medium-high speed:	70 % of full scale

sensor and RH sensor as controllers for a particular dwelling and compared with manual control of a balanced ventilation system. Figure 7.12 shows the percentage of operating time in which the fan was running at high speed. With the manually controlled system the high fan speed is concentrated in the afternoon and evening, while the IAQ/RH control results in a more diffuse use of the high fan speed. A control strategy was used based on the RH control strategy using setpoint as f(T$_e$) (see table 7.5, control strategy no 2); the setpoint was based on avoiding condensation on double-pane windows with T$_i$ = 20°C. For this particular dwelling this control strategy resulted in an exclusively low fan speed for the ventilation system. Table 7.6 shows the percentages of the time for which the different fan speeds were used in this experiment.

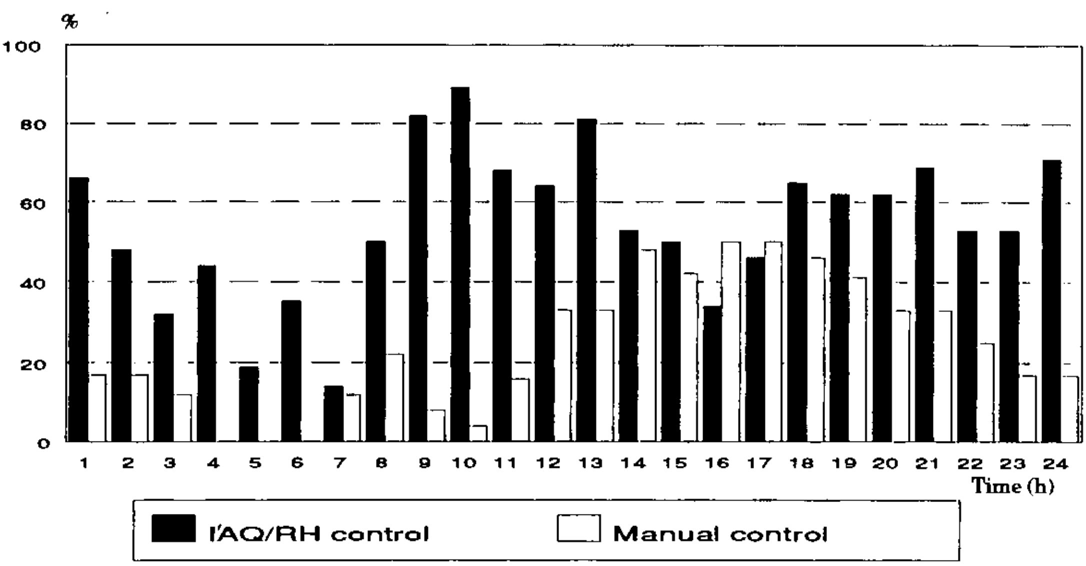


Figure 7.12. Percentage of time of fan operation at high speed as a function of time of the day

Table 7.6 shows that for this well insulated house, an RH-controlled DCV system results in a minimum of ventilation. The IAQ/RH controller (mostly reacting on the mixed gas sensor) leads to more ventilation in comparison with the manual control situation but this type of controlling was preferred by the occupants.

The resulting saving in airflow is 58% in the case of an advanced RH control strategy. But there is no saving for the situation where the control strategy is based on a fixed RH setpoint in combination with a mixed gas sensor. For that situation the controller was mostly reacting on the mixed gas sensor on behalf of the fast response of this sensor.

With reference to the application of the mechanical RH sensor (in either natural ventilation or mechanical exhaust systems), no reports of energy savings are available.

7.7 Recommendations

DCV systems in dwellings result in energy savings when unpredictable occupant- generated pollutants are dominant in comparison with building-generated pollutants. Source control of building-generated pollutants is therefore essential. DCV systems are effective at reducing peak pollutant concentrations from the point of view of IAQ.

DCV can be integrated in most ventilation systems of dwellings. An important condition is that the DCV system may not be short-circuited through other, non-controlled airflows such as leaks in the building envelope. In the case of DCV-natural supply and DCV-balanced ventilation the airtightness of the building envelope must be high. For natural DCV ventilation only RH-controlled systems are on the market today.

For mechanical exhaust and balanced ventilation systems the useful indicators are:

* RH, especially if the DCV system is intended to protect the building fabric against mould growth and surface condensation
* CO_2 if the DCV system must react on human occupancy
* mixed gasses, which means that the indicator is not very well defined.

In general the correlation between RH and CO_2 concentration is weak. Activities that give a high production of moisture require a higher air flow rate than that needed to keep a good IAQ with respect to body odour. Given today's technology, RH control is currently the most viable option. A fixed setpoint of the RH sensor results in an unnecessary increase of the air flow in autumn and spring; so it is at least necessary to change the setpoint during the year. A varying RH setpoint as mentioned in table 7.4 is recommended.

Mixed gas sensors react more to activities in the dwelling than to absolute values of the different indicators. The use of these sensors was judged positive by the occupants but the resulting energy saving is less. The choice of the setpoint is purely subjective because there is as yet no objective relation between the sensor and the IAQ.

The sensors must be installed at a representative location to give an appropriate reading. The sensor should not be located in or be directly hit by the supply air. For exhaust systems, the number of sensors can be reduced by installing a sensor in the exhaust duct instead of in several rooms. The disadvantage of this solution is the fact that one will measure a mean value of the indicator(s), so the setpoint must be chosen lower taking into account the exhaust airflows from the different rooms.

8 Schools and Day Nurseries

8.1 Purpose

This Chapter discusses the suitability of DCV systems for application to typical schools and day nurseries. It describes the characteristics of such buildings and their occupancy profiles, and the specific factors governing DCV feasibility.

The configuration of a ventilation system for a school building or a day nursery is very much dependant on:

* Building layout
* Building structure
* Climate
* Internal load in time and space

This discussion focuses on the building layout and the influence of the internal load caused by persons. The building structure is not discussed with the exception of a possible accumulation used to eliminate large temperature rise caused by temporary heat load. The influence of climate is discussed in Chapter 6.

Laboratories and other types of special rooms must be treated according to regulations (i.e. exhaust

Figure 8.1 Pavilion school or landscape school

hoods) and specifications for such rooms and components in general. These types of rooms and equipment are not dealt with in this discussion. Teachers' rooms, office rooms, photocopier rooms should be dealt with as offices.

Kitchens and other types of special rooms must be treated according to regulations (i.e. exhaust hoods) and specifications for such rooms in general. These types of rooms are dealt with only superficially in this book.

8.1.1 Building Types

School buildings are often designed in one of the following forms also illustrated in figures 8.1, and 8.2.

1 Pavilion school: A pavilion school, if not equipped with a natural ventilation system, is usually equipped with a centralized supply system and a local exhaust system. In some cases there is additional exhaust ventilation for toilets.

2 Landscape school: The sound attenuation required in a landscape school is often achieved by using fitted carpets and noise absorbers, which contribute to a rather high emission of pollutants. The venti-

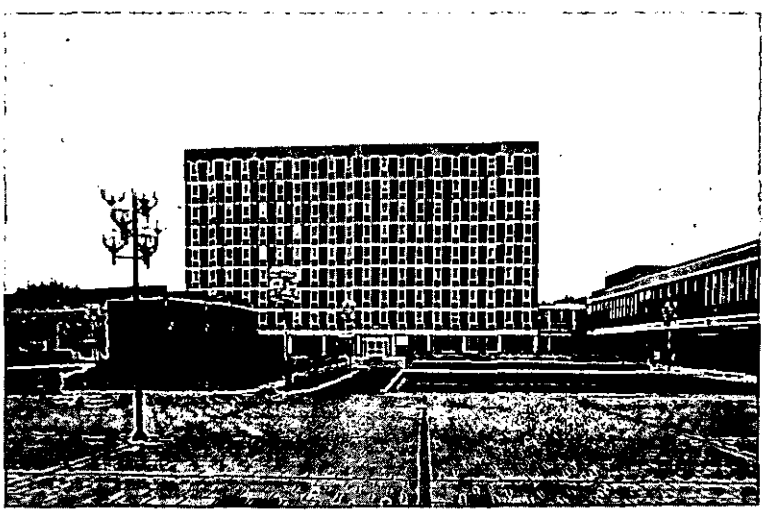


Figure 8.2 Multi-storey school

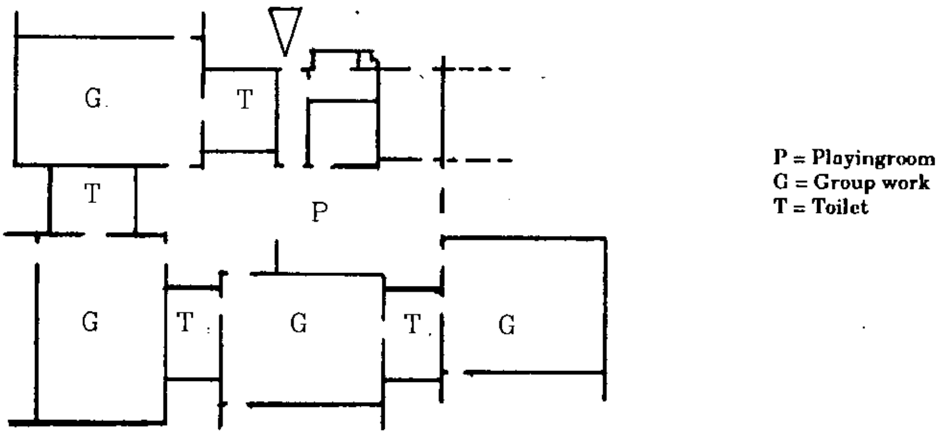


Figure 8.3 Layout of typical day nursery

lation system must be designed to give a high basic ventilation rate as well as a rather high ventilation during work hours. This necessitates an energy recovery system with high performance, hence a full mechanical ventilation system.

3 Multi-storey school: In many countries this represents an older type of school building. If not equipped with a natural ventilation system, it is usually equipped with a centralized exhaust system.

Day nurseries are often integrated with other activities and may for instance be hosted in:

* Single-family house
* Pavilion day nursery
* Multi-storey building
* Elementary school

Figure 8.3 shows a typical layout of a pavilion day nursery.

8.1.2 Ventilating System Types

Ventilating systems can be designed as centralized plants or local installations, the latter normally in the form of exhaust systems. Ventilation systems in to-day's schools and day nurseries are mainly formed in one of the following ways (in order of complexity):

1. Natural ventilation
2. Mechanical exhaust ventilation
3. Supply and exhaust by mechanical ventilation
4. Supply and exhaust by mechanical ventilation, furnished with a heat recovery system

DCV systems are normally formed with the system types 2, 3 or 4 as a basis. As a rule, system types 3 and 4 have been designed to work with mixing ventilation. Systems using displacement ventilation have become more and more interesting as a way to improve room air quality in the occupied zone.

Forced airing during breaks using windows or doors is usually a good solution for schools from an economical point of view as the necessary time for ventilation is short. This type of airing is in fact a type of demand controlled ventilation. In some cases the use of window airing might cause inconvenience in the form of draught (due to cold air or high local air velocity), noise from outdoor activities, and sometimes pollen. In day nurseries, window airing can be used only under certain conditions, because the children seldom take their breaks outside the room that has to be ventilated.

Although economically attractive, forced airing during breaks calls for strict discipline, especially during the winter, as energy use will increase with airing time. Besides, if windows are left open for a period of time longer than necessary the interior of the room will become chilled to an unacceptable level.

8.1.3 Building Use and Occupant Load

The dimensioning of a classroom and its installations must be made in accordance with local regulations. Although the number of persons in a classroom or a day nursery is usually known, the real load must be considered with respect to occupants of different ages engaged in various activities. A school timetable usually governs the presence of children in a classroom, but in a day nursery the presence is usually more unpredictable. In certain countries there might be a time-bound presence in day nurseries like that of a school.

The main heat load in a classroom usually comes from the occupants, provided that proper solar shading is installed and used, and that lighting is provided by fluorescent lights. Variations in production of heat, CO_2 and moisture as a function of age at equal activity levels is discussed in Chapter 3.

When ventilation demand is considered the differences between low and high grade elementary schools and colleges ought to be discussed. Normally the following distinctions can be used:

Low grade elementary schools (pupils up to 10 years of age): There is usually a fixed number of pupils in the classes, which means that ventilation demand is predictable. In most cases there are 20-25 pupils.

High grade elementary schools (pupils 11-15 years of age): There is usually an upper limit of 30 pupils per class. Often the classes are split into two halves in order to study different subjects.

High schools or colleges (pupils 15-16 years of age and up): The number of persons present in a class differs widely and in an unpredictable way. Thus the ventilation rate must be controlled according to the actual load of persons.

Universities: College-type teaching rooms often show a very high personal load, comparable to that of a meeting room in an office. See

Chapter 9 *Auditoriums* and Chapter 10 *Offices* for comments.

Day nurseries (children up to 6-7 years of age): There is usually a fixed upper limit of children in day nurseries, which means that the maximum ventilation demand can be foreseen. In most cases there are about 20 persons in a day nursery group (including four nurses), comparable to 10-15 adults. The main heating load is from the children, and it is necessary to distinguish between rooms where the children are active and rooms where they rest or sleep.

8.2 Driving Pollutant

A description of pollutants and indicators is provided in Chapter 3. The driving pollutant in schools and day nurseries is carbon dioxide. Moisture and VOCs are less critical.

8.2.1 Carbon Dioxide

The main driving component in a school or a day nursery, with respect to regulating ability, is CO_2. Carbon dioxide may be present in low concentrations in rooms with an acceptable indoor air quality (IAQ), in which case it is not regarded as a pollutant but as an indicator of odour and other emissions from persons. Heat and moisture dissipation often follow the emission of CO_2.

This way of observing the air quality has been used for more than one hundred years. (Pettenkofer about 1850; Heyman 1880, in Swedish; Yaglou 1930; Fanger et al. 1984.)

Schools: Heat dissipation in classrooms and day nurseries can normally be dealt with by accumulation in the building structure. Table 8.1 shows the necessary air flow rate for transporting CO_2 and heat from a classroom with 30 seated pupils (activity level comparable to office work, 30 adults).

Day nurseries: Table 8.2 shows the necessary air flow rate for transporting carbon dioxide from a day nursery with 16 children and 4 adults.

Table 8.1. Carbon dioxide dissipation in classrooms with 30 pupils and necessary air flow rates

CO_2 dissipation l/s	Air flow rate l/s (dc ppm)*	Air changes h^{-1}
0.15	150 (800)	2-2.5

* dc = difference in CO_2 content in ppm between supply air (outdoor air) and exhaust air

Table 8.2. Carbon dioxide dissipation and necessary air flow rate in a day nursery with 16 children and 4 adults

CO_2 dissipation l/s	Air flow rate l/s (dc ppm)[1]	Air changes h^{-1}
0.06	160 (800)	0.8

1 dc = difference in CO_2 content in ppm between supply air (outdoor air) and exhaust air

8.2.2 Moisture

Moisture dissipation often follows the emission of carbon dioxide but the moisture dissipation is not critical, as can be seen by comparing the table 8.3 with the preceding tables.

8.2.3 Volatile Organic Compounds

The foremost pollutants that will be detected using the CO_2 concentration as an indicator, are heat, organic compounds (from paper, books, glue, colours, and so on), and particles. Newly installed materials under decay conditions (outgassing) may cause IAQ problems. The owner should deal with that problem by demanding declarations on material to be used from the manufacturer or the contractor. The dealer should also be able to give information regarding dissipation of pollutants from installed materials when moistened, heated or wetted. A school environment is usually characterized by furniture and other equipment having a rather small adsorption area. One exception might be schools where wall-to-wall carpeting is used (in an attempt to reduce noise level or increase the home-feeling).

Restricted use of cleansing compounds is recommended. Only well defined and low risk chemicals should be used, especially for on-site carpet cleaning.

Table 8.3. Moisture dissipation from occupants in a classroom and day nursery

Room type	Moisture dissipation	Air flow rate l/s [dx* (g/kg)]	Air changes h^{-1}
School: 200 m^3, 30 pupils	0.3	60 [4]	1.1
Day nursery: 300 m^3, 16 children, 4 adults	0.1	20 [4]	0.3

* dx = difference in moisture content between supply air (outdoor air) and exhaust air

In general, airing by opening windows or by forced mechanical ventilation during the cleaning up procedure and during breaks between lessons will reduce problems caused by emission and result in an acceptable IAQ.

8.2.4 Thermal Comfort

Under some circumstances the heat dissipation from people and lighting or solar heat gain may be the main factor to consider for governing the air flow rate. Too high temperatures should not be cured by a DCV system but rather by opening windows or by using cooling devices. Comfort criteria must be observed as to room air velocity variations caused by DCV action of the system.

8.3 Ventilation Principles

8.3.1 Ventilation Strategy

Pollutants generated in a normal situation in a school or day nursery are dissipated to the air and cannot be exhausted in a concentrated form. They must be taken away via the general ventilating system. Even so, exhaust terminal devices should be placed where the concentration of pollutants is expected to be highest.

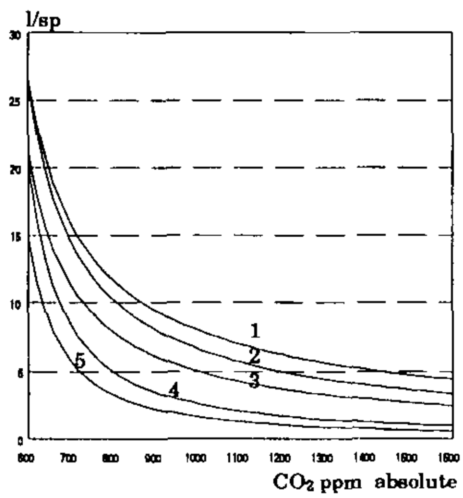
Schools: Demand controlled ventilating systems are justified in schools because the load varies over time and each classroom also has an individual time schedule for its use.

Day nurseries: The main reason for using a demand controlled ventilating system in a day nursery is the unpredictability of the load, because children arrive and leave the nursery at very different times of the day. Besides, children's activities vary during the day (in activity rooms and sleeping rooms) and from day to day (because of weather conditions and time of the year). Thus the emission load varies from time to time and from room to room during the day and must be considered when designing and operating the ventilating system.

Some day nurseries are managed in the same way as a school, with a time schedule for the activities of the children. Such day nurseries can be dealt with as a school in terms of the occupant load.

8.3.2 Ventilation System Operation

Base ventilation, defined in Chapter 5 as the rate of ventilation required to remove continuous-source pollutants, is usually in operation to prevent indoor air from accumulating pollutants. Pre-airing of indoor areas in some occasions is a necessary complement to base ventilation, to further reduce pollutant level or temperature. This can be



Explanation of curve

1 Room volume 0 m^3/person, staying in the classroom
2 Room volume 20 m^3/person, staying in the classroom.
3 Room volume 20 m^3/person, leaving the classroom during the 10 min pause
4 Room volume 10 m^3/person, leaving the classroom during the 10 min pause. Window airing 5 h^{-1}. If 1200 ppm CO_2 increase is accepted no mechanical ventilation is needed if window airing during 10 min/lesson.
5 Room volume 20 m^3/person leaving the classroom during the 10 min pause. Window airing 5 h^{-1}.

Note 1: If 600 ppm CO_2 increase is accepted no mechanical ventilation is neded when airing 10 min.

Note 2: If 900 ppm CO_2 increase is accepted no mechanical ventilation is needed when airing 6 min.

Note 3: If 1200 ppm CO_2 increase is accepted no mechanical ventilation is needed when airing 4 min.

Figure 8.4. Classroom ventilation and forced airing during breaks

accomplished by mechanical means or by opening windows.

A DCV system should be considered in those cases where the load varies in an unforeseeable way and where energy savings and improved IAQ can be achieved. A mechanical system or the opening of windows can be practised.

The necessary mechanical air flow rate can be calculated at different room volume per person and with different acceptable CO_2 levels. In figure 8.4 is given 5 curves with various room volumes, people staying in the classroom or leaving it during the pause, with and without additional window airing.

Background data for figure 8.4 are:

* activity level as sitting adults
* giving CO_2 dissipation 18/l/(p·h)
* heat output 100 W/p
* lesson time 40 minutes
* balance time for classroom air volume 5 h

Background data: Adults, sitting, CO_2 dissipation 18 l/(p·h), heat output 100 W, lesson time 40 minutes, break 10 minutes (80 % of time usage), 5 hours balance time for classroom air volume. Equation 1 is used. Average values are given.

8.3.3 Comparative Flow Rate Demands

In most cases, according to indoor environmental regulations, an average value of maximum allowable concentration of a pollutant is given together with a short time maximum. The CO_2 concentration, according to these regulations, should never exceed an average of 5 000 ppm for a workday and never exceed 10 000 ppm as an average for 15 minutes. It is thus relevant to discuss the average value of the CO_2 concentration in room air rather than momentary peak values. A calculation of outdoor air flow rate can be made for classrooms of different sizes with 30 pupils, equivalent to 30 adult persons, with lesson time 40 minutes and 90 minutes and breaks of 10 minutes the following outdoor air flow will be normal. The values in table 8.4 have been calculated under consideration of accumulation in room air according to **Equation 8.1**.

Equation 8.1

$$q_o = [(10^6 \cdot q_{CO2}) / (dc_{CO2})] - \mathbf{V} \cdot [l / t_b + n \cdot (t_v / t_t)]$$

where:

q_o	=	necessary outdoor air flow rate	m^3/h
q_{CO2}	=	production of CO_2	m^3/h
dc_{CO2}	=	increase of concentration, compared to outdoor air	ppm
V	=	room volume	m^3
t_b	=	calculation balance time (usually part of a day, > 1 h)	h
t_v	=	time of window airing	h
t_t	=	total school time (lesson+break)	h
n	=	number of air changes from window airing	h^{-1}

The question is frequently asked whether room air quality should satisfy those visiting the room or "only" be adequate for the occupants. The first criterion calls for a flow rate of about 10 l/(p.s), while the other sets the demand to about 5 l/(p.s) and gives an acceptable air quality for visitors after a 10-minute break. The CO_2 concentration in the room air as a function of time after school day start in the morning for different ventilation flow rates by mechanical system and in combination with window airing can be found in table 8.5. The calculation of the CO_2 concentration in the room air has been made according to the **Equation 8.2.**

Particles caused by human activities must be dealt with by source control: hard floor surface, good cleaning. In rooms for use by

Equation 8.2

$$c = c_r \cdot e^{-nt} + c_o \cdot (1 - e^{-nt}) + (q_c/q_o) \cdot (1 - e^{-nt}) \cdot 10^6$$

where:

c_r	=	concentration in the room air at t = 0	ppm
c_o	=	concentration in the outdoor air	ppm
n	=	air changes per hour = q_o / V	h^{-1}
V	=	room volume	m^3
t	=	time after start	h
q_c	=	Volume flow rate of CO_2 (here 0.15 m^3/s for 30 persons)	m^3/h
q_o	=	outdoor air flow rate	m^3/h

Table 8.4. Air flow rates from mechanical system combined with window airing

Room type and load	Necessary mechanical flow rate (l/s)**					
	Lesson time 40 minutes Window airing (h^{-1})			Lesson time 90 minutes Window airing (h^{-1})		
	0	5	10	0	5	10
School: 30 persons, 200 m^3	150	95	40	155	130	100
School: 30 persons. 300 m^3	130	50	[8 min]	140	100	55
Day nursery: 15 persons, 300 m^3	40	[5 min]	[3 min]	45	2	[3 min]

* The table shows flow rates necessary to keep CO_2 concentration increase below an average of 800 ppm (0.08 %) during normal operation in a classroom with sizes 200 and 300 m^3 and in a day nursery with room volume 300 m3 at 40 and 90 minutes of lesson time.
Number of persons = adult equivalents.

** If continuous flow rate less than 0 the necessary window airing time in minutes is given in brackets.

persons with allergic reactions, the ventilation system must be designed to reduce the number of particles in the room air. Such a design might call for an air change rate that is higher than that necessary for the dissipation of bioeffluents. It is recommended that allergic persons be placed near the supply devices but well outside the area of high air velocity.

Schools nearly always have relatively large windows. Thus the heat from sun may become a serious problem if the solar shading is not sufficient or is used improperly. The combined effect of heat from lighting and from sun calls for cooling equipment if outdoor air temperature is too high for the ventilation air to produce the cooling and if night cooling cannot be used to accumulate cooling capacity for the following day. This calls for a special type of demand control related only to temperature.

*Table 8.5. Change in CO_2 concentration in classroom air**

Flow rate	Window airing	CO_2 concentration (ppm abs) at time in minutes after morning start					
l/s	ac/h	40	50	90	100	140	150
300	0	900	720	900	720	900	720
150	0	1200	800	1400	900	1400	900
100	0	1450	1070	1900	1400	1900	1400
100	5	1450	470	1500	480	1500	480
50	0	1950	1680	3000	2600	3400	2900
50	10	1950	400	1950	400	1950	400

* Change is shown as a function of time in minutes after start cf school day. Lesson time 40 minutes, break time 10 minutes, 30 persons, room volume 200 m^3.

8.3.4 Window Airing

The window airing flow rate is dependant on the temperature difference between the room air and the outdoor air, following approximately the **Equation 8.3**, ref. 1:

In order to verify the air change rates chosen in the calculation table 8.6 has been derived using the above flow rate formula:

Equation 8.3

$$q = C \cdot (b/3) \cdot (g')^{0.5} \cdot h^{1.5} \ m^3/s$$

where:

C	= area coefficient:	about 0.9 for dT 20°C about 0.8 for dT 2°C	
b	= breadth of opening		m
h	= height		m
g'	= $g \cdot d\rho/\rho$		m/s^2
g	= earth acceleration 9.81		m/s^2

$d\rho/\rho$ = relative density difference calculated by:

$$d\rho/\rho = [\,2 \cdot (1 - T1/T2)\,] / \ (1 + T1/T2)$$

When $T1$= 273 K (0°C), and $T2$= 293 K (20°C) the relative density difference becomes 0.0683 and g'= 0.694 m/s^2.

*Table 8.6. Air flow rate as a function of temperature difference**

dT°C	T1 K	T2 K	breath m	q m^3/s	V m^3	n h^{-1}
1.0	292	293	1.0 3.0	0.09 0.27	200 200	1.6 4.9
10	283	293	1.0 2.0	0.32 0.64	200 200	5.8 11.6
20	273	293	1.0 2.0	0.46 0.92	200 200	8.3 16.6
30	263	293	1.0 2.0	0.57 1.14	200 200	10.3 20.6

* Air flow rate through an open window of height 1.5 m and breadth 1.0 or 2.0 m as a function of temperature difference between room air and outdoor air. No wind.

8.3.5 System Regulation

Transportation of pollutants by using exhaust air is often designed with regard to the demand for continuity in the transportation caused by the uninterrupted emission of pollutants from building material. Many buildings are furnished with a mechanical ventilating system where the flow rate can be chosen for at least two operational conditions, as defined in chapter 5:

* Base ventilation (low flow rate) to remove continuous-source pollutants;
* Occupancy-related ventilation to remove pollutants associated with the presence or activities of occupants and their equipment (activities before, during and after school time)

Most gaseous pollutants are produced in combination with heat and therefore have a tendency to rise. For the use of CO_2 as the driving contaminant it is therefore recommended that the exhaust air terminal devices be placed at a high level in the treated room.

The supply air should be introduced as near the breathing zone as possible of the persons present, see figure 8.5. One way of fulfilling this is to keep the supply air colder than the room air and introduce it via an air terminal device that spreads the air along the floor. As the air becomes warmer in its contact with convectional air streams along the bodies it rises and takes away both heat and pollutants.

An ideal system of that type works without recirculation of room air and is often named a displacement ventilating system, see figure 8.6. Observe that air streams along the floor cannot be accepted in sleeping areas where children are sleeping on low beds or directly on the floor.

Displacement ventilation systems can be used only in rooms where the occupants are not placed too near the supply air terminal devices. In day nurseries such devices can be used in rooms where the children are supposed to be awake and moving around, while sleeping departments should be ventilated by secondary air from the activity zones or supply air devices with a mixing action.

The opposite of a displacement system is a mixing system, in which the supply air is completely mixed with the room air and its pollutants.

In many cases the heat dissipation from persons, apparatuses and lighting fixtures cause a circulating air flow in the order of 10 air changes per hour in the room. Thus, a ventilating system meant to act as a displacement system in such cases will become a mixing system, especially in the upper part of the room, see Figure 8.6.

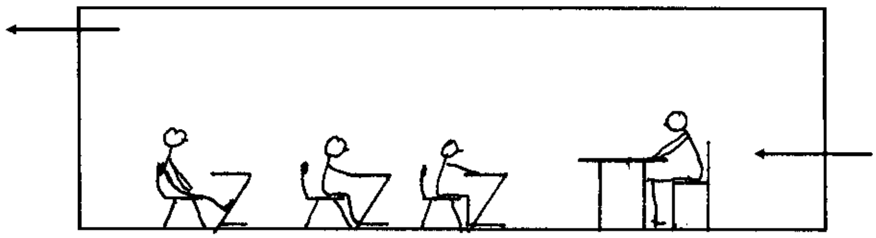


Figure 8.5. Supply air at breathing zone

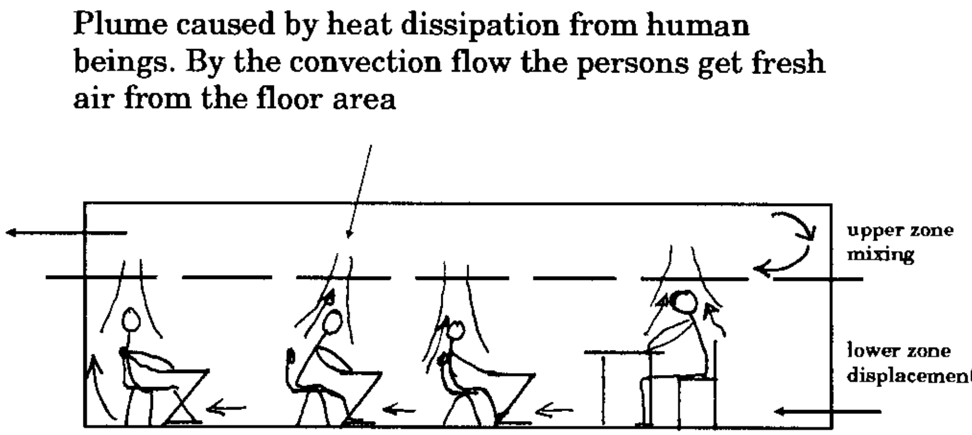


Figure 8.6. Principle function of a ventilating system with displacement devices

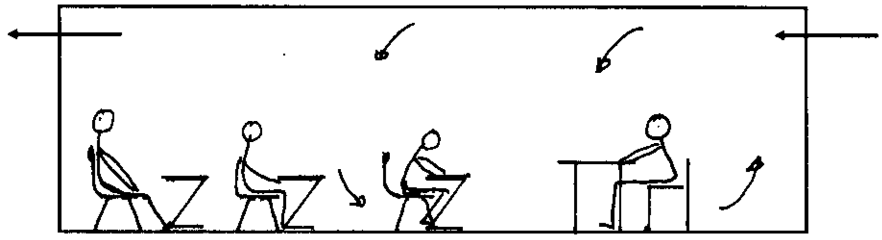


Figure 8.7. Principle function of a ventilating system with mixing devices.

8.3.6 System Response Time

There is no demand for a fast-reacting control system during class time. For ventilation during breaks, on the other hand, a relatively fast system (with high air flow rate) is needed, if a mechanical system is used. As has been shown above, window airing during short break is an acceptable solution.

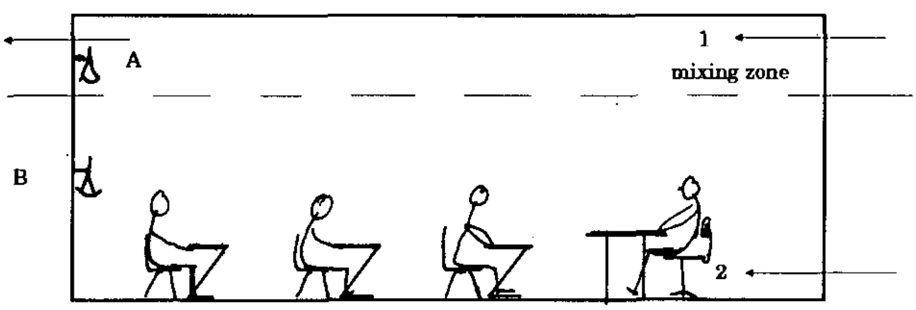
8.4 System Design

In most cases, to transport heat and body odour and in order to achieve an acceptable room air quality in the occupied zone, a displacement ventilation system is preferable. The displacement function is usually prevalent in the lower part of the room, while in the upper part a typical mixing situation is at hand. A somewhat higher air flow rate is needed for a system using mixing ventilation (about 20 %) compared with that of a displacement ventilation system. Displacement ventilation may cause local draught and is thus not fitted for rooms where the occupants are sitting or lying on the floor.

8.4.1 Ventilation Equipment in the Room

Schools Low-impulse type supply air devices (used to achieve displacement ventilation) should be used. They should if possible be placed in the lower front part of the class room. Exhaust air devices should be placed at the back part of the room close to the ceiling. Sensor(s) should be placed according to ventilation system layout, see figure 8.8. Windows should be openable and preferably have a high vertical extension in order to work properly during window airing.

Day nurseries Supply air devices designed for mixing systems should be used and preferably be placed so



Ssupply	Sensor location
1	A
2	B prefered

Figure 8.8 Classroom with ventilating and sensoring devices

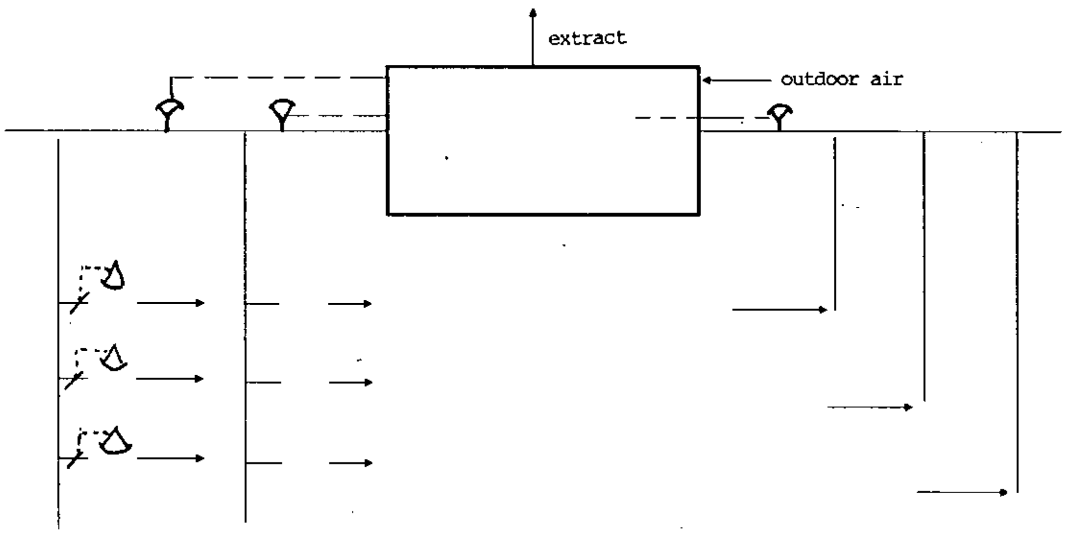


Figure 8.9. Example of central system design and equipment

as not to cause to high local air velocities in the occupied zone. The supply devices should be able to operate with air flow rates form 25 % to 100 % of full flow rate without causing disturbances. For other functional criteria, see *Schools* above.

8.4.2 Central System

A centralized system is one with mechanical ventilation for both supply and exhaust. An example is shown in figure 8.9. Systems designed with high pressure drop in the air terminal devices are not apt to give low power demand per flow rate unit. A DCV action is difficult to achieve, as the pressure drop in the system increases with the second power of the flow rate. A centralized system designed for DCV should have air terminal devices and duct system with a low pressure drop. Thus such a system is not apt to be used in a high rise building (> 5 floors). Pavilion schools with a relatively short extension are suitable for DCV systems. Long buildings should be sectioned.

8.4.3 Distributed System

Local systems with mechanical ventilation for both supply and exhaust are well suited for DCV. The same stands for mechanical exhaust as far as the occupants are not exposed to the direct air flow from the supply devices in the external wall.

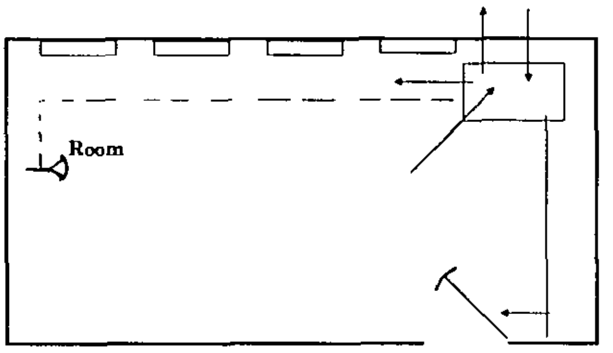


Figure 8.10. Example of distributed system design and equipment

8.4.4 Combined Systems

Central supply, local exhaust A DCV action is difficult to achieve, as the pressure drop in the supply system increases with the second power of the flow rate. Besides, the exhaust often is accomplished via openings in doors and exhaust devices in the toilets, which does not give the wanted ventilation efficiency in the room.

Central exhaust, local supply A system with local supply and central exhaust is comparable to a typical ventilation system for a domestic building. The performance of such a system used for DCV has been tested and found to be acceptable, see Chapter 7, Dwellings.

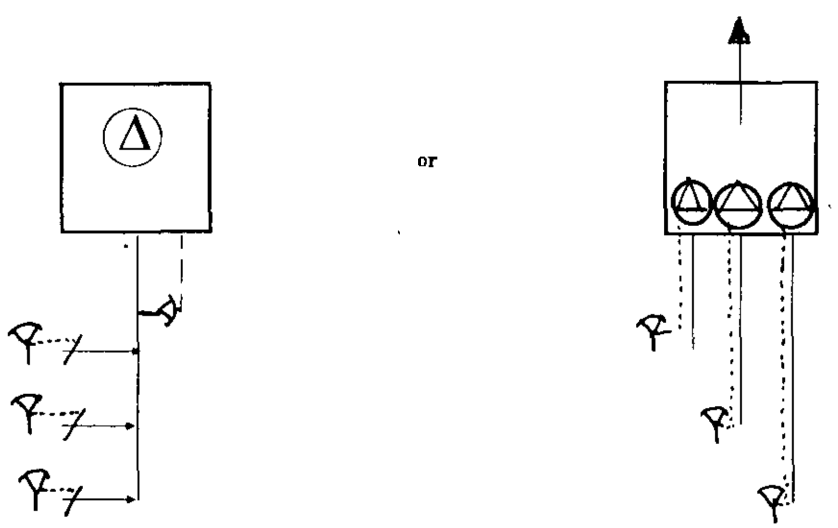


Figure 8.11. Combined system and equipment, example

Table 8.7. Occupancy time in schools and day nurseries

Building type	Occupancy time		
	h/day	h/year	%/year
School	6	1200	14
Day nursery	9	2000	23

8.4.5 Quality and Risk

School time is a "part-time risk", since the pupils are in school for only part of the day and during only part of their lives. The occupancy time is approximately as shown in table 8.7.

The discussion on the build-up of allergic reactions in younger children due to long-term exposure at school seems somewhat exaggerated light of the comparatively short time that pupils spend in schools and day nurseries. It should be noted that smoking parents at home might have a much stronger influence on diseases of this type.

8.5 Sensor Type and Location

In table 8.8 are given the different types of sensors used in practice or in test rooms as well as their advantages and disadvantages.

Comment: Day nurseries where the occupancy pattern is practically equal to that of a school, can use the same solution as a school for governing the ventilation system.

8.6 Energy Savings

In discussing energy demand and energy saving the main topic should be to save heat. In most cases there is a natural connection between ventilation demand and energy use. On the other hand, there are other factors influencing the total energy demand for ventilation:

* Ventilation effectiveness
* Degree of occupancy related ventilation
* Use of internal heat load
* Possible heat recovery
* Air transportation energy

The first three can usually be improved with profit. However, the cost of installing the fourth (heat recovery equipment) would be prohibitive in many present-day schools with decentralized systems. In most cases it is also very expensive to change the distribution system in order to make a heat recovery installation possible. There is a dualism between the wish to recover heat by centralizing the ventilation system and the wish to reduce the transportation energy for ventilation air, ref. 5.

Table 8.8. Sensor type and characteristics

Type of sensor	Advantage	Disadvantage
Carbon dioxide	Senses personal load	Insensitive to other pollutants*
Presence**	Fast-reacting Inexpensive Mechanically stable Useful at cleaning periods	Insensitive to load Causes higher energy consumption
Mixed gas	Senses oxidable compounds	Unstable imprecise Only relative levels can be measured
Humidity		Slow in all normal buildings

* Especially pollutants from cleansing compounds
** Can be combined with other sensors

In the future, when electric energy will be more scarce and thus more expensive, there will be even more necessary than today to reduce power needed for the transportation of air. A power demand of more than 3 kW/(m^3/s), which is normal today, will have to be reduced to less than 1 kW/(m^3/s). This can be done by increasing the cross section of the ducts, by shortening the length of the ducts and by improving the efficiency of the ventilator and its connections to the system.

8.6.1 Window Airing

One way to reduce energy demand for the transportation of air is to reduce the flow rate transported by the mechanical ventilation system. The necessary outdoor air flow rate can then be reached by using temporary window airing without reducing the perceived quality level of the room air when entering the room after a break when window airing has been used. As the heat produced by the 30 occupants of the classroom is about 2 kWh per lesson of 40 minutes (power 3 kW) heating of supply air taken through windows is normally not needed (or wanted).

Mostly the energy demand for that airing lies below the heat released from the classroom occupants. Only if the airing takes place under too long a period the airing might cause an extra heat demand. The energy demand for window airing can be seen in figure 8.12

The energy needed for window airing increases rapidly with the duration of airing and the difference between room temperature and outdoor temperature. Where window airing is used and the outdoor temperature is low, the airing time must be kept short in order not to waste energy. If the “class guardian“ is not committed to energy conservation, there is a risk that the windows will be left open for a longer time than necessary during the cold season. In this case a mechanical system with heat recovery and DCV could be a better solution.

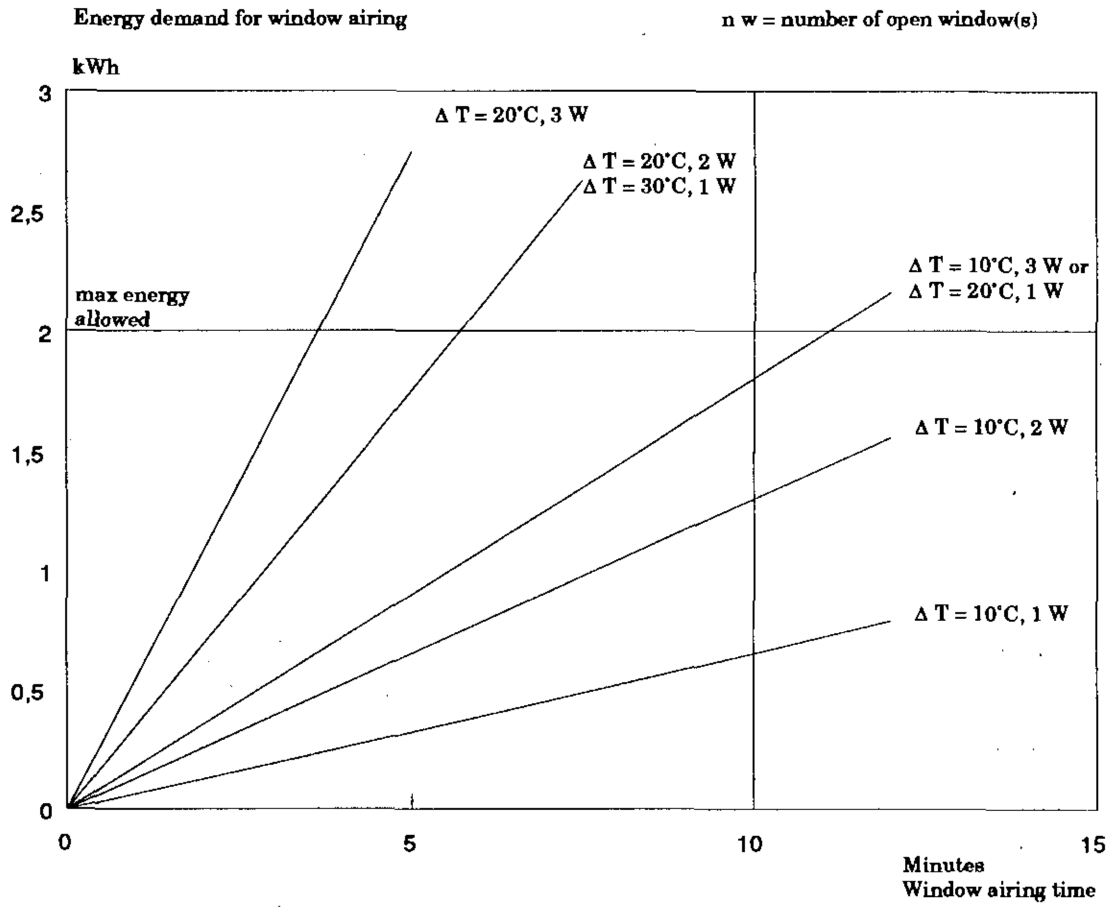


Figure 8.12. Energy demand for window airing as a function of airing time in minutes for various temperature differences and number of opened windows. Airing demand is shown in table 8.4. The breadth of one window is 1.0 m

Figure 8.12 shows that 10 minutes of airing is nearly always balanced by internal heat production. All airing time longer than 20 minutes during the heating season might cause larger energy demand than that of a mechanical system working with DCV and heat recovery.

A short calculation shows the effects of airing on energy demand, as shown in table 8.9. The table shows air flow rates and energy demand for a classroom with 30 pupils. The average temperature difference between indoor and outdoor air is 10°C. Room volume is 200 m^3. Maximum CO_2 concentration is 1200 ppm.

8.6.2 Comparison of Strategies

In a system built on the combination of mechanical ventilation and window airing caution must be given to limiting the window airing time to that necessary. As this time varies with the outdoor air tempera-

Table 8.9. Comparison between a fully mechanical system and a combination mechanical / window airing system

System solution		Air flow m^3/day	Energy kWh/day
Mechanical ventilation:	150 l/s 10 h/d (occupancy)	5400	18.0
	0.5 h^{-1} 14 h/d (base)	1400	4.7
	Total	6800	22.7
Mechanical ventilation:	100 l/s 10 h/d (occupancy)	3600	12.0
	0.5 h^{-1} 14 h/d (base)	1400	4.7
Window airing: 6 openings 10 min each gives 1.67 h^{-1} in 10 min		2000	(6.7)*
	Total	7000	16.7

* 30 pupils, 7 h/day in school produce about 14 kWh/day, which is enough for heating outdoor air from windows, even at low outdoor temperature.

ture the user must be able to judge by experience the time of window airing. This might be a problem, which may lead to the conclusion that in many cases a mechanical system only might be a better solution. A study of such solutions is given in Figure 8.13, where the

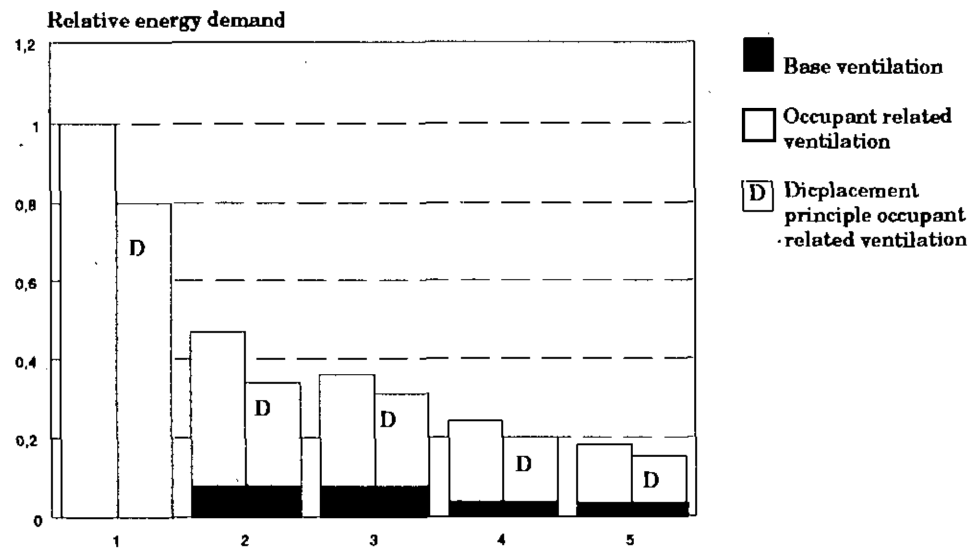


Figure 8.13. Effect of different ventilation strategies on energy demand for a classroom with 30 persons

Basic data used in figure 8.13 and table 8.10	
Room volume:	200 m3
Base rate ventilation	0.5 h^{-1} (100 m^3/h)
Number of persons:	30
Occupant related ventilation	10 l/(p.s), base rate included
Displacement ventilation function:	20 % reduction of occupant related flow rate

Table 8.10. Ventilation strategies used in figure 8.13

No	Strategy	Rel. demand
1.	Full flow 24 h/d, 10 l/(p.s) = 1080 m^3/h. Resulting energy demand:	1.0
2.	10 h/d full flow, 10/24·(1080-100) = 408 m^3/h 14 h/d base rate flow 0.5 h^{-1} = 100 m^3/h Resulting energy demand (time control):	0.38 0.09 0.47
3.	10 h/d school time, 1 h lunch break, 40 min lessons. 10 min breaks result in 7 h/d eff. occ. time 14h/d base rate flow, adequate mech vent Resulting energy demand (precense control):	 0.27 0.09 0.36
4.	As case 2 + 50 % heat recovery on base and occupant-related vent. Resulting energy demand (time control):	 0.24
5.	As case 3 + heat recovery. Resulting energy demand 0.36 · 0.5 (precense control):	 0.18

Note: 20 % of occupant related flow rate might be saved by using displacement ventilation

relative energy demand resulting from five ventilation strategies are shown. The strategies are defined in table 8.10 following the graph.

8.6.3 Dilution of Pollutants

The ventilation system should be allowed to run for a period of time before occupancy that is long enough to reduce the concentration of pollutants. This period of time can be calculated from the values given in table 8.10.

Necessary relative airing time is calculatedas a function of rise of CO_2 concentration, room volume per person, and air change rate during pauses. No one leaves the room during pauses and expires 18 l/p·h of CO_2. Note that infiltration through the building envelope can reduce the calculated necessary operating times of the mechanical ventilation system for the dilution of pollutants.

Table 8.10. Necessary relative airing time in percent of total time.

CO_2 increase	V = 10 m^3/p			V = 20 m^3/p		
	window opening gives the air change rate					
	5 h^{-1}	10 h^{-1}	20 h^{-1}	5 h^{-1}	10 h^{-1}	20 h^{-1}
1200	0.03	0.015	0.008	0.015	0.008	0.004
900	0.04	0.02	0.01	0.2	0.01	0.005
600	0.06	0.03	0.015	0.03	0.015	0.008
300	0.12	0.06	0.03	0.06	0.03	0.015
200	0.18	0.09	0.045	0.09	0.045	0.023

8.7 Recommendations

8.7.1 General

1. Base ventilation should operate when the classrooms are not used for lessons.
2. If mechanical DCV is used, a CO_2 sensor or a presence sensor is the best option.
3. Where mechanical DCV is not used, window ventilation is recommended during breaks.
4. An efficient forced ventilation system is recommended for classrooms in temperate latitudes.

8.7.2 Design

1. For a centralized mechanical system with locally adjustable air flow rate governed by sensor(s) in room, the governing system should be capable of giving balanced flow rates of supply and exhaust air.

2. For a centralized mechanical exhaust system and locally placed mechanical supply systems, all with locally adjustable flow rates governed by sensor(s) in room, the governing system should be capable of giving balanced flow rates of supply and exhaust air.

3. A centralized mechanical exhaust system may be used with locally placed booster fans, the latter with adjustable flow rate governed by sensor(s) in room or activated by user. Supply air is from openings in outer walls. Window airing is used during breaks. This type is equal to a domestic building system and may be used specially in day nurseries.

4. Locally placed supply and exhaust air unit placed on the floor in each room. Unit furnished with high efficiency heat recovery. The operation is governed by sensor(s) in room or activated by user. Governing system should be capable of giving balanced flow rates of supply and exhaust air. Window airing may be used during breaks.

5. Centralized mechanical exhaust system. Supply air from openings in outer walls. Window airing during breaks. An airing time schedule should be set up (and followed), in order to reduce the airing time as the outdoor temperature is getting lower.

The main function of a ventilating system for a classroom should be to keep the IAQ as high as to satisfy the occupants, which means to keep the concentration of contaminants at an acceptable level. In all normal cases there should be no need to adjust the outdoor air flow rate to a level necessary for a visitor to feel no smell at all when entering an occupied classroom.

Too high a temperature can be cured by opening windows, if the noise level outside does not cause unacceptable sound levels inside the room and the extra airing does not cause too much draught.

In mechanical supply air ventilation heating to 8°C below room air temperature is needed to prevent draught in a mixing system, 3°C in a displacement system. A displacement ventilation system can give a saving of about 20 % compared to a mixing ventilation system. When using a displacement system seats must be situated at such a distance (about 5 times the core equivelent/Eurovent/ of the air terminal device) from the supply air terminal device that cold air does not "pour" over the feet of the persons, ref. 3.

A heat recovery system should be designed to give good performance data, i.e. high energy recovery efficiency (50 % or more on enthalpy), good reliability and control possibilities, and low maintenance costs. Heat storage in the structure of a heavy building reduces air flow rate need for transporting heat to a level lower than that caused by CO_2 dissipation. The same stands for solar heat gain if solar shading is provided during actual time of insolation. Caution should be taken when buildings with a light structure are being used.

8.7.3 Operation

1. Exhaust ventilation running continuously on low rate.
2. System starts to operate at normal running conditions at signal from presence sensor.
3. Forced ventilation by window airing during breaks if mechanical ventilation system does not give adequate room air quality.

8.8 Checklist

The following points should be considered by the designer when considering a DCV system for a school or a day nursery:

1. Number and age of pupils
2. Time schedule for lessons
3. Occupancy and volume of room (to calculate pollutant accumulation)
4. Heat accumulation
5. Solar heat gain and necessary shading
6. Outdoor air temperature and humidity
7. Dissipation of volatile matter (room surface materials)
8. Air flow rate at operating and non-operating times
9. Entrance hall and corridor ventilation
10. Ventilation strategy
11. Ventilation system choice (supply Air Terminal Devices)
12. Control system choice
13. Operation and maintenance instructions
14. Economy: Investment and life cycle cost

9. Auditoriums

9.1 Purpose

This Chapter presents the experience gained from full-scale trials with ventilating systems in auditoriums. For purposes of this discussion, an auditorium is characterized by a heavy occupant load when fully occupied and includes assembly halls, lecture halls, churches, courtrooms, cinemas, theatres, and congress halls.

9.1.1 Auditorium Ventilation

Auditoriums are usually ventilated mechanically with balanced supply and exhaust systems. The ventilation principle is based on either complete mixing or displacement ventilation.

Complete mixing: One way to achieve complete mixing is to position diffusors in the ceiling and exhaust devices under the seats. In large spaces, jets for local recirculation may be added to help mix the air.

Displacement ventilation: Displacement ventilation is achieved by supplying outdoor air in the occupied zone, and extracting the exhaust air from the upper zone of the room. Air supply devices may be located under the seats, in front or at the back of the auditorium or along the sides. The supply air temperature is critical for this ventilation principle. A temperature that is two or three degrees below the room temperature is necessary to ensure a satisfactory air distribution.

9.1.2 Driving Pollutant

Inside an auditorium, pollutants are generated by the occupants, their activities, the building materials, the furnishing and the cleaning and maintenance products. In addition, outdoor pollutants enter the room through the ventilation system and via infiltration. Pollutants may also be generated in the ventilation plant.

Human occupants produce carbon dioxide, water vapour, particles, biological aerosols, odour, heat, and other pollutants. Building-generated pollutants are the result of out-gassing of flooring, painting, sealing wax, adhesives, and other building or furnishing materials. Acoustic ceilings and insulation may introduce mineral fibres. Micro-organisms and dust may originate from carpets and ventilation components.

Experience shows that when low or medium emission materials are used and there is an adequately constructed and maintained ventilation system, the dominant

Table 9.1. Ventilation rate based on subjective / objective IAQ response methods

Method	Fanger	ScanVac
Base vent. rate [m^3/h]	2620	2970
Max. vent. rate [m^3/h]	108301	1250

The subjective method in ref. 1 is based on a 20 % dissatisfaction rate. The objective method in ref. 2 is based on a medium/high emission rate from the building materials.

pollutants in an auditorium are generated by the occupants. Because auditoriums experience such wide fluctuations in occupancy, thermal comfort is a serious concern as well as other occupancy-related air pollutants. Selection of thermal comfort or indoor air quality (IAQ) as the chief design criterion must be evaluated in each case, bearing in mind that this will also be influenced by the ventilating principle that is chosen. In auditoriums, CO_2 is a good indicator of the air quality. An acceptable level of CO_2 ranges from 800 ppm to 1200 ppm.

9.1.3 Subjective IAQ Response versus Objective Data

Several methods for calculating the IAQ-related ventilation rate as a function of occupancy and selected building materials have lately been presented. A method has been developed based on the odour dissipation from human beings, building material, furnishing etc. ref. 1. Another method has been developed based on a material emitting coefficient, ref. 2.

These methods give approximately the same ventilation rate under the same conditions. They can be used to calculate both the base ventilation and the occupancy ventilation rate. A comparison of results of calculations of IAQ-related ventilation rate for both methods is provided in table 9.1. The calculations were carried out for an auditorium with a spatial volume of 1600 m^3, with a seating capacity of 320 students and a floor area of 340 m^2. The building construction is made of light concrete. The floor and front wall are covered with wood panelling. The surfaces are treated with paint and cellulose.

9.1.4 Other Pollutants

The humidity level may vary from 30-75 % RH without affecting the thermal sensation. Too high or too low humidity may however have implications regarding the comfort and health of the occupants.

Calculation of ventilation rate based on moisture production may be carried out with the dilution equation 9.1.

Equation 9.1

$dc/dq = -(E/q^2)$

where

dc	=	difference in concentration
dq	=	difference in air flow rate
E	=	emission kg/s
q	=	air flow rate m^3/s

Accumulation of humidity can be high on a short-term basis. Pollutant concentration can be reduced by raising the flow rate, and thus q^2.

Observations from full-scale trials with auditorium EL5 (Trondheim) have indicated that humidity may be used as an indicator for occupant loads. Humidity as an indicator of occupancy involves monitoring both the internal and supplied air, since the water vapour content in the outdoor air may vary considerably (2-10 g/kg).

9.1.5 Comfort

In an auditorium that is filled at or near its capacity, thermal comfort becomes a cause for concern more quickly than odour. At such times the system is working at its design maximum and is the platform from which any DCV savings can be made when the auditorium is less than fully occupied.

Thermal comfort may be the main criterion in the design of a ventilation system. The room temperature is influenced by the internal heat load, the ventilation rate and the boundary conditions (building construction and surrounding climate). If the room temperature exceeds the acceptable level, heat must be removed either by the ventilation system, or by activating a local cooling unit.

Using the ventilation system to remove heat requires calculations of the ventilation rate based on minimum air supply temperature, building mass, surrounding climate, quantity and duration of the heat load. Several commercially available computer applications will handle such calculations.

Table 9.2 shows calculations of the thermal comfort related ventilation rate as a function of fully-occupied lessons in the Trondheim auditorium EL5 throughout a day. The maximum room temperature is set at 22°C, and the supply air temperature is set at 19°C. The construction is made of light concrete. Heat transfer to the surroundings is neglected (summer time). Lessons are 45 minutes with 15-minute breaks.

Table 9.2. Thermal comfort related ventilation rate, auditorium EL5.

	1 lesson	3 lessons	5 lessons	7 lessons
Vent. rate	12300 m^3/h	18000 m^3/h	21000 m^3/h	23500 m^3/h

A ventilation rate of 12300 m^3/h throughout the day causes the room temperature to rise to 24°C at the end of 7th lesson. Steady state conditions achieve a temperature of 27°C.

9.2 Control Strategy

DCV systems for auditoriums should be designed with a base ventilation rate designed to control pollutants from building material and furnishing, and an occupancy ventilation rate to control pollutants generated by occupants and their activities. A clock relay (on/off) can control the day/night running.

It is important that the control strategy is arranged so the ventilation rate always covers the most conservative condition. For instance, the controlling parameter may be IAQ during the cold season and thermal comfort during the summer months.

In practical terms this means that we may need a controller algorithm using both temperature and IAQ (CO_2) as input, controlling the ventilation rate based on the parameter that is most critical.

Two basic principles may be used to control the temperature and air quality inside an auditorium:

* Return air
* Variable air flow

When using the return air principle, this means changing the ratio of outdoor/exhaust air in the supply duct. The ventilation rate becomes invariable, with a fixed energy consumption for running the fans.

Variable air flow is established by installing variable speed-controlled fans, multi-speed fans, throttling dampers or by on/off running. All these methods have the same common factor that the energy consumption used for running the fans becomes a function of the air flow rate.

Displacement ventilation is based on low impulse injection of the supply air. Decreasing the ventilation rate therefore does not affect the air flow pattern inside the auditorium. Combining displacement ventilation and variable air flow rate in a DCV system is therefore a good solution. Variable air flow in combination with diffusors is not a good solution, unless the diffusors are matched for the variable air flow rate.

9.2.1 System Regulating Ability

The controlling complexity (Kt) for a system is given by the lags, delays, time constant and gain factors, and may be defined by equation 9.2

Equation 9.2

$Kt = Ks \cdot Tu / Tg$

where:

Ks is the gain factor

Tu is the lags and delays

Tg the time constant.

In a DCV system, delays are caused by the air flow pattern inside the room and by the transportation of air through the ducts. The time constant is given by the room volume, but is also affected by the air flow pattern. The gain factor is related to the ventilation rate and the CO_2 dissipation from the occupants. The air flow pattern is again affected by the ventilation principle, the number of students, the seating pattern, the boundary conditions and the room geometry.

Simplifying the system we may describe it by the equations 9.3 and 9.4.

Equation 9.3

$V(ap)\, dc/dt = q(c_i - c) + P(n) \cdot 10^6$

Equation 9.4

$y = c\,[\tau - (ap,ld)]$

where:

V(ap):	room volume	[m^3]
P(n):	CO_2 production	[m^3/h]
q:	ventilation rate	[m^3/h]
t:	time	[h]
n:	number of occupants	
τ:	time delay	[h]
y:	measured CO2	[ppm]
ap:	air flow pattern	
ci:	CO_2 conc. - supply air	[ppm]
ld:	duct length	

This system may contain three essential nonlinearities: the time delay (τ), the accumulation volume (V) and the control variable (q).

Ventilation by displacement may show significant variations in the time delay and the time constant. This makes it difficult to find a controller structure that will be stable when Tu/Tg is large, and fast enough when Tu/Tg is smaller. For the EL5 auditorium we have used a PID controller tuned to be stable at 50 % occupancy, and accepting some slower response when fully occupied. Occupancy below 33 % is covered by the base ventilation rate.

If complete is assumed, the accumulation volume equals the room volume and the time delay through the room will be small and almost constant. The controller complexity is not to difficult, and the system may be handled by a P or PI controller.

9.3. Ventilation strategy

A DCV system for auditoriums requires a mechanical ventilation system with balanced supply and exhaust. A system with a number of ventilation plants with common exhaust air or outdoor air louvres is not recommended. Separate louvres will avoid interaction between the plants which may lead to unwanted control characteristics.

The HVAC controlling functions, including DCV operations, may be handled by a centralized control system based on Distributed Data Computer (DDC) technic or by local equipment based on analog controllers.

If the ventilation system is shut down during the night or weekend, it is important that the auditorium be pre-ventilated before occupation. Accumulated building pollutants may be removed by activating the ventilation system some time before the occupants arrive. An air change of 6-7 should clean up the room.

The ventilation principle may be based on complete mixing or displacement. It is important to stress that short circuiting between air supply devices and exhaust devices inside the room must be kept to a minimum. This is taken care of through careful design.

9.3.1 Air Flow Pattern

Auditorium design varies considerably in terms of seating levels and room proportion. Some auditoriums are terraced, others are designed with all seats on the same level. Computational Fluid Dynamics (CFD) calculations and measurements have shown that the air flow pattern is affected by several factors. Among these are room design, capacity and location of heat source, aspects of building materials and construction, furnishing and ventilation principle. Figure 9.1 compares the air flow patterns for ventilation systems based on complete mixing and displacement. The calculations are computed with the KAMELEON computer application.

Both IAQ and thermal comfort may be used as controlling parameters for the ventilation rate. If displacement ventilation is used, this will affect the ventilation rate. The goal of this ventilation principle is to make a "clean" occupied zone by displacing the pollutants from the lower to the upper zone.

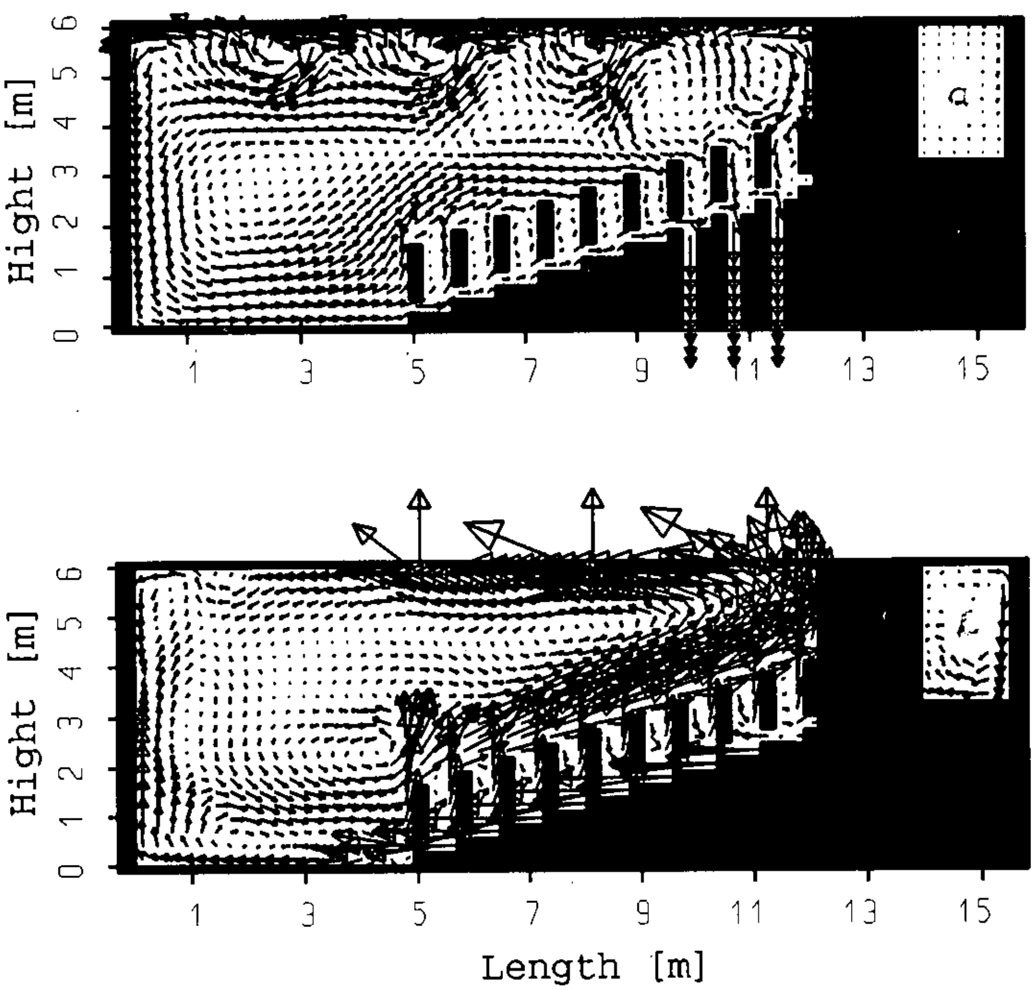


Figure 9.1. CFD calculations of air flow patterns in an auditorium: (a) complete mixing (b) displacement

The height of the lower clean zone is a function of the ventilation rate and the heat gain. Several equations given in ref. 3 may be used in these calculations.

A height of 1 m from top of the head to the upper zone requires a ventilation rate of 90 m^3/hp for a standing person. Locating the upper zone just above the head requires a ventilation rate of 50 m^3/hp.

9.4 System Description

Several DCV system configurations are possible by combining different ventilation principles with methods of varying the amount of outdoor air. Adding other cost effective energy saving measures results in even more combinations. This section will not go into detail with all these configurations, but some basic principle will be described.

It is important that the heating system covering the transmission losses and the ventilation system function separately. A system using the ventilation air for heating is not suitable for demand-controlled ventilation.

9.4.1 Variable Air Flow

System 1: Variable speed-controlled ventilating rate. Figure 9.2 shows a DCV system with variable air flow. The ventilation principle is based on displacement ventilation. Using the signals from the sensors located in the exhaust air, the controller sets the rpm of the fans via a frequency converter. A separate controller (not shown) takes care of the heating supply the heat exchanger. The supply air temperature is fixed,

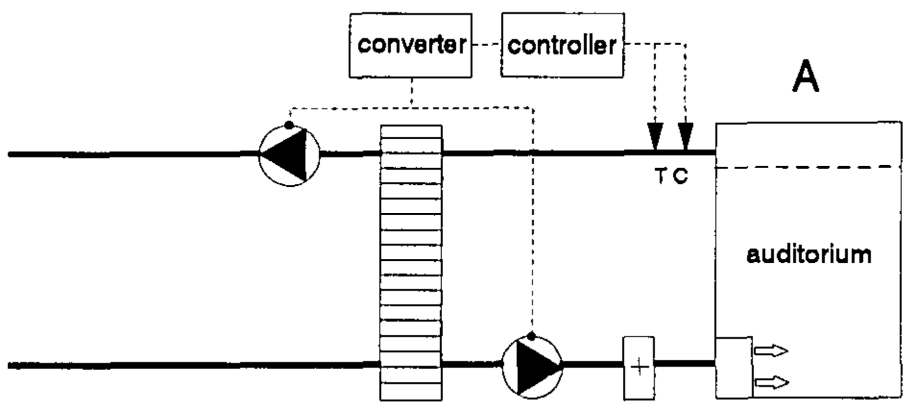


Figure 9.2. DCV system with variable speed-controlled fans.

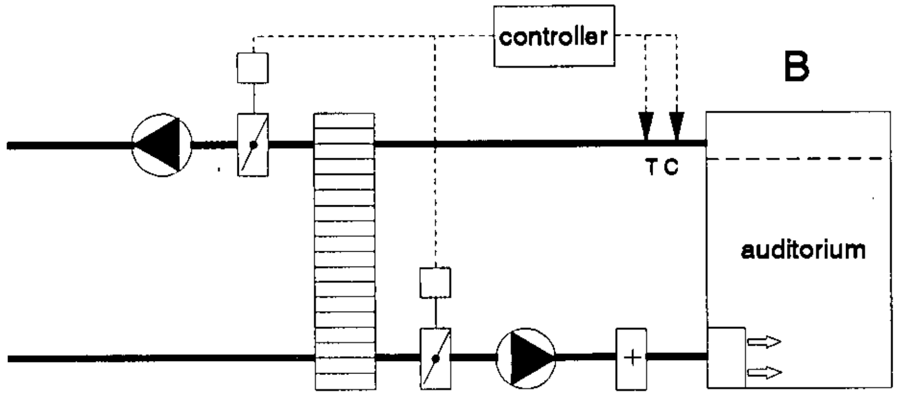


Figure 9.3. DCV system with throttling dampers.

and the heating coil and the heat exchanger are operated in sequence.

System 2: Damper-Controlled Ventilation Rate Figure 9.3 is similar to figure 9.2, but now the ventilation rate is controlled by throttling dampers.

9.4.2 Return Air

System 3: Ventilation Rate Controlled by Return Air Figure 9.4 shows a DCV system based on return air. The auditorium is ventilated by complete mixing. The damper position is set by the controller via an actuator. The DCV sensors are located in the exhaust air. The heating coil and the heat exchanger are handled by a separate controller (not shown), and operated in sequences. The supply air temperature may be fixed, or out-door compensated for cooling purposes.

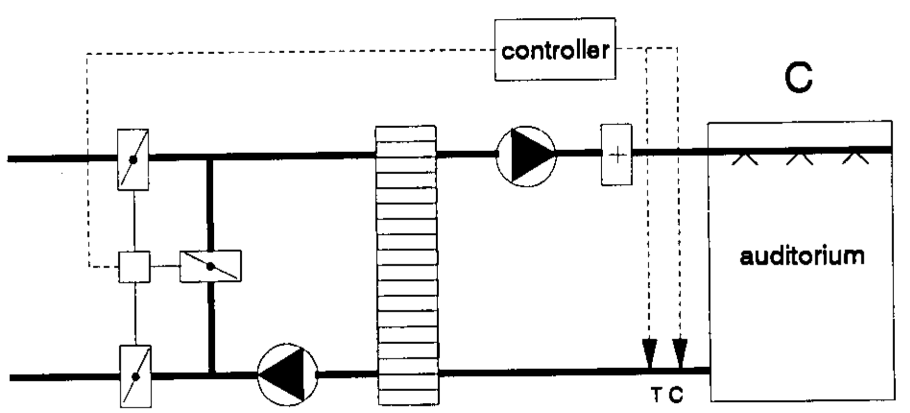


Figure 9.4. DCV system with return air

9.5 Sensor Type and Location

Several studies have shown that CO_2 dissipation from human beings can provide a good indication of body odour and occupancy. Since the outdoor concentration of CO_2 is almost constant (350 - 400 ppm), there is no need for outdoor measurements. One sensor inside the room or in the exhaust duct should be sufficient.

Using humidity as an indicator of occupancy involves a recording of absolute humidity both in exhaust and supply air, since the outdoor conditions of the air may vary a lot.

Temperature sensors are used to control the thermal comfort. The sensing principle may be interlocked with the IAQ sensing principle. The air flow pattern in an auditorium may be very complex and affected by several factors. Those of importance are room geometry, strength and location of heat source, furnishing, aspects of building material and construction, ventilation principle, supply air temperature, leakages and the surrounding climate.

Observations of the air flow pattern from full scale trials with displacement ventilation, have revealed zones with stratification, zones that are completely mixed and poor ventilated zones. Where these zones occur depend on occupancy and seating pattern.

Recommendations concerning sensor location are therefore difficult. A particular sensor location inside the auditorium may cover some situations but not all. Since the concentration in the exhaust equals the one we get with complete mixing, we recommend that the sensor is located in the exhaust duct. This location would give a good indication of occupancy, but will not cover poorly ventilated zones.

Using a ventilation principle that completely mixes air in the room should be easier to handle. The concentration level of pollutants inside the room should be uniform. Thus the sensor may be located arbitrarily in the room or in the exhaust duct, a location next to the pollutant source must be avoided.

9.6 Performance

Before installing a DCV system, the room and the ventilation plant should be examined by tracer gas to reveal possible leakages. Any short circuiting of significance must be reduced to a minimum. Short circuiting may occur inside the auditorium between the supply and exhaust devices, and outside the building if the supply and exhaust louvres are located too close and in the ventilation plant. Short circuiting via components in the ventilation plant may occur if sufficient care has not been taken in the design or commissioning.

Figure 9.5 gives an example of configurations that will cause short circuiting and poor controllability.

The reason for this short circuiting is that the fans are positioned in a

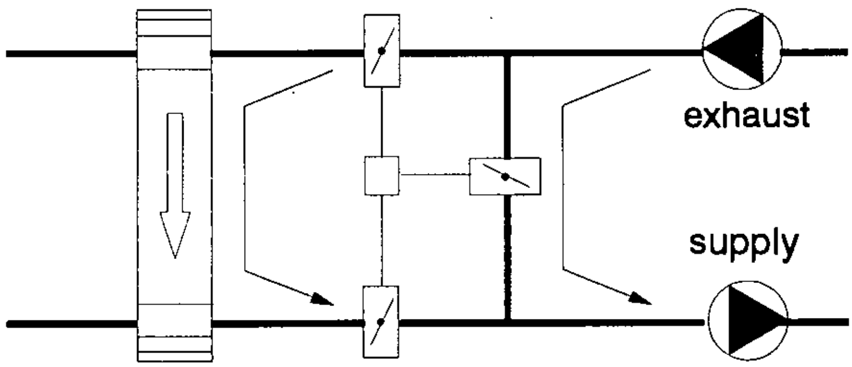


Figure 9.5. Configurations that will result in short circuiting.

way that pressurize the exhaust side, while creating a negative pressure in the supply side.

9.6.1 Energy Savings

Energy savings related to DCV systems are closely connected to variations in the occupancy load. Greatest savings are achieved when the seating capacity is moderately used.

However significant savings related to the DCV system also depend on the effect of other energy saving measures like for instance a heating pump or a heat exchanger installation. How the combination of a DCV system and a heating recovery unit affect the energy consumption for heating the ventilation air is presented in figure 9.6.

Computer simulations have been made of the auditorium EL5 at the Norwegian Institute of Technology. The auditorium is ventilated by displacement ventilation, and the DCV system is based on variable air flow. More information about the auditorium is given in the volume on case studies.

The calculations were based on two different heat exchanger efficiencies and two different load situations. They are presented as functions of the outdoor temperature.

As we can see from figure 9.6, the savings are about 2.5 times greater if the heat exchanger efficiency is 50 % instead of 80 %. It is also evident that the profitability for a DCV system is greatest when the climate is cold.

Another parameter that affects the savings is the threshold value for acceptable IAQ. Energy savings as a function of acceptable carbon dioxide concentration is shown in figure 9.7 and 9.8. Figure 9.7 shows results from computer simulations of auditorium EL5, while figure 9.8

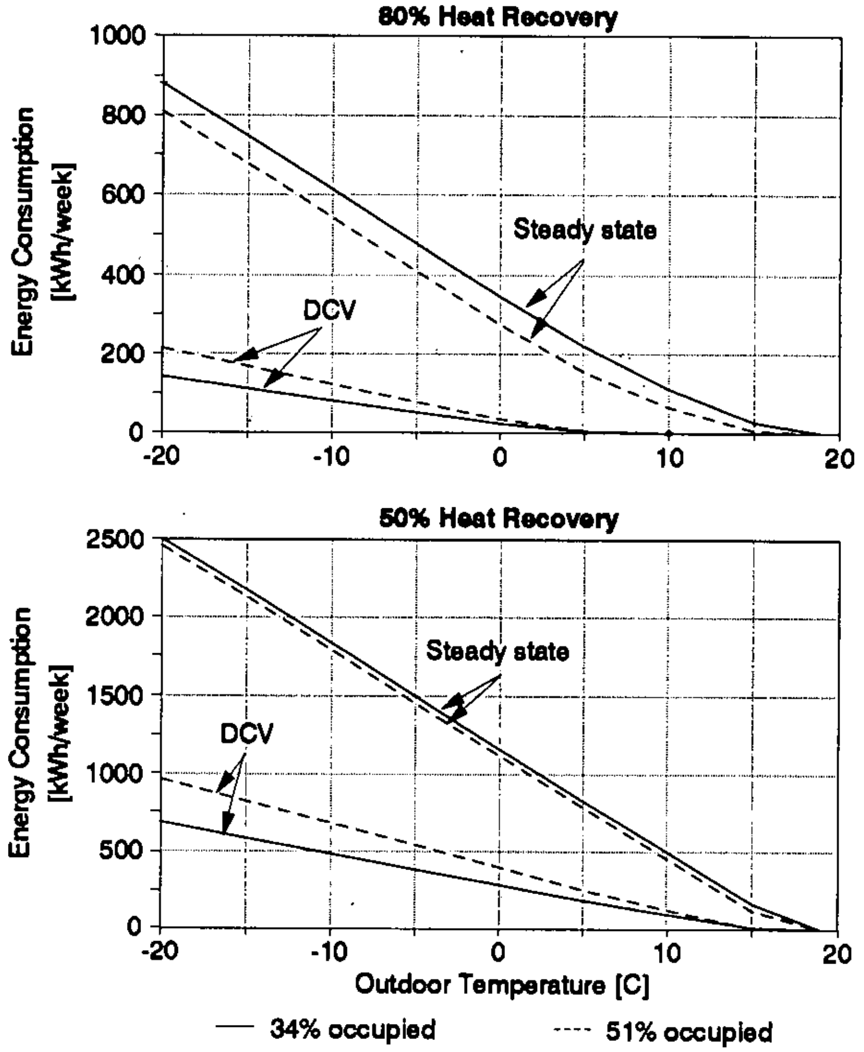


Figure 9.6. Energy consumption as a function of heat exchanger efficiency, outdoor temperature and occupancy.

shows the results from a computer simulation of the HG D auditorium at the Swiss Federal Institute of Technology (for more information see the volume on case studies).

There are two different philosophies behind these diagrams. Each DCV simulation of the EL5 auditorium was compared to a steadily operating system designed to keep the CO_2 level at the specific reference when the auditorium is fully occupied. This means that the plant capacity is reduced when the threshold value for IAQ is made more liberal. As figure 9.7 shows, the energy savings decrease when the CO_2 set point is increased.

The DCV simulations of the HG D auditorium are compared with a steady state system of constant capacity capable of handling the most conservative situation. In this case the savings are increased when the CO_2 set point is raised.

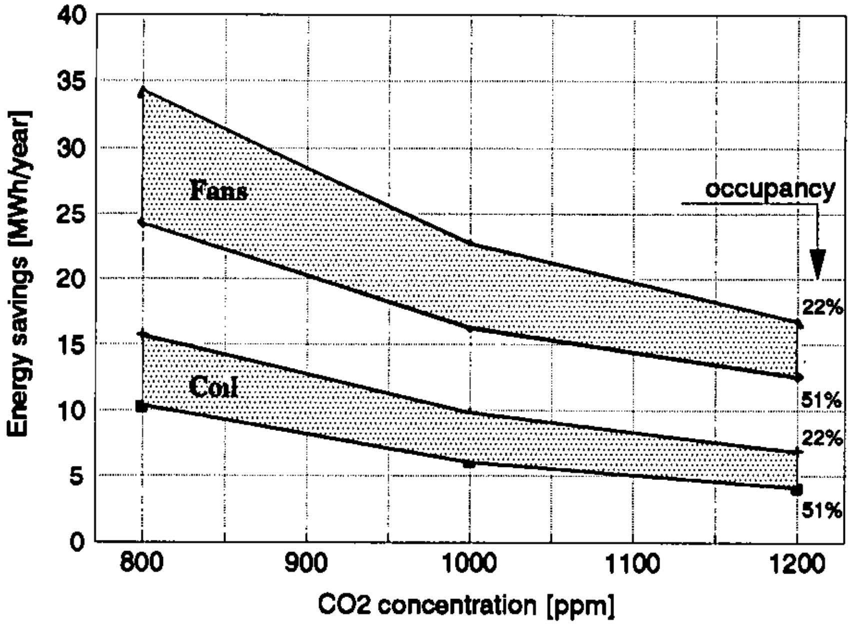


Figure 9.7. Energy savings in the auditorium EL5

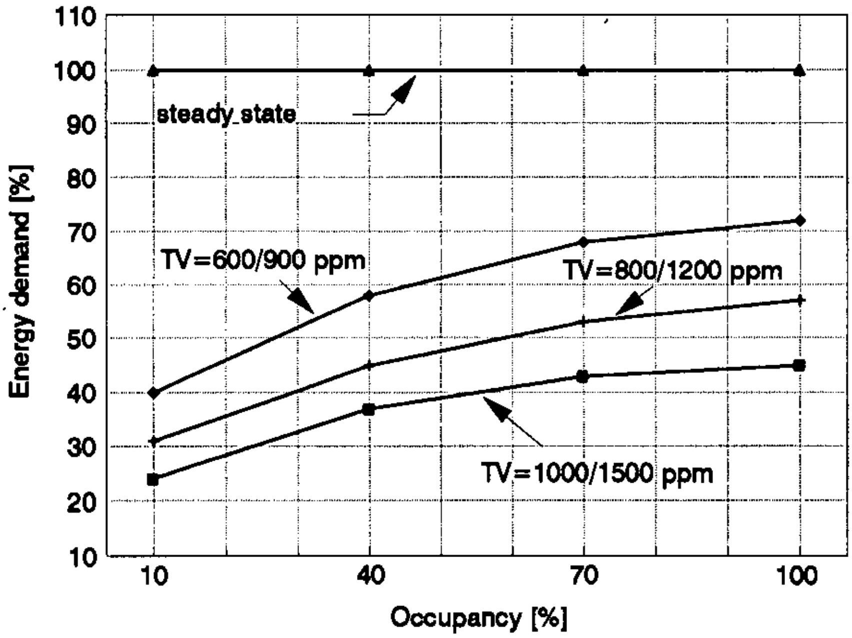


Figure 9.8. Energy savings in the auditorium HG D. TV=Threshold value

9.7 Recommendations

1. The DCV system for auditoriums should be designed with a basic ventilation rate covering pollutants from the building material, and an occupancy dependent ventilation rate. A clock relay should control the day/night running.

2. The control strategy must cover both IAQ and the thermal comfort aspect.

3. The indicator for air quality is to be CO_2, the indicator for thermal comfort is to be temperature.

4. Sensor(s) should be located in or near the exhaust device(s).

5. In cases where time schedule is known and the occupancy load is fixed, a clock relay may be used to operate the DCV system.

6. A system using displacement ventilation is preferred because it gives better control of the air flow pattern inside the room. A displacement ventilating system could be implemented by using:
   * a few large supply devices located in front, at the back or along the sides of the auditorium
   * small devices under or in combination with the seats

7. In new or refurbished auditoriums the ventilation should be run continuously for a period of time until the emittence form building materials and surface coatings has reached steady state conditions.

8. The design must prevent short circuiting in the ventilation plant, inside the room and at the louvres. Possible leakages and short circuiting can be indicated by use of tracer gas techniques.

9. Tests are normally necessary

9.8 Checklist

1. Emissions from the building fabric should be low enough to be diluted by base ventilation, to get a fresh first impression.

2. Time schedule should be variable.

3. Occupancy density should be highly unpredictable.

4. Ventilation principles should be examined.

5. Location of terminal devices must be determined.

10. Offices and Office Buildings

10.1 Purpose

This chapter discusses the suitability of DCV systems for office buildings and for specific enclosed areas within business premises such as meeting rooms, boardrooms or classrooms. For entire buildings, the discussion is applicable only if mechanical ventilation is present and the outdoor air ventilation rate is variable. For enclosed interior areas, the discussion applies only if the occupancy is highly variable.

10.2 Driving Pollutant

The driving pollutant of sensor governed demand controlled ventilating systems in offices is normally carbon dioxide, which serves to indicate the number of occupants. Standard practice is to vary ventilation in office buildings according to occupancy. It is assumed by most ventilation standards that odours and other pollutants that are associated with normal office activities will be controlled satisfactorily in this way.

10.3 Ventilation Strategy

In general, the ventilation strategy will follow the principles illustrated in Chapter 5, *Control Principles*. It is assumed that the enclosed rooms or small areas draw their ventilation air from the building's central systems. If they have their own outdoor air ventilation systems, then the chapter on auditoriums would be more applicable. The building ventilation system need not be demand-controlled in order that individual rooms be so equipped. The minimum or base ventilation rate required to meet code requirements, provide thermal control and to control continuous-source pollutants must be lower than the ventilation rate required to control CO_2 levels. In the case of existing buildings, it should also be verified that the systems are capable of being reduced to the desired outdoor air ventilation rate. If the dampers are leaky this may not be possible.

10.3.1 "Free Cooling Cycles"

In order to provide controlled ventilation for the building as a whole, the building ventilation system must be designed to provide a variable outdoor air rate. This is usually associated with a "free cooling" or "economizer" cycle. In such a building, the outdoor air rate varies according to the enthalpy of the outdoor air. The minimum desired outdoor air rate is usually reached only during hot, humid or very cold

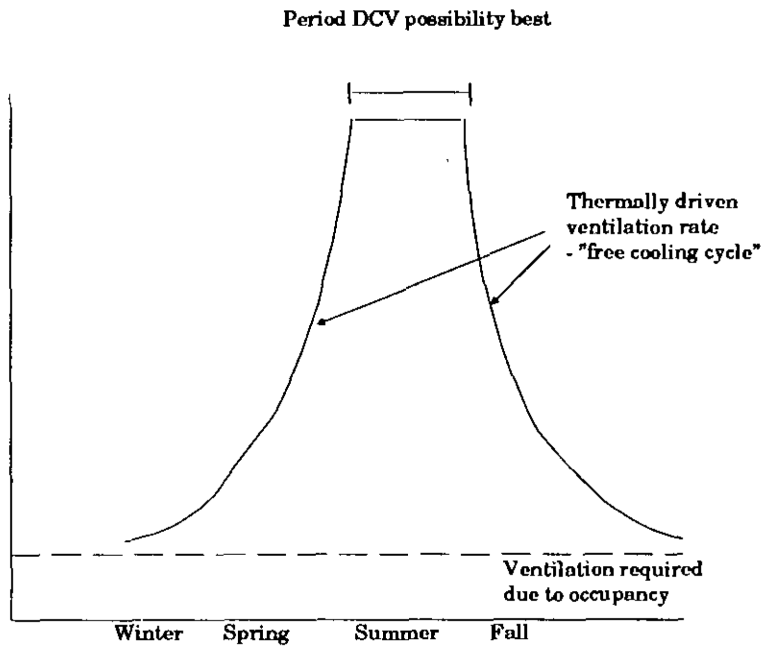


Figure 10.1. Seasonal ventilation rate with economizer cycle

weather. As shown in figure 10.1, it is often only during these periods of the year that DCV and its associated energy savings are possible. "Free cooling" ventilation requirements must be given precedence. Otherwise energy consumption will be needlessly increased.

10.3.2 Air Leakage

At first glance, it might seem that a DCV system is not feasible in a leaky building and would not result in any benefits. This is not the case.

The mechanical ventilation strategy for a leaky building often assumes that little or no leakage is present. Even under weather conditions where considerable leakage is present, the outdoor air ventilation usually continues at full flow. If the CO_2 levels are measured, then at times it may even be possible to turn the outdoor air component off entirely.

Note that in a tall building that is kept pressurized using the ventilation systems, it may not be possible to reduce the outdoor air rates to the extent desired. Of course, the energy efficient solution in this case is to repair the leakage. This will also help preserve the building envelope.

10.3.3Other Pollutants

In some buildings, especially new or refurbished buildings where outgassing from new materials is a major source of pollutants, the base rate of ventilation required to purge these continuous-source pollutants may at most times exceed that required to remove human generated contaminants. The case will be similar for buildings with a low occupancy. Table 5.1 in chapter 5 shows that the base ventilation rate required to purge building-generated odours may exceed ventilation required to purge occupancy-driven odours.

In order to apply a DCV system for efficient control of a whole building, it must first be ensured that as many non-ocupancy related sources are removed as possible.

In the case of enclosed meeting rooms, the population density and hence human generated odour per square meter, would normally be much higher than illustrated in table 5.1 when fully occupied. The building need not be so clean for DCV to become a practical alternative.

10.4 Subjective Response versus Objective Data

No subjective data is available concerning control of office buildings as a whole. In a study conducted in a boardroom, subjective response data, although very limited, suggests that people prefer a CO_2-controlled system to other ventilation strategies such as manual control, continuously running supplemental ventilation and presence detectors. It must be cautioned, however, that this preference was noted under clearly experimental conditions and may be short-lived.

In theory, a manual DCV system should also have beneficial effects regarding the occupant's perception of indoor air quality (IAQ). Where occupants have control over almost any aspect of their environment, they will often perceive it as being better.

10.5 Comfort

Care must be taken that thermal control is not compromised when designing a CO_2 controlled DCV system. Although this is not usually a problem in whole building control, it may be more difficult in the case of a boardroom.

Solutions are possible, and are dependent on the specific ventilation system used. For example, when controlling a boardroom, it may be as simple as satisfying CO_2 control requirements by drawing upon thermally neutral return air from another area, leaving temperature to be controlled by other more conventional systems such as one with variable air flow rate.

10.6 Energy Savings

In theory, by ensuring that supplemental ventilation is present only when required, energy savings will result. In practice, the extent of savings will determined by the degree to which occupant-driven ventilation exceeds the base ventilation rate.

In general, potential energy savings are greatest under the following conditions:

* More extreme climate
* Smaller buildings
* Variable occupancy
* Inefficient ventilation system

The extent of savings varies from none to 30 % of the ventilation energy. Each case must be analysed separately, using a computer simulation if possible.

For a DCV system in a small enclosed area, the energy savings will be small. In one example, using a CO_2-controlled system, savings were found to be in the order of 300 to 500 kWh per year in a small meeting room of 15 m^2. In contrast, an occupant-controlled system was not as energy efficient, but was certainly much less costly to install.

10.7 Control Strategies

10.7.1 Meeting Rooms and Small Offices

For small areas within a larger building, the energy savings available with DCV control are small. The approach must therefore be kept simple and inexpensive, both for initial installation and for periodic maintenance and calibration.

For small interior areas, a simple off-on controller regulating a supplementary supply or exhaust fan may be optimum. Of course, more sophisticated control is possible, but more difficult to justify on economic grounds. At its simplest, the system may draw additional air from other rooms when CO_2 levels rise. The controller may be CO_2 sensor-driven or may be as simple as an on-off switch controlled directly by the room occupants.

10.7.2 Whole Building Control - Automatic

For the control of the whole building, a computerized controller would normally be used. This can react either to peak levels or to a combination of the current level and the rate of rise and fall of CO_2. The latter approach is preferable if predictor algorithms are used since discomfort levels of CO_2 would occur less frequently. As a spinoff benefit, records may be kept of the CO_2 levels attained from which the ventilation rate per person may be estimated. This also provides proof that code requirements were met.

10.7.3 Whole Building Control - Manual

Manual DCV systems for whole buildings does not mean that the building as a whole would be controlled manually. Portable instruments would be used to monitor CO_2 levels over a period of time and then using the data generated, the building's minimum ventilation rate would be reset. This could be achieved by physically adjusting dampers or by changing minimum settings using the building's computerized control system.

This approach is appropriate in buildings where the occupancy is constant or where it is desired only to monitor ventilation rates. It allows the operator to ensure that the building is neither overventilated nor underventilated and will allow adaptation of the ventilation systems to occasional occupancy fluctuations. Depending on sensor location, this approach may also be used to ensure occupant satisfaction in key areas.

10.8 Sensors and Sensor Location

There is no special requirement for sensor type except that it be robust, sufficiently accurate and not require frequent recalibration.

For control of a single area within a building, the sensor should be located in the area's exhaust. This approach allows the sensor to be physically protected and to sample how the room is performing as a whole. Care must be taken to ensure that there is not significant short circuiting between ventilation supply and exhaust, however, as this would give false readings. For the same reason, sensors should not be located too close to occupants.

For control of the whole building, the sensor would usually be located in the building's exhaust. In this manner, the building's ventilation system is used as a sampling network. If the ventilation system is poorly balanced, however, this approach may lead to problems. It is also possible (but usually less practical) to locate the sensor in a key "worst case" location.

10.9 Quality and Risk

DCV systems may be used to ensure that the building as a whole or areas within the building are neither underventilated nor overventilated compared to code requirements; and when the dominant ventilation requirement is related to occupancy.

Concerning whole office buildings, when compared to the other costs associated with computerized ventilation control systems, additional costs will be small. The DCV system will periodically require recalibration and maintenance. It should be possible to design the system so that in the event of failure, it does so safely.

Concerning the control of boardrooms, failure of an automatic DCV control system would likely result in underventilation. Discomfort and complaints would likely follow. If a reasonable minimum base ventilation rate is provided, however, no safety hazard would be likely to result.

In the case of an occupant-controlled supplemental ventilation system in a boardroom, there is little to fail. One assumes that discomfort will drive the occupants to energize the system before the situation becomes too serious. The effects of failure would be similar to failure of the automatic system.

10.10 Conclusions

CO_2-driven DCV systems are technically feasible for office buildings and enclosed meeting rooms within conventionally ventilated buildings. In many buildings, they may not be cost effective. In buildings with an existing computerized energy monitoring and control system, the addition of such a system may not be costly and, at the least, will serve as a warning when under or overventilation exists and will provide a proof that code and other occupancy-related ventilation requirements were met.

10.11 Recommendations

10.11.1 Meeting Rooms

Until the costs of automatic DCV technology are substantially reduced, other less costly alternatives will prove more attractive. Except for very special applications such as courtrooms and other very large areas with highly variable occupancy, the use of sensor governed DCV systems is currently not recommended on economic grounds.

Occupant-controlled DCV systems are recommended for small high-occupancy areas such as boardrooms or waiting rooms. These systems will not result in significant energy savings, but better occupant comfort is likely to follow.

10.11.2 Office Buildings

The use of CO_2 monitoring systems is recommended on the grounds that it provides an indirect record of ventilation rates compared to occupancy. In this fashion, the ventilation rate can be confirmed to exceed code requirements and to be not unduly high. In most office buildings where the occupancy is stable, this will be sufficient.

In buildings where the occupancy-related pollution ventilation requirement is dominant and unpredictably variable, DCV systems should be considered. Energy analyses should first be conducted to ensure that theoretically, there can be significant savings. If the building already exists, it should be carefully inspected to ensure that the ventilation systems are capable of being controlled in the manner desired.

10.12 Checklist

In order for sensor-driven DCV energy savings to be significant for overall control of a large building, several conditions must exist:

* Outdoor air rates must be variable
* Occupancy must be unpredictably variable
* The supply air must be either heated or cooled for a very significant portion of the year
* The density of occupancy in the controlled areas must be high and the emissions from other sources must be low

11 Operation and Maintenance

11.1 Purpose

This chapter discusses the operation and maintenance (O&M) considerations for DCV systems. It is assumed that the reader is familiar with general O&M principles, which are mentioned only briefly. Factors pertaining specifically to DCV systems are examined in more depth.

11.2 Operation and Maintenance Strategies

In general, the goal of any O&M program should be to reduce the operation and maintenance costs and to minimize the life cycle cost of the building.

With regard to DCV systems, the strategy to achieve that goal will entail:

* Operation of the building systems in a manner that will help maintain good room air conditions

* Ensuring that the rate of air changes is sufficient to satisfy indoor air quality (IAQ) requirements and occupant comfort

* Monitoring the use of heating and cooling systems in the interests of energy savings

Maintenance of DCV systems should be based on a time and functionability schedule in order not to let room air quality and energy demand diverge more than a certain amount from the ideal level.

Many DCV systems are to be designed so as to facilitate user-controlled operation.

11.3 Balancing

For any system, balancing is essential for serving all parts of a building with the required indoor air temperature and air flow rate. Balancing a DCV system is accomplished by testing not only constant flow rate operation but also operation under conditions where the flow rate has to be varied due to load from people, solar heat gain, and installed equipment.

Special interest should be devoted to the operational properties of the control and supervision systems which are an almost necessary part of any modern large ventilation system.

11.4 Quality assurance

The following definitions are taken from ISO 8402-1986:

Quality: The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.

Quality assurance: All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality.

Quality control: The operational techniques and activities that are used to fulfil requirements for quality. The following remarks given in ISO 8402-1986 also apply:

"The term quality is not used to express a degree of excellence in a comparative sense, nor is it used in a quantitative sense for technical evaluations. In these cases a qualifying adjective shall be used. For example, use can be made of the following terms:

a) Relative quality

b) Quality level and Quality measure"

O&M procedures for DCV systems should include measures for verification of system performance regarding its ability to produce and maintain an acceptable to good IAQ level and an acceptable indoor climate. The measurement of air quality should include the following:

* Air quality at the time of final inspection
* Air quality during commissioning tests
* Air quality during normal and extreme operating conditions. Special attention must be given to the necessary period for outgassing of building materials and furnishings
* Room air velocities
* Ventilation effectiveness
* Effectiveness of energy conservation measures
* Stability of the control system
* Clarity and accuracy of instructions
* Maintainability of components

11.5 Commissioning

Handing over a building to its operational staff calls for very careful information and instruction on systems and products used and on their proper operation and maintenance. No system should be handed over without manuals for operation and maintenance. This is particularly true for a DCV system.

11.6 Operational Routines

Any operation with a quality aspect demands regular routines to ensure that the system is consistently meeting stated requirements. It is the duty of the O&M staff to create the necessary individual routines for the operation of the building and its installations. This is especially true for DCV systems.

11.7 Inspection Routines

11.7.1 Final Inspection and Commissioning

Final inspection should follow general routines for the inspection of ventilation and air conditioning plants. It should also include special checks with regard to DCV functions and their way of operation, compared to general functional requests and specifications in the contract.

11.7.2 Regular Routine Inspections by the Operator

Special routines with regard to DCV systems in the building should be included in the operator's instructions.

11.7.3 Periodical Audit of Energy Conservation and Function

In many countries a periodic audit function (each year or each second year) is discussed. This has its roots in operational problems causing so-called sick buildings, where ventilation with too low flow rates often is one of the essential factors. Even if this audit function is not compulsory it is highly recommended. A check of the system by a competent and experienced person from outside the owner's personnel is a valuable instrument for accruing knowledge, preventing damage, and controlling operational costs. This holds true especially for DCV systems where the installation is often made as a result of profitability calculations.

Table 11.1 Maintenance intervals for DCV equipment

Measure	Interval, months
Calibration of sensors:	
VOC	6
RH,	12
CO_2 RH for domestic use	18
Replacement of VOC sensors	36
Calibration of control unit	36
Check of electrical and mechanical components	12
Cleaning components	3

11.8 Maintenance and Renewal Routines

The importance of maintenance can never be overemphasized. This stands for both the building and its installations. For DCV equipment especially, the system and its components must be chosen and installed so that function can be checked and cleaning, maintenance and so on be carried out. A stable function is very much dependant on the

Table 11.2 Expected life time and maintenance cost for different types of installations in buildings

Component	Life span (years)	Annual Maintenance Cost, % of investment
Air conditioning units	15	4
Air heaters, water	20	2
Air heaters, steam	20	2
Air heaters, electric	15	2
Air coolers	20	2
Burners, oil and gas	10	4
Condensers	20	2
Control equipment	15	4
Cooling compressors	15	4
Dampers	20	1
Dampers with control motor	15	4
Diffusers	20	4
Dual duct boxes	15	4
Duct system	30	1
Evaporators	20	2
Exhaust air grilles	20	4
Expansion vessels,		
steel	15	2
stainless	30	1
copper	30	1
Fans	20	4
Fans with variable flow	15	6
Fan coil units	15	4
Filter frames	15	4
Filter, cleaned	10	10
exchanged	1	10
Grilles	30	1
Heat exchangers, static	15	4
rotary	10	4
Heat pumps	15	4
Humidifiers, water	10	6
steam	10	4
Motors, electric	20	1
diesel	10	4
Pipes,		
steel,open systems	15	1
steel closed systems	30	1
stainless	30	1
copper	30	1
Pumps, open system	15	2
closed system	20	2
Sound traps	30	1
Valves,		
manual control	30	4
automatic control	15	6
manual shut off	30	2
automatic shut off	15	4
V-belt drive	10	6
Wiring	30	1

Source: CEN/TC 156/WG 7, Work document, June 1991 maintenance operations. Precise intervals between such maintenance measures are not yet well known, but general guidelines are provided in table 11.1.

Table 11.2 provides some figures on life expectancies of different parts of a building, with estimated maintenance costs in relation to investment.

11.9 Operator's Manual

All operational routines with respect to DCV systems should be presented as a specific chapter or section in the O&M manual for the building and its installations. General instructions can be accepted only if they concern unitary installations of a standardized (mass produced) type. There should be provision for regular revision of the manual and the opportunity for feedback and input from the O&M staff.

11.10 Regular Staff Training

All routine work has a tendency to deteriorate in quality. It is therefore necessary to break the grey routines from time to time. Such breaks in the form of training courses or visits to interesting plants will give the staff better knowledge of new techniques, ideas and hints on operation and maintenance, as well as providing important contacts with other people in similar work situations.

11.11 Checklist for the Design of DCV Systems

As a conclusion, a checklist should be set up with respect to quality assurance factors for design, construction, commissioning, operation and maintenance. An example of such a checklist is shown in table 11.3.

According to work regarding systems in buildings by CEN/TC 156 (ventilation), TC 228 (heating), and TC 247 (control), the quality demands on systems should serve as a basis for the quality demands on products installed. However, the production of components should be dealt with in a separate quality chain, set up by production standardization bodies.

Table 11.3 Checklist for the design of DCV systems

Quality Assurance Factor	Design	Construction	Operation and Maintenance
General programming	✓		✓
Design	✓	✓	
Contracting		✓	✓
Balancing	✓	✓	✓
Comissioning		✓	✓
Routine inspection	✓		✓
Audit inspection			✓
Service	✓		✓
Renewal	✓	✓	✓
Staff training	✓	✓	✓
Manuals	✓	✓	✓

12 Conclusions and Recommendations

These findings are based on Annex 18's broad definition of DCV as including systems with either manual or automatic (clock or sensor) controls. Annex 18 defines a DCV system as a ventilating system where the air flow rate is governed by a sensor detecting humidity or airborne pollutants, in order to keep the concentration level of the detected substance(s) below a preset value. Such a DCV system can utilize manual or automatic controls. The sensor can be a person (based on subjective perception) or an automatic device (based on measured data).

12.1 Potential Benefits

Energy Savings The potential energy savings to be gained from installation of a DCV system cab be up to 60 % of ventilation energy costs, depending on the building type and use and on the local climate. Achieved savings will probably be somewhat less.

Pollutant control and indoor air quality (IAQ) A DCV system can be used to provide improved control of pollutants and of IAQ in general by providing more ventilation air when it is really needed.

Building preservation By controlling RH, a DCV system can help protect and preserve the building fabric.

Easier operational settings If ventilation rates are to be adjusted according to changes in pollutant load or occupancy, this would normally have to be done by an operator. With a DCV system, this is done automatically and hence more reliably.

Proof of code requirements can be achieved by using the DCV sensor as a measuring device and connecting it to a recording device.

Early warning system can be achieved as the DCV sensor signal can be used to alarm for abnormal values.

Increased occupant satisfaction Under some conditions, occupants may perceive an improvement in air quality with a DCV system.

12.2 DCV Strategies

12.2.1 Prerequisites

The main prerequisite for installing a DCV system in a building is that the pollutant emission rate is known or predicted to be one or more of the following:

* High enough as to require the installation of additional (natural or mechanically assisted) ventilation in combination with that provided by natural infiltration

* Variable in time

* Unpredictable as to time and location of the source

In order for energy savings to be significant, several conditions must be met:

* Outdoor air rates in the HVAC system must be variable or control is not possible

* Occupancy must vary unpredictably (if the occupancy profile is predictable, a simple clock control would be cheaper and as effective)

* The climate must be such that the indoor air supply must be heated or cooled for a very significant portion of the year

* The density of occupancy in the controlled area must be high and the emissions from other sources must be low

12.2.2 Design Considerations

A DCV system strategy must contain many of the essential elements of a more conventional ventilation approach and should be designed to fulfil the following operational requests:

Base ventilation rate to cope with the emissions from the building and its furnishings. It must be designed in consideration of the age and type of material in the building.

Occupancy ventilation rate to cope with emissions generated by occupants and their activities, which must be designed in consideration of the number of occupants and the type of activities taking place in the building.

Seasonal influence of ventilation rates used for other purposes than room air quality, i.e. free cooling with outdoor air, is to be considered when programming the automatic operational control system. So should leakage through the building envelope, which is normally higher at low outdoor temperature.

New furnishings often cause a relatively high emission of pollutants during the initial time of operation (up to two years). This calls for an increased base ventilation rate during this period, the length of which has to be deduced from operational data.

Preventilation is nearly always appropriate. Without it there would be a poor first impression in the morning when the nose is fresh and an even worse impression after a weekend, especially after a long or hot weekend.

Air flow rate control can be achieved in one or more of the following ways, which are well known ventilation techniques:

* Openable windows or slots
* Damper control (duct system or wall orifice)
* Variable fan speed
* Variable flow rate air terminal devices

12.2.3 Cautions

DCV systems are only as efficient as their ability to detect the precise level of a specific pollutant or pollutants. Many sensors, human and manufactured, have limitations in terms of sensitivity, response time, expense or reliability. Only a few sensors on today's market are stable and accurate in long term operation. Only CO_2, humidity and presence sensors are available at a reasonable price level. When building materials or furnishings are new they tend to outgas, releasing odours and other irritants. DCV systems will not be appropriate at this time.

A DCV system, even well functioning, is not a guarantee for the health situation in a building since only a very limited number of pollutants may be sensed.

The "olf" value, as it has been defined, cannot be measured objectively or used to control DCV systems since the required sensors do not exist.

Combined effects from different types of VOCs cannot be properly sensed by to-day's VOC sensors. In cases where smoking is allowed the CO_2 concentration cannot be used as an indicator of the odour level. In those cases the ventilation rate should be set by the number of people smoking and the intensity thereof.

12.3 Applications

In general, typical occupancy profiles associated with the building types discussed will provide a very preliminary indication of the suitability for a DCV system. Occupancy-related pollutants, particularly heat and odour (IAQ), are most prevalent and noticeable after a sudden increase in occupancy and related activities. The occupancy profile is thus an important guide when considering a DCV system. Occupancy patterns that are both highly variable and unpredictable are most likely candidates, as shown in table 12.1.

Table 12.1. Suitability of building types to DCV systems

Building type	Suitability to DCV
Auditoriums, board rooms	Almost always
Schools and day nurseries	Usually
Dwellings	Often
Office buildings	Seldom

Table 12.2. Systems used for DCV actions in different types of buildings

DCV system type	Suitable to building type	Remarks
Manual		Foreseen situation or instrument reading
Humidity	Domestic	
		High-low, continuous fan speed
Carbon dioxide	Schools, Nurseries	
Particles	All	
Automatic		Pre-airing
Clock relay	Offices, schools	
		Combined with clock relay to achieve post-ventilation
Light switch	Bathrooms, toilets	
Sensor governed		
Presence	Offices, schools	System on-off
Humidity	Dwellings	High-low, continuous fan speed
Carbon dioxide	High occupancy	
Odour	Any type	Sensor development needed
Tobacco smoke	Designated smoking areas	Mixed gas sensor

In addition to an occupancy profile that is variable and unpredictable, there should be a driving pollutant or key indicator for which a reliable sensor is available. Combining these factors, application opportunities are summarized in table 12.2.

Based on figures from,ref. 4 chapter 5 and on the definition of 1 olf being equivalent to the dissipation from one person, the total load from building and people can be assumed to fall within the ranges given in table 12.3.

A DCV system is relevant mainly in those cases where the personal load is relatively large compared to the load from the building itself. Note that when the objective of a DCV system is to provide satisfactory control of odour, this data also generally supports the ranking of suitability of different building types presented in table 12.1.

Table 12.3. Pollutant load ranges from Building and Occupants in a building

Building type	Pollution load (olf/m^2, floor area)		
	Building Min-max	Occupants Min-max	Total Min-Max
Dwellings	No data	No data	No data
Schools	0.12 - 0.54	0.00 - 0.30	0.12 - 0.84
Offices	0.02 - 0.95	0.00 - 0.08	0.02 - 1.03
Auditoriums	0.09 - 1.32	0.00 - 1.10	0.09 - 2.42
Day nurseries	0.02 - 0.74	0.00 - 0.20	0.02 - 0.94

12.4 Recommendations

12.4.1 DCV Option for Energy Savings

DCV systems should continue to be developed in order to reduce the life cycle cost for operation and maintenance of a building and its installations for ventilation. Often more than 80% of the LCC is the cost of energy. This share will probably increase in the future. Thus there should be an increasing market for DCV systems, provided that they can show good long term stability and low maintenance costs and at the same time serve as a means for keeping up acceptable IAQ. An increased use of DCV systems should lead to more developed and robust components giving lower component and system costs and higher operational life time.

12.4.2 Systems to Support DCV

Ventilation systems for DCV applications should be developed to operate within large spans of flow rate. This calls for research on supply air terminal devices for hot and cold air as well as air supply streams from low impulse devices. Improved ventilation efficiency can lead to reduced base rate ventilation and also better use of ventilation air during time of occupation of the treated space.

If the outdoor air is highly polluted compared to the pollution level of the indoor air, then a return air system with good filtering, irrespective of return air rate, may improve the room air quality. Here a further field of research is opened. The potential can be very much increased if tobacco smoking indoors is not allowed.

12.4.3 Building Design

Research into reduced pollution emissions from building materials and furnishing should be supported. By reducing such emissions, the necessary air exchange and hence the operating costs can be diminished. Building material may account for up to 60-90 % of the emission in a building during time of operation with full occupant load. Emissions from building materials cannot usually be filtered out, as the pollutants are gaseous.

12.4.4 Building Use

It is critical that the overall pollution generation rate is kept as low as possible if DCV is to be successful. In this regard, it is helpful if indoor smoking is forbidden.

Other potential pollution-generating activities should be examined for means of reducing the pollutants and the associated odours.

12.4.5 Sensors

Presence sensors and CO_2 sensors now function at acceptable levels of accuracy and stability. Humidity sensors can provide good accuracy and acceptable stability, but those sensors are too expensive for a mass-produced system. Thus there is a need for development of low-cost humidity sensors. VOC sensors need further development as to accuracy, stability, and sensitivity to other factors before they can be recommended for general use.

The limiting factors for the application of DCV systems are often the initial costs and increased maintenance costs associated with the control system. Inexpensive sensors and associated controls should be developed further to become more reliable and require less frequent calibration. With reliable, reasonably-priced sensors, the feasibility of DCV systems will be increased significantly.

12.5 Future Developments

From the findings reported here, the most likely potential for DCV development and application is in buildings or large rooms with widely divergent occupancy rates such as auditoriums, courtrooms, or meeting rooms.

Although with today's energy prices and building practices DCV systems have a limited application, they could become a more realistic option within the next 25 years. Increasing energy costs and changes in building envelope techniques, along with development of low-cost reliable sensors, will be major catalysts in DCV feasibility.

Future use of DCV systems may be motivated not only by the economics of energy savings, but by increased expectations from occupants regarding the quality of the internal environment. This, combined with a desire to minimise the impact of the building on the external environment, may propel DCV technology toward further developments and wider applications.

Appendix A: Terminology

Air change rate
Quotient of ventilation flow rate and room volume.

Air exchange efficiency
The average time of stay of the room air in a room with an ideal displacement ventilation and the actual average time of stay.

Air conditioning
Air treatment including the control of temperature, humidity, purity and velocity.

Air quality
Time-weighted mean concentration of airborne pollutants. The period shall be stated (8, 24 hours). The SI unit is $\mu g/m^3$.

Air terminal device
Device which serves as the border between the treated space and a duct system and is normally designed to cause a certain air velocity in the occupied zone. The short form ATD is sometimes used. An ATD can be a Supply air terminal device, an Exhaust air terminal device, or a Transfer air terminal device.

Automatic DCV
See Demand controlled ventilating (DCV) system

Balancing
Adjustment of devices in distribution networks for fluid or gas in order to obtain calculated or prescribed flow rates in all parts of the system. Balancing of a DCV system should be accomplished by testing not only constant flow rate operation but also operation under conditions where the flow rate has to be varied due to load from people, solar heat gain, and technical installations.

Bioeffluent
Pollutant in the form of odours from human beings, cloths or animals. Forms part of the VOC:s.

Carbon dioxide
Oxide of carbon, with the chemical formula CO_2. Carbon dioxide is formed as a result of the complete oxidization at the combustion of material containing carbon. Carbon dioxide in normally existing concentrations in room air is not a pollutant, but its presence can be used to indicate human activities.

Commissioning
Handing over a building to its operational staff at the time of completion. This operation calls for very careful information and instruction on systems and products used and on their proper operation and maintenance. No system should be handed over without manuals for operation and maintenance. This is even more true for a DCV system.

Contaminant
See Pollutant.

Demand controlled ventilation (DCV)
Ventilation where the air flow rate is governed by airborne pollutants.

Demand controlled ventilating (DCV) system
According to Annex 18, a ventilating system where the air flow rate is governed by a sensor for humidity or other airborne indicators, in order to keep concentration level below a preset value.

A ventilating system should normally be able to control temperature. A DCV system responds primarily to an air quality indicator. The ventilation strategy must be carefully chosen to maintain thermal control and to avoid inadvertently creating other Indoor Air Quality problems.

The intention of a DCV system is to ventilate more efficiently by tailoring the air flow rate according to time dependant needs. Depending on the application, this can lead to better energy efficiency, improved Indoor Air Quality (IAQ) or a combination of both.

For the work within IEA Annex 18, a DCV system should be specially designed to do one or more of the following:

a) control room air quality in order to limit contamination levels within the occupied zone, while also fulfilling the other roles of a ventilation system

b) control moisture content in building material and room air, thereby reducing the risk of mould growth and degradation of the building, or

c) reduce energy consumption without unacceptably interfering with indoor climate

The necessity of including humidity limitation in a DCV system is called upon by the fact that a high humidity concentration level is apt to cause building damage in the form of mould and rot, corrosion, ice damages, which in due course will lead to expensive repairs, comfort degradation or dangerous air borne contaminants.

- *Automatic DCV*
DCV where the air flow rate is governed by an automatic control device

- *Manual DCV*
DCV where the air flow rate is governed by the user who activates the system by his own indications. A DCV system can consist of a clock control and/or a presence control and/or a sensor control, where the latter is activated by suitable gases such as carbon dioxide, humidity or hydrocarbons to keep air quality at a desired level.

Control
Deliberate influence. Control can be subdivided into Manoeuvring, Programmed control, and Feedback control.

- *Differential control*
Control where the action of the control device is a function of change per time in difference between the set point value and the actual value. Often named D-control.

- *Feedback control*
Closed loop control where the difference between the set value and the controlled value causes an operation to diminish that difference.

- ***Integrating control***
Control where the action of the control device is a function of the difference between the set point value and the actual value as well as the time. Often named I-control.

- ***PID-control***
Control where Proportional, Integral and Differential control is practised in a system.

- ***Proportional control***
Control where the action of the control device is proportional to the difference between the set point value and the actual value. Often named P-control.

Energy management
The efficient use of energy supplied to a system.

Free cooling
Cooling of a treated space by using outdoor air with or without adding water. Adding water to the supply means application of evaporative cooling.

Indoor climate
The synthesis of day-to-day values of physical variables in a building, e.g. temperature, humidity, air movement and air quality, etc, which effect the health or comfort or both of the occupants.

Inspection
Check of systems and components made by specialist and resulting in an inspection report. Final inspection and commissioning should follow general routines for the inspection of ventilation and air conditioning plants and include special check with regard to DCV functions and their way of operation, compared to general functional requests and specifications in the contract.

Iterative method
Method of computation in which a solution compatible with the known facts emerges following a series of calculations made by ascribing values, successively changed by small steps, to the unknown variable(s). Normally the calculations are made practicable by using computers.

Life Cycle Cost
The sum of capital, operational and maintenance costs during the expected or observed lifetime of an object.

Maintenance
Measures to keep or restore original functions of a system. Maintenance of DCV systems should be based on a time and functionability schedule in order not to let room air quality and energy demand diverge more than a certain amount from the ideal level.

Manual DCV
See Demand controlled ventilating (DCV) system

Mechanical ventilation
See Ventilation.

Mixed gas sensor
A sensor that reacts to gases that can be oxidized. Such gases are hydrocarbons, VOC:s and carbon monoxide.

Moisture
Water content in the air, in the building material or in the interior materials. Moisture must be kept at a concentration level that is not

damaging for the building and also below a certain level in order not to promote growth of mould (75 % RH) and house dust mites (55 % RH).

Natural ventilation
See Ventilation.

Operator's manual
Manual for the operational routines for the actual building and its installations. General instructions can be accepted only if they concern unitary installations of a standardized (mass produced) type. Special respect should be given to DCV systems where actual. There should be a routine for regularly revising the manual.

Periodical audit of energy management and function
A check of the function made by a competent and experienced person from outside the owner's personnel at time chosen by the inspector. In many countries an audit function for a periodical (each or each second year) is discussed. This has its roots in operational problems causing so called sick buildings, where ventilation with too low flow rates often is one of the essential factors. Even if this audit function is not compulsory it is highly recommended.

Pollutant
An unwanted airborne constituent that may reduce the acceptability of the air. The most important pollutants affecting the indoor air quality of buildings discussed in this book are bioeffluents, moisture and volatile organic compounds.

Presence detector
Sensor that can be used to detect movement of or low temperature radiation from human beings. A presence detector can be used to change the operational state of a ventilation system. Such a detector cannot, however, be used to control the quality of the room air. Thus a presence detector must be accompanied by some other device reacting to room air quality, if the pollutant load cannot be foreseen.

Quality
The totality of features and characteristics of a product of service that bear on its ability to satisfy stated or implied needs. ISO 8402-1986

Quality assurance
All those planned and systematic actions necessary to provide adequate confidence that a product of service will satisfy given requirements for quality.

Quality control
The operational techniques and activities that are used to fulfil requirements for quality.

Remarks given in ISO 8402-1986:

The term quality is not used to express a degree of excellence in a comparative sense, nor is it used in a quantitative sense for technical evaluations. In these cases a qualifying adjective shall be used. For example, use can be made of the following terms:

* Relative quality
* Quality level and Quality measure

Quality of a DCV system should be verified with respect to the ability of producing and maintaining an acceptable to good indoor room air quality and also an acceptable indoor climate. The measurement of quality should contain the following quantities:

* Air quality at the time of final inspection
* Air quality during commissioning tests
* Air quality during normal and extreme operating conditions. Special observations should be made as to the necessary period of outgassing of furnishing
* Room air velocities
* Ventilation effectiveness
* Energy conservation performance
* Stability of the control system
* Maintainability of components

Sensor
Device designed to detect changes in a defined quantity and to react by giving a signal to a monitoring or control system. A sensor can be designed to react on humidity, gases, particles, visibility, heat radiation, radioactivity, etc.

Set point
Preset value of quantity to control, i.e. concentration level of pollutant.

Supervision system
System for the operational check of an installation, often furnished with an automatic report and alarm function. A supervision system is an almost necessary part of any modern large ventilation system.

Temperature difference ratio
Difference between the indoor air temperature and the temperature of the inner surface, divided by the difference between the indoor air temperature and the outdoor temperature, calculated with a heat transfer resistance at the inner surface. (CEN/TC 89 N126) The temperature difference ratio is used in computer aided calculations, which should be run until a maximum error of ± 0.01 °C is reached.

Temperature factor
Difference between the temperature at the inner surface and the outdoor air temperature, divided by the difference between the indoor air temperature and the outdoor temperature, calculated with a heat transfer resistance at the inner surface. (CEN/TC 89 N126)

The temperature factor is used in computer aided calculations, which should be run until a maximum error of ± 0.01 °C is reached.

Temperature weighting factors
Factors which state the relative influence of the air temperatures of the thermal environments upon the surface temperature at the point under consideration.(CEN/TC 89 N126) The temperature weighting factor is used in computer aided calculations where more than two boundary temperatures have to be considered. The sum of all factors should add up to 1.000 ± 0.002.

Threshold value
Concentration level of a pollutant or indicator at which
a) a human reaction might occur
b) a sensor reacts

Tracer gas
A gas used with a detection device to determine the rate of air interchange with a space. Measuring air changes by using a tracer gas can follow one of the methods:

a) constant concentration
b) constant emission flow
c) rate of decay

Turnover time

a) Quotient of room volume and ventilation flow rate.
b) Period of time in which the room air is theoretically fully exchanged
c) Inverse value of air change rate

Volatile organic compound (VOC)

Organic matter that, in air of 20°C, has a saturation concentration of at least 4700 ppm or a relative evaporation rate of > 0.02, compared to that of ethylic ether. (Kemikontoret, Sweden)

A VOC, in this document, is an organic matter that evaporates pollutants at any rate.

A VOC that has its origin in a human being is named a bioeffluent.

VOCs cause gaseous pollution of the air. VOCs stem from mainly three sources: building material, cleaning material, and activities of human beings. In some cases also the ventilation system can contribute to the VOC level. Part of the VOCs call for a base rate ventilation, while another part is to be dealt with as a function of activity level. *VOCs can be grouped as in table A.1 and the concentrations of VOCs often found in buildings see table A.2.*

- *Non-volatile organic compound*

Organic matter that, in air of 20°C, has a saturation concentration of less than 300 ppm or a relative evaporation rate of less than 0.002, compared to that of ethylic ether. (Kemikontoret, Sweden)

Ventilation

Air treatment by transportation and exchange of air. Ventilation is a summarising term for air distri-

Table A.1. Explanations of VOCs

Group	Explanation	Boiling point °C
VVOC	very volatile	< 0 .. 50-100
VOC	volatile	50-100 ... 240-260
SVOC	semivolatile	240-260 ... 380-400
POM	particulate organic matter	> 380

Table A.2 VOCs in buildings:

Environment	VOC mg/m³
Outdoor air	0.01-0.04
Dwellings	0.1-0.4
Offices	0.1-0.8
Schools and day nurseries	0.2-0.3

bution, air diffusion and air exchange. See figure A.1

- Natural ventilation
Ventilation using only natural forces such as wind pressure or difference in air density.

- Mechanical ventilation
Ventilation using one or more fans to supply air to or exhaust air from a treated space.

Ventilation efficiency
The concentration of pollutants in the exhaust air divided by the concentration of pollutants in the room air.

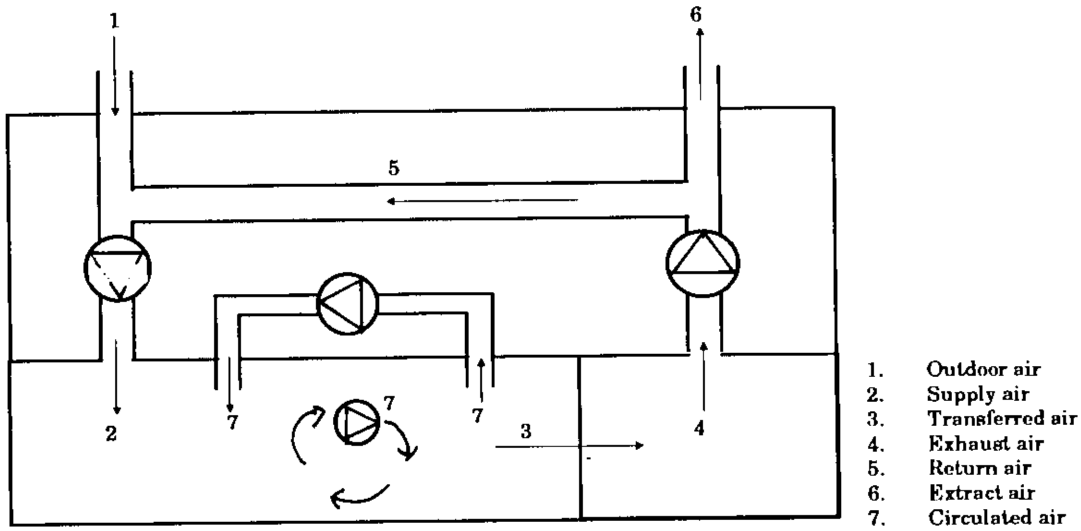


Figure A.1 Ventilation system

Appendix B: Calculations for Feasibility Analysis

This Appendix contains detailed calculations in support of Chapter 6, Feasibility Analysis. The calculations proceed according to the following steps:

B1. Equation of Continuity for Multizone (Zero-Dimension) Model
B2. Calculation of Ventilation Heat Loss
B3. Calculation of Energy Savings
B4. Development of Reference System
B5. Development of DCV System
B6. Development of Calculation for Ventilation Energy Savings
B7. Example: DCV Application in a School

B1. Equation of Continuity for Multizone (Zero-dimension) Model

A simple relation between pollutant emission rate, air flow rate and pollutant concentration can be derived from the equation of continuity under the following hypotheses:

1. Perfect mixing;
2. Steady state;
3. No background concentration of pollutant or constant known concentration;
4. No absorption or desorption by building materials.

In differential form, under the hypothesis of perfect mixing, the equation of continuity for room "i" yields:

Equation B1

$$P_i + \Sigma\, q_{j,i} \cdot C_j - n_i \cdot V_i \cdot C_i + B \cdot S_i (C_{max} - C_i) = V_i \cdot dC_i / dt$$

where

$q_{j,i}$	=	air flow rate from room j (including outdoors) to room i (m^3/h).
B	=	pollutant absorption or desorption resistance (m/h), equal to zero when $C < C_{max}$ and there is no pollutant left on the surfaces.
C_{max}	=	maximum pollutant concentration on the surface (kg/m^3). For moisture, this will correspond to the saturation conditions at the surface temperature.
S	=	area of absorbing or desorbing walls and furniture, (m^2).
t	=	time h.
P_i	=	production of pollutants, (kg/h).
n_i	=	air change rate, (h^{-1}).
V_i	=	room volume (m^3).

B2. Calculation of Ventilation Heat Loss

The energy needed to heat (or cool) outside air is called ventilation heat loss (or gain). This is equal to the difference between air enthalpy flow out and into the building:

Equation B2.1

$$\Phi_v = G \cdot (h_i - h_e)$$

where

Φ_v = ventilation losses (W)
G = mass flow rate (kg/s)
h = air enthalpy (J/kg)

and subscripts i and e will respectively refer to "indoor" and "outdoor".
Air enthalpy is given in its turn by

Equation B2.2

$$h = r_o \cdot x + (cp + c_{pv} \cdot x)T$$

where

r_o = evaporation heat at 0°C (J/kg)
c_p = specific heat of air (J/kgK)
c_{pv} = specific heat of water vapour (J/kgK)
x = water vapour content (kg/kg)
T = temperature (°C)

Moisture content variations can be ignored whenever latent heat contributions to indoor heat gains have been ignored, since they generally lead to enthalpy differences which are of the same order of magnitude as those created by temperature differences.

Ignoring moisture content variations and introducing the volume flow rate one gets:

Equation B2.3

$$\Phi_v = \rho c_p \cdot q \cdot (T_i - T_e) / 3600$$

where

q = volume flow rate (m^3/h)
ρ = air density (kg/m^3)
T = air temperature (°C)

Introducing the average values of ρ and c_p one obtains:

Equation B2.4

$$\Phi_v = 0.34 \cdot n \cdot V \cdot (T_i - T_e)$$

where

0.34	=	dimensioned coefficient, equal to $\rho c_p/3600$ ($Wh/m^3 \cdot K$)
n	=	number of air changes per hour (h^{-1})
V	=	volume of the building (m^3)

The corresponding ventilation energy losses may be calculated by integrating equation B2.4:

Equation B2.5

$$Ev = \int_0^t 0.34 \cdot n \cdot V \cdot (T_i - T_e) dt = 0.34 \cdot V \cdot \int_0^t n \cdot (T_i - T_e) dt$$

B3. Calculation of Energy Savings

In order to estimate the energy savings achievable with DCV the following input data should be known:

* typical daily pollutant emission schedule, and particularly the ratio between average (ave) and maximum (max) design, emission rates P_{ave}/P_{max}
* base ventilation rate n_o
* maximum ventilation rate n_{max}

The reduction of ventilation energy losses, ΔE_v, consequent to replacing a reference ventilation system with a DCV system will be:

Equation B3.1

$$\Delta E_v = 0.34 \cdot V \cdot [\int_0^t n_{ref} \cdot (T_i - T_e)\, dt - \int_0^t n_{DCV} \cdot (T_i - T_e)\, dt\,]$$

and the relative energy savings R will be:

Equation B3.2

$$R = \Delta E_v / E_{v,ref} = 1 - \left[\int_0^t n_{DCV} \cdot (T_i - T_e)\ dt\right] / \left[\int_0^t n_{ref} \cdot (T_i - T_e)\ dt\right]$$

To evaluate R, the reference and DCV systems must be defined as described in B4 and B5.

B4. Development of Reference System

We will assume for the reference case that the ventilation rate is constant, and equal to n_{max}, during the operational period of the building

$n_{ref} = n_{max}$

In the steady-state n is proportional, as seen in 6.3 step 2.2 to the emission rate P of the driving pollutant.

Thus:

$n_{max} = K \cdot P_{max}$

where K is a constant equal to $(C_o V)^{-1}$, with C_o being the setpoint concentration adopted. During the non-operational period we will have infiltration-driven air changes

$n_{ref} = n_{inf}$

B5. Development of DCV System

We will assume for the DCV system a base ventilation rate n_o and a variable ventilation rate, which maintains the driving pollutant concentration constant at its set-point C_o. That is

$n_{DCV} = n_o$ for $P < Po$

$n_{DCV} = K \cdot P$ for $P > P_o$

and

$n_{DCV} = n_{inf}$ during the non-operational period of the building.

This information is summarized in figure B1.

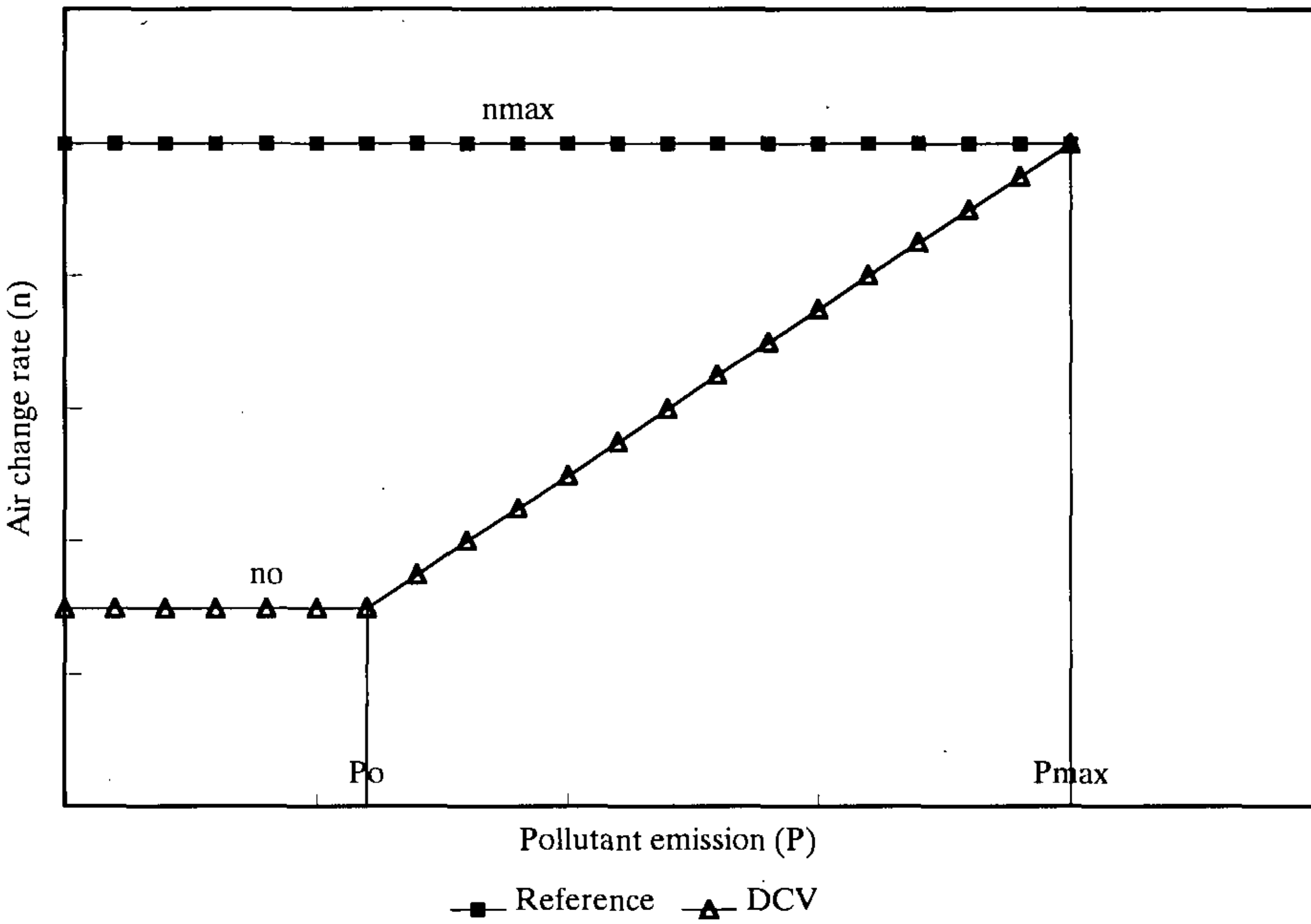


Figure B.1. Air Change Rates versus Pollutant Emission

With these assumptions, the driving pollutant concentration will always be lower or equal (during peak emissions) to C_o in the reference case, and will be lower (during base ventilation periods) or constantly equal to C_o for the DCV case. According to the calculations developed in B6, we find equation 5.1.

Values of α may be determined from typical climate data. Although α may usually be neglected at this level of approximation, its values for a typical situation may be desumed from Table B1, which assumes $T_{e,ave}$ = 5° C during the whole day, and $T_{e,max}$ - $T_{e,min}$ = 10°C.

Table B.1. Approximate values of coefficient α as a function of time of the day, for 24-hour operational period[1]

time	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24
α	1.15	1.20	1.25	1.15	1.00	0.90	0.70	0.75	0.85	0.90	1.05	1.10

[1] For different operational periods, calculate α_{ave} on that period using this table and divide all values by.

Equation B5.1

$R = 1 - [\ \beta + \alpha \cdot (A + B - A \cdot B)\ ]\ /\ [\ \beta + 1\ ]$

where

β is the ratio between infiltration heat losses (during non operational periods) and mechanical ventilation heat losses (constant flow, during operational periods).

α is a coefficient taking into account whether the highest ventilation rates in the DCV system occur during cold or warm hours.

A is the ratio between base ventilation and design ventilation rates:

$A = n_o / n_{max} < 1$

B is the ratio between average pollutant emission (during operational time) and maximum pollutant emission:

$B = P_{ave} / P_{max} < 1$

Although *A* and *B* may differ from case to case, typical ranges are given in Table B.2 for some building categories.

A nomogram for the calculation of energy savings *R* is shown in figure B.2.

Table B.2. Ranges of values for coefficients A and B, as a function of building category

Building type	Driving pollutant	A	B
Dwelling	CO_2	0.2 - 0.3	0.4 - 0.6
Dwelling	RH[1]	0.3 - 0.4	0.2 - 0.3
Offices	CO_2	0.6 - 0.7	0.4 - 0.6
Schools	CO_2	0.2 - 0.3	0.2 - 0.6
Auditoriums	CO_2	0.2 - 0.3	0.1 - 0.2

1 This calculation is not intended for RH-driven DCV systems aiming to maintain constant relative humidity at the coldest surface indoors.

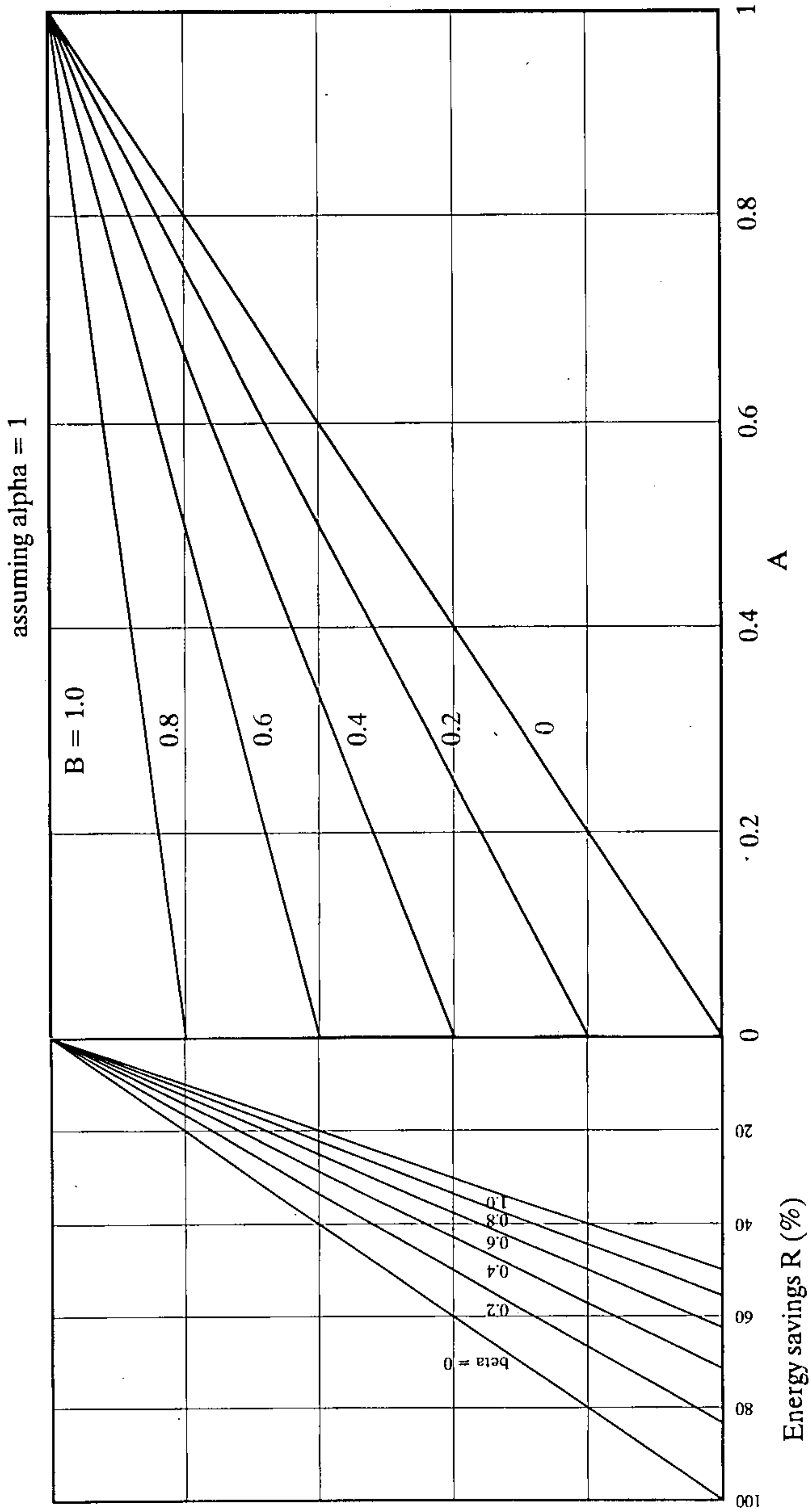


Figure B.2. Nomogram for Calculaion of Energy Savings

B6. Development of Calculation for Ventilation Energy Savings

Integration of Equation B3.2, assuming that the operational periods in the reference and DCV cases are the same, yields:

Equation 6.1

$R = 1 - (n_{ave,inf} \cdot D_1 + n'_{ave} \cdot D_2) / (n_{ave,inf} \cdot D_1 + n_{max} \cdot D_2)$

where

D_1 = degree-days during non operational periods

D_2 = degree-days during operational periods

n'_{ave} = weighted average of n over the considered period, i e

$$n'_{ave} >= [n \cdot \int_0^t (T_i - T_e) \cdot dt] / [\int_0^t (T_i - T_e) \cdot dt]$$

If the arithmetic average n_{ave} is

$$n_{ave} = (1/t) \int_0^t n \cdot dt$$

then we may assume:

$$n'_{ave} = \alpha \cdot n_{ave}$$

with α depending on the time when the peak pollution loads occur:

Equation B6.2

$\alpha = [T_i - T_e(t_{max})] / (T_i - T_{ave})$

where

T_i	=indoor air temperature (supposed to be constant)
$T_{e,ave}$	=average outdoor air temperature during operational period
$T_e(t_{max})$	=average temperature during peak emission times

Values of α may be determined from typical climate data. For example, for $T_{e,ave}$ = 5°C during the whole day, and $T_{e,max} - T_{e,min}$ = 10°C, the α values will be approximately those listed in table B1.

If the operational period is from 08:00 to 20:00 and the climatic data are the same, we will have:

time	8-10	10-12	12-14	14-16	16-18	18-20
α	1.18	1.06	0.82	0.88	1.00	1.06

Dividing Equation B6.1 by $(n_{max} \cdot D_2)$ gives equation B6.3

Equation B6.3

$R = 1 - [(\beta + \alpha \cdot \Gamma)/(\beta + 1)]$

where

$\beta = n_{inf,ave} \cdot D_1 / (n_{max} \cdot D_2)$

$\Gamma = n_{ave} / n_{max}$

Equation B6.3 shows clearly that the energy savings will increase with decreasing β (little natural infiltration or little non-operational time) - compared with mechanical ventilation):

- decreasing Γ (this will be described afterwards)
- decreasing α (pollutant emission located in warm hours of the day)

It should also be noted that the concentration setpoint does not influence the energy savings, provided it is the same for the reference and DCV case. Γ is the most important term in equation B6.3, and unfortunately the most difficult to determine. Clearly, it depends on the two terms

$A = n_o / n_{max} < 1$

which is the ratio between base ventilation rate and design ventilation rate, and

$B = P_{ave} / P_{max} < 1$

which is the ratio between average pollutant emission and peak emission.

We also know that:

for $n_o = 0$ $(A = 0)$, $\Gamma = B$

and that:

for $n_o = n_{max}$ $(A = 1)$, $\Gamma = 1$

Its value in between will depend on the standard deviation of *P's* (pollutants). Assuming a linear connection corresponds to assume a high standard deviation of *P* and to slightly overestimate Γ (conservative hypothesis), see equation B6.4

Equation B6.4

$\Gamma = A + B - A \cdot B$

As expected, it may be seen that Γ decreases (thus leading to higher energy savings) with decreasing A and B

So, finally, R becomes:

Equation B6.5

$R = 1 - [\beta + \alpha \cdot (A + B - A \cdot B)] / (\beta + 1)$

which is the same as **Equation B5.1**

B7. Example: DCV Application in a School

Assumptions for the example of DCV application in a school is given below. The operational time is 08.00 - 17.00 and the occupancy schedule is given in figure B3

The building is rather tight, and infiltration losses from 17:00 to 08:00 may be considered around 20 % respect to ventilation losses of the reference mechanical system during operational time:

$\beta = 0.20$

We also see from the occupancy schedule that the peak emission of the driving pollutant CO_2 is from 08:00 to 10:00 and from 13:45 to 15:30. Therefore, from Table B.2 we get approximately

$\alpha = 1.0$

and again from the occupancy schedule we see that

$B = P_{ave} / P_{max} = 0.60$

Assuming a base ventilation rate of 25 % of maximum (A = 0.25) we get:

$\Gamma = A + B - A \cdot B = 0.25 + 0.60 - 0.15 = 0.70$

$R = 1 - (\beta + \alpha \cdot \Gamma) / (\beta + 1)$
$= 1 - (0.2 + 1.0 \cdot 0.70)/(0.2 + 1)$
$= 0.25$
or 25 % savings

Adopting no base ventilation ($A = 0$) we would have:

$R = 1 - (\beta + \alpha \cdot \Gamma) / (\beta + 1)$
$= 1 - (0.2 + 1.0 \cdot 0.60)/(0.2 + 1)$
$= 0.33$
or 33 % savings

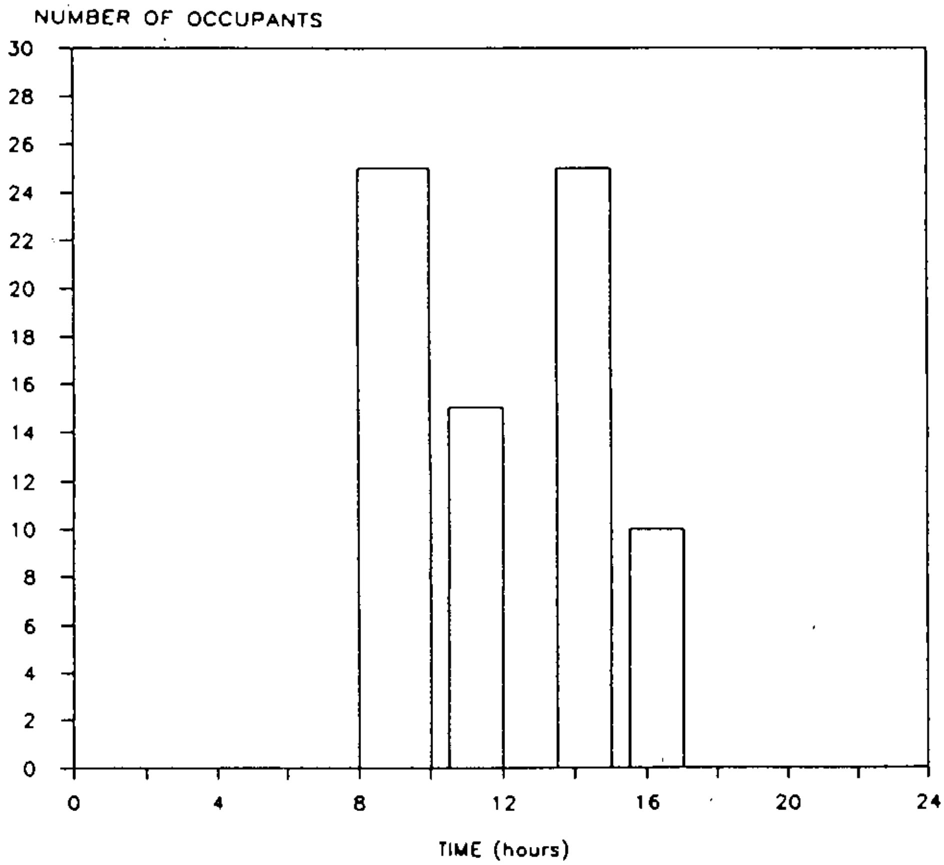


Figure B.3 Occupancy pattern of the classroom

Appendix C: Calculation of RH on Surfaces

In steady state or slowly changing conditions mould growth can be prevented if the RH on a surface can be kept below 80% (CEN/TC 89 DOC N 126, March 1991). Specific values for different mould species are given in IEA Annex XIV Con densation and Energy Source Book (March 1991).

The saturation pressure P_{si} is a function of the surface temperature; in the case of mould growth this means the minimum surface temperature that occurs on thermal bridges. According to CEN/TC 89 the surface temperature can be calculated from equation C1

Equation C1

$$T_{si} = T_i - [(U/h_{si})(T_i - T_e)]$$

Equation C2

$$T_{si} = T_e + \tau \cdot (T_i - T_e)$$

where:

T_{si}	=	surface temperature in °C
T_e	=	exterior temperature in °C
T_i	=	indoor temperature in °C
τ	=	temperature difference ratio (TC 89)
U	=	heat transmission coefficient $W/(m^2K)$
h_{si}	=	heat transfer coefficient, inner surface, $W/(m^2K)$

In order to check the accuracy of the calculation, the expression in equation C2 is recommended by CEN/TC 89 (derived from computer calculations on thermal bridges):

The temperature factor is a purely thermal property of each point of a wall. It is a function of the geometry, the surface film coefficients and the thermal properties. It can be calculated by known theoretical thermal procedures (CEN ITC 89: ISO DP 6946/2) or it can be measured. The relation between T_{si} and P_{si} is also known, see equation C3 to be used for a temperature range of $0°C < T_{si} < 40°C$

Equation C3

$$P_{si} = 611 \exp(72.5 \cdot 10^{-3} T_{si} - 288.1 \cdot 10^{-6} T^2_{si} + 0.79 \cdot 10^{-6} \cdot T^3_{si})$$

The ideal control strategy is therefore to keep the RH at the surface at the coldest spot (thermal bridge) equal to or less than a weekly average level of 80 %. Assuming that the vapour pressure of the indoor air in a room is consistent throughout the room, the DCV system must be designed to ensure that the RH of the air does not exceed RH_{max}, see equation C4.

Equation C4

$RH_{max} = P_{si} / P_i$

where:

P_i = saturation pressure in Pa, at indoor air temperature.

Thus the RH of the indoor air can be taken as the indicator with RH_{max}, calculated from equation C4 as the setpoint.

Notice that RH_{max} is dependent on U / h_{si} as well as on T_e and T_i. Figure C.1 demonstrates this dependence of T_e for a single-pane window and for some other exterior wall constructions.

Controlling the RH as described above needs a microprocessor-based control system. Figure C2 gives two possible designs.

A simplification of the control circuit is possible on the assumption that the indoor air temperature varies only within a small bandwidth, for example about 4°C. Then the information of the indoor air temperature can be processed directly in the control algorithm so that no indoor temperature measuring point is necessary.

A further simplification would be to use only a fixed value of RH as the setpoint. A hygrostat would provide such control.

The vapour pressure of the indoor air can be calculated according to equation C5 under steady state conditions.

Equation C5

$P_i = P_e + \{[462 (273+T_i) G] / q\}$

where:

P_i	=	vapour pressure of the indoor air	Pa
P_e	=	vapour pressure of the outdoor air	Pa
G	=	indoor moisture production	kg/s
q	=	flow rate	m^3/s
462	=	water vapour constant	J/(kg·K)

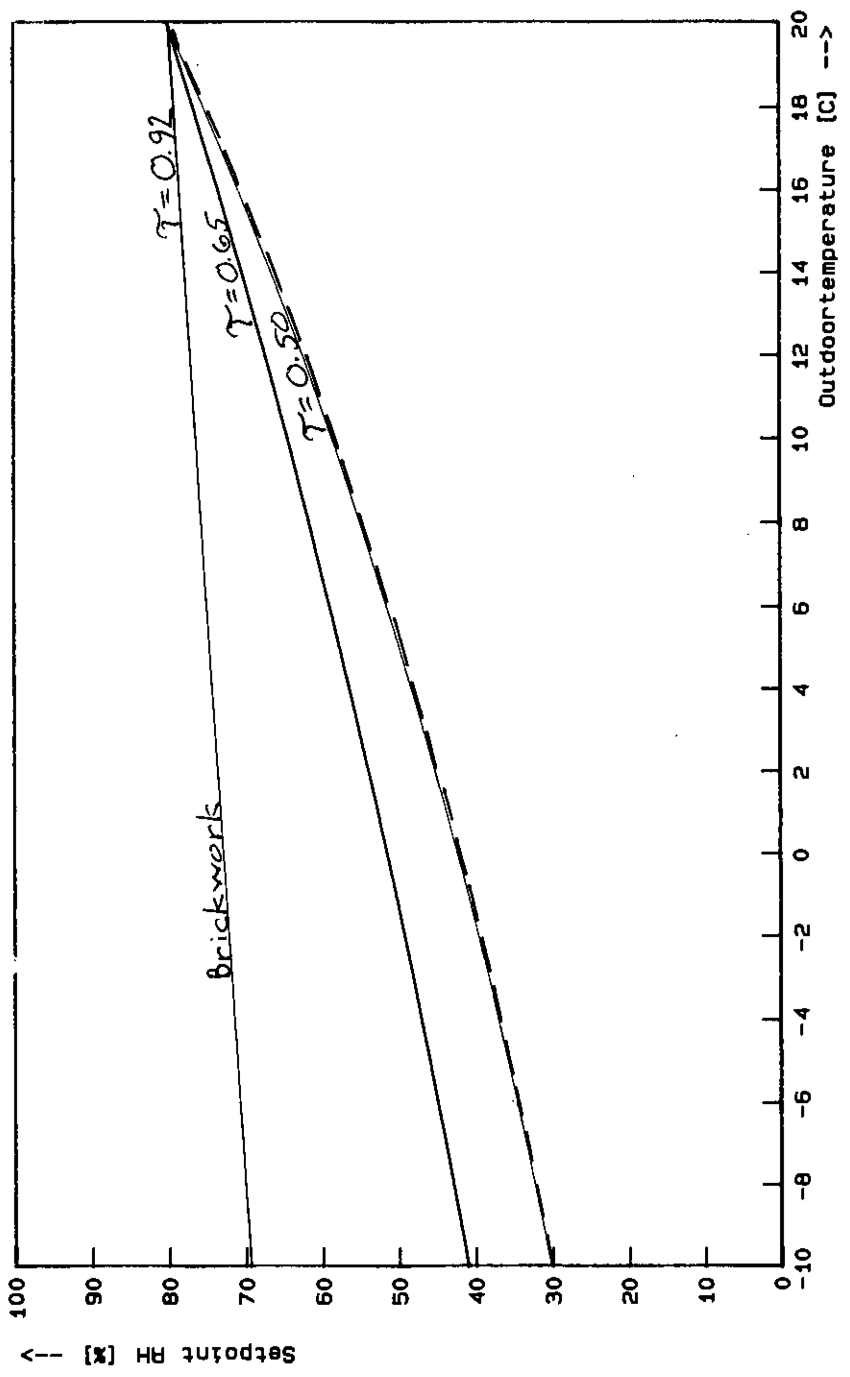
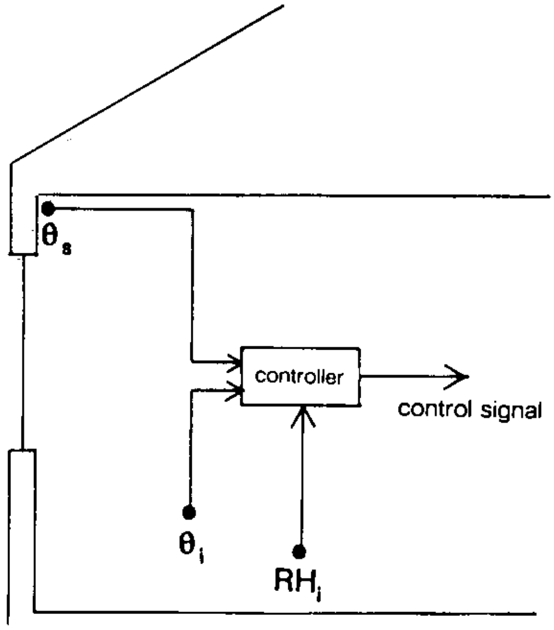
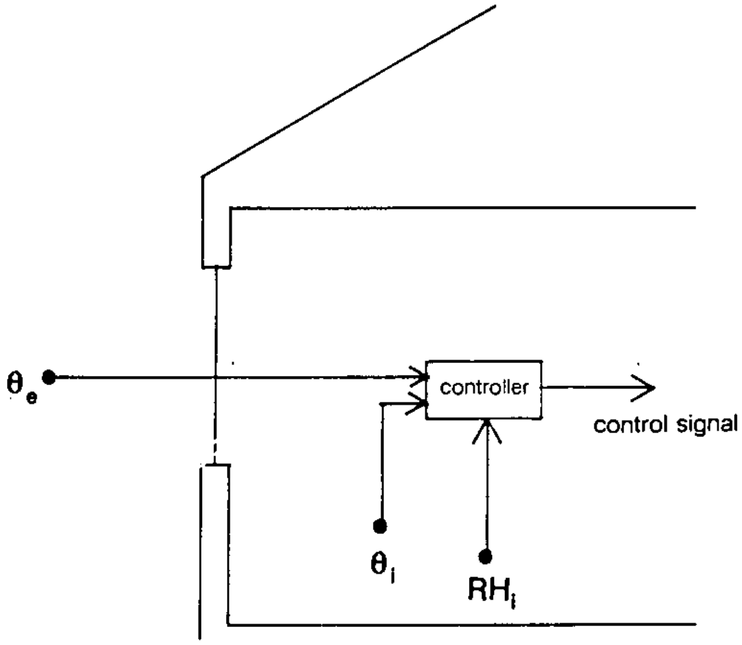


Figure C.1. Setpoint of RH for moisture-controlled DCV system



The surface temperature is directly measured at the critical/coldest spot of the wall (see [4]).



If the surface temperature θ_s can not be directly measured, it can be calculated if the temperature ratio at the critical spot is know; however, the extension temperature has to be measured.

Figure C.2. Principle layout of advanced RH-controlled system

Appendix D: List of References

Chapter 3: Pollutants and Indicators

[1] Handbook 1958 and 1963. Swedish Society of Heating and Air Conditioning Engineers. Stockholm 1963

[2] Tables and diagrammes. Swedish Society of Heating and Air Conditioning Engineers. Stockholm 1974

[3] Gullberg, Jan: Fluid, Gas, Energy. Application on fluid balance, blood, and nuitritional physiology. OPEX, Umeå, 1979. ISBN 91-7260-173-6

[4] Fanger, P.O.: Thermal comfort. Mc Graw Hill, New York 1972. ISBN 0-07-019915-9.

[5] DANVAK, Grundbok. Danish Society for Heating and Air Cond. København 1988. ISBN 87-982652-1-0.

[6] Gustavsson Jan: Survey of standards in the field of contamination control. Inst. Heat. and Vent, Roy. Inst. of Techn. Stockholm, Tekn Medd no 110, Stockholm 1977.

[7] Möller Åke: Cleaning of air from particulate pollutants in return air systems (in Swedish). Inst. Heat. and Vent, Roy. Inst. of Techn. Stockholm, Tekn Medd no 111, Stockholm 1977.

[8] Gustavsson Jan: Return air (in Swedish). Inst. Heat. and Vent, Roy. Inst. of Techn. Stockholm, Tekn Medd no 106, Stockholm 1977.

[9] From Indoor Air 1987, Berlin, Vol 1, ISBN 3-89254-032-2: Grimsrud D.T., et al: Commercial Building Ventilation Rates and Particle Concentrations.

[10] From Indoor Air 1987, Berlin, Vol 2, ISBN 3-89254-032-2: Korsgaard, Jens, et al: Tobacco smoking and the indoor suspended particulate matter

[11] Minamino O, Nagashima M, Domae J: Experimental study on the outside air supply to be required when exposed to environmental tobacco under different conditioned rooms. Indoor Air 1990. Toronto Vol 1

[12] Skov P: The Danish Town-Hall Study - A one year follow-up. Indoor Air 1990. Toronto Vol 1

[13] Lebowitz M.D, et al: Multipollutant exposures and health responses - Epidemiological aspects of particulate matter. Indoor Air 1990. Toronto Vol 1

[14] Spengler J.D., et al: Personal exposure to particulate matter - Findings from the particle total exposure assessment methodology prepilot study. Indoor Air 1990, Toronto Vol 2

[15] Spengler J.D., et al: Particulate matter exposures estimated from an indoor - outdoor source apportionment study. Indoor Air 1990, Toronto Vol 2

[16] Fredriksen E: Practical attempts to predict indoor air quality Indoor Air 1990, Toronto Vol 3

[17] Grot R.A., Hodgson A.T., Daisey J.M., Persily A.: Indoor air quality evaluation of a new office building. Indoor Air 1990, Toronto Vol 3

[18] Colombo A., De Bortoli M., Knöppel H, et al: Determination of volatile organic compounds emitted from household products in small test chambers and comparison with head space analysis. Indoor Air 1990, Toronto Vol 3

[19 From IEA Annex 14, "Condensation and Energy", Sourcebook, Chapter 6: "Boundary Conditions"

[20] Nevander L.E., Elmarsson B.: Fukthandbok (Moisture Handbook) Sv Byggtjänst, Stockholm 1981. ISBN 91-7332-158-3

[21] Blomsterfrämjandet (Swedish Flower Council): The occurence of pot flowers in homes. Stockholm 1988. Confidential market research report. Personal communication.

[22] National Institute of Occupational Health: List of allowed concentrations in room air. ASS, Stockholm 1990:13

[23] Berg-Munch B., Clausen G., Fanger P.O.: Ventilation requirement for the control of odour in spaces occupied by women. Envir. Int. Vol 12, 1986 pp 193-199.

[24] Andersen I., Korsgaard J.: Indoor Air' 84 Vol 1 Astma and the Indoor Environment Assessment of the Health Implications of High Indoor Air Humidity ISBN 91-540-4191-0.

[25] IEA Annex 18: Demand controlled ventilating system - State of the art review. Report D9:1990, ISBN 91-540-5169-X, Swedish Council for Building Research, Stockholm, Sweden.

Chapter 4: Sensor Types

[1] ASHRAE Brochure on psychrometry. ISBN 0-910110-07-7, 1977, ASHRAE, Atlanta, USA.

[2] Bergsten, L, Laaksonen, L, Petersen, B, 1987. A catalogue of environmental test rocedures- A demonstration and a discussion of the idea. (The Swedish National-Testing & Research Institute.) Technical report SP-rapp 1987:05 and Nordtest Technical report 078. Borås, Sweden.

[3] IEA Annex 18: Demand controlled ventilating system - State of the art review. Report D9:1990, ISBN 91-540-5169-X, Swedish Council for Building Research, Stockholm, Sweden.

[4] Fahlén, P, 1989. Testing of DCV sensors. (The Swedish National Testing & Research Institute.) Project description and test program. 1989-01-19. Borås, Sweden.

[5] Fahlén, P, Andersson, H, Ruud, S, 1992. Demand controlled ventilation systems. Sensor Tests. Swedish National Testing and Research Institute ISBN 91-7848-331-X

[6] Raatschen, W, 1991. Advanced Humidity Conrolled Ventilation - Case study. (Dornier GmbH.) January 1991. Fiedrichshafen, Germany.

[7] Raatschen, W, 1991. Advanced Humidity Conrol Device for the Prevention of Mould . Proceedings of the 12th AIVC Conference, vol. 2, September 1991, Ottawa, Canada.

[8] Raatschen, W, 1991. IEA Annex 18 - Demand Controlled Ventilating Systems - Sensor Market Survey. Report D:1992, ISBN 91-540-5417-6 Swedish Council for Building Research, Stockholm, Sweden.

[9] Till, C E, Handegord, G O, 1961. Proposed humidity standard. (National Research Council.) Research paper no. 134, September 1961. Ottawa, Canada.

Chapter 5: Control Principles

[1] ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality; Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers; 1989

[2] Fanger P.O. (1988); Introduction of the olf and decipol units to quantify air pollution perceived by humans indoors and outdoors; Energy and Buildings, Vol. 12, pp. 1-6; 1988

[3] Kegel B., Prohaska V., Schreiber A. (1991); Control algorithms for rooms with displacement ventilation; 12th AIVC Conference, Ottawa; September 1991

[4] Pejtersen J., Fanger P.O. (1991); Measurement of air pollution sources in buildings; CIB working group W77-Indoor climate, New Haven; September 1991

[5] Raatschen W. (1990); Demand controlled ventilating systems; State of the art review; Final report of the IEA-Annex 18, Subtask A; February 1990

[6] Stymne H., Sandberg M., Mattson M. (1991); Dispersion of contaminants in a displacement ventilated room - implications for demand control; 12th AIVC Conference, Ottawa; September 1991

[7] Liddament, M W: "A Review of Building Air Flow Simulation". AIVC Technical Note 33, March 1991.

Chapter 6: Feasibility Analysis

[1] Fantozzi C, Fracastoro G V, and Masoero M: "Assessing the performance of passive humidity controlled ventilation systems". 11th AIVC Conf, Belgirate, Italy 1990.

[2] Goodfellow H D: "Advanced design of Ventilation Systems for Contaminant Control". Elsevier, Amsterdam, 1985.

[3] IEA, Annex XIV Sourcebook "Condensation and Energy", March 1991.

[4] Raatschen, W., IEA Annex XVIII: "Demand Controlled Ventilating Systems - State of the Art Review". Swedish Council for Building Research, D9:1990, Stockholm, 1990.

Chapter 7: Dwellings

[1] Fehlmann I, Wanner H.U., Gay J.B. Air change rate and indoor air quality in bedrooms of well tightened residential buildings.

[2] IEA Annex XIV Condensation and Energy Sourcebook; March 1991

[3] Canada Mortgage and Housing Corporation. Demand controlled ventilation. A primer for builders and designers; March 1991.

[4] W. Raatschen. Advanced Humidity Controlled Ventilation; January 1991.

[5] Canada Mortgage and Housing Corporation. Demand controlled Ventilation. Final Report; March 1991.

[6] C. Roulet, L. Vandale. Airflow patterns within buildings, measurements techniques.

[7] CEN ITC 89: ISO DP 6946/2

[8] Seifert, B. Indoor air pollutant: sources, concentrations and control. IAQ Management CEC Workshop, Lausanne, 1991.

Chapter 8: Schools and Day Nurseries

[1] Isfält E.: Air exchange through open doors by thermal forces (in Swedish). Dep. of Build. Serv. Engineering, Royal Institute of Techn. Stockholm 1991.

[2] Shaw B.H., White W.: Air movement through doorways - the influence of temperature and its control by forced airflow. Building Services Research Unit, University of Glasgow. Building Services Engineering Vol 42, Dec 1974.

[3] Egedorf Morten: Ventilation demand in day nurseries (in Danish). Teknologisk Institut Forlag, Copenhagen 1987. ISBN 87-7511-803-3.

[4] Mundt Elisabeth: Temperature gradients and convectional flows in displacement ventilation (in Swedish). Dep. of Building Serv. Engineering, Roy. Inst. of Techn, Stockholm, Publ no 16, 1991. ISSN 0284-141X. Survey on allergic reactions, SOU 1989: 76-78.

Chapter 9: Auditoriums

[1] P.O. Fanger. New Principles for a Future Ventilation Standard, Indoor Air 90, Ottawa, Canada.

[2] Scanvac. Classified Indoor Climate Systems, Guidelines and Specifications R1-English version

[3] Skåret, Mathisen. Effektiv ventilasjon, STF15 A89015, SINTEF Applied Thermodynamics, Trondheim, Norway, 1989.

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Within the IEA (International Energy Agency) program on Energy Conservation 10 countries have co-operated in the project on Demand Controlled Ventilating (DCV) Systems. The main goal was to jointly develop a "Source Book".

Basis for the development has been State of the Art Review finalized 1989, Sensor Tests carried out 1991, and Case Studies 1990-91 as well as calculations.

In the first chapters this Source Book contains an outline of a strategy for DCV Systems, including an analysis of the prerequisites for their use. Pollutants and indicators and different types of usable sensors are described.

Various control principles have been developed for base ventilation and occupant related ventilation. A method has been developed to calculate the energy savings at a certain room air quality. Energy savings using DCV-systems in auditoriums has been shown to be 50%. The pay-off time is less than one year. In the last chapters are described the application of DCV-systems in dwellings, schools and day-nurseries, auditoriums, and offices.

The Source Book presents the application and the benefit of DCV but also the limitations and development needed.

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