



**International
Energy
Agency**

Demand Controlled Ventilating Systems

Case Studies

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Demand Controlled Ventilating Systems

Case Studies

Energy Conservation in Buildings and
Community Systems Program

Annex 18

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IEA Energy Conservation

Caution:

The information contained herein does not supersede any advice or requirements given in any national codes or regulations, neither is its suitability for any particular application guaranteed. No responsibility can be accepted for any inaccuracies resulting from the use of this publication.

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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) coordinates 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 System" 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 *

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.

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

The Annex 18 National Representatives, experts, and authors involved in the Case Studies are listed next. Full addresses, telephone numbers and fax numbers for the national representatives are provided in the Appendix.

Participants, experts, and authors of the case studies

In this annex 10 countries have participated. In the case studies have been involved a lot of experts. Those are generally the authors of the reports compiled in this book.

Country	Name affiliation	Annex 18 National Representative	Expert	Case study Author
Belgium	Peter Wouters, CSTC/WTCB	x	x	x
	P. Jardiner, Aereco, France			x
	J. Simonnot, Serva, France			x
Canada	Bob Davidge, Public Works	x	x	x
	Tom Hamlin, CMHC			x
	Peter Moffatt, Sheltair Scientific Ltd			x
Denmark	Peter Collet, Technological Geo Clausen, DTH	x	x	
Finland	Marianna Luoma, VTT	x	x	
Germany	Willigert Raatschen, Dornier GmbH	x	x	x
Italy	Gian V. Fracastoro, Politecnico di Torino	x	x	x
	Marco Masoero Politecnico di Torino			x
Netherlands	J.J.M. Cauberg	x	x	x
	Cauberg - Huygen Ing BV Hans J. Pfaff, TNO			x
Norway	Finn Drangsholt, NTH/SINTEF	x	x	x
Sweden	Lars-Göran Månsson	Operating Agent	x	
	LGM Consult AB			
	Sven A. Svernnberg	x	x	
	RAMAS/Royal Inst. Tech.			
	Hans Stymne, Nat. Swedish Inst. for Building Research (SIB)		x	x
	Mats Sandberg Nat. Swedish Inst. for Building Research (SIB)			x
	Magnus Mattsson Nat. Swedish Inst. for Building Research (SIB)			x
	Leif Norell, Fläkt IC		x	x
	Per Fahlén, Swedish Nat. Testing and Research Inst.		x	x
	Helena Andersson Nat. Testing and Research Inst.			x
	Svein H. Ruud Nat. Testing and Research Inst.			x
Ove Strindehag Fläkt/Chalmers Univ of Tech.		x	x	
Switzerland	Charles Filleux, Basler & Hofmann	x	x	
	Marco Zamboni, Basler & Hofmann			x
	Jürg Fehlmann Federal Inst. of Tech. (ETH)			x
	Claude-Alain Roulet, LESO, Lausanne			x

IEA Annex 5, Air Infiltration and Ventilation Centre (AIVC) is acting as a vehicle for disseminating the results of Annex 18.

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 five reports.

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

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.

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

Reports

The results of Annex 18 work are contained in five reports

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 Case Studies

The main purpose with the case studies was to demonstrate the technical possibilities implemented in various building types and give good examples how to save energy and offer acceptable indoor air quality.

With regard to the specific goals of IEA Annex 18 and the ongoing research work, a demand controlled ventilating system (DCV system) is defined in the following way:

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

In the first subtask of this Annex a State of the Art Review was undertaken. It was found that considerable research work had gone into DCV systems over the past 10 - 15 years. About 30 papers were identified. Of those papers were 21 reports of case studies (dwellings 3,

auditoriums 13, offices 5). Further details can be found in table 1:1

However, it was not easy to draw very definite conclusions. The results just indicated that there might be benefits for energy conservation and indoor air quality or both aspects. The aims of the various projects reviewed varied but could in general be grouped into the following categories

- * control system function (the sensor and the electronic equipment)
- * monitoring more than control function studies
- * energy savings
- * indoor air quality consequences

When reviewing the projects discussing energy savings one of the difficulties was that the comparison level was not easy to identify.

The conclusions from the review were:

DCV system benefits will vary depending on climate, building type, ventilation system design and occupancy patterns.

Energy savings must be well defined, and must always be reported in relation to a defined reference system. Using this reference system, different control strategies can be examined back times etc.. It is also very important to report savings with regard to the achieved air quality.

In many studies where the indoor air quality has been monitored

Table 1:1 Contents of reviewed papers. The codes are given in State of the art Review D9:1990 Swedish Council for Building Research Editor W. Raatschen

Contents of reviewed paper Code of reviewed paper	Building type			Control strategy						Savings		Others		Comments	
	office	halls, theatres, schools	dwellings	use of sensors	* air quality control	CO ₂ control	smoke control	vapor control	temperature control	time clock or manual or presence control	energy	costs	sensor location		user acceptability
1975/a		x				x					x	x			
1981/a				x		x					x		x		
1982/a		x				x					x	x		x	detailed calculat. techn
1982/b						x			x		x				
1982/c		x		x		x			x		x				
1983/a	x			x		x				x	x		x		
1983/b		x				x					x				
1983/c				x		x									
1983/d			x	x							x	x			passive system
1983/e			x												
1983/f		x		x		x			x						
1984/a						x								x	
1984/b		x				x							x		
1984/c		x				x	x				x				
1985/a	x			x	x	x	x								P, PI, PID-contr. comparison
1985/b		x		x	x	x									
1985/c			x								x				passive system
1986/a	x	x		x		x				x	x			x	
1986/b		x				x				x	x				
1986/c		x		x		x			x					x	
1987/a			x												theoretical approach
1987/b	x			x		x							x		
1987/c	x				x	x									
1987/d				x	x	x					x				
1987/e		x		x	x	x	x								
1987/f		x				x				x					
1987/g	x	x		x	x	x	x								
1988/a		x		x		x								x	
1988/b						x			x						
1988/c			x	x		x									passive system
1989/a		x		x		x									

*) air quality control means by use of a broad band sensor which reacts to non-oxidized gases

Table 1.2 Case studies reported

Country	Case studies								
	Lab tests	Dwellings			Office		Auditorium		Schools
		RH	CO ₂	Mixed gas	CO ₂	time	CO ₂	time	preence
Belgium		x							
Canada		x	x	x	x	x			
Germany		x							
Italy		x							
Netherlands		x		x					
Norway							x		
Sweden	x				x				x
Switzerland							x	x	

hundreds of various compounds have been identified. Most of those compounds can not be the governing pollutant, mainly because of a too expensive sensor or analyzing equipment. The main prerequisites are that the pollutants vary in time and the base level from the material is low compared to the occupant generated pollution. The prerequisites and control principles are in detail discussed in the Source Book.

The indicators and pollutants are identified to be carbon dioxide (CO₂) water vapour (RH=relative humidity), mixed gases. Within the Annex work detailed sensor tests have been reported separately.

Theoretical calculations gave that energy savings were possible to achieve with keeping an acceptable indoor air quality

Case studies have been made on DCV-systems in dwellings, schools, auditoriums, and offices. These building types represent about 80 % of all the volume in non industrial buildings. In table 1.2 is given an overview of the countries involved and the building types studied. The results from the Case Studies will give application hints for other building types described in Table 1.3.

The results of the case studies have been an important input into the Source Book in which is discussed

Table 1.3 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

how to use DCV systems in various building types.

The case study report is arranged in five chapters reporting on tests in unoccupied rooms and on tests in buildings in use.

Tests in unoccupied rooms

The first project reported gives the dispersion patterns from CO₂ generated by the occupants in an office with a ventilation system giving a mixing air flow pattern.

The second study is carried out in a single room with a displacement system. The result gives recommendations on sensor location in rooms equipped with such systems.

Dwellings

In four apartment buildings RH has been used as the governing indicator. Totally 35 dwellings equipped with RH sensors have been involved in the studies.

The studies in seven single family houses aimed to investigate combined RH and IAQ sensor, new developed RH sensor, RH sensor on market, CO₂ sensor, and IAQ sensor.

School

In most cases a classroom is occupied with a certain number of pupils. However the time when the room is used may vary from day to day. In this case a presence sensor was used to indicate the need for more outdoor air. The test was carried out in 4 classrooms of which one was equipped with a displacement supply air terminal device.

Auditoriums

Two case studies reporting results from a lecture hall with 320 seats and an auditorium with 80 seats. In both studies were used CO₂-sensors. In the Swiss study this strategy was compared to time control

Offices

All three reports are case studies on meeting rooms. In this type of a room the occupancy load is varying in time and strength. In administrative offices most of the occupants are present and can be predicted in time and location. Both CO₂ sensor control and time control have been used.

Conclusions

The conclusion of the case studies can be summarized with the following:

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

The examples presented are cases with a real background and must be suitably treated when used in an individual situation.

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

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

2 Tests in unoccupied rooms

- 2.1 Dispersion pattern of carbon dioxide from human sources (Sweden)**
- 2.2 Contaminant distribution and sensor position in a displacement ventilated room (Sweden)**

2.1 Dispersion pattern of carbon dioxide from human sources a factor to consider in demand controlled ventilation systems

Summary

Research institute:
**The National Swedish
Institute for Building
Research (SIB)**

**P.O. Box 785
S-801 29 GÄVLE
Sweden**

Researchers:
**Hans Stymne
Mats Sandberg**

Aim:
To draw conclusions regarding position of a sensor.

Means:
To study distribution pattern and variations of carbon dioxide concentration.

Carbon dioxide from (simulated) people distributes fairly evenly in a closed office room, but can show an irregular height distribution when the door to a connecting space is open. The distribution and room to room transfer of carbon dioxide is evaluated in a 4-room test building and is discussed in terms of its implication for CO₂-controlled ventilation.

Project description

Background

In the present work the dispersion pattern of carbon dioxide (CO₂) (from simulated people) is investigated in an indoor test building. The goal is to achieve useful general information regarding the distribution of carbon dioxide from human sources which is necessary in order to be able to design an optimal CO₂ controlled ventilation system. Carbon dioxide concentration has been widely accepted as a useful control variable in buildings with a fluctuating personal load.

Generally the aim of a demand controlled ventilation system is to keep the total ventilation flow rate to a building at the minimum required in order to meet with some air quality requirement for the people who are using it. In a well designed system an unnecessarily high ventilation rate is avoided, thus saving energy.

Some of the factors which must be considered when designing a CO₂-controlled regulation system in a multi-room environment, and the ventilation concepts that describe these, factors are

1. The transfer of carbon dioxide from the sources to different locations - **the transfer probabilities (P_{ij})**
2. The expected equilibrium concentration at a location - **the purging flow rate U_i**
3. The rate constant for approaching equilibrium from a non-equilibrium state - **the local mean ages of air τ_i**

4. Concentration fluctuations- amplitude and frequency of variations.

A short interpretation of the first two concepts is given below. A more detailed treatment is given in references (1, 2).

1. The **transfer probability** of a contaminant is the ratio between the rate at which a contaminant is transferred to a location *i* and that with which it is produced at a location *j*. Thus the total rate of transfer of a contaminant to a space *i* can be expressed as $r = \sum_{ij} P_{ij} \cdot m_j$ where m_j is the rate of contaminant production in space *j*
2. The **purging flow rate** of a space *i* is the equivalent fresh air flow rate which transports the transferred contaminant away from that space. Thus the equilibrium concentration in space *i* will be $c_i^{eq} = \frac{r}{U_i}$. The purging flow rate of a space *i* can be calculated from the transfer probabilities of air from several fresh air inlets *j*, each with a fresh air flow rate of q_j . $U_i = \sum_j P_{ij} q_j$

Building investigated

Indoor test building with four rooms.

Mixing ventilation.

Typical ventilation strategy for offices.

This investigation is carried out in an indoor test building of 175 m³ (see Fig. 1). The building contains four rooms connected to a common corridor via doorways. There is a balanced ventilation system with air inlets in the ceiling of each room. The air stream from an inlet port is directed along the ceiling towards the middle of the room and away from the doorway. Exhaust air is extracted from the corridor. Overflow of air from the rooms is made possible by means of openings (grills) above the doors. This type of ventilation system is not uncommon in offices in Sweden.

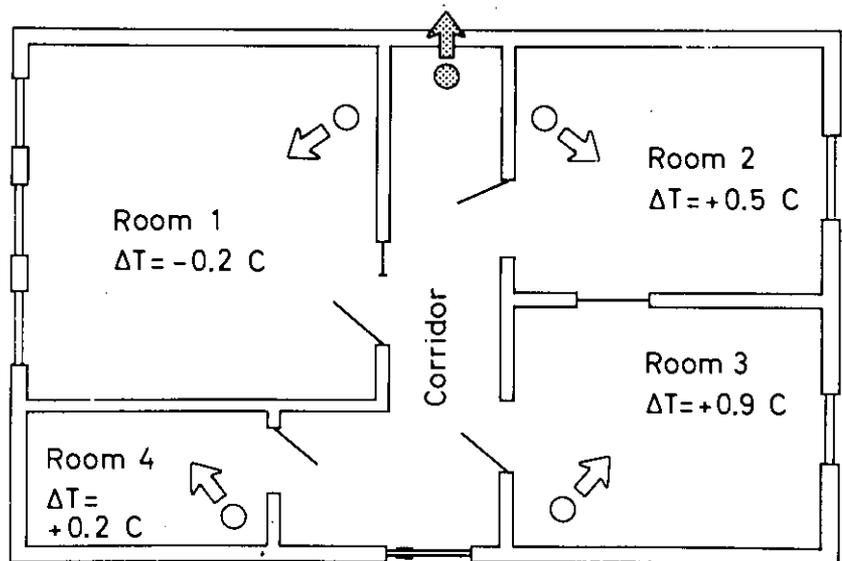


Figure 1. Plan of the test building. The south wall is an external wall of the laboratory hall, while all other walls are inside the laboratory hall. The ΔT -figures denote the difference between the mean room temperature and the temperature in the corridor when the room is a source room

Monitoring

Two different air flow rates:
 $120 \text{ m}^3/\text{h}$ and $240 \text{ m}^3/\text{h}$.

People are simulated by
 heated metallic dummies.

Carbon dioxide (25 l/h) are
 emitted from each dummy.

The fractions of the total ventilation flow rate into the different rooms are kept fixed at 37.5%, 25%, 25% and 12.5% to room 1, 2, 3 and 4 respectively throughout the whole experiment. The total flow rate to the building is changed between two values ($120 \text{ m}^3/\text{h}$ and $240 \text{ m}^3/\text{h}$).

People are simulated by metallic bodies which are heated from the inside by a 100 W bulb. Each simulated person continuously emits approximately 25 l of carbon dioxide per hour mixed with 0.6 m^3 pre-warmed air. The total flow rate of carbon dioxide and air is measured with a rotameter. The air is sampled at 19 different points inside the building and at one point outside of the building. Analysis of carbon dioxide and nitrous oxide concentration is performed by a non-diffractive infra-red photometer (Binos).

Carbon dioxide is spread in one room at a time via the simulated persons. The chosen loads are three persons in room 1, two in rooms 2 and 3, and one in room 4. Simultaneously with the emission of carbon dioxide, dynamically passive $\text{N}_2\text{O}/\text{He}$ tracer gas mixture is spread at a height of 30 cm above the floor level and 1 m away from the "persons". The experiments are carried out both with open doors and closed doors. Conventional tracer decay experiments and constant concentration measurements are also carried out.

Results

The bar graphs shown in figure 2 display the averaged concentration of CO₂ (ppm) at different locations in the 4-room office shown in Fig. 1. From left to right, the bars in a group represent the concentrations at 0.1 m, 1.2 m, and 2.4 m above the floor in the middle of the room. The last bar in a group represents the concentration in the overflow grill above the door, except in the corridor group, where it represents the concentration in the common extract in the corridor. All doors are open and one room is occupied by the indicated number of simulated persons. The nominal total ventilation flow rate is 240 m³/h. The bars are extended above the atmospheric background concentration (340 ppm).

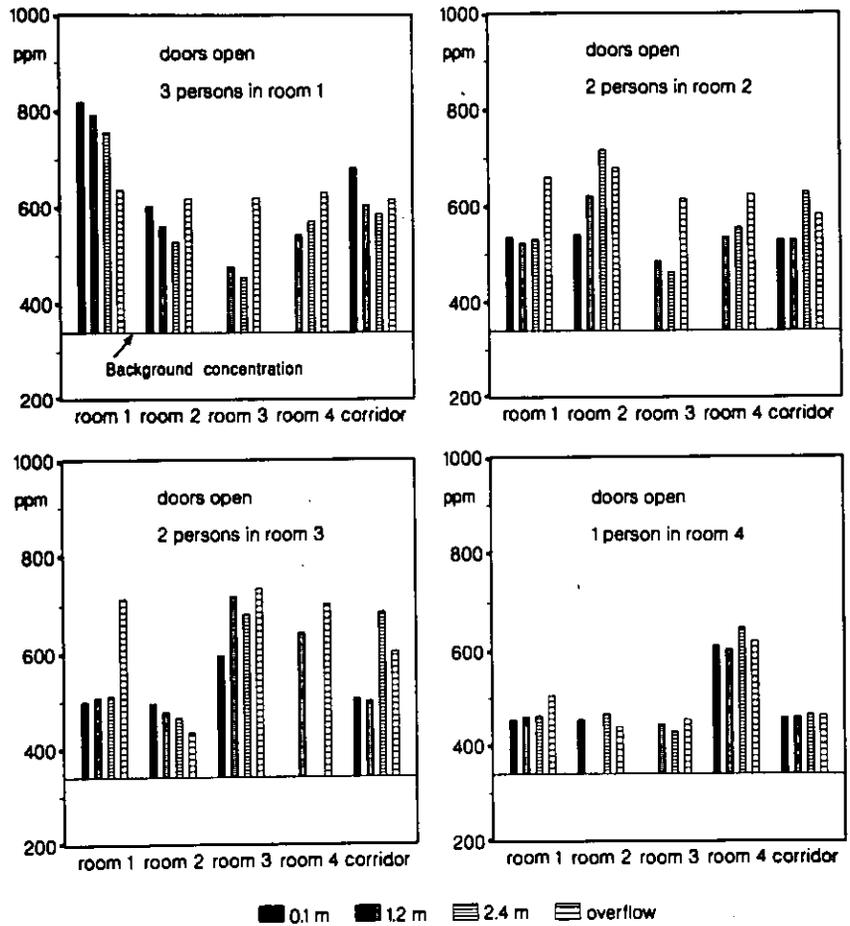


Figure 2

Discussion

Closed doors

The distribution is rather even, when the doors are closed.

The measurements show that when the door to an occupied office room is closed then a relatively good mixing is achieved within the room, with only a slight tendency for higher concentration of carbon dioxide at the ceiling level (max difference 10% of the room average $\Delta(\text{CO}_2)$). The concentration fluctuations are small. This means that the question of where to place the sensor is not a critical one. A tendency for a higher CO_2 concentration at the ceiling level in occupied rooms is a common observation. See Homma (3) for a classroom investigation and a literature review.

Open doors

Uneven distribution, when the doors are open.

When the doors are open the differences in concentration of carbon dioxide at different heights are more pronounced, not only in a source room, but also in unoccupied rooms connected to the corridor by open doors. Concentration differences as large as 75% of the room average $\Delta(\text{CO}_2)$ have been observed (room 2 as a source room at high flow rate). Generally there is no preferred direction of concentration increase. Referring to Fig. 2, the highest concentration can appear at the floor level (room 1), the ceiling level (room 2), or the mid level (room 3).

Air exchange through the door-ways affects the height distribution of contaminants.

A comparison between the distribution pattern of carbon dioxide and the simultaneously emitted nitrous oxide tracer gas shows great similarities. Accordingly, it is not the fact that the carbon dioxide is released in the air convection current around the heated bodies that determines the distribution pattern. The reason for the uneven distribution is the large air exchange through the open doorways and its interaction with other air movements set up by the convection currents around the heated bodies, the radiators, cold external walls, and the jet from the inlet duct.

Distribution is unstable - thermal disturbances can cause variations.

The air flow pattern is unstable, as can be seen from the relatively large standard deviation of the concentrations (10-20% of $\Delta(\text{CO}_2)$ in source rooms). This instability is dramatically illustrated in Fig. 3 which shows the observed carbon dioxide concentration in the different rooms when room 1 is the source room. The periodical oscillation was shown to be correlated with the on/off regulation of the radiators in room 1. Unlike the other rooms, room 1 had a large external wall with three windows.

The transport of air between a room and the corridor is primarily due to the air exchange through the door opening which is driven by air temperature differences.

Temperature differences between rooms determine the air exchange pattern.

The approximate air temperature differences between the rooms and the corridor are given (valid when the room acts as source rooms) in the plan of the building (Fig. 1). Much of the observations regarding concentration differences in a room can successfully be explained in terms of such temperature differences. For example, room 2 has a higher mean temperature than the corridor. Therefore air from the corridor enters at the floor level, giving a better dilution and a lower concentration at this level than at the ceiling level. In contrast to this, room 1 is cooler than the corridor and will show a reverse concentration gradient.

The transfer probabilities of contaminants and the purging flow rates determine the concentration levels.

The room to room transfer of contaminants and ventilation air can best be quantified in terms of the concepts transfer probabilities and purging flow rates. Though the transfer probabilities and purging flow rates are dependent on air temperature differences and ventilation air flow rate and distribution, it is of interest to know the magnitude of these factors as determined from tracer gas experiments in the present case.

Table 1 shows the experimentally determined transfer probabilities, purging flow rates, and mean ages of air in the different rooms with their doors open at two different nominal total flow rates. Values at the low flow rate (120 m³/h) are given within brackets, while those valid for 240 m³/h are given without brackets.

Table 1 Transfer probability matrix (P_{ij}), purging flow rates (U) and air mean ages (τ). Figures within brackets refer to a nominal total flow rate of 120 m³/h, while figures without brackets refer to 240 m³/h

	Source room				Purging flow rate m ³ /h	Mean age of air h
	I	2	3	4		
Room 1	1 (1)	0.5 (0.7)	0.3 (0.5)	0.5 (0.7)	145 (100)	0.69 (1.31)
Room 2	0.5 (0.7)	1 (1)	0.3 (0.4)	0.6 (0.8)	141 (93)	0.74 (1.43)
Room 3	0.3 (0.6)	0.3 (0.7)	1 (1)	0.4 (0.6)	152 (108)	0.75 (1.47)
Room 4	0.2 (0.3)	0.2 (0.4)	0.3 (0.4)	1 (1)	57 (53)	0.74 (1.38)

An example of how to use the table may be illustrative. A transfer probability of $P_{12} = 0.5$ from room 2 to room 1 means that 2 persons in room 2 contribute to the equivalent of carbon dioxide of 1 person (25 l/h) in room 1. However, the purging flow rate of room 1 is 145 m³/h, so if the 2 persons in room 2 are the only ones in the office then the $\Delta(\text{CO}_2)$ -concentration in room 1 will be $25 \cdot 10^{-3} / 145 = 172$ ppm, that is a CO₂ concentration of 172 + 340 = 512 ppm. Note that because the room to room transfer is

mainly due to air exchange through the door openings, the transfer probabilities will increase as the mean age of the contaminants increases, i.e. as the total ventilation flow rate decreases.

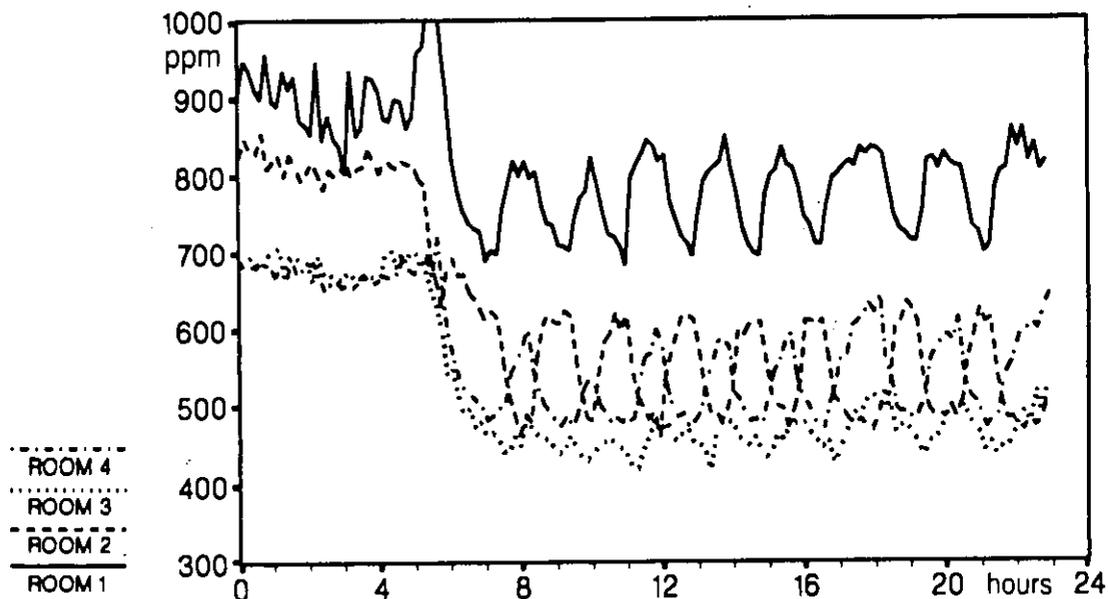


Figure 3 Concentration histories at 1.2 m height in the four rooms, when room 1 is the source room with three simulated persons. The total flow rate is 120 m³/h during the first 5 hours, thereafter 240 m³/h. The doors are open

Conclusion

The results and the conclusions below are valid only for the special type of ventilation system investigated here, but much of the reasoning is also useful for other systems, where short circuiting in the ventilation system is not a problem.

If a room is going to be ventilated by demand control then the position of the sensor is not critical if the doors to connecting spaces are normally closed.

However, if the room is connected to surrounding spaces by open doors then large differences and instabilities in the carbon dioxide concentration may occur, which implies problems both with regard to the positioning of the sensor and the possibility of achieving a stable ventilation control. It is not recommended to locate the sensor in an overflow duct. A sensor should preferably be placed at a mid-height in a room, and away from doorways, radiators, windows, people and air inlet devices. This requirement may not be possible to fulfill in practice. The regulation of ventilation air to a room must be made with a large time constant in order not to react to fluctuations.

Sensor position is not critical in a room with closed doors.

Difficult to find a satisfactory position for sensor, when the doors are open.

A large time constant is required.

One sensor in each room - to control the air distribution.
One sensor in the common extract - to control the total flow rate.

A regulation system for an office building must function satisfactory regardless of whether the doors to individual rooms are open or closed. In every room there should therefore be a measuring point which controls the distribution of ventilation air to the room. However, the total flow rate to the system can be governed by a sensor in the combined air extract.

Aknowledgement

This work was initiated by the IEA annex 18 "Energy Conservations in Buildings and Community Systems - Demand Controlled Ventilating Systems", and is partly financed by the Swedish Council for Building Research through grant no BFR: 880614-8, which is here gratefully acknowledged.

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2.2 Contaminant distribution and sensor position in a displacement ventilated room.

Summary

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**The National Swedish
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The distribution of contaminants in a laboratory test room with displacement ventilation has been experimentally investigated using a passive tracer gas technique. Contaminants are simulated by using two different tracer gases. Humans are simulated by heated metallic bodies. The distribution of tracer concentration in the breathing zone (exposure) is shown to be greatly influenced by both the position of the tracer source and the air convection current around the bodies. It is shown that pollutants emitted close to a body are completely and directly transported to the upper mixed zone and not mixed into the lower zone. Pollutants emitted at a weak heat source or close to a wall in the lower zone are transported to, but do not directly penetrate the boundary between the two zones, thus accumulating below the interface. By natural convection currents, occupants will draw uncontaminated air from the lower zone, and experience a better air quality at the breathing level than that of the surrounding air - even if the interface is below the head.

It is concluded that air quality demand control of the supply air flow rate is a suitable means of securing the excellent air quality possible in a displacement ventilated room. A carbon dioxide sensor should preferably be positioned, so that the interface height can be maintained at a level slightly above the head of the occupants.

Project Description

aim:

to draw conclusions on position and target value for sensor.

means:

study distribution pattern of contaminants.

The objective of this project is to investigate the possibilities and limitations of utilizing a demand controlled ventilation strategy in a room ventilated by the displacement principle. More specifically, the dispersion patterns of carbon dioxide from humans and contaminants from other sources are investigated in order to draw conclusion about the most suitable position of a carbon dioxide sensor for demand control of the ventilation rate in a room ventilated by displacement. In addition, a suitable target value for the carbon dioxide concentration is discussed.

Background

The background is only shortly given here. A more comprehensive analysis is given by Stymne *et al.* (1991).

Principles for ventilation by displacement

The principle of ventilation by displacement is schematically illustrated in figure 1. Low temperature "clean" air is supplied at the floor level, whilst warmed polluted air is extracted at the ceiling level. Heat and pollutants are transported from the lower part of the room to the upper part mainly by the plume flows generated by internal heat sources (e.g. people, machines). Essentially, two zones are created in the room - one lower displacement zone with "clean" air and one upper, mixed zone, which is contaminated with pollutants from the heat sources. The height of the interface between the two zones is controlled by the ventilation air flow rate and the power of internal heat sources.

Displacement ventilation not suitable for heating.

Polluted air in upper zone.

Clean air in occupation zone

Interface between clean and polluted air.

No contaminant transport from upper to lower zone.

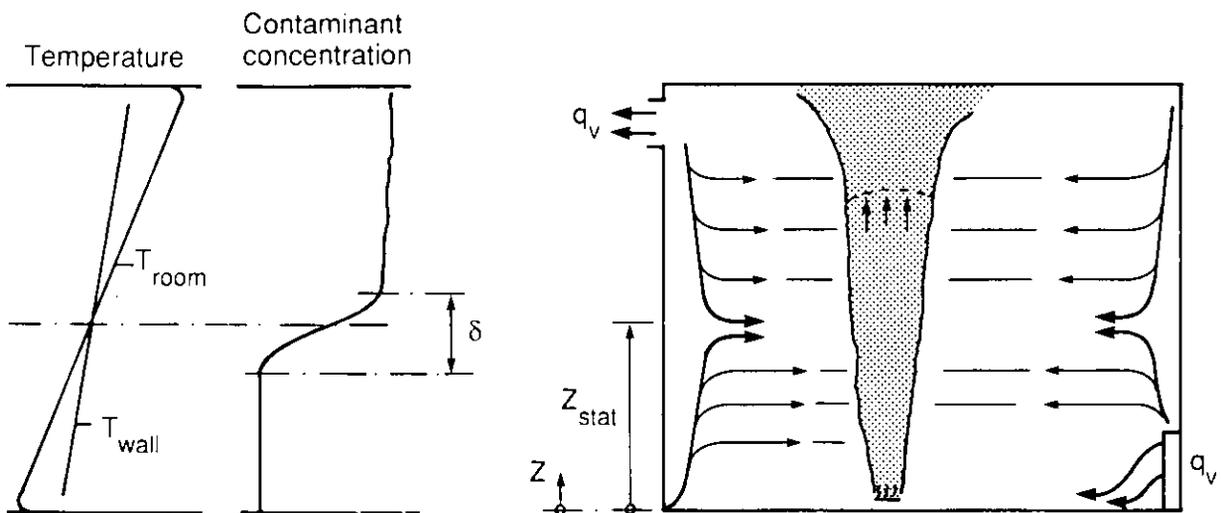


Figure 1 Principle of ventilation by displacement

Possibilities for demand control

The principle of demand controlled ventilation is to continuously adjust the flow of ventilation air to the lowest possible rate to meet an air quality demand. In rooms where the contaminant release rate shows large variations in time, such control could yield substantial energy savings. This energy savings comes from reduced power for heating or cooling of unnecessary ventilation air and reduced power for fans when the demand for ventilation air is below the design level due to decreased contamination rate.

Demand control saves energy.

Figure 2 schematically shows how the distribution of contaminants depends on the ventilation air flow rate in a displacement ventilated room. It is also indicated how the flow can be minimized to meet an air quality demand in the breathing zone.

The ventilation flow rate determines the level of the interface.

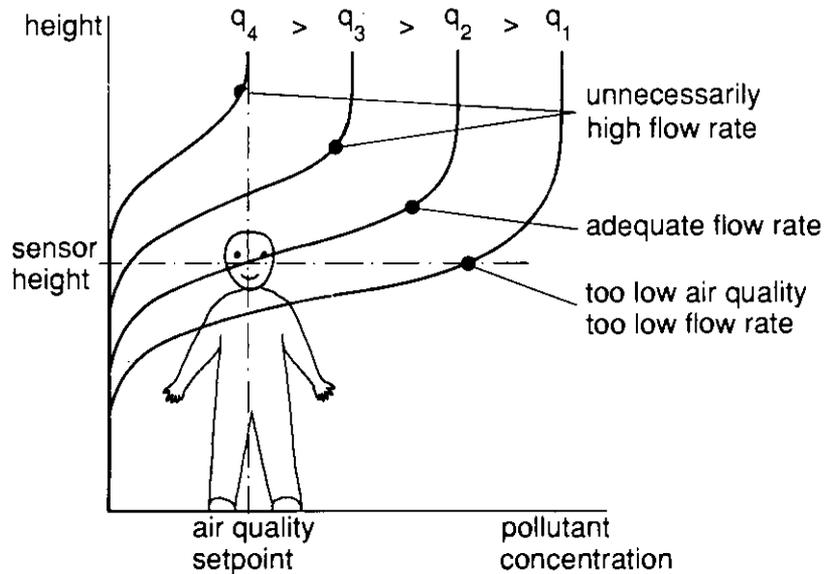


Figure 2 Principles for demand control of ventilation rate in a room ventilated by displacement.

Ventilation demand contra cooling demand

In a displacement ventilated system, the cooling need can often be more critical for the demand of supply air flow rate, than are common criteria for good air quality. This is because the cooling demand must be satisfied with under-temperature of the supply air and that too low supply air temperatures can not be tolerated. This would lead to discomfort due to both the low temperature at the floor level and a steep vertical temperature gradient. An acceptable under-temperature of the supply air is 5-7 K. A special air diffuser equipped with an induction chamber which allows a ΔT of 10K has, however, been suggested (Holmberg et al. 1990).

Displacement ventilation is especially advantageous when there is a high demand of good air quality. It can also advantageously be used in rooms where unusually polluting activities, such as smoking, are present. An acceptable breathing zone air quality can be achieved even in this extreme case, without increased demand for ventilation air, because the interface level is determined only by the strength of the heat sources - not the pollutant emission rate.

Cooling demand may control the necessary air flow rate.

Especially advantageous when there is a high demand for excellent air quality or, when there are specially polluting activities.

Air quality sensor

The control of the ventilation rate in a demand controlled ventilation system is usually governed by feedback from an air quality sensor. Two crucial questions are, **where to position the sensor** and **what set point (target value)** of air quality should be used.

Air quality target value

Because there is no way of directly measuring the air quality as such, it is necessary to use some easily measured air quality indicator.

In surroundings where people themselves and their activities are the main pollutant sources, the carbon dioxide concentration is a useful indicator. The target value of carbon dioxide concentration to yield an acceptable air quality, is however dependant on type of human activity.

The background concentration of carbon dioxide is 340-380 ppm. People contribute with 15-25 liter per person and hour for light body activity. In absence of other pollutant sources than people, 1000 ppm is usually recommended as the highest recommended value in indoor air. This recommendation is based on the perception of human odour by newly entered visitors in the room.

However, in connection with demand control a somewhat lower value (700-800 ppm) is usually recommended as a target value.

Sensor position

The most common type of ventilation strategy is the so called mixing ventilation. With this type of ventilation one tries to attain as good mixing as possible between ventilation air and the polluted room air in order to dilute the contaminants. However, there always are some spatial variations of contaminant concentration due to incomplete mixing, especially in rooms with open doors (Stymne et al 1990). Though it is not self-evident where to position a sensor in a mixing ventilation system, it is not a very crucial question in a wellbehaved system.

In a room ventilated by displacement on the other hand, one tries to avoid mixing between the ventilation air and the polluted air, so this type of ventilation constitutes an example of extremely uneven mixing. The behaviour of demand control is therefore strongly dependant on the position of the sensor.

CO₂-target value must be chosen depending on the activity.

800 ppm is usually adequate.

Sensor location more crucial on displacement ventilation than in mixing ventilation.

Building investigated

Site and location

Laboratory test-room.

The test space used for this investigation is a full scale office room module built in the laboratory hall of the ventilation laboratory at the Swedish building research institute.,

Building form

Dimensions:

4 x 3.45 x 2.5 m (LxWxH)

The dimensions of the room is 4m x 3.45m (L x W) with 2.5 m height. The four walls are insulated with 5 cm styro-foam, while the floor, which is elevated above the concrete floor of the laboratory hall consists of a 2.5 cm hard particle board covered with a 1.5 cm plywood sheet. The ceiling consists of un-insulated glass panels.

Zone investigated

Simulated personal load.

Sitting persons are simulated by dummies constructed from metallic air duct tubes (20 cm diameter). The dummies which are of 135 cm height are heated from the inside with two bulbs (60 + 40 W). One or two dummies are used in the experiments. They are positioned in the measurement plane which divides the room into two equal halves. The ventilation air is entering from the supply unit at the center of a wall parallel to the measuring plane.

Local ventilation system

Low velocity air supply unit.

The room is equipped with a conventional low velocity air supply unit with a face area of 0.15 m^2 (22% perforation degree) at the floor level. The extract terminal is situated on the same wall as the supply unit 0.2 m below the ceiling.

Air flow rate:

$80 \text{ m}^3/\text{h}$ (2.3 room volumes per hour).

The experiment is carried out with nearly balanced flows, leaving a slight overpressure in the room. The supply air flow rate is appr. $80 \text{ m}^3/\text{h}$ (2.3 room volumes per hour) and its temperature is kept at appr. 17°C .

Balanced ventilation.

Demand control strategy

No demand control strategy is used.

The aim of this investigation is to draw conclusions about a suitable strategy for demand control in a room ventilated by the displacement principle. This is done by a detailed study of the dispersion pattern of contaminant dispersion during constant contamination and heat load. No demand control strategy was therefore used during the experiment.

Monitoring

Two different tracer gases simulate pollutants.

Integrating monitoring with passive samplers.

Passive tracer gas technique.

Two different tracer gases in permeation tubes were used to simulate pollutants. One tracer source (perfluorbenzene or PB for short) was positioned close to the ceiling (away from the measuring plane) in all experiments. The other tracer source (perfluormethylbenzene, PMB) was positioned in the measuring plane in the lower part of the room to simulate pollutants emitted in this region. 150-200 passive sampling tubes for tracer gas made up a grid of measurement points in the measuring plane. The sampling tubes were positioned closer to each other in interesting regions. The integrating sampling was allowed to continue for 1-3 weeks under steady conditions. After an experiment, the passive samplers were analysed for the amount of adsorbed tracer gases with a gas chromatograph (GC) equipped with an electron capture detector (ECD). The analysis technique is described elsewhere (Stymne & Eliasson 1991). During an experiment both the vertical air temperature and wall temperature distributions were intermittently monitored.

Three different experiments with displacement ventilation are reported here:

Tracer close to a body.

- *Two heated dummies - one tracer source close to the ceiling and one tracer source close to one body.*

Tracer close to a weak heat source.

- *Two heated dummies - tracer source above an extra 4 W heat source between the bodies.*

Tracer close to a wall.

- *One heated dummy - both tracer gas sources located close to a wall in the measuring plane - one in the upper part of the room and the other in the lower part of the room.*

For comparison an experiment with mixing ventilation was carried out with the same tracer positions as in a above.

Results

The results of the measurements are displayed in graphic form in figures 3-8. The figures show the two-dimensional interpolated iso-concentration lines in the measuring plane. All concentrations are given relative to that found in the extracted air. Also displayed are the positions of the dummies and the tracer gas sources. In figure 3, the vertical temperature gradients in the air and at the wall are also shown.

Below are the main findings from the tracer gas distribution measurements.

Two heated dummies - tracer close to one body

Interface below head level.

Local upward displacement of interface around people.

Fig. 3 shows how a tracer emitted in the upper zone is spread when there are two heated dummies in the room. The interface is at a height lower than the "breathing level" - at 0.85 m above the floor. Evidently, the ventilation flow rate (11 l/s, person) is too low to raise the interface above the head of sitting people. However, it is also obvious that there are regions above the heat sources that are depleted of tracer gas due to the dilution from the plume flows. This behaviour has also been observed by Holmberg et al (1990). The interface between the lower clean air zone and the upper contaminated zone is locally displaced appr. 0.2 m upwards around the heated bodies. In the upper zone, the tracer is otherwise relatively well mixed. The thickness of the interface is less than 0.2 m.

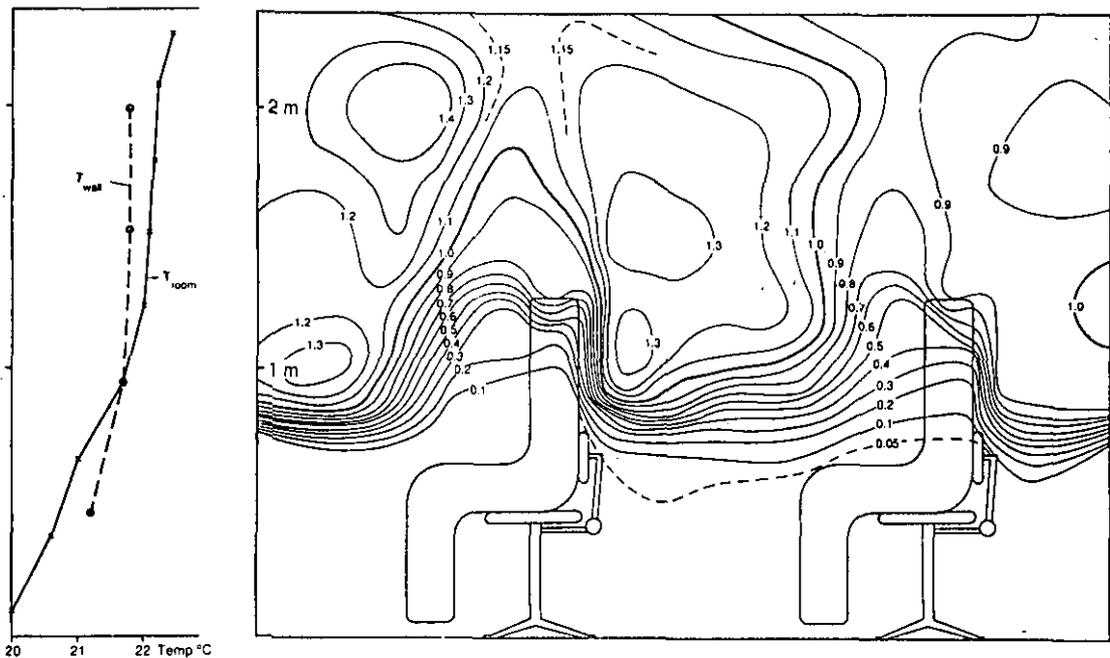


Figure 3 Iso-concentration map showing the dispersion pattern of a tracer gas emitted close to the ceiling. The concentration figures are given relative to the concentration in the extract. The dummies are situated in the measuring plane and are heated with 100 W power. Also shown are the vertical temperature profiles at the wall and in the room air.

Plume flow injects pollutants into upper zone.

People are "flushed" with fresh air.

Figure 4 shows the dispersion pattern of a tracer emitted close to one heated dummy. The tracer is directly and completely transported into the upper mixed zone. Moreover, it is apparent, that, although the "heads" of the dummies are above the transition zone, a person at that level is exposed to pollutants emitted from the other person to only a limited extent. This is due to the fact that the contaminants are transported directly to the upper zone and that each person is fed by fresh air from the lower zone.

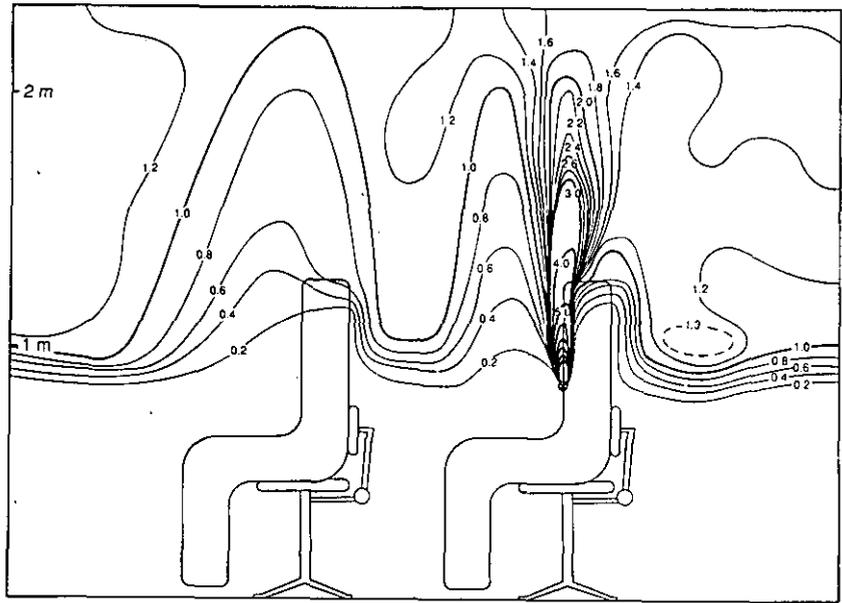


Figure 4 Iso-concentration map showing the dispersion pattern of a tracer gas emitted close to one of the two heated dummies. Concentrations are given relative to that in the extract

Two heated dummies - tracer at a low power heat source

Contaminants from low power heat sources accumulate below the interface.

Fig 5 shows how pollutants emitted from a low power heat source (4 W) do not penetrate directly through the interface. On the contrary they accumulate just below the interface and are transported into the upper zone only at the "holes" generated by the heated bodies. There is, however, only limited mixing within the lower zone. This type of accumulation of contaminants below the interface has been observed earlier (Sandberg & Blomqvist 1989).

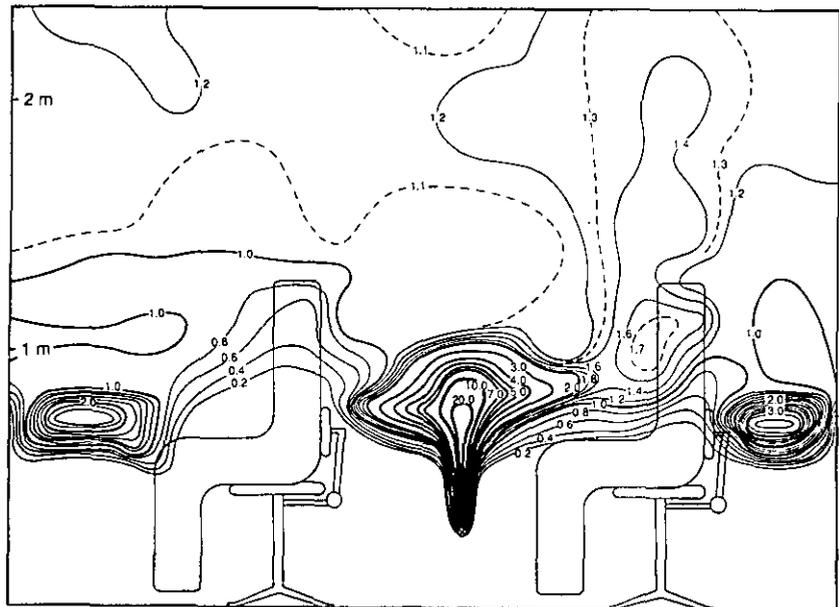


Figure 5 Iso-concentration map showing the dispersion pattern of a tracer gas emitted directly above a 4 W heat source in the lower zone. Concentrations are given relative to that in the extract.

One heated dummy - tracer close to a wall

Fig 6 and Fig 7 illustrate how a contaminant emitted close to a wall is transported in a room. In this case only one heated dummy was used, but the ventilation flow rate (22 l/s) was kept the same. Consequently the interface now appears at a considerably higher level (1.8 m).

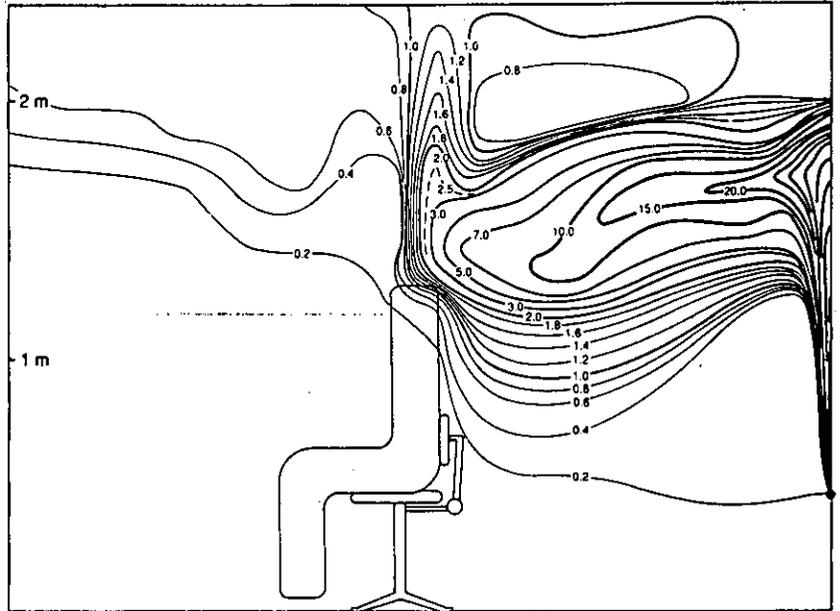


Figure 6 Iso-concentration map showing the dispersion pattern of a tracer emitted close to the wall in the lower zone. One heated dummy is present. Concentrations are given relative to that in the extract.

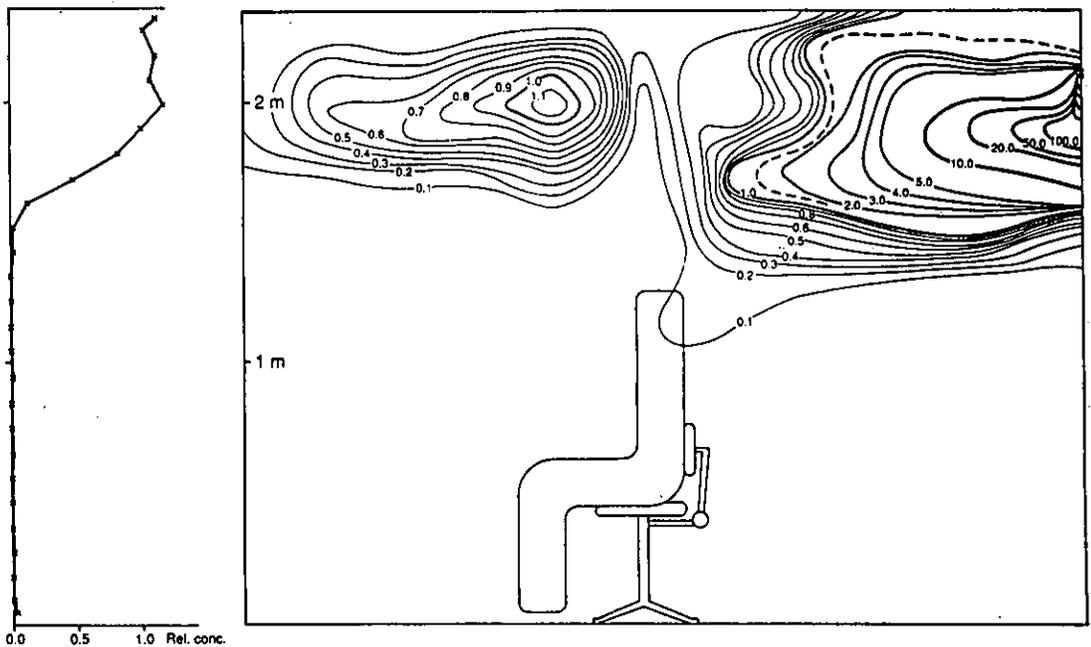


Figure 7 Iso-concentration map showing the dispersion pattern of a tracer gas emitted close to the wall in the upper zone. Concentrations are given relative to that in the extract. Also shown (to the right) is the vertical concentration profile of a tracer released close to the ceiling.

Vertical convective flow along walls transport contaminants towards the interface.

Fig. 6 shows how the tracer released close to the wall in the lower zone, follows the wall upwards. When it reaches the interface it is deflected and transported along the interface to the plume, where it is entrained and transported upwards.

Fig 7 shows how the tracer released close to the wall in the upper zone flows downwards along the wall until it reaches the interface, before mixing into the upper zone. No evidence of the tracer emitted in the upper zone is found in the lower zone.

The observed behaviour can be explained by considering the heat balance in the room. In the lower zone, the wall temperature is higher than the room air temperature, whilst the conditions in the upper zone are the opposite. On the whole, the vertical temperature gradient of the walls is less steep than in the room air. This behaviour is illustrated from measurements displayed in fig 2. The levelling out of temperature differences at the walls is due to the radiative heat transfer between the surfaces in the room. The center of the interface is found at a "neutral point" where the wall temperature is equal to the room air temperature. The created temperature differences between the walls and the room air will cause natural convection flows downwards above the neutral point and upwards below the neutral point. The observed kind of flow pattern has been noticed earlier in water model experiments (Sandberg & Lindström 1990).

Mixing ventilation

Mixing ventilation:

Plume flow still important.

Effective mixing in the rest of the room.

One experiment with mixing ventilation, utilizing a high velocity supply device close to the ceiling was also carried out.

As seen in figure 8 the plume flow above the dummies were not affected, This is evident from the locally high tracer concentrations above the tracer gas source located close to one dummy. The concentration profile over the dummy shows that the plume extends nearly unaffected to the roof level similarly as shown in fig 4. Outside the plume, however, the tracer concentration was uniform in the whole room and close to the concentration found in the extract. This indicates a complete mixing of contaminants in the supply air.

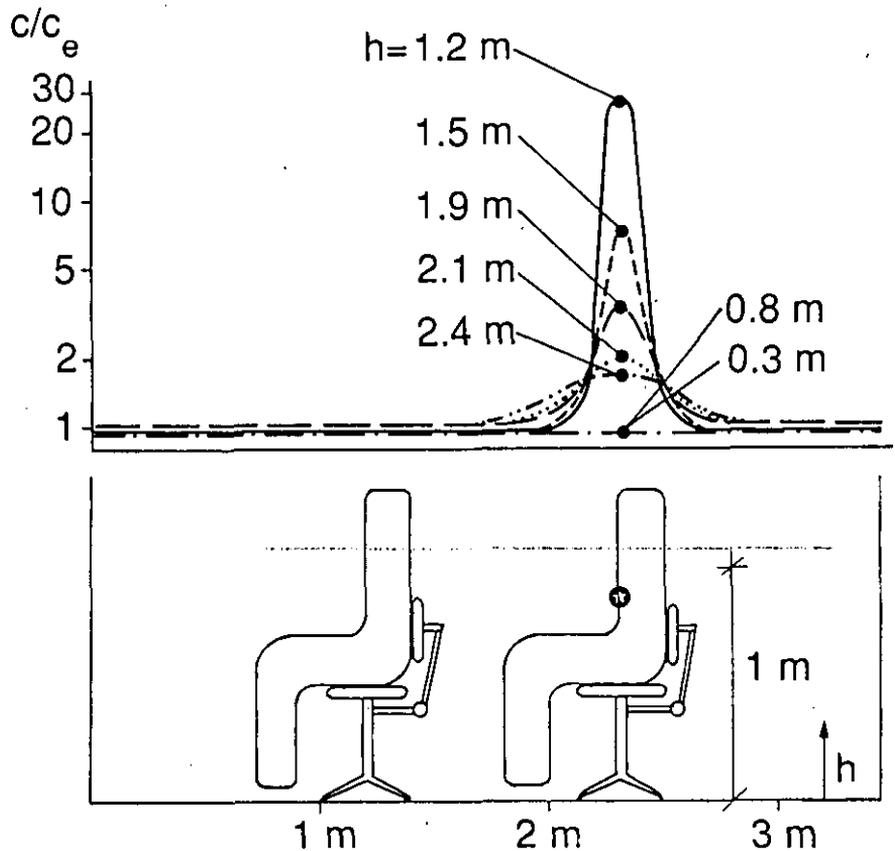


Figure 8 Mixing ventilation. Concentration profiles at different heights above the floor. The tracer gas source is positioned close to the heated body at 0.85 m height.

Discussion

It should be noted that this laboratory experiment has a number of limitations, which make conclusions uncertain for behaviour in a real case. The main limitations are the absence of normal disturbances such as:

A number of normal disturbances are not accounted for in this study.

- Body movements
- Breathing
- Heat sources other than people
- Lighting
- Solar heat gain

The disturbances mentioned contribute to a more or less increased mixing, and consequently a lowering of the interface level. In the extreme case, there will be a complete disappearance of temperature and pollutant stratification.

There are few detailed measurements reported for real occupied rooms with displacement ventilation. There are, however, indications that the interface is lowered, and the thickness of the transition zone increased, by mixing actions created by human movement. The local displacement of the interface around heat sources are probably especially influenced by such movement.

Concentration fluctuations caused by disturbances.

Sensor time constant is important.

Disturbances may modify the conclusions.

Interface as low as possible in order to save energy.

Interface above breathing-zone in order to guarantee good air quality.

Use the sensor to control the level of the interface.

Sensor at head height.

CO₂-target value 500 ppm.

Sensor away from people, heat sources and walls.

There are probably large local fluctuations of the carbon dioxide concentration. Such fluctuations can severely influence the behaviour of a demand controlled system governed by the carbon dioxide concentration close to the interface. The amplitudes and frequencies of such fluctuations caused by human movement, and other disturbances must be investigated further, before any firm conclusions can be drawn on the set point and location of the air quality sensor. A proper time-constant must be introduced in the regulation system.

For the time being it is not possible to estimate the effect of such disturbances. The conclusions are mainly valid for the extreme case of no such disturbances.

Concentration setting and location of an air quality sensor

The leading principle for controlling a displacement ventilation system by demand should be to establish the interface as low as possible, whilst at the same time allowing people to breathe air from the lower zone. This would secure the lowest possible flow rate from an air quality point of view.

To ensure the excellent air quality achievable with displacement ventilation, it is important to adjust the supply air flow rate, so that the interface level appears above the breathing zone of the occupants.

Demand control of supply air governed by an air quality sensor seems to be an excellent means of controlling the level of the interface. Carbon dioxide is a suitable indicator, both because it is emitted from heat sources (people) and because it indicates the presence or absence of people, requiring air quality control.

To ensure that the interface is at a sufficiently high level, the sensor should be located at the same height as the normal breathing zone. For sitting people this is at appr. 1.1 m above the floor.

The set point for the carbon dioxide concentration at the sensor position should be appreciably lower than that normally suggested for mixing ventilation (700-1000 ppm, $\Delta\text{CO}_2 = 350\text{-}650$ ppm). A reasonable value might be 500 ppm ($\Delta\text{CO}_2 = 150$ ppm). This value is low enough to ensure that the mixed zone is above the height of the sensor, but not so low that the interface is far above the sensor.

To monitor a typical concentration at this level the sensor should not be positioned in the vicinity of people or heat sources. Nor should it be positioned very close to a wall, because of the natural convection currents occurring along the walls mentioned earlier.

At a set ΔCO_2 -value of 150 ppm a demand controlled system will respond quickly even for one person present in a room of normal size.

Thermal comfort considerations

The temperature of the supply air must also be controlled.

As in the case of a mixing ventilation system, there must be some indicator and feed back system for temperature and thermal comfort. While, in a mixing system the thermal comfort can be regulated with radiators, convectors etc., the thermal comfort in a displacement system has to be regulated by means of the temperature of the supply air.

Keep temperature gradients small.

The criteria for thermal comfort in displacement system, not only refers to the average room temperature, but also to the vertical temperature gradient and the supply air temperature. The temperature difference between 0.1 m and 1.1 m should not exceed 3K according to ISO/DIS 7730 (1984). An even lower difference (e.g. 2K) might be necessary in connection with displacement systems. The supply air temperature should not be lower than 17°C and the difference in temperature between extract and supply air should not exceed 7K.

30 W/m² maximum cooling load.

The regulation interval for the supply air temperature (17°C-21°C) is rather limited. Internal heat loads of more than 30 W/m² can hardly be taken care of without thermal discomfort (Wyon & Sandberg 1990).

Conclusions

The following conclusions refers to a ventilated space of simple geometry, where the air movement is not disturbed by the mixing action of human movement.

It has been shown from tracer gas distribution experiments, that pollutants emitted from a (simulated) person are transported directly to the upper mixed zone in a space ventilated by displacement system. Pollutants emitted close to a wall or a weak power heat source in the lower zone flow towards the interface between the zones, but do not directly penetrate to the upper zone. They are accumulated below the interface and transported to the upper zone only at the "holes" generated in the interface by the natural convection plumes from the heated bodies.

The interface is locally displaced upwards around the heated bodies, thus ensuring the occupants a better air quality than in the surrounding air, even if their heads are below the interface level. Pollutants, which are emitted in the upper mixed zone or transported to that zone from the lower zone do not appear in the lower zone.

It is also shown that the plume above a heated dummy is similar in a mixing ventilation system compared to the plume created in a displacement ventilation system. However, outside the plume, there is no sign of any vertical concentration stratification in the case of mixing ventilation.

It is concluded that demand control of the supply air flow rate in a room ventilated by displacement is a suitable means of controlling the level of the interface between uncontaminated air in the lower zone and the mixed upper zone. The location of an air quality sensor for demand control should preferably be positioned at the height of the heads of the occupants, thereby ensuring an excellent air quality in the breathing zone at the lowest possible air flow rate. The concentration set point for the sensor should be at an appreciably lower value than that normally considered to be appropriate for the air quality (e.g. 800 ppm CO₂). A suggested value is 500 ppm. Otherwise, thermal factors will control the air flow rate and the air quality sensor would seldom take the control.

Acknowledgements

This work was initiated by the IEA annex 18 - Demand Controlled Ventilation. It has been partly financed with grant BFR-880614-8 from the Swedish Council for Building Research, which is here gratefully acknowledged.

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3 Dwellings

- 3.1 H₂O Controlled Ventilation in a 9 Storey Apartment Building in Namur (Belgium)**
- 3.2 H₂O Controlled Ventilation in a 10 Storey Apartment Building in Schiedam (Netherlands)**
- 3.3 H₂O Controlled Ventilation in a 4 Storey Apartment Building in Paris (France)**
- 3.4 Performance assessment of a humidity controlled ventilation system in Northern Italy (Italy)**
- 3.5 A demand controlled balanced ventilation system in an energy efficient dwelling in practice (Netherlands)**
- 3.6 A Demonstration of Low Cost DCV Technology on Five Canadian Houses (Canada)**
- 3.7 Advanced Humidity Controlled Ventilation (Germany)**

3.1 H2O CONTROLLED VENTILATION IN A 9 STOREY APARTMENT BUILDING IN NAMUR (B)

Project description

Introduction

Research participants :

- WTCB/GSTC, Brussels (B)
- TNO Building division, Delft- (NL)
- CETIAT, Orsay(F)
- EDF(F)
- Aereco(F)

Contact person :

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B.B.R.I.
32/2/653.88.01
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Belgium

This case study is the second building of 3 buildings which were monitored in the framework of a CEC demonstration project on humidity controlled natural ventilation.

In order to stimulate the introduction of new technologies, the Commission of the European Communities (CEC), DG XVII promotes the testing of such new technologies by supporting demonstration projects.

In 1986, the CEC accepted the proposal to support a demonstration project on the humidity controlled natural ventilation system of the French firm Aereco.

In important boundary condition in order to get CEC support was the application of the technology in at least 50 apartments. In order to achieve this, it was decided to perform tests in buildings in Les Ulis(F), Namur(B) and Schiedam(NL). The measurement campaigns as well as the majority of the analysis were finished at the beginning of 1992.

Given the fact that the results and conclusions differ very much for the 3 buildings, 3 different case studies are reported. In order to avoid duplication of the common aspects in the 3 case-studies, the reader is suggested to first read this case-study on the Schiedam building in which more detailed information can be found.

Objectives

The major objective of this study was the evaluation of the impact of the humidity controlled natural ventilation on the energy demand and the indoor air quality.

Energy saving through humidity control

Improved indoor air quality

Comparison of reference and humidity controlled apartments.

The monitoring campaigns aimed also to allow a better indication of the limits of applicability of the system as well as indications for further improvements. Furthermore, it was expected that the very intensive monitoring campaign would also give a lot of information on natural ventilation in general as well as on pollutant concentrations and emission rates (CO₂ and H₂O)

The main work focused on the comparison of so-called reference apartments (R) which have a more classical natural ventilation system and the so-called humidity controlled apartments (H). In the Namur building, 9 reference apartments and 9 humidity controlled apartments were intensively monitored during more than 100 days.

Building and Site

Climate Namur :

Winter average temp. : 6 °C.

60 km from Brussels

The field measurements were carried out in a 9-storey apartment building in Namur, 60 km East of Brussels. The building is in an unsheltered position.

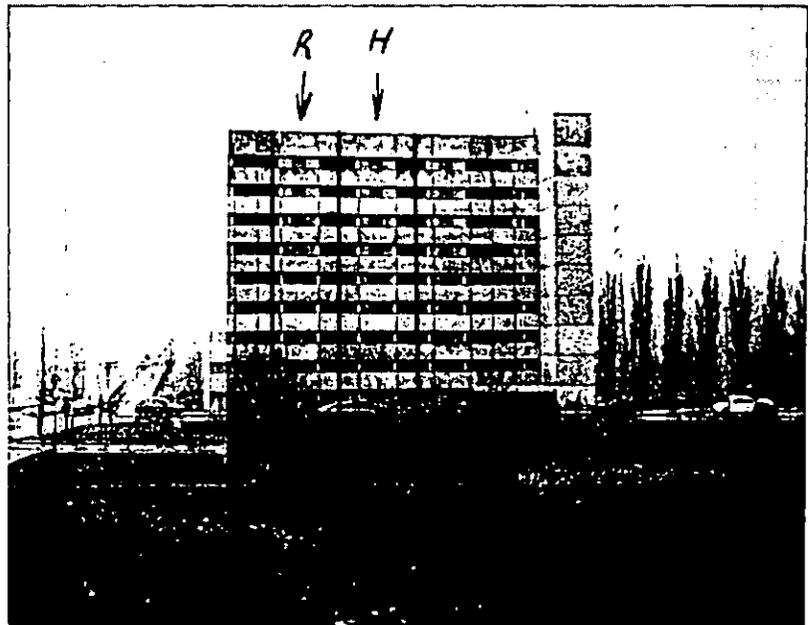


Figure 1 : The Namur building (monitored apartments indicated with R(eference) and H(umidity))

INVESTIGATED BUILDING

Apartments

Area : 66 m²

Volume : 165 m³

3.3 occ./apartm.

9 Ref. Apartments
9 Humid. Apartments

The building dates from 1978. All the investigated apartments are identical 2-bedroom apartments. The reference apartments are symmetrical to the humidity controlled apartments. They are terraced apartments which means that the entrance door is a balcony door. This is very exceptional in Belgium.

This building was selected out of 7 visited buildings. The reason for selecting this building was the fact that there were already natural ventilation ducts of the Shunt type in the bathroom and in the WC. Their cross section was sufficient. It is not evident to find apartment buildings in Belgium with such ductwork. Unfortunately, no ventilation duct existed in the kitchen.

This apartment building is the property of a local society for social housing. The average occupation is rather high and in most of the apartments, at least 1 person is at home during the whole day.

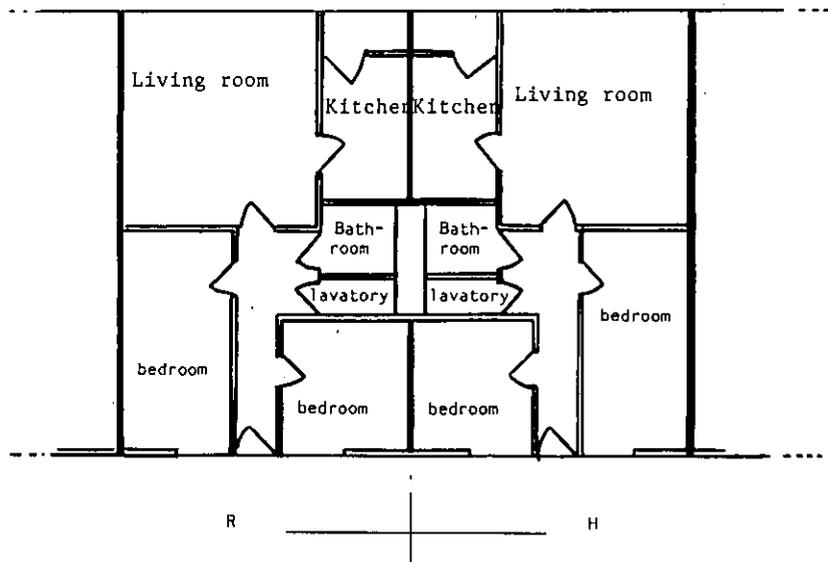


Figure 2 : Ground plan one reference and one humidity controlled apartment of the Namur Building

Heating and ventilation system

Heating : hot water radiators

All apartments are equipped with hot water radiators. There is a central boiler for the whole building.

Natural ventilated apartments with shunt ducts

The calculation of the energy bill is based on evaporator meters.

All bedrooms in this building are situated at the corridor side. They dispose of a window ($0.3 \times 1.2 \text{ m}^2$) which is protected by a large wooden store (see fig.3) This is also rather unique.

In the framework of preparing the monitoring campaigns, extensive preparation work was required.

Range of operation :

R.H. < 30% : minimum opening

R.H. > 70% : maximum opening

Supply : living room and bedrooms

Extraction : kitchen, bathroom and WC



Fig. 3 : view of bedroom window with large ventilation grill

Air supply provisions in the living room of the reference apartments were added. In each bedroom, a rather large grill in line with the Belgian standard NBN D50-001 was installed in one of the openable windows.

In order to have exhaust ventilation in the kitchen, a natural ventilation ductwork system (Shunt) was installed in all the apartments.

In the humidity controlled apartments, 1 humidity controlled air supply grill was installed in each of the bedrooms. Two grills were installed in the living room. All extraction openings in kitchen, bathroom and WC were equipped with the humidity controlled extraction grill. For more details about the characteristics of these devices, see the case study of Schiedam.

The cowl on the roof was not appropriate and resulted in problems of reverse flow. In order to solve this problem, a modified cowl was installed after the first monitoring campaign. After this modification, problems of reverse flow were almost eliminated.

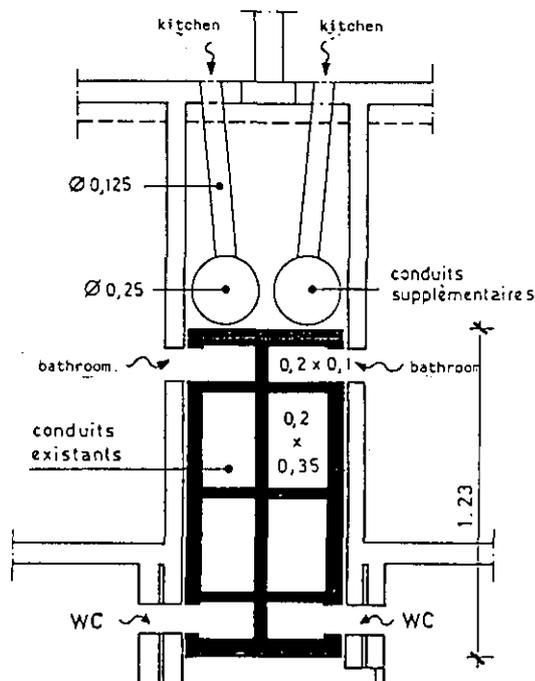


Fig. 4 : Sections of ventilation ducts in Namur building

MONITORING PROGRAMME

Monitoring Equipment

60-channel tracer gas system

Measurements of :

- Air flow rates
- CO₂-levels and flow rates
- H₂O-levels and flow rates
- temperatures

The intention to simultaneously monitor up to 20 apartments resulted in the need of a 60-channel tracer gas system allowing to measure air flow rates, CO₂- and H₂O-concentrations as well as the flow rates of these pollutants.

A rather detailed description of the characteristics of the MATE system is given in [1].

For more details on the monitoring, see the case study on the Schiedam building.

Monitoring campaigns

3 Monitoring campaigns between 6.89 and 1.91

110 measuring days

Detailed monitoring campaigns were carried out during 3 periods : June - July 1989, February-March 1990 and November 1990 - January 1991. In total, 110 days of measurements were done.

Monitored parameters

Measurement intervals : 25 minutes

Median values :

- T_a : 6 °C
- Wind : 2.7 m/s
- Rel. Hum. : 85%

During the monitoring periods, the following variables were measured with an interval of some 25 minutes between 2 measurements :

Outside climate :

Temperature, wind speed and direction, relative humidity, CO₂-concentration

Kitchen, bathroom and WC :

Temperature close to air outlet, air flow rate, CO₂-level and relative humidity.

The flow rates of H₂O and CO₂ were calculated by multiplying the concentration difference(inside-outside) by the air flow rate.

The ventilation losses were calculated by multiplying the air flow rates with the temperature difference (inside-outside).

These measured data were analyzed in various ways.

As mentioned earlier, the monitoring was due to practical reasons focused on the duct work. This means that no direct measurements were done in the living room and in the bedrooms.

RESULTS

Airtightness measurements

n_{50} -values :
 - average : 2.9 h⁻¹
 - minimum : 1.8 h⁻¹
 - maximum : 4.4 h⁻¹

The airtightness of all apartments was measured in detail. The global airtightness as well as the leakage distribution room by room was determined.

Detailed information on leakage distribution

The global airtightness is expressed for a pressure difference of 50 Pa. The airtightness ranged from 1.8 to 4.4 h⁻¹, with an average value of 2.9 h⁻¹. This level of airtightness does not meet the requirement of the manufacturer ($n_{50} \leq 2$ h⁻¹)

The measurements on the leakage distribution gave a distribution as indicated in table 1.

Room	Average	Minimum	Maximum
Living	147	54	239
Bedroom 1	43	22	70
Bedroom 2	45	19	82
Kitchen	64	30	136
Bathroom	61	16	167
WC	36	1	64
Entry door	64	5	156

Table 1 : overview of measured leakage distribution for the 18 apartments in the Namur building.

Basic results from monitoring periods

An indication of type of collected information is given in the Schiedam case study.

An example for the Namur building is given in fig. 5.

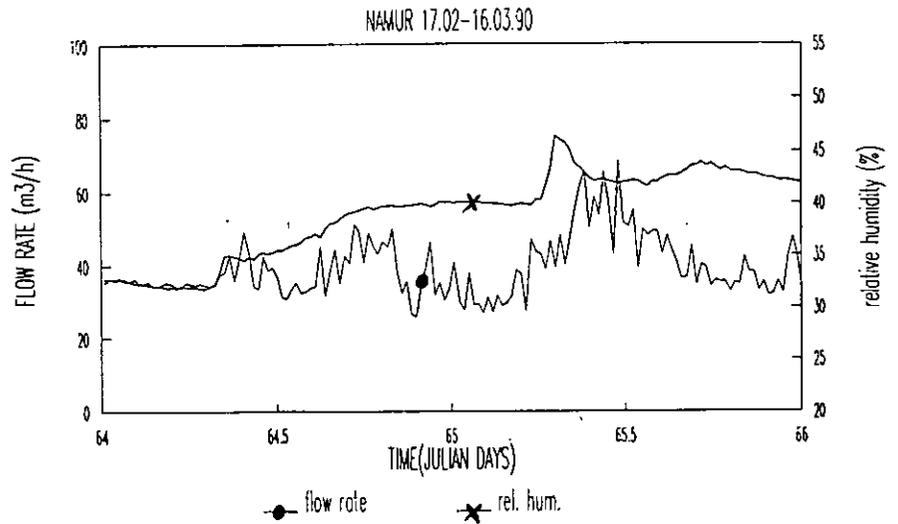


Fig. 5 : example of the measured variables (reference apartment)

Detailed interpretation of the results

Very little variation of indoor temperature as function of outdoor temperature

The average temperatures in kitchen, bathroom and WC varies only slightly as a function of the outside temperature. The indoor temperature is almost independent from the outside temperature: variations between the apartments range from 20 °C and 23 °C .

An overview of the average relative humidities in some of the humidity controlled apartments is given in fig. 6. The maximum values are found for outside temperatures between 5 and 15°C. An explanation for this tendency is given in the case-study of the Schiedam building.

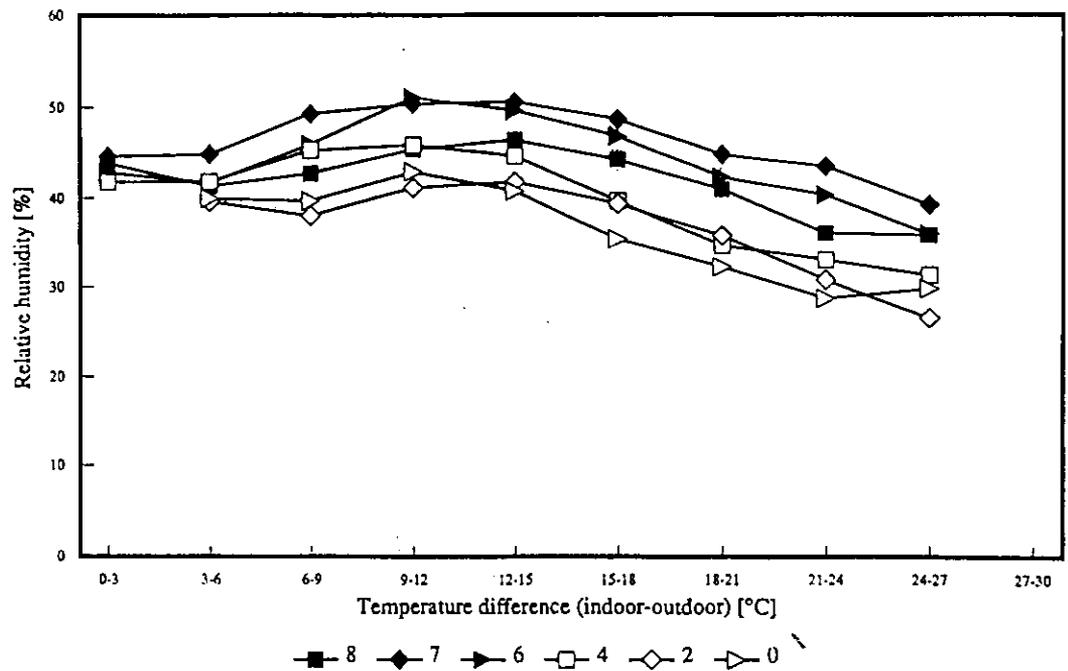


Fig. 6 : variation of the average relative humidity as function of the temperature difference between inside and outside, Namur, humidity controlled apartments (wind speed 0.2 m/s)

The calculated extracted water vapour quantities are given in fig. 7. The trend is not the same as the one found for the Schiedam building. This might be due to the fact that the occupants in Schiedam have a much longer tradition to use their small openable windows. It is also interesting to see the absolute values of the extracted water vapour rates.

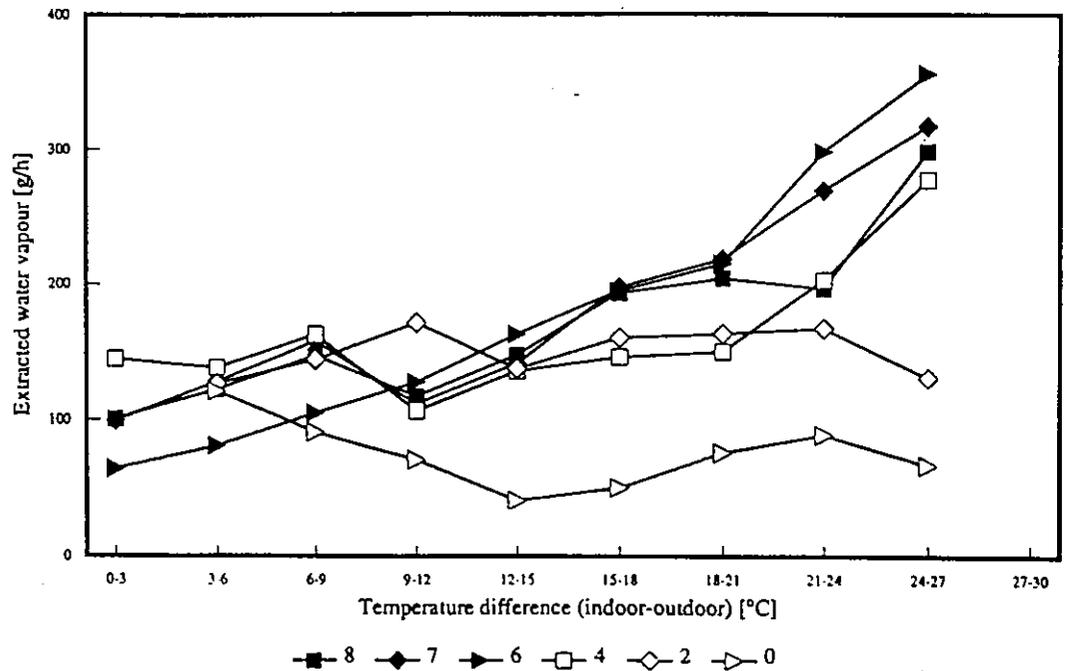


Fig. 7 : daily extracted water vapour quantities as function of temperature difference. (wind speed 0.2 m/s)

An overview of the average values for the daily extracted water vapour rates in the three buildings is given in fig. 8. A comparison with the data of the final report of annexe 14 'Energy and Condensation' indicate that the observed values for the monitored apartments never reach the upper values mentioned in the annexe 14 report. This might be due to the fact that some of the values given in this report are derived from measurements in extreme conditions or for occupation patterns which don't occur in this type of buildings. Another reason can be the fact that the values obtained in the framework of these case studies are averages, including periods of absence. Also the effect of cross ventilation may partly explain the differences.

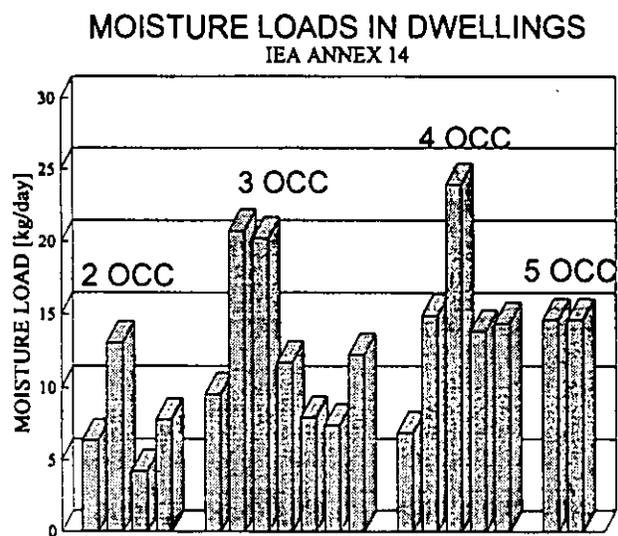
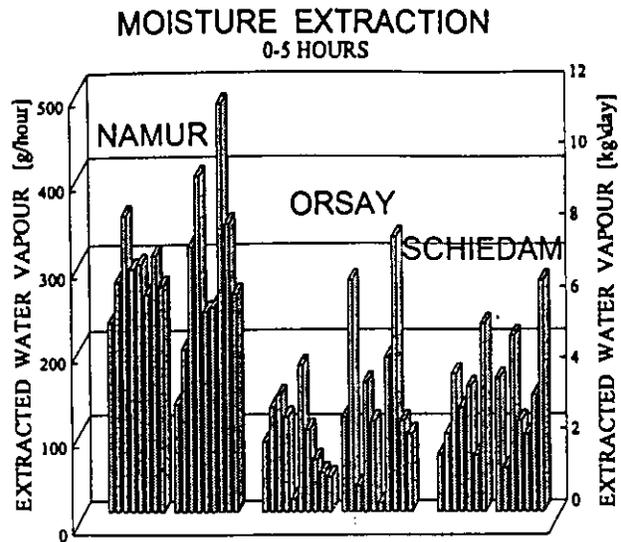


Fig. 8 : Overview of average extracted water vapour quantities through ventilation ducts for all the monitored apartments and comparison with values reported in IEA annexe 14.

The average CO_2 -concentrations are of the order of 800 to 1200 ppm. Somewhat higher concentrations are found in a few humidity controlled apartments. The average CO_2 -concentration is in only 1 of the apartments above 1500 ppm. In this apartment, there is a very intensive cooking activity by using a gas cooker which may explain the high CO_2 -concentrations.

It is of course not enough to look only to the average CO_2 -concentrations. An example of the distribution of measured CO_2 -concentrations is given in fig. 9.

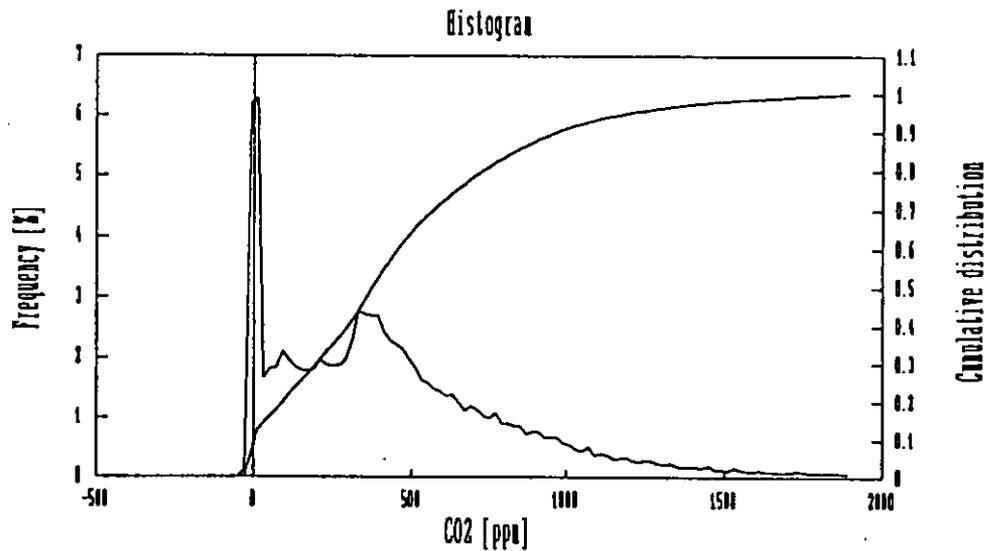


Fig. 9 : histogram of measured CO₂-concentrations and cumulative histogram, Namur building, reference apartments (difference between indoor and outdoor)

A comparison of the three buildings was made with respect to the CO₂-concentrations. Table 2 gives the percentage of the time that the CO₂-concentrations were below 1000 and 1500 ppm.

	< 1000 ppm		< 1500 ppm	
	REF.	HYGRO	REF.	HYGRO
Orsay	77 %	93 %	97 %	100 %
Namur	69 %	83 %	92 %	97 %
Schiedam	49 %	63 %	94 %	96 %

Table 2 : Percentage of time that the CO₂-concentrations were below 1000 or 1500 ppm, all apartments

These results show that there is apparently a clear ranking of the building performance : the building in Les Ulis is the best performing, the Namur building gives somewhat higher values and the Schiedam building is the worst. However, in general are these values not so bad. It is important to stress that no measurements were done in the living room and the bedroom.

It is also interesting to see that the humidity controlled system gives always the best result.

Fig. 10 shows interesting measurements on daily extracted CO₂-rates. Apartment R 0 was unoccupied during this measurement campaign. One can clearly observe that the calculated CO₂-rate is very close to zero. Apartment R 3 was empty during days 27 till 35. This is clearly seen from the CO₂-flow rates.

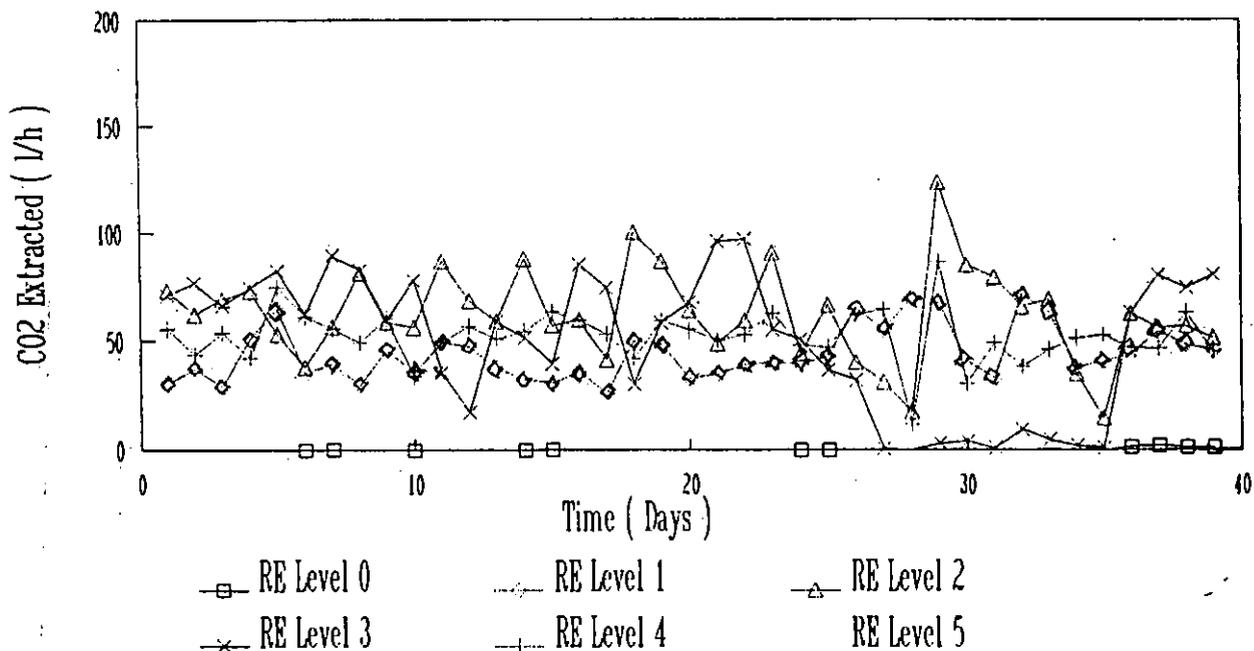


Fig. 10 : daily averages for extracted CO₂-rates for several reference apartments in the Namur building (28.11.90-15.01.91)

The relation between the extracted water vapour rates and the extracted CO₂-rates is given in fig. 11. Such trend is observed for the majority of the ventilation grills. It clearly show that on the average, there is a very good correlation between both pollutant rates. However, there is a large scatter on these results. This is indicated by the two other curves on the figure which indicate the standard deviation. Each point on the curve corresponds with a group of 50 observations.

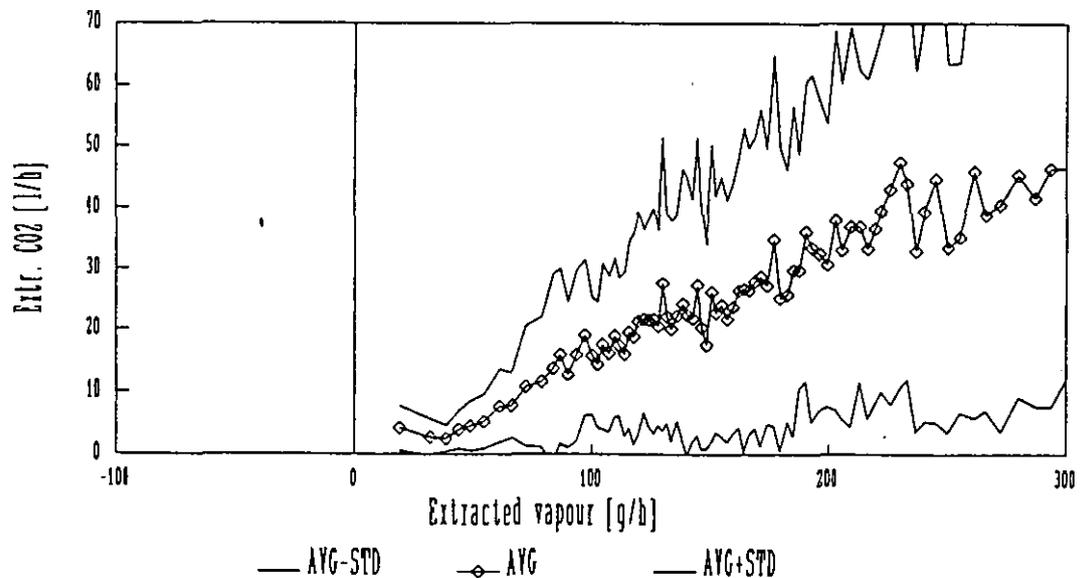


Fig. 11 : relation between extracted water vapour and CO₂-rates, Namur, reference apartment 6, bathroom, whole period.

Results of enquiry

An enquiry was carried out in all 18 apartments. One important observation concerned the complaints of draught with the humidity controlled air inlets. The majority of them in the living were closed by the occupants. Draught problems in practice lead to blocking the devices since there is no possibility for closing them in a normal way. It must be stressed that this problem of draught has nothing to do with the humidity control but with the classical concept of the air inlet devices used in France. The challenge is to make in general more comfortable air inlet devices.

The fact of observing less problems in the reference apartments does not automatically mean that the devices used in

these apartments are fully satisfying. The position of the air inlets in the living room of the reference apartments was continuously monitored during more than 3 months. An example is given in fig. 12.

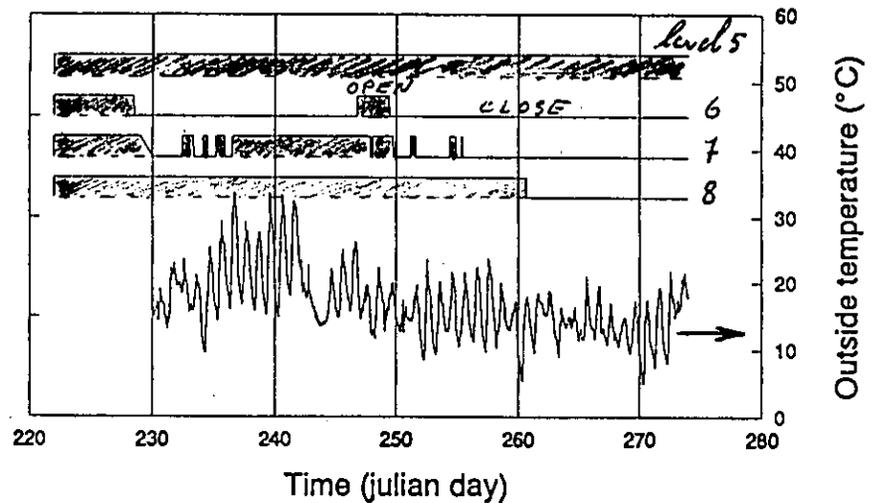


Fig. 12 : use of ventilation grills in reference apartments in Namur building (Augustus-September 1990, floor 5 to 8)

These observations indicate that many of the classical air inlets are in several of the apartments closed for rather long periods or even the whole time. Although not directly related to the issue of demand controlled ventilation, it is clear that improving the performances of air inlets with respect to draught aspects is a real challenge for the ventilation industry.

Conclusions

The application of a humidity controlled natural ventilation system leads in the apartments in the Namur building to a rather significant modification of the air flow rates.

Interesting results with respect to the daily extracted water vapour quantities were collected. They confirm the order of magnitude reported in the IEA annexe 14 report although the extreme high values were not found.

There is a clear ordering between the Schiedam, Namur and Les Ulis building with respect to the CO₂-concentrations. Also the reference apartments show systematically a higher percentage of high CO₂-concentrations.

PUBLICATIONS

- [1] Dubrul C., Final report Annex 8 'Inhabitants behaviour with regard to ventilation', A.I.V.C., Warrick, 1988
- [2] Wouters, P., Humidity in dwellings : important pollutant source as well as a parameter for ventilation control, Symposium Zurich, May 1992
- [3] Jardinier, P., Simonnot, J., Principle and aim of a natural humidity-controlled ventilation system, CIB W67 Symposium, Rotterdam (NL), September 1990

3.2 HUMIDITY CONTROLLED VENTILATION IN A 10 STOREY APARTMENT BUILDING IN SCHIEDAM (NL)

Project description

Introduction

Research participants :

- WTCB/CSTC, Brussels (B)
- TNO Building division, Delft (NL)
- CETIAT, Orsay(F)
- EDF(F)
- Aereco(F)

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Optimization of dwelling ventilation by using demand controlled ventilation has to be based on the activities in the concerned dwellings, the occupance acceptation and must take into account the building characteristics.

The Commission of the European Communities, DG XVII promotes the development of new technologies by supporting demonstration projects.

In 1986, they accepted the proposal to support a demonstration project on the humidity controlled natural ventilation system of the French firm Aereco.

An important boundary condition in order to get CEC support was the application of the technology in at least 50 apartments. In order to achieve this, it was decided to perform tests in buildings in Les Ulis(F), Namur(B) and Schiedam(NL). The measurement campaigns as well as the majority of the analysis were finished at the beginning of 1992. Given the fact that the results and conclusions differ very much for the 3 buildings, 3 different case studies are reported. In order to avoid duplication of the common aspects in the 3 case-studies, the reader is suggested to first read this case-study on the Schiedam building.

Objectives

Energy saving through humidity control

Improved indoor air quality

Comparison of reference and humidity controlled apartments.

The major objective of this study was the evaluation of the impact of the humidity controlled natural ventilation on the energy demand and the indoor air quality. The monitoring campaigns aimed also to allow a better indication of the limits of applicability of the system as well as indications for further improvements. Furthermore, it was expected that the very intensive monitoring campaign would also give a lot of

information on natural ventilation in general as well as on pollutant concentrations and emission rates (CO_2 and H_2O) The main work focused on the comparison of so-called reference apartments (R) which have a more classical natural ventilation system and the so-called humidity controlled apartments (H). In the Schiedam building, 7 reference apartments and 7 humidity controlled apartments were intensively monitored during more than 70 days.

Building and Site

Climate Schiedam :

Annual average temp. : 5 °C.
(heating season)

10 km from Northsea (high wind speeds)

The field measurements were carried out in a 10-storey apartment building in Schiedam, some 10 km North-West of Rotterdam. This building was studied in the past in the framework of IEA annexe 8 on 'Occupants behaviour with regard to ventilation'. The building is in a more or less unsheltered position and in a region with high wind velocities due to the nearby Northsea.

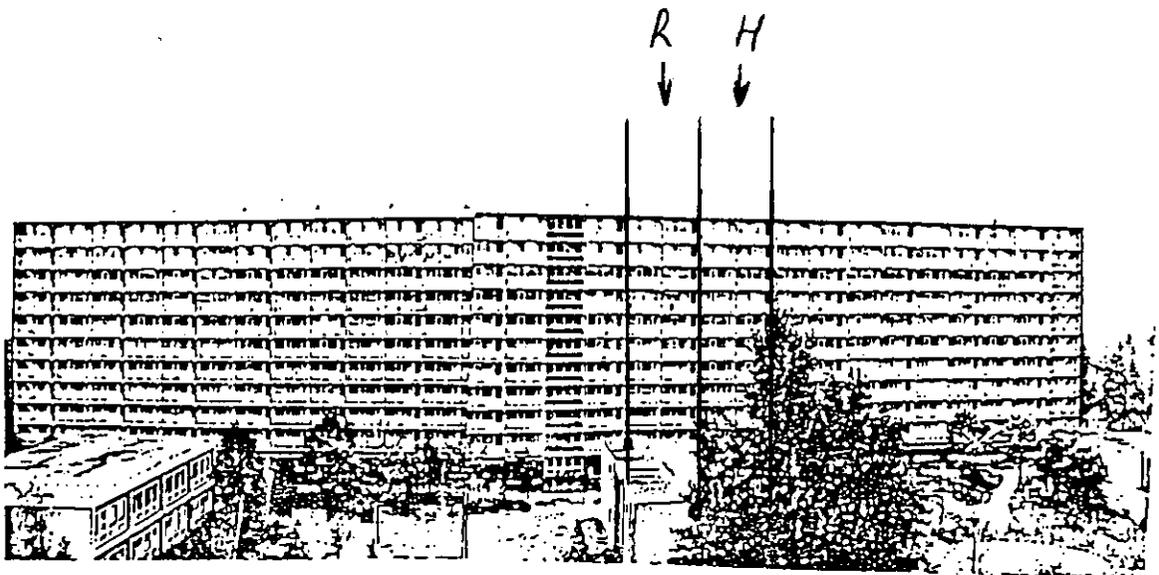


Figure 1: The Schiedam building (monitored apartments indicated with R(eference) and H(umidity))

INVESTIGATED BUILDING

Apartments

Area : 90 m²

Volume : 250 m³

7 Ref. Apartments

7 Humid. Apartments

The building dates from 1965. All the investigated apartments are identical 3-bedroom apartments. They are terraced apartments which means that the entrance door is a balcony door.

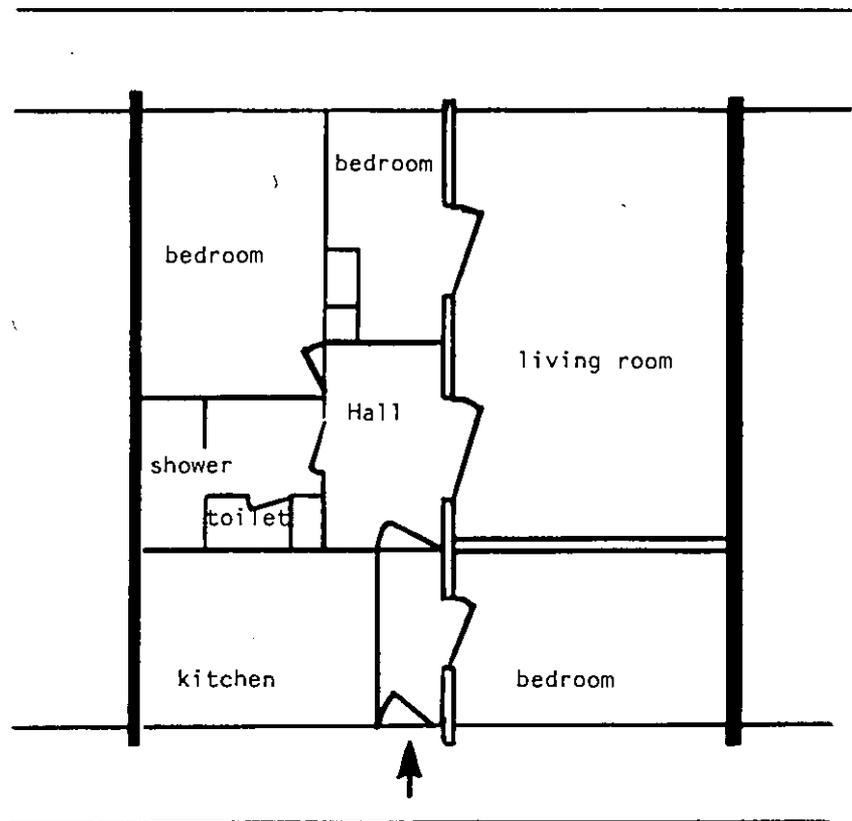


Figure 2 : Ground plan of one of the reference apartments in the Schiedam building

Heating and ventilation system

Heating : hot water radiators

Sanitary hot water with flueless gas boiler in kitchen

Natural ventilated apartments with shunt ducts (bathroom and WC combined)

All apartments are equipped with hot water radiators. There is a central boiler for the whole building. The sanitary hot water is produced by a flueless gas boiler installed in the kitchen. This type of equipment was at the time of construction of the building allowed.

The air supply provisions in the reference apartments consist of small openable windows in the living room, bedrooms and kitchen. In kitchen, bathroom and WC, natural ventilation so called Shunt ducts are installed. However, these ducts represents some particularities which influence strongly the performances of the ventilation system:

- bathroom and WC are connected to the same main duct.
- the ducts have rather small sizes.
- the cowl on the roof was not situated at an appropriate place inducing severe reverse flow problems. This problem was solved between one of the measurement campaigns.

The kitchen have an unvented gas boiler for domestic water.

Range of operation :

R.H. < 30% : minimum opening

R.H. > 70% : maximum opening

Supply : living room and bedrooms

Extraction : kitchen, bathroom and WC

In the humidity controlled apartments, humidity controlled air inlet devices were installed in the bedrooms and the living room. These grills were placed in a wooden panel replacing the small openable windows. It is important to mention that the humidity controlled grills were non-closable whereas the small openable windows can be closed by the occupants. A humidity controlled extraction grill for natural ventilation was installed in bathroom and WC. The characteristics are given in fig. 3.

In kitchen a classical not closable grill was installed.

Intensive tests with respects to aging behaviour and durability were carried out on these grills [2]

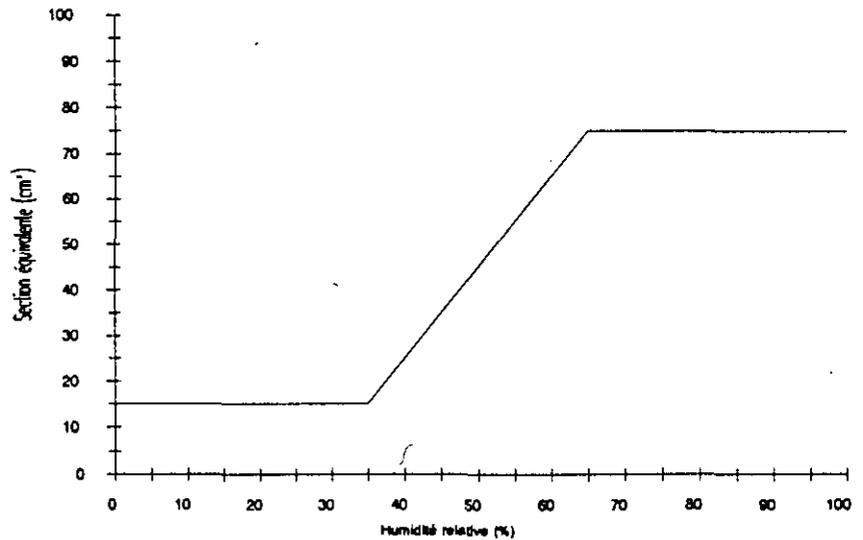


Fig. 3 : characteristics of humidity controlled ventilation grills

MONITORING PROGRAMME

Monitoring Equipment

60-channel tracer gas system

Measurements of :

- Air flow rates
- CO₂-levels and flow rates
- H₂O-levels and flow rates
- temperatures

The intention to simultaneously monitor up to 20 apartments resulted in the need of a 60-channel tracer gas system allowing to measure air flow rates, CO₂- and H₂O-concentrations as well as the flow rates of these pollutants. A rather detailed description of the characteristics of the MATE system is given in [1].

One of the main advantages of the measurement system was the use of only 1 measuring sensor for the CO₂- and H₂O-concentrations and also the calculation of these pollutant flow rates. In order to achieve this, air samples of the ducts were pumped to these central measuring sensors. The pollutant flow rates were calculated by multiplying the difference between indoor and outdoor concentration by the air flow rates through the ducts.

The major limitation of this demonstration project is the fact that no detailed measurements were carried out in the bedrooms and the living room. Financial reasons as well as practical installation aspects didn't allow such measurements.

Monitoring campaigns

3 Monitoring campaigns between
11.89 and 2.91

72 measuring days

Detailed monitoring campaigns were carried out during 3 periods : November-December 1989, March-May 1990 and January-February 1991. In total, 72 days of measurements were done.

Monitored parameters

Measurement intervals : 25
minutes

Median values :

- * T_a : 3.9 °C
- * Wind : 3.0 m/s
- * Rel. Hum. : 88%

During the monitoring periods, the following variables were measured with an interval of some 25 minutes between 2 measurements :

Outside climate :

Temperature, wind speed and direction, relative humidity, CO₂-concentration

Kitchen, bathroom and WC :

Temperature close to air outlet, air flow rate, CO₂-level and relative humidity.

The flow rates of H₂O and CO₂ were calculated by multiplying the concentration difference(inside-outside) by the air flow rate.

The ventilation losses were calculated by multiplying the air flow rates with the temperature difference(inside-outside).

These measured data were analyzed in various ways.

As mentioned earlier, the monitoring was due to practical reasons focused on the duct work. This means that no direct measurements were done in the living room and in the bedrooms.

RESULTS

Airtightness measurements

The airtightness of some of the apartments was measured. Expressed for a pressure difference of 50 Pa, the airtightness ranged from 3 to 4 h⁻¹. This level of airtightness does not meet the requirement of the manufacturer ($n_{50} < 2 \text{ h}^{-1}$)

The airtightness of the entry door to bathroom and WC was very high. It means in practice that the doors itself represent a very high resistance. This combined with the small dimensions of the ductwork significantly reduce the control capabilities of the humidity controlled ventilation grills.

Basic results from monitoring periods

An indication of the measured fluctuations of air flow rates, CO₂-concentrations and flow rates as well as for the relative humidity and the extracted water vapour is given in fig. 4.

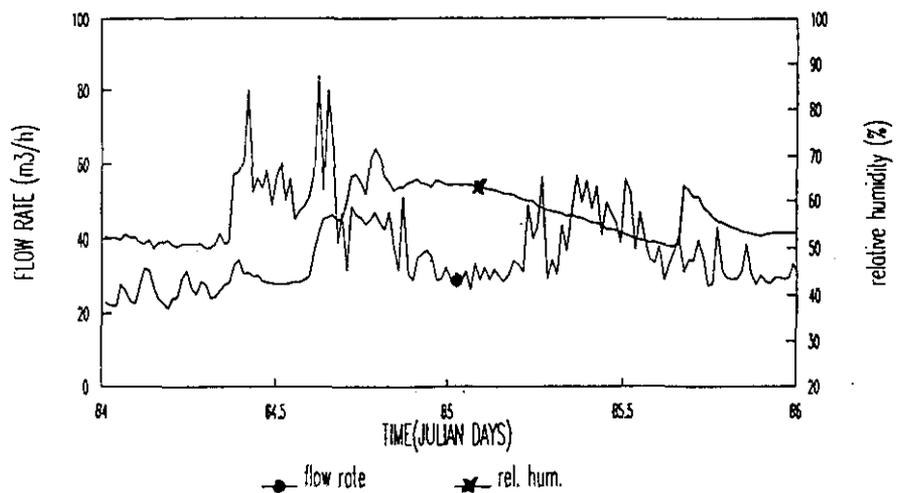


Fig. 4 : example of the measured variables (reference apartment)

Detailed interpretation of the results

The average temperatures in kitchen, bathroom and WC varies only slightly as a function of the outside temperature. The indoor temperature on the average drops from some 21.5 °C for outdoor temperatures of 15... 20 °C to 19 °C for outside temperatures of 0...5 °C. Differences of up to 3°C are found between the apartments.

An overview of the average relative humidities in some of the reference apartments is given in fig. 5. The variation between the apartments is rather small. Somewhat lower values are found for lower external temperatures. This is due to the lower absolute humidity for low outside temperatures. It is important to mention that for small temperature differences, this tendency is not longer explicit. The reason might be that for high outside temperatures, people open more frequently the windows which increases the cross ventilation. A very similar trend was found for the humidity controlled apartments.

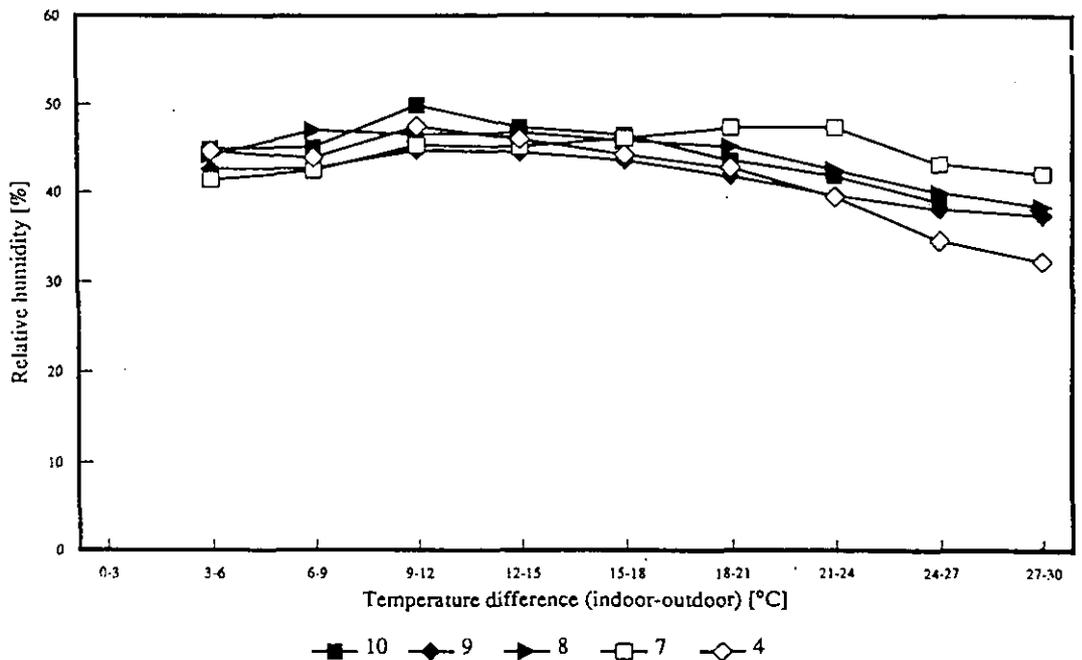


Fig. 5: variation of the average relative humidity as function of the temperature difference between inside and outside, Schiedam, reference apartments (wind speed 0-2 m/s)

The calculated extracted water vapour quantities seem to confirm the use of open windows for higher outside temperatures. As indicated in fig. 6, there is a systematical decrease of the extracted water vapour content for decreasing temperature differences between inside and outside. The most evident reason seems to be the use of the windows. It is also interesting to see the absolute values of the extracted water vapour rates. For outside temperatures around 0 °C, the values range between 2.5 and 8 kg/day.

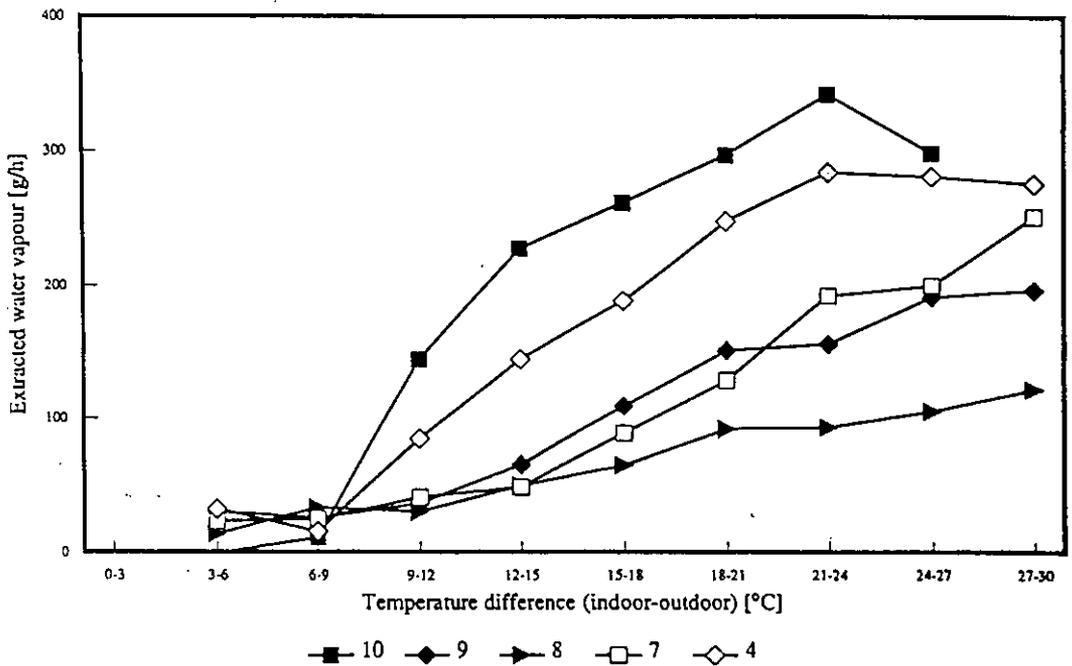


Fig. 6: calculated average values for extracted quantities of water vapour, Schiedam, reference apartments (wind speed 0.2 m/s).

The dependency of window use in this building as a function of the outside temperature was clearly shown in the framework of the IEA annexe 8 project. Fig. ** shows the relation between the weekly average of open windows for the whole apartment building (80 apartments) and the outside temperature.

The average CO₂ concentrations for some of the apartments is given in fig. 8. The average concentrations are of the order of 800 to 1200 ppm. Somewhat higher concentrations are found in a few humidity controlled apartments, probably due to a higher occupation load. Also here, much lower CO₂-concentrations are found for higher outside temperatures (12...20 °C)

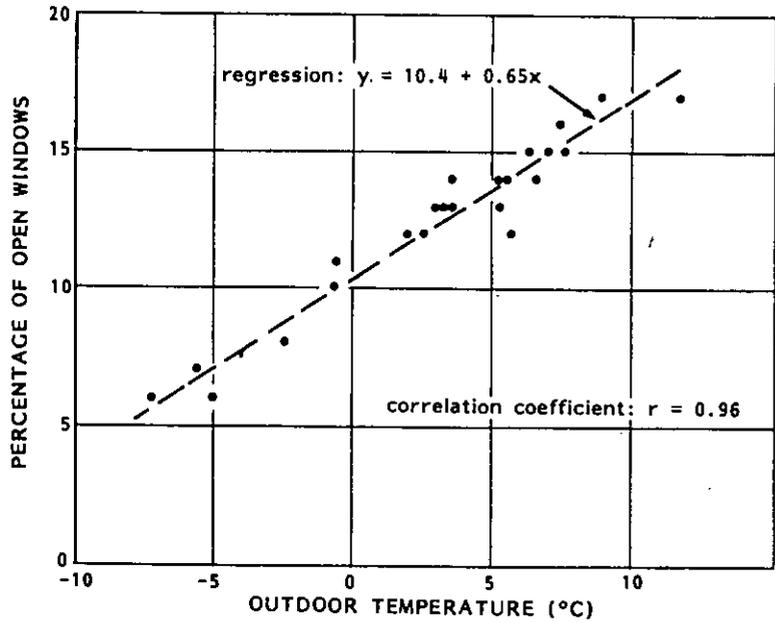


Fig. 7 : Relationship between the average use of windows and doors and the average outdoor temperature (schiedam project) [1]

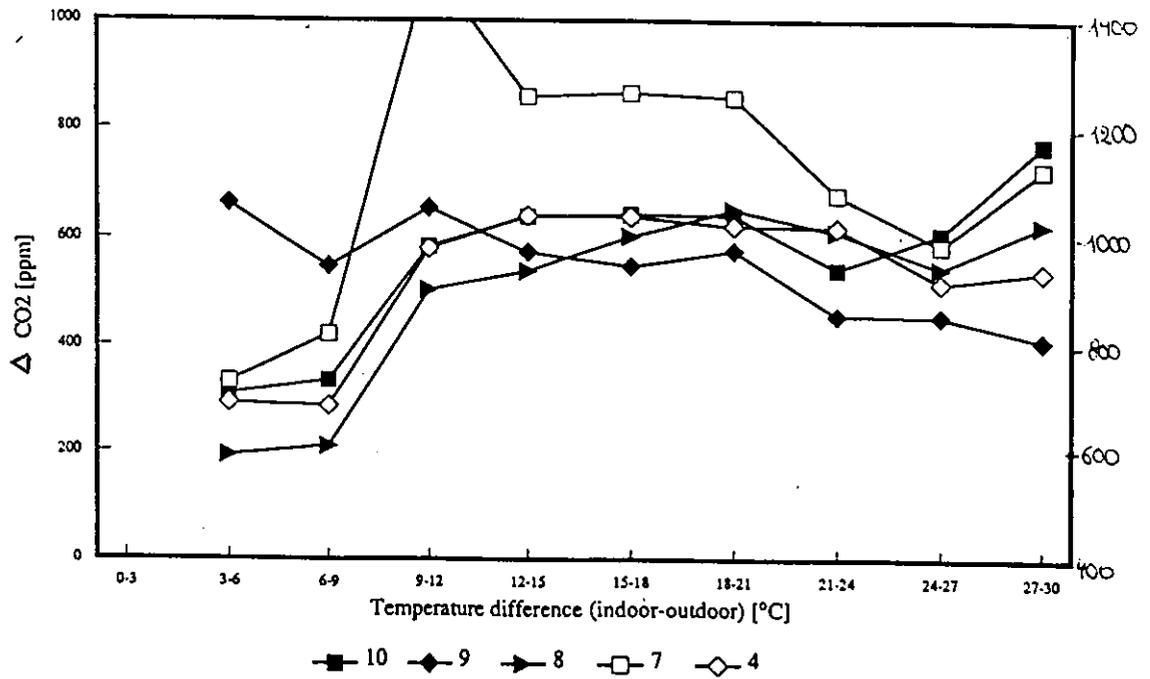


Fig. 8 : Average CO₂-concentrations in various humidity controlled apartments (wind velocity 0.2 m/s)

Conclusions

The application of a humidity controlled natural ventilation systems leads in the apartments in the Schiedam building not a significant improvement of the indoor air quality nor to a reduction of the energy consumption.

The major reasons for explaining the poor results are the following :

- the ducts are too small for allowing a real influence of the humidity controlled extraction grills on the duct flow rates
- the bathroom and WC doors are very airtight which again reduces the control possibilities of the extraction grills.

The important problems of reverse flow have been largely eliminated by modifying the air outlet on the roof.

The sum of the average air flow rates through the ventilation ducts is of the order of 50 m³/h

The effect of open windows for high outside temperatures (>10°C) on the pollutant concentrations and extracted pollutant rates is clearly observed.

PUBLICATIONS

- [1] Dubrul C., Final report Annex 8 'Inhabitants behaviour with regard to ventilation', A.I.V.C., Warrick, 1988
- [2] French report on common experiences on aging and durability
- [3] Dubrul, C., Inhabitants' Behaviour with regard to Ventilation, AIVC, 1988
- [4] Jardinier, P., Simonnot, J., Principle and aim of a natural humidity-controlled ventilation system, CIB W67 Symposium, Rotterdam (NI), September 1990
- [5] Wouters, P., Humidity in dwellings : important pollutant source as well as a parameter for ventilation control, Symposium Zurich, May 1992

3.3 H2O CONTROLLED VENTILATION IN A 5 STOREY APARTMENT BUILDING IN LES ULIS (F)

Project description

Introduction

Research participants :

- Aereco (F)
- WTCB/CSTC, Brussels (B)
- TNO Building division, Delft(NL)
- CETIAT, Orsay(F)
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France

This case study is the third building of 3 buildings which were monitored in the framework of a CEC demonstration project on humidity controlled natural ventilation.

In order to stimulate the introduction of new technologies, the Commission of the European Communities (CEC), DG XVII promotes the testing of such new technologies by supporting demonstration projects.

In 1986, the CEC accepted the proposal to support a demonstration project on the humidity controlled natural ventilation system of the French firm Aereco.

An important boundary condition in order to get CEC support was the application of the technology in at least 50 apartments. In order to achieve this, it was decided to perform tests in buildings in Les Ulis(F), Namur(B) and Schiedam(NL). The measurement campaigns as well as the majority of the analysis were finished at the beginning of 1992.

Given the fact that the results and conclusions differ very much for the 3 buildings, 3 different case studies are reported. In order to avoid duplication of the common aspects in the 3 case-studies, the reader is suggested to first read this case-study on the Schiedam building in which more detailed information can be found. Also the Namur case-study gives useful information for the reader of this case-study

Objectives

Energy saving through humidity control

The major objective of this study was the evaluation of the impact of the humidity controlled natural ventilation on the energy demand and the indoor air quality.

Improved indoor air quality
Comparison of reference and humidity controlled apartments.

The monitoring campaigns aimed also to allow a better indication of the limits of applicability of the system as well as indications for further improvements. Furthermore, it was expected that the very intensive monitoring campaign would also give a lot of information on natural ventilation in general as well as on pollutant concentrations and emission rates (CO₂ and H₂O)

The main work focused on the comparison of so-called reference apartments (R) which have a more classical natural ventilation system and the so-called humidity controlled apartments (H). In the Les Ulis building, 10 reference apartments and 10 humidity controlled apartments were intensively monitored during more than 140 days.

The objectives with respect to the ventilation performances to be realized during heating periods were the following :

- the total air flow rate at apartment should be during at least 90% of the time between 60 and 100 m³/h.
- an automatic distribution of the air supply flow rates as function of their needs (expressed by the relative humidity)
- a stabilization of the air flow rates for wind velocities above 4 m/s.

Building and Site

30 km from Paris

The field measurements were carried out in a 5-storey apartment building in Les Ulis, some 30 km South of Paris. The building is in an urban environment and surrounded by buildings of a similar height.



Figure 1 : The Les Uis building

INVESTIGATED BUILDING

Apartments

Area : 65 or 76 m²

Volume : 162 or 190 m³

10 Ref. Apartments
10 Humid. Apartments

The building dates from 1970. There are 2 types of apartments: 2- and 3-bedroom apartments. The reference apartments are symmetrical to the humidity controlled apartments. There is an internal entrance door with a central staircase.

This building can be considered as a rather typical apartment building constructed in the 70-ties. It is important to mention that all windows were in 1988 replaced. All windows are in PVC with double glazing. They have a good airtightness.

This apartment building is a so-called HLM building, HLM stands for 'Habitation à Loyer Modéré' or Social dwelling apartment building. It are all rented apartments. The average occupation is moderate in most of the apartments.

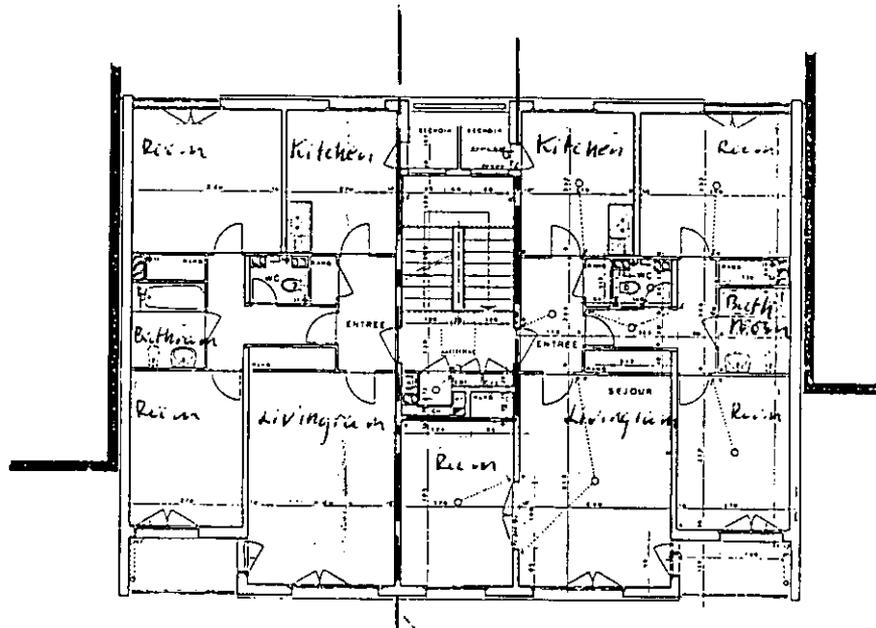


Figure 2 : Ground plan of one of the reference apartments in the Ulis building

Heating and ventilation system

Heating : floor heating

All apartments are equipped with a floor heating system. There is a central gas boiler for the whole building.

Natural ventilated apartments with shunt ducts

All windows were in the framework of the window replacement equipped with the so-called self regulating air supply ventilation grills. These are built in the PVC window frame.

Range of operation :
R.H. < 30% : minimum opening
R.H. > 70% : maximum opening

Supply : living room and bedrooms

Extraction : kitchen, bathroom
and WC

Fixed grills in all kitchen (security
reasons)

The following characteristics concerning the humidity controlled apartments were realized :

- Two humidity controlled air supply grills are installed in the living room and each bedroom,
- the airtightness of the entrance doors to the apartments has been improved (also in the reference apartments),
- the total background leakage of the apartments is lower than the air flow through the humidity controlled air supply openings when they are in an average opening position.
- in order to have limited pressure drops across the internal doors, there is a free opening section of some 200 cm² in the kitchen door and some 150 cm² in the other doors. (also in the reference apartments)
- humidity controlled air extraction grills are installed in the bathroom and the toilet. For security reasons (open gas combustion equipment), there is a fixed grill in the kitchen (100 m³/h at 10 Pa difference).

The characteristics of the ventilation ducts are the following :

- the shunt duct has dimensions 13 cm * 20 cm (260 cm²)
- the main duct has dimensions 20 cm * 20 cm (400 cm²)
- the cowl of the main duct is some 1.2 m above the roof level, and about 1 m above the edge of the roof.

The humidity controlled ventilation grills were installed in May 1989, no maintenance was done till the end of the measurement campaigns.

MONITORING PROGRAMME

Monitoring Equipment

60-channel tracer gas system

The intention to simultaneously monitor up to 20 apartments resulted in the need of a 60-channel tracer gas system allowing to measure air flow rates, CO₂- and H₂O-concentrations as well as the flow rates of these pollutants.

Measurements of :

- Air flow rates
- CO₂-levels and flow rates
- H₂O-levels and flow rates
- temperatures

A rather detailed description of the characteristics of the MATE system is given in [1].

For more details on the monitoring, see the case study on the Schiedam building.

Monitoring campaigns

4 Monitoring campaigns between
10.89 and 4.91

143 measuring days

Detailed monitoring campaigns were carried out during 4 periods : October 1989, January 1990, October-November 1990 and February-April 1991. In total, 143 days of measurements were done. The first measurement campaign essentially aimed to check the good functioning of the whole monitoring system. These results were not incorporated in the final analysis.

Monitored parameters

Measurement intervals : 25
minutes

Median values :

- T_e : 8.3 °C
- Wind : 1.5 m/s
- Rel. Hum. : 88 %

During the monitoring periods, the following variables were measured with an interval of some 25 minutes between 2 measurements :

Outside climate :

Temperature, wind speed and direction, relative humidity, CO₂-concentration

Kitchen, bathroom and WC :

Temperature close to air outlet, air flow rate, CO₂-level and relative humidity.

The flow rates of H₂O and CO₂ were calculated by multiplying the concentration difference(inside-outside) by the air flow rate.

The ventilation losses were calculated by multiplying the air flow rates with the temperature difference(inside-outside).

These measured data were analyzed in various ways. As mentioned earlier, the monitoring was due to practical limitations mainly focused on the duct work and the kitchen, bathroom and toilet. This means that no direct measurements were done in the living room and in the bedrooms.

RESULTS

Airtightness measurements

n_{50} -values :
- average : 1.3 h^{-1}
- minimum : 0.8 h^{-1}
- maximum : 2.4 h^{-1}

The airtightness of all apartments was measured in detail. The global airtightness as well as the leakage distribution room by room was determined.

The global airtightness is expressed for a pressure difference of 50 Pa. The airtightness ranged from 0.8 to 2.4 h^{-1} , with an average value of 1.3 h^{-1} . This level of airtightness is fully in line with the requirements of the manufacturer ($n_{50} < 2 \text{ h}^{-1}$)

The measure n_{50} -values for the Les Ulis building and for the Namur building are shown in fig. 4.

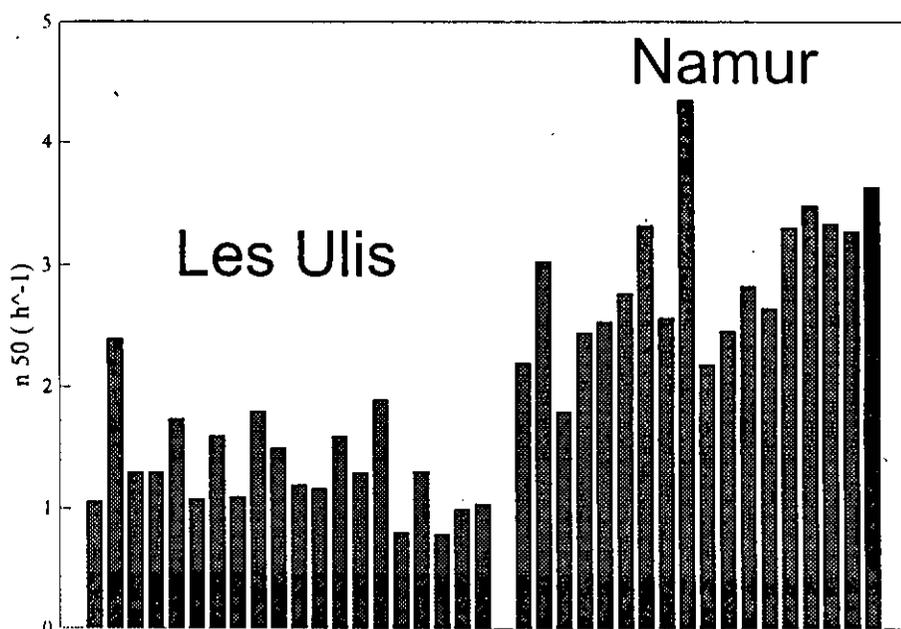


Fig. 4 : overview of measured airtightness values for the 20 apartments in the Les Ulis building and for the 18 apartments in the Namur building.

Climatic conditions during monitoring periods

An indication of climatic conditions during the monitoring periods is given in fig. 5 (outside temperature) and 6 (wind speed). The average outside absolute humidity as a function of the outside temperature is given in fig. 7.

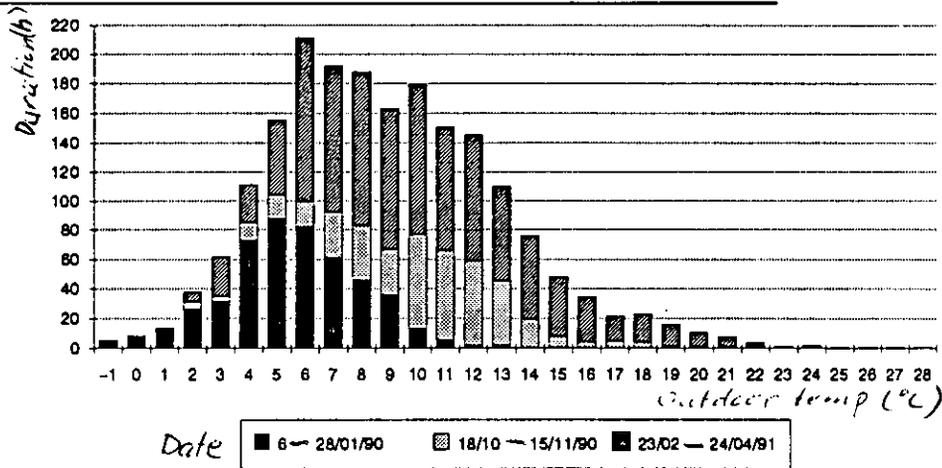


Fig. 5 : Histogram of measured outside temperature during the various monitoring campaigns in Les Ulis[1]

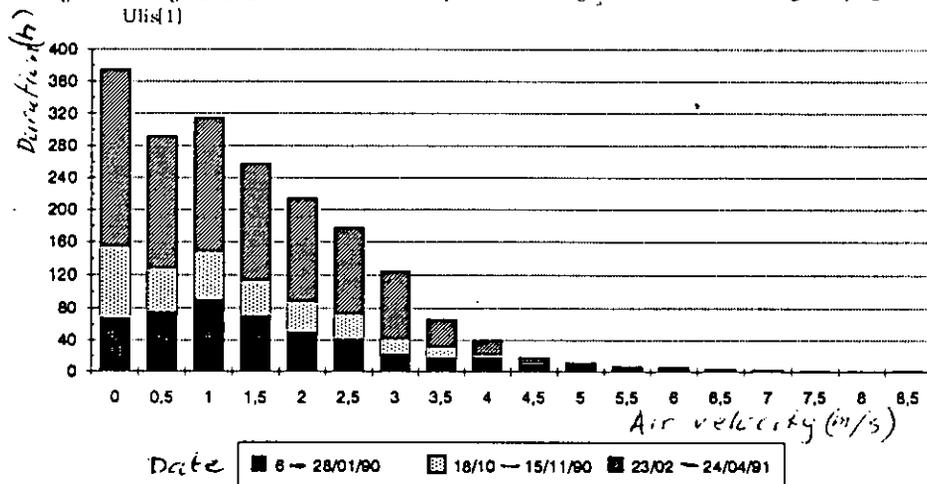


Fig. 6 : Histogram of measured wind velocity during the various monitoring campaigns in Les Ulis[1]

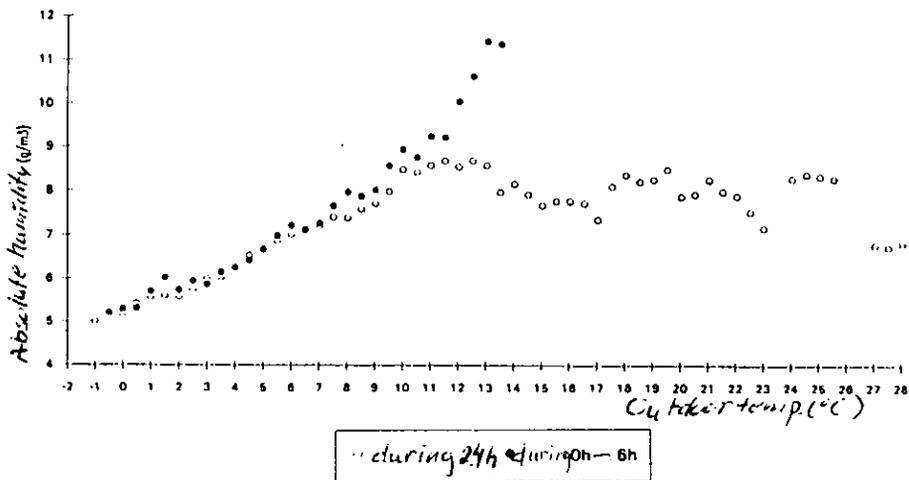


Fig. 7 : Measured average absolute humidity as a function of the outside temperature during the monitoring campaigns in Les Ulis[1]

Variation of air flow rate as a function of indoor relative humidity.

The humidity controlled ventilation grills open and close as a function of the relative humidity. Therefore one should see an increase in air flow rate each time a significant increase in relative humidity occurs such sudden variations are in these apartments mostly found in the bathrooms (when taking a shower,...).

A good example of such correlation during a 2-days period is given in fig. 8. One sees the rather good correlation of the variations in air flow rate and of relative humidity.

It must be mentioned that such good correlation is not always observed.

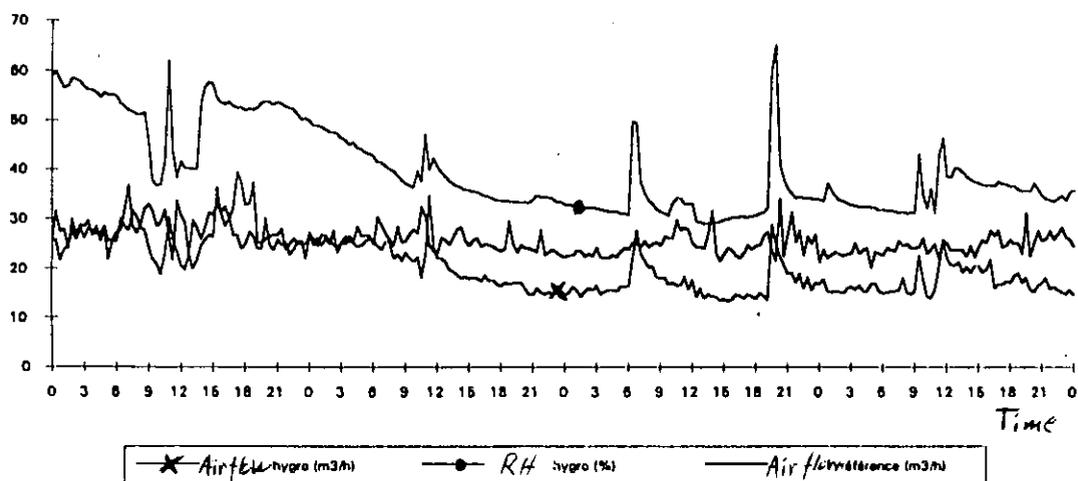


Fig. 8 : air flow rates in a similar reference and humidity controlled apartment as well as the relative humidity in the humidity controlled apartment, Les Ulis, January 1990[1]

The relation during a 20-days period for the daily average values is given in fig. 9. Two humidity controlled apartments are compared. One can clearly observe the relation between variations in relative humidity and air flow rates.

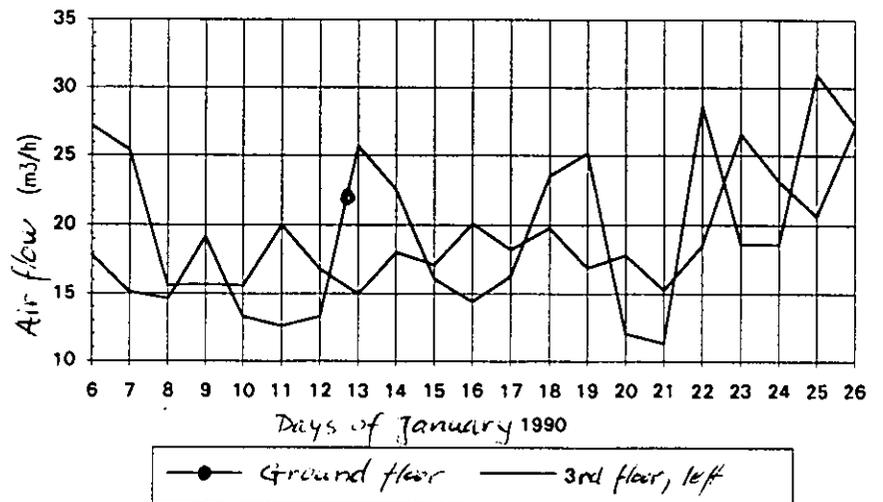
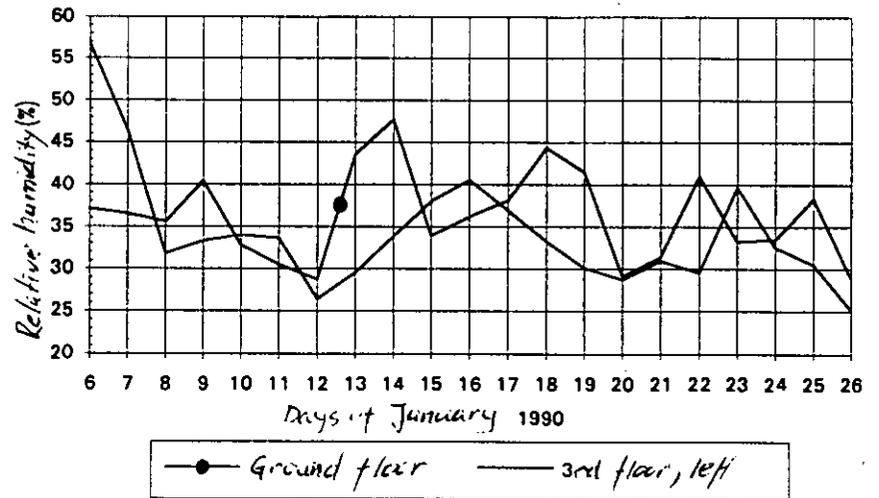


Fig. 9 : daily average air flow rates and relative humidity levels in 2 humidity controlled apartments Les Ulis, 6 to 26 January 1990[1]

Influence of outside temperature and wind speed on air flow rates

The variation of the air flow rate as a function of outside temperature and floor level for wind velocities of less than 2m/s is shown in fig. 10. The effect of the wind speed is shown in fig. 11.

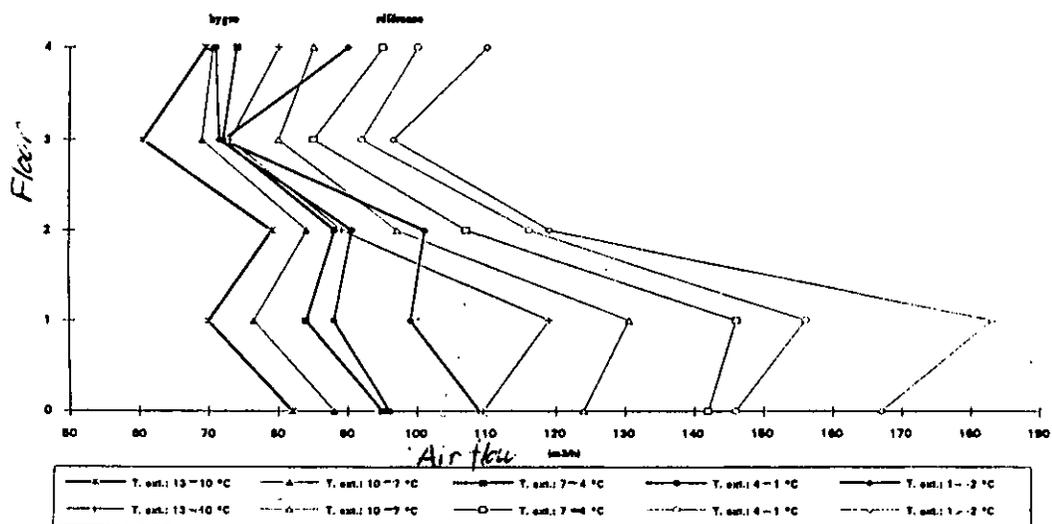


Fig. 10: variation of the average air flow rates as function of the outside temperature, wind velocities between 0 and 2 m/s, Les Ulis[1]

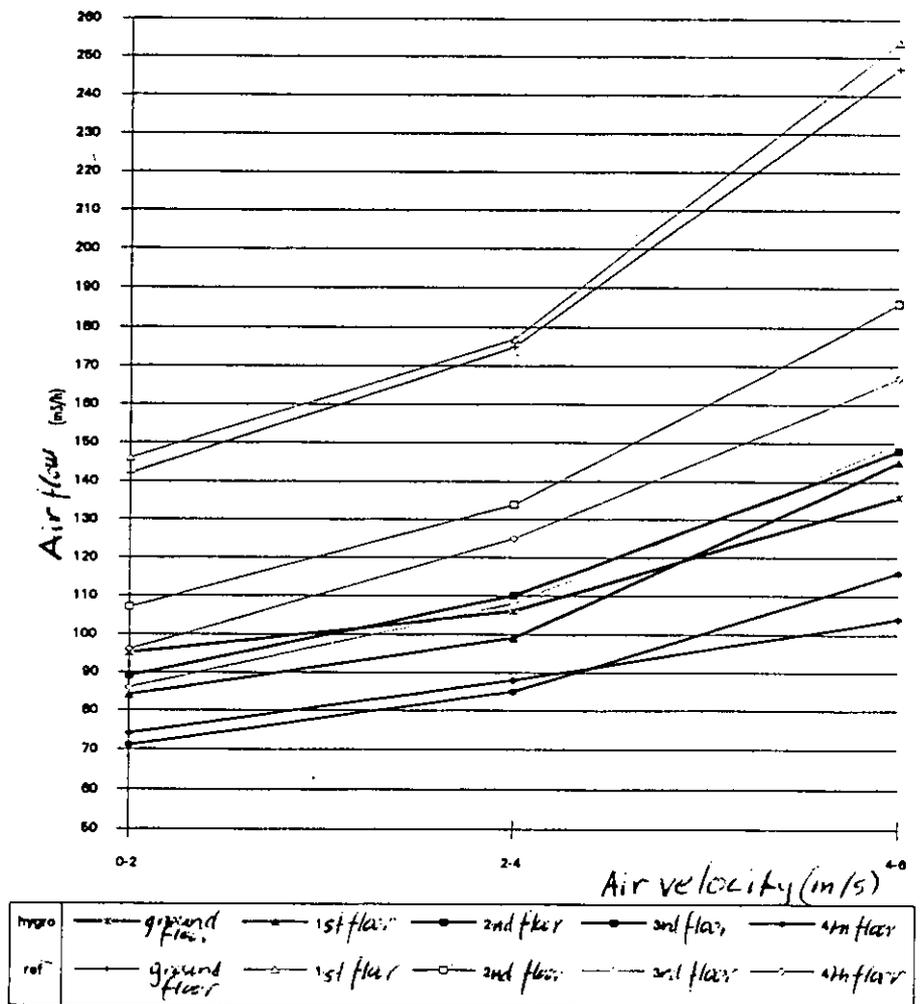


Fig. 11 : variation of the average air flow rates as function of the wind velocity, outside temperature between 4 and 7 °C, Les Ulis [1]

The relation between the difference in absolute humidity (inside-outside) and the difference in CO₂-concentration(inside-outside) is given in fig. 12. These are averages for all 20 apartments. One sees an extremely good correlation for small differences. For higher differences in absolute humidity, the scattering becomes rather large.

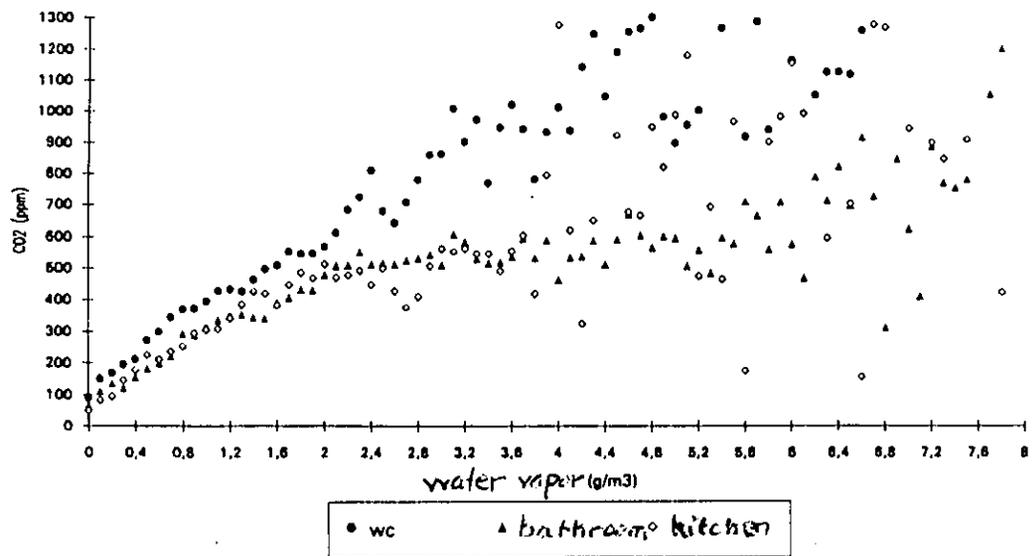


Fig. 12 : relation between difference in average absolute humidity(inside-outside) and difference in average CO₂-concentration, average for 20 apartments, Les Ulis [1]

Energy consumption for ventilation

The monitored results allowed also to calculate the average energy losses (W) due to the duct ventilation (temperature difference between inside and outside * air flow rate * specific heat losses of 1 m3).

The seasonal energy consumption Q_{en} can also be estimated by using the following formulae :

$$Q_{en} = 0.34 * N * \Sigma(Q_{air,Te} * F_{Te} * (T_i - T_e))$$

where :

N = length of the heating season in hours

F_{Te} = percentage of the time that the outside temperature is between $T_e - 0.5$ °C and $T_e + 0.5$ °C

Q_{Te} = average total air flow for an outside temperature T_e

T_{in} = inside temperature of the extracted air. In order to allow a first estimation, an inside temperature of 21 °C is assumed.

The results of the calculations are given in table 1.

Table 1 : Estimation of seasonal energy demand (kWh) for various apartments(1)

	R(eference)	H(umidity)	Difference
Floor 0	3465	2335	1130
Floor 4	2335	1760	575
Mean (all)	2890	2040	850

Conclusions

From the three monitored buildings in France, Belgium and the Netherlands, the humidity controlled ventilation system in Les Ulis gives clearly the best results. This could to a certain extent be expected since the building has a very good airtightness and the ventilation ducts are well appropriate for this kind of ventilation system.

As a result of it, the application of a humidity controlled natural ventilation system leads in the apartments in the Les Ulis building to a significant modification of the air flow rates. This is clearly seen when analyzing the trends themselves as when looking to the relation between the various variables.

The objectives as mentioned in the introduction of this case-study are to a large extent reached in the case of the Les Ulis building.

The 2 year monitoring experiment has also shown that there are in general no serious aging problems. A prediction of the energy conservation potential is always a difficult issue, but the estimations are of the order of some 500 to 1200 kWh for a heating season.

PUBLICATIONS

- [1] Final report CEC demonstration project on Aereco humidity controlled natural ventilation for dwelling applications, expected in autumn 1992
- [2] Wouters, P., Humidity in dwellings : important pollutant source as well as a parameter for ventilation control, Symposium Zurich, May 1992
- [3] Jardinier, P., Simonnot, J., Principle and aim of a natural humidity controlled ventilation system, CIB W67 Symposium, Rotterdam (NL), September 1990

3.4 Performance assessment of a humidity controlled ventilation system in Northern Italy

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2. Introductory considerations

Mechanical ventilation is seldom adopted in residential buildings in Italy. However, the synergic effect of recently developed factors (e.g., supertight windows, lower indoor temperatures, and cold bridges frequently caused by incorrectly placed thermal insulation) are now often creating condensation problems, particularly in Northern Italy, where cold and rather humid winters are common. As a consequence, mechanical ventilation is now being considered as a useful technique to avoid condensation. Among ventilation techniques, novel technologies such as demand controlled ventilation, based on humidity control, appear particularly interesting.

3. Project description

A multifamily building, equipped with a passive humidity controlled mechanical ventilation system, has been instrumented in order to assess the performance of this type of installation under field conditions in the climate of Torino (northwestern Italy).

4. Goals of the investigation

- To check the resulting air humidity levels in terms of preservation of the building constructive elements and thermal comfort of the occupants;
- to determine if the air change rates resulting from the adoption of this ventilation strategy are sufficient to provide an acceptable indoor air quality (IAQ);
- to compare the adopted ventilation strategy with natural ventilation and traditional (i.e., without feedback) mechanical ventilation systems on the grounds of energy savings and IAQ.
- to verify the subjective reactions of the occupants to the adoption of an unconventional ventilation system.

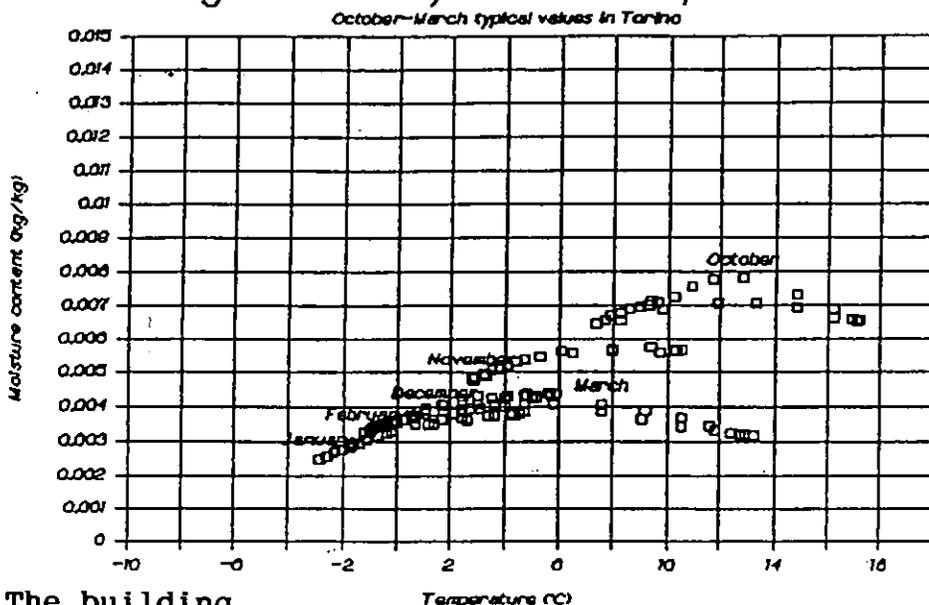
5. Site and location

The measurements were performed in the center of Torino, a one-million inhabitants city in Northwestern Italy. The climate of Torino is summarized by the following data:

- length of heating season: 180 days (October 15 to April 15)
- heating degree-days (20/12°C): 2700
- wind velocity: <1.0 m/s in winter
- relative humidity (RH): above 70 % in winter

See also Fig. 1 (plot of typical outdoor RH vs. temperature in the heating season).

Fig. 1 - Humidity ratio vs. temperature



6. The building

The object of the investigation is a six-stories multifamily building accommodating ten flats (two at each floor), plus a small "conciergerie" at the ground floor. It has an overall volume of 3500 m³, and a heated area of about 1400 m².

7. Building services

Each flat is equipped with an individual heating system, consisting of a gas boiler and hot water radiators.

The ventilation system is centralized, with one extraction fan in each building having a nominal power of 0.55 kW and a nominal flow rate of 3,000-4,000 m³/h with a pressure head of 150-200 Pa. Air is evacuated from each flat through three extraction grilles, located in the two bathrooms and in the kitchen. Exhaust air from each flat is driven through two vertical ducts (I.D. = 125 mm) into the attic, and then collected by a horizontal duct (I.D. = 250 mm) to the fan. Fresh outdoor air is introduced into the flats through the hygro-controlled immission grilles located in the roller blind boxes of the living room and the bedrooms.

8. Type of DCV system

The buildings were equipped with a forced Humidity Controlled Ventilation (HCV) system, manufactured by the French companies AERECO (hygroregulating grilles) and ALDES (ducts and fans). The size of the immission grille opening varies with relative humidity, due to a polyamidic fibre strip, treated and stabilized by the producer, which varies its length with RH. The grille opening area varies linearly between RH = 40 % (A = 5 cm²) and RH = 75 % (A = 30 cm²).

9. Monitoring programme

The measurement campaign started on October 20, 1989 and ended two months later.

The experimental apparatus consisted in 10 mechanical thermo-hygrometers continuously recording temperature and humidity profiles outdoors and in nine rooms of three of the ten flats.

Two questionnaires were distributed to the occupants.

The first was employed to collect information about the occupants' behaviour, allowing the definition of the typical daily and weekly activity schedules of the tenants in the instrumented flats, from which the water vapour production was estimated. They included questions about the location of the vapour producing electrical equipment, the cooking habits, the use of sanitary hot water, the presence of plants in the rooms, etc.

The second questionnaire (see Table I) was used to define the reaction of the occupants to the ventilation system.

Table I - Questionnaire filled by the occupants.

1. Did you notice humidity problems in the building components?
 2. Are you satisfied with indoor temperature levels?
 3. Are you satisfied with indoor humidity levels?
 4. Did you notice any malfunctioning of the system, such as:
 - a - noise
 - b - air draughts
 - c - insufficient ventilation
 - d - excessive ventilation
 5. Did you try to modify the operation of the ventilation system?
 6. Did you modify your habits regarding window opening for airing?
 7. Are there any modifications you would like to suggest about the installation or use of the ventilation system?
-

10. Results

Indoor Air Quality considerations

Figures 2 and 3 show respectively the frequency distribution and the cumulated frequency distribution plots of indoor RH (relative to about two months of hourly data) in the different rooms of Flat # 1 (kitchen, bathroom, living room, and bedroom). From these figures it can be seen that, although the highest vapour production occurs in the kitchen and the bathroom, in these two rooms only 10 % of RH values are above 50%, and 2-3% are above 55%. The lowest RH values have been detected in the living room, and the highest ones in the bedrooms.

Fig. 2 - Frequency distribution of RH

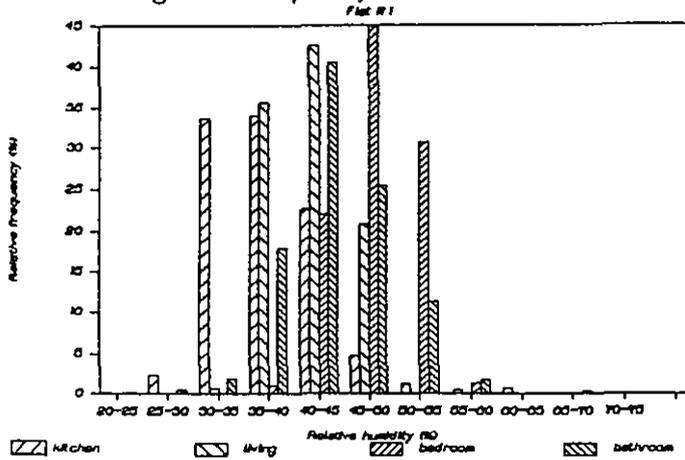
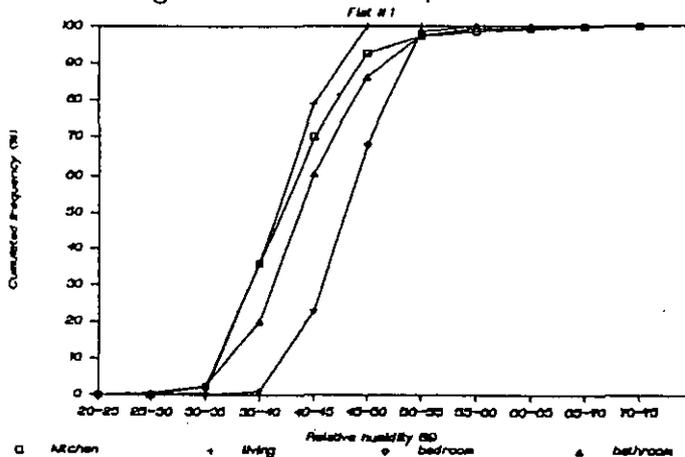


Fig. 3 - Cumulated freq. distr. of RH



Surface condensation problems

A second type of analysis refers to surface condensation problems and, in particular, to the condensation events on the aluminum frame of the windows, which is usually the coldest spot indoors.

The analysis consists of three steps:

- determination of the indoor frame surface temperature (T_s)

vs. outdoor and indoor temperature, using a numerical code;
 - determination of dew point temperature (T_d) as a function of indoor air temperature and relative humidity;
 - construction of frequency distribution plots for ($T_s - T_d$).

Results for the kitchen of Flat # 1 are given in Figures 4 and 5; the two bar graphs respectively show the absolute frequency of condensation events as a function of outdoor temperature and time of the day. The risk of surface condensation appears to be related to special times of the day when a high vapour production rate (i.e., preparation of meals: see Fig. 5) occurred.

Fig.4- Condensation events

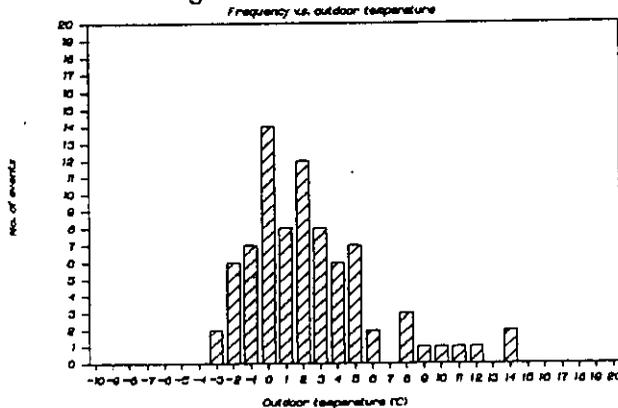
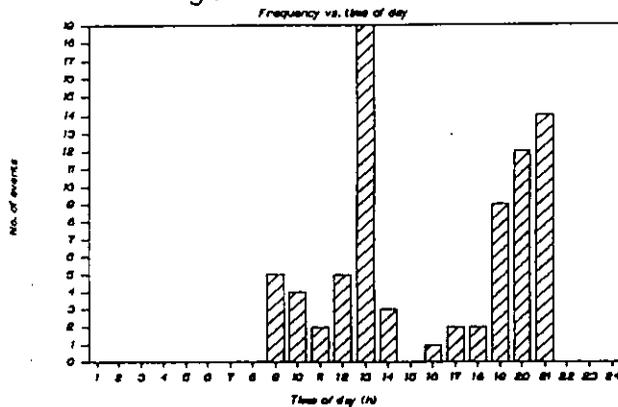


Fig.5 - Condensation events



Energy savings evaluations

The evaluation of energy savings requires the determination of i) the actual number of air changes, and ii) the theoretical number of air changes required by a constant ventilation system providing the same peak value of RH. The number of ach's was calculated assuming perfect mixing and dividing each flat into two zones: a night-zone including bedrooms and bathroom, and a day-zone including living room and kitchen. Measuring moisture content in the two zones and outdoors, and estimating the water vapour production in both zones, the air flows from outdoors to each zone and between the zones can be determined. As an example, the results of the calculation are reported

for a 12 hours period. Total extracted air flow (m_{20}) and disaggregation of flow rates (i.e., m_{20} , m_{12} , and m_{02}) are presented in Fig. 6. The average values of flow rates during this period are reported in Table II.

Fig. 6 - Calculated air flows

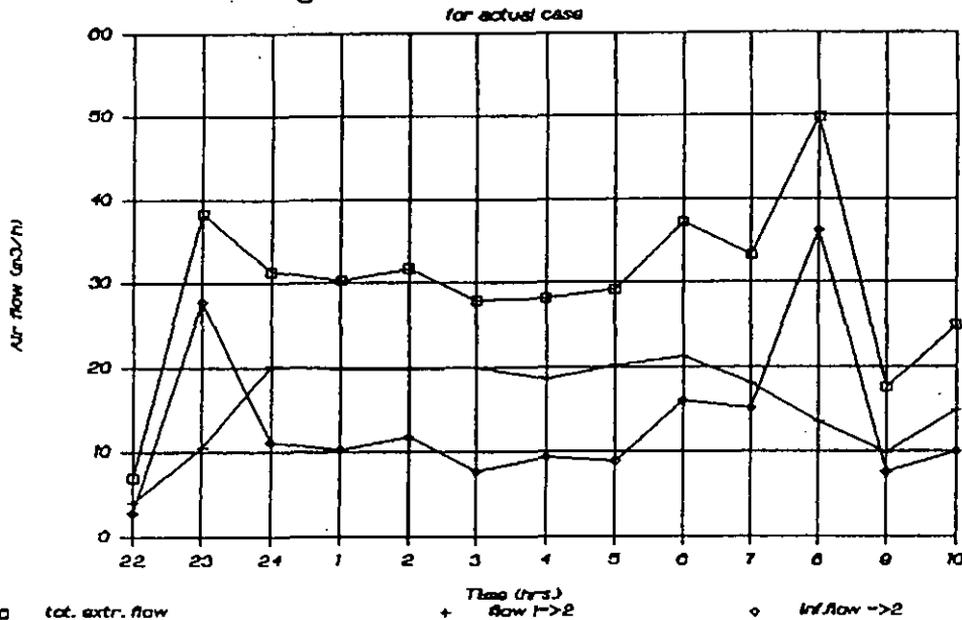


Table II - Average flow rates and air changes

Flows: Total		From outd. to room 1		From outd. to room 2	
m_{320} m^3/h	n_{tot} h^{-1}	m_{320} m^3/h	n_1 h^{-1}	m_{320} m^3/h	n_2 h^{-1}
29.8	0.50	16.3	0.35	13.5	1.00

The total average ach's was close to 0.50, while the peak number of ach's was 0.83, indicating an air flow reduction of 40 %, whether a constant ventilation system would have been adopted.

It should be stressed that, assuming a perfect mixing situation, which may be far from being true, the air flow rates are probably overestimated by a factor of 1.5-2, because the location of the extraction grilles (e.g., right above the cooking equipment in the kitchens), allows to realize rather high ventilation efficiencies.

Occupants' acceptance

The results of the questionnaire shown in Table I are listed in Table III. A total of 20 questionnaires were distributed to the tenants. Twelve families did not reply. Six questionnaires were returned, one of which incomplete. Two tenants refused to fill the questionnaire and declared to be globally unsatisfied with the system, without explaining their reasons. In general, the tenants that answered the questionnaire (probably, those who paid more attention to the operation of the system) expressed a global satisfaction,

while pointing out some relatively minor problem. The most frequent problem that was detected is the condensation of water vapour on the aluminum window frames in the bathroom. A few of the tenants have expressed some annoyance, especially in the coldest days, for the cold draughts creeping into the bedrooms through the grilles during the night, and have also tried (successfully) to outdo the system by taping the inlet grilles. Other annoyances which were claimed, such as temperature differences between rooms, may be not attributable to the ventilation system.

On the positive side, several tenants noticed that the HCV system allowed them to reduce airing and that indoor humidity was acceptable even under "severe" (e.g., cooking time) conditions. The quality of indoor air was also considered satisfactory.

Table III - Results of the questionnaire.

Question #	YES		NO		NOTES
	#	%	#	%	
1	4	67	2	33	Condensation on bathroom windows
2	4	67	2	33	Temp. differences between rooms
3	6	100	0	0	
4a	1	17	5	83	
4b	0	0	6	100	
4c	1	17	5	83	
4d	0	0	6	100	
5	1	20	4	80	Inlets plugged due to low temp.
6	4	80	1	20	Reduced need of airing
7	0	0	5	100	

11. Conclusions

The performance of the tested system may be so summarized:

- i- the system was able to maintain low levels of relative humidity and simultaneously required
- ii- a reduced amount of fresh air compared to a traditional system (with constant flow rates).
- iii- Thanks to the low indoor RH condensation on the walls was avoided, except on the metal frames of the windows.
- iv- There was an apparently "cool" or even "hostile" reaction of some of the occupants to this type of ventilation system. It may be due to its novelty for the Italian habits.

12. References

- AERECO, Technical documentation.
- ALDES, Technical documentation.

Fantozzi, C., Sistemi di ventilazione meccanica controllata per edifici residenziali (Controlled mechanical ventilation for residential buildings), Thesis in Mechanical Engineering, unpublished, Torino, 1990.

Raatschen, W. (Ed.), Demand Controlled Ventilating System - State of the Art Review. Annex 18, IEA. Swedish Council for Building Research D9:1990. Stockholm, 1990.

3.5 A demand controlled balanced ventilation system in an energy efficient dwelling in practice

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2. Project description

To analyse the practical behaviour of a balanced ventilation system which was controlled by a sensor in several ways:

- manual control, as a reference
- RH sensor in living room with setpoint adjusted as a function of the outside air temperature
- RH sensor in exhaust air with setpoint adjusted as a function of the outside air temperature
- RH sensor and IAQ sensor in exhaust air with fixed setpoints.

The application of DCV for balanced ventilation for dwellings should be given on the basis of the analysis.

3. Site and location

The dwelling was located in Maasbree, the Netherlands. The dwelling forms a part of energy efficient dwellings (high insulation and heat recovery of the ventilation air).

4. Building form

The building form is given in figure 1.

The air tightness of the dwelling is $2,6 \text{ h}^{-1}$.

The U-values are:

roof	=	0,37 W/m ² K
walls	=	0,25 W/m ² K
glazing	=	1,31 W/m ² K living/kitchen 3,00 W/m ² K first floor

5. Building services

The dwelling was heated by radiators. The ventilation of the dwelling takes place by means of a balanced ventilation system with heat recovery. The principle of the balanced system is given in figure 2.

6. Utilization

In the dwelling live 2 adults and 2 children, also in day-time.

7. Basic ventilation strategy

The balanced ventilation system can be used by the occupant by means of a manual switch in 3 levels with the following ventilation output:

high	220	m ³ /h
middle	155	m ³ /h
laag	35	m ³ /h

8. Demand control strategy

3 different demand control strategies are used during 2 weeks:

DCV1 Controlled a RH sensor in the living room. If the RH in the living room is higher than the setpoint, the fan will work in highlevel.

If the RH is lower than the setpoint the fan will work in low level. The middle level will not be used. Because the RH in a dwelling is not only a function of the moisture production in the dwelling but also of the outside air temperature is not chosen for a fixed setpoint but for 4 setpoints as a function of the outside air temperature, see figure 3, curve a.

DCV2 Controlled by a RV sensor in the exhaust air. There is here also a setpoint installation bound to the outside air; see curve b. in figure 3.

DCV3 Controlled by RH sensor and IAQ sensor in the exhaust air.

Both sensors are connected in parallel so that the overstep of the setpoint of the sensor switches the fan in more revolutions per minute. Per sensor 2 setpoints are possible so that as well the low level (basic ventilation), the middle level as the high level will be used.

Setpoint installation:

RH-sensor:

low RH = 55%

high RH = 65%

IAQ-sensor: *low* IAQ = 65%

high IAQ = 70%

9. Monitoring

Except for the switch behaviour of the ventilation-unit also the indoor climate parameters RH and CO₂ concentration are determined; also the output of this sensor is recorded via a so called IAQ sensor (mixed gassensors). The monitoring scheme is given in figure 4.

10. Results

The fan levels as a function of the control strategy show:

control type	fan level in %		
	high	middle	low
manual	24	3	73
DCV1	--	--	100
DCV2	--	--	100
DCV3	55	16	29

The control DCV3 with the IAQ sensor (most important property) leads to a considerable higher working cycle in the high level than manual control. Figure 5 (with the division of the high level of the day for DCV3 and manual control) shows that the reaction of the IAQ sensor of the day is high handed divided. In case of manual control the high level takes place mostly in the afternoon and in the evening.

DCV1 and DCV 2 mostly characterized by a RH installation related to the existence of condensation and mould growth does not switch on the high level. On the basis of this criterion the basis ventilation gives enough ventilation for this dwelling.

DCV3 has mostly controlled on the IAQ sensor and practically not on the RH sensor.

It appeared that there is no relation between the value of the IAQ-sensor and the RH in the living room.

There is a good relation between the RH in the living and the RH in the exhaust duct, nl.

$RH(\text{living}) = 0,78 RH(\text{exhaust}) - 0,03$ with a correlation of 0,9.

The relation between RH exhaust and RH (sleepingroom) resp. RH (bath) are much weaker, the correlation factor was 0,7.

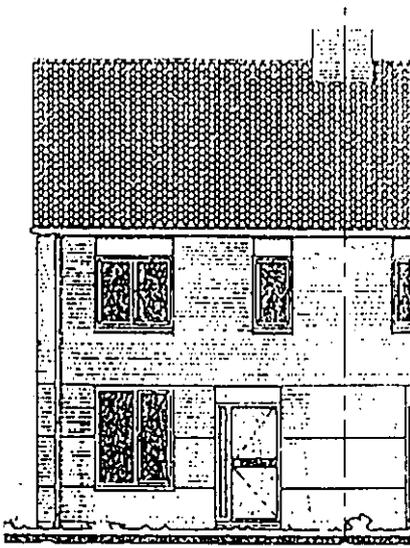
The average CO₂ concentration in the bedroom was:

manual control	=	900	ppm
DCV1	=	1050	ppm
DCV2	=	890	ppm
DCV3	=	575-790	ppm

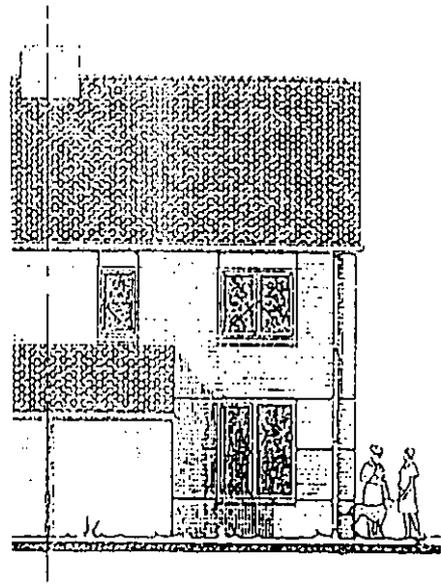
11. Conclusions and recommendations

The totale ventilation quantities vary considerable per adjustment. The application of a IAQ sensor lead to an increase of the working cycle in high level and thus to a higher energy level. The occupants (not by means of a detailed enquiry) appreciated this adjustment as the best. The lowest ventilation takes place if it will be adjusted on a RH sensor with setpoint adjusted to the prevention of surface condensation.

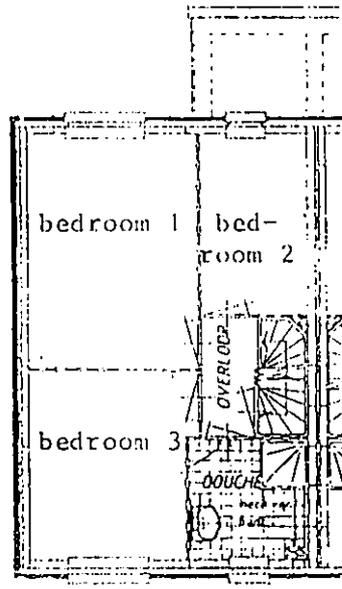
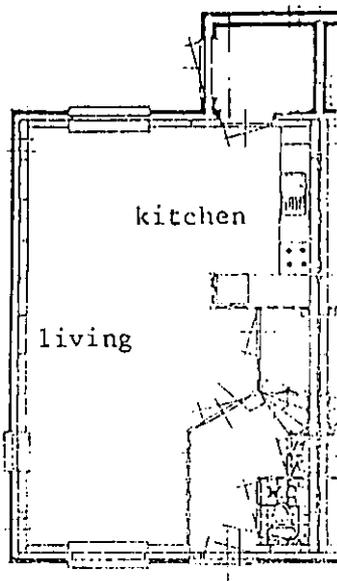
A RH sensor can be installed in the living room or in the exhaust duct. The use of a RH sensor besides a IAQ sensor does not give always a better adjustment. The IAQ sensor reacts also on the RH and is faster.



front facade



rear facade



first floor

Figure 1. Ground level and first floor.

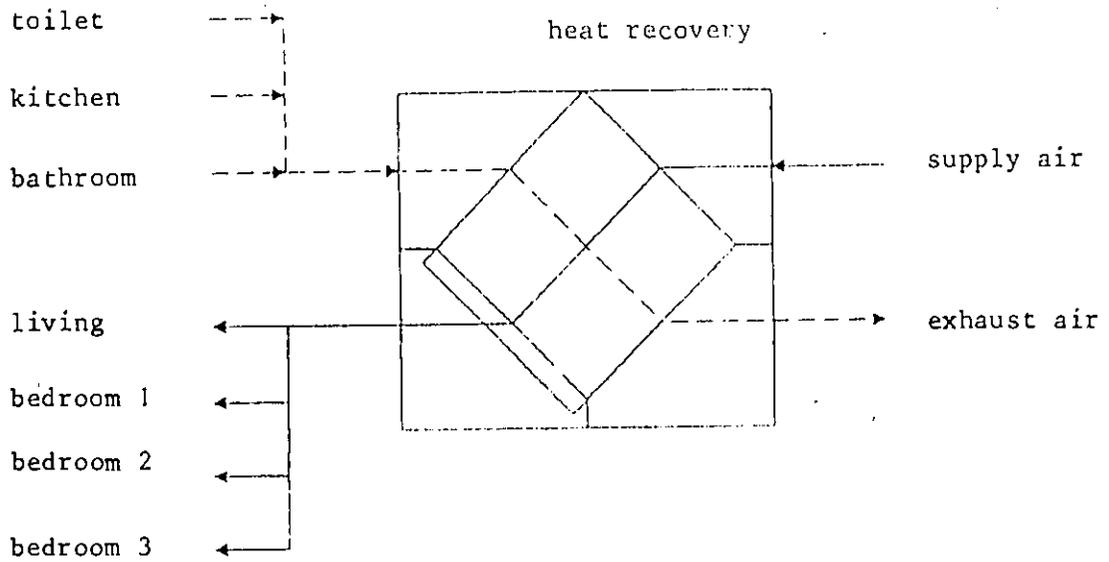


Figure 2. Principle scheme of the balanced ventilation system with heat recovery.

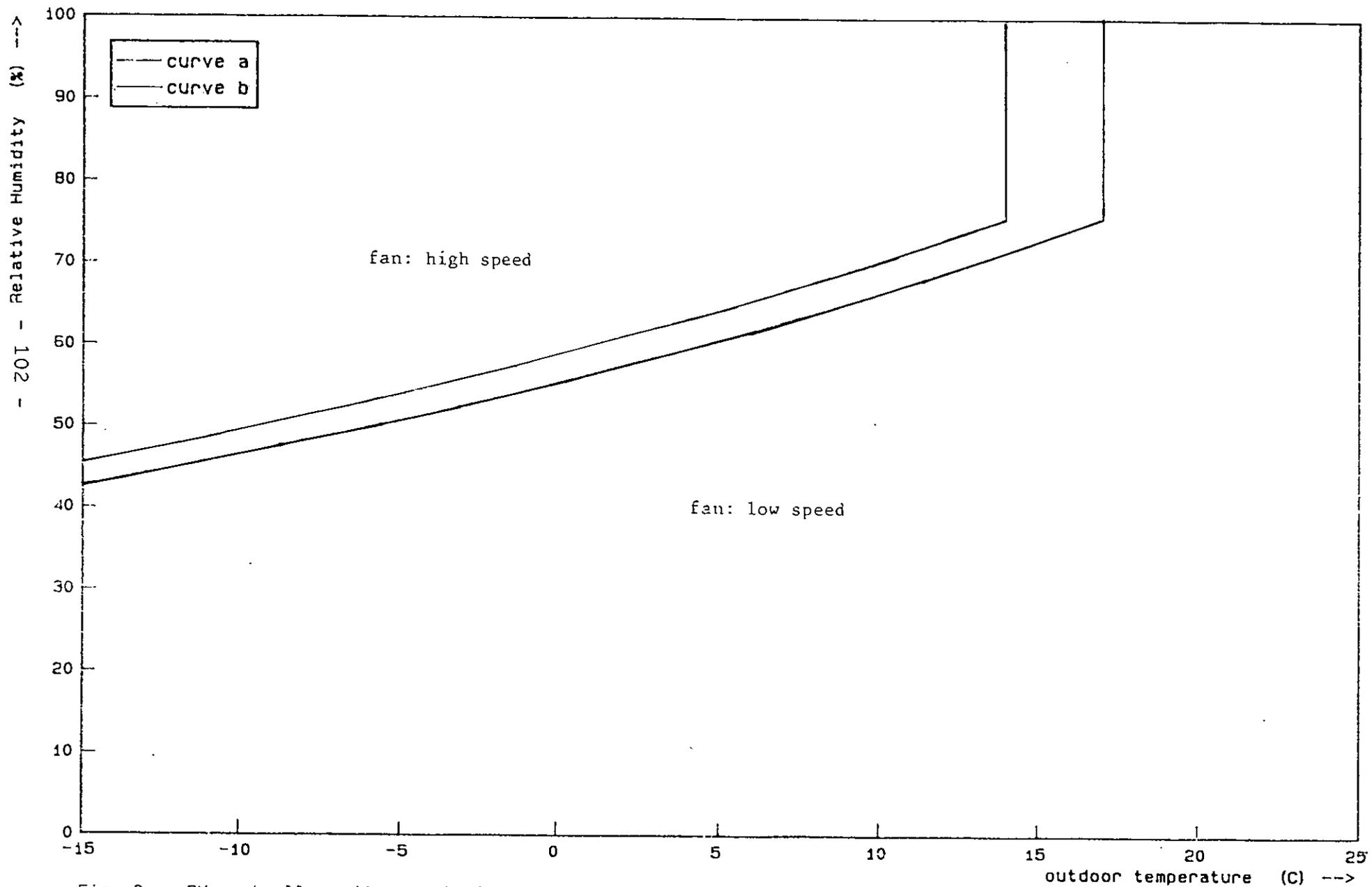


Fig. 3 RH controller with a setpoint varying with the outdoor temperature

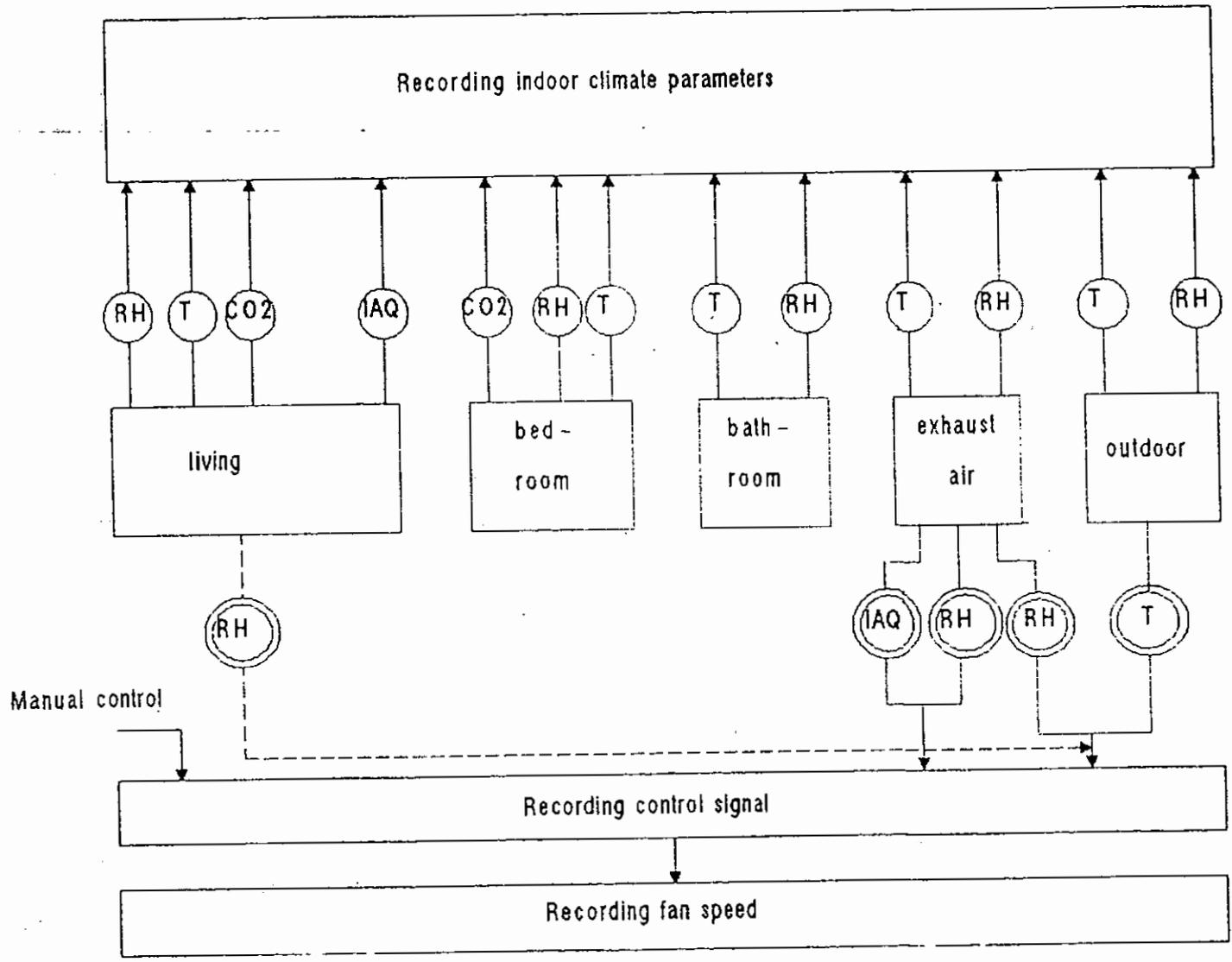


Figure 4. Monitoring scheme of the measuring set up.

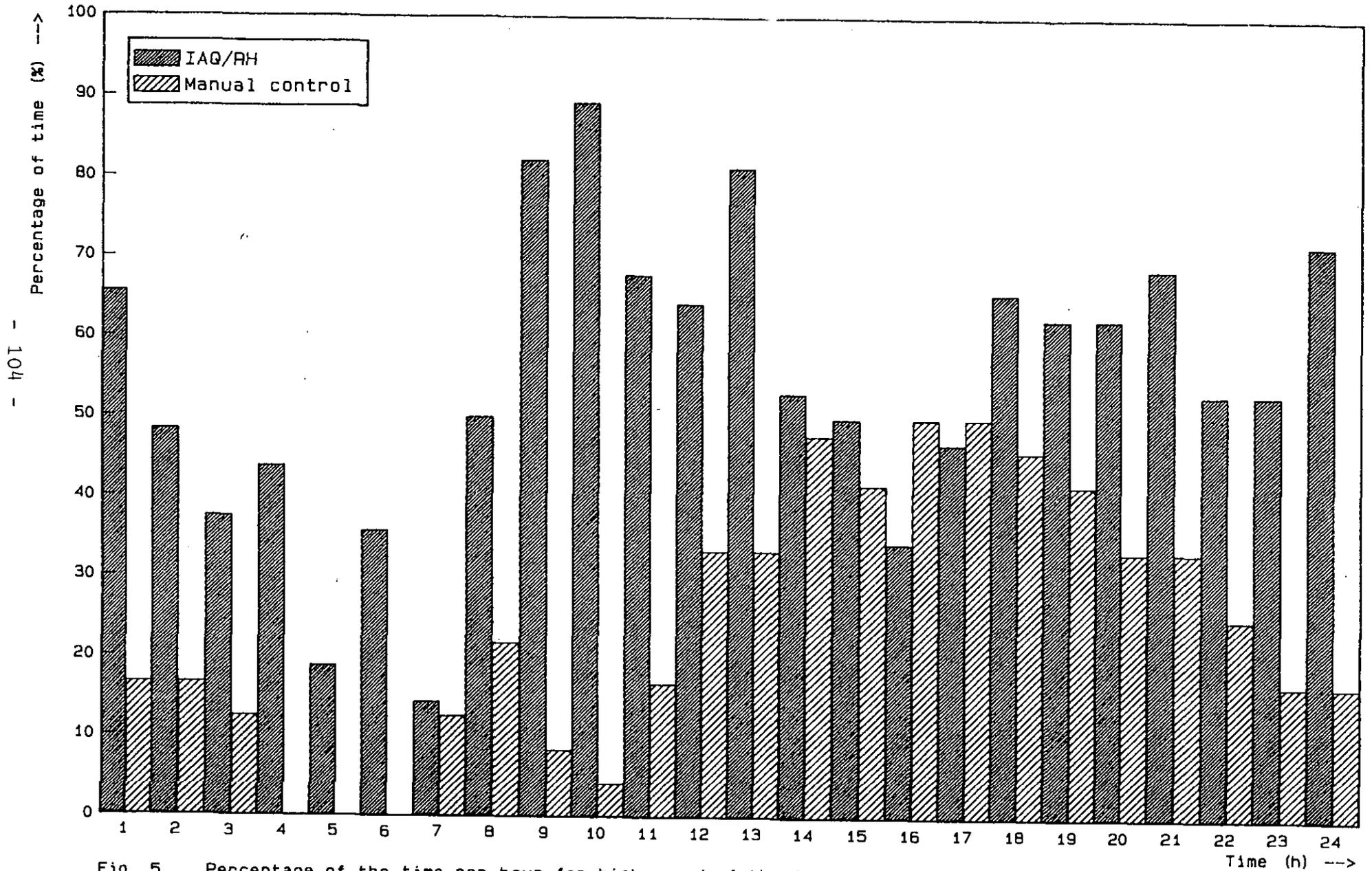


Fig. 5 Percentage of the time per hour for high speed of the fan, controlled by IAQ/RH and manual control.

Table 2: Description of ventilation systems in the Five Research Houses

Sue house	HRV with recirculating system
Jones house	HRV without a recirculation system
Smith house	Exhaust only ventilation with recirculating system
Morewood house	Exhaust only ventilation without a recirculating system
Helma house	Multiple sensor DCV system, HRV with recirculating system

The floorplans show some details of the systems used.

Monitoring

The Sue, Jones and Smith houses were extensively monitored and retrofitted as part of the research. The Morewood house had an existing DCV system which was tested as found. The Helma house was new construction, and incorporated ventilation design specifications prepared as part of this project.

Field investigations began with extensive commissioning tests on existing ventilation systems, followed by minor up-grades and installation of long term monitoring equipment. After three months of monitoring house performance and air quality without DCV, each house was retrofitted with a new DCV system.

The new DCV systems employed a variety of sensors, to permit continuous measurement of such parameters as CO₂ levels, pressure differentials, temperatures indoors and out, relative humidity, absolute humidity, air flow through the ventilation system, activity levels within the house, operation of heating equipment and clothes dryers, and air flows through variable exhaust equipment and furnace blowers. Several patented devices for gauging air quality measurement were also employed in the houses, including the Massawa Vital Air Purity meter (with sensors for oxygen, particles and humidity), and the Halitech Sensor (for odours and combustibles). Different combinations of sensors were used in each house, as dictated by the type of systems. Spot

measurements were also conducted for measuring formaldehyde, organics and other pollutants.

Intensive monitoring of activity scenarios was conducted in four of the research houses, to measure how the systems responded to very different kinds of activities within the home. The intensive monitoring included: a tracer gas growth test in each house, to measure ventilation effectiveness; a tracer gas decay test, to measure ventilation efficiency; a mass balance moisture test, to measure the capture efficiency of the exhaust inlets; and a multi-point absolute humidity test, to measure the moisture absorption and desorption rates of the entire house.

Results

General

The results of field monitoring on three of the research houses is presented in the following table.

Table 3: Summary of Low Level Monitoring - Before and After DCV

	Sue house		Jones house		Smith house	
	Before RH	After Activ.	Before RH	After CO2	Before RH	After Abs-H
Hours of Monitoring Data	856	580	1158	189	1385	846
Outside Temperature (C)	3.8	10.5	2.7	n.a.	7.1	13.4
Inside Temperature (C)	20.9	21.4	21.2	22.1	24.4	24.0
Relative Humidity (%)	40	42	38	n.a.	31	n.a.
Average CO2 (ppm)	571	544	584	558	542	472
Max. Hourly CO2 (ppm)	2250	948	996	726	2767	1029
Ventilation Flow Rate (L/s)	80	75	62	49	25	32
Ventilation - Time Off (%)	0	23	0	34	0	0
Activity Counts Family Rm	75	67	39	35	79	68
Activity Counts Bedroom	4	4	15	13	4	5

Note: n.a. - not available due to data collection problems

With demand control, ventilation reductions of 6% to 21% resulted for the period monitored. This will result in a corresponding reduction in energy required to heat the ventilation air. In addition, fan electrical energy was reduced from 23% to 34%.

While generally reducing energy use, all three DCV systems achieved slight reductions in average CO2 levels, and significant reductions in peak CO2 levels.

Jones house

Three figures from the Jones houses are presented as an example of the data that was analyzed prior to choosing a DCV strategy for this house. A similar procedure was followed for the Sue house and the Smith house.

Figure 1: Typical Working Day presents a typical working day in the Jones house. The house has 335 square meters of living area and is a super energy efficient rated under the Canadian R2000 Program. The house is heated with a hot water radiant boiler and is ventilated with a fully ducted HRV running continuously. Two adults and four children live in the Jones house. The mother works at a nearby school and the children are all school age.

CO₂ levels slowly rise during the night with 6 people sleeping with a ventilation rate at 62 L/s. CO₂ levels are constant through the night and peak at 8:30 AM as the family prepares to start the day.

The HRV is activated either by relative humidity sensors or by manual controls. The maximum HRV flow is at 7:30 AM and likely corresponds to showers. CO₂ levels decay slowly over the day but begin to rise when the children first arrive home from school at 3:00 PM. The maximum peak for CO₂ (850 ppm) is reached at 11:00 PM just before bedtime. Activity Sensors detect some slight movement during the night as occupants use the washroom and a burst of activity in the morning. Activity sensors detect the arrival home of the youngest children in the early afternoon. Weekends were found to only vary slightly from this typical working day.

Figure 2: Evaluation of Absolute Humidity Sensor for DCV Control presents intensive monitoring of the same house at the same time of year, but over several days. Absolute humidity and CO₂ are being sampled every 5 seconds and averaged and stored on a 3 minute basis by the data acquisition system. Only a rough visual correlation exists between peaks in CO₂ and absolute humidity. Humidity and CO₂ peaks

tend to coincide, however the CO2 peaks are usually one to three hours later. During unoccupied periods, CO2 concentrations drop from peaks of 800 - 900 ppm to 500 - 600 ppm (about 35%). For the same period, absolute humidity drops about 15% to 20%. At night, when the six occupants are sleeping, CO2 concentrations remains relatively stable, while the absolute humidity tends to fall.

Figure 3: CO-Pilot CO2 DCV Control shows the Co-pilot data acquisition control program acting as a DCV controller in the Jones house. This trial of the software shows that the feedback gain set for the ventilation system controller was too high, causing an erratic fluctuation in the ventilation rates. Further experimentation was required to obtain a smooth transition. With a CO2 set point of 650 ppm the DCV system was unable to match the load during breakfast. However, during most of the night flows of either 40 L/s or 88 L/s were able to control the load.

Helma House

The Helma house was a new house, designed to demonstrate DCV technology, and to validate the insights obtained from the other 4 houses. Commissioning of the new DCV house showed the suitability of using low cost sensors for detecting VOCs, absolute humidity, air flow and activity levels. The Helma house DCV system has five main features that are presented in Table 4.

Table 4: Features of DCV Control Strategy in Helma House

Feature 1	The system automatically turns on when people are at home and cycles on and off when people are away. The ventilation rate is calculated by the software program based on activity levels and the number of people at home. (Alternatively, a CO2 sensor could have been used.)
Feature 2	An air quality sensor will detect when pollutants are produced and will increase ventilation rates. The Figaro semi-conductor sensor operating in AC mode with a breather will sense toxic cleaning chemicals, off-gassing from construction materials and cigar smoke.
Feature 3	The system automatically monitors moisture levels in the home and outdoor temperatures. The system will automatically lower humidity levels to prevent condensation from occurring on window surfaces if outdoor temperatures drop.
Feature 4	The information that is being monitored is continuously displayed on a video monitor in the living room. The occupant can always be aware of how the system and the house is performing.
Feature 5	The software written to control the system is able to achieve any ventilation rate by switching between two motor windings and four motor speeds. Moving averages are used to dampen variability and slowly target a given ventilation rate.
Feature 6	The occupant can override the system at any time to set minimum and maximum ventilation rates by turning a dial and flicking switches. The occupant can choose when to rely on the automatic system.

Conclusions and Recommendations

A number of useful guidelines for designing DCV systems in Canadian housing were discovered by analyzing data from the before and after low level and intensive monitoring. The guidelines apply to the 5 research houses and we believe can be safely applied to other Canadian homes.

- DCV offers benefits only when time-varying occupant generated pollutants exceed building related pollutants
- Source control of building generated pollutants at the construction stage is essential for applying DCV control strategies in new Canadian homes.
- CO2 is an excellent indicator of occupancy and ventilation requirements in residential buildings. A small, moderately priced passive CO2 gas analyzer performed well in

three research houses. However, the cost of the technology is too expensive for the bulk of Canadian houses.

- Activity related pollutants are best controlled by special purpose high capacity, directly vented, exhaust fans with high capture efficiencies.

- Relative humidity is a poor indicator of occupancy. Response times are slow and often there is no discernible change in RH despite major changes in occupancy and CO2 concentrations. Absolute humidity is a much better indicator of occupancy than relative humidity but still displays a lag time that is due to absorption and desorption characteristics of the house. Ventilation control based on absolute humidity is limited to the heating season, and is best combined with a window inside surface temperature to provide condensation control.

- The dehumidistats commonly employed for RH control were found to be grossly inaccurate as supplied by the manufacturers, subject to drift over time, and lacking any convenient means for re-calibration.

- Passive Infra red (PIR) activity sensors proved low cost and reliable during the field trials. They have a poor short term correlation with CO2 but excellent long term correlation. The poor short term correlation is due to the fact that activity is sensed instantly whereas pollutant concentrations rise over time. Short term correlations could be improved with more sampling points, and a software program that is able to gauge the level of activity over time and allow the system to respond to the rhythms of the household.

- Semi-conductor sensors (e.g. Figaro T68800) appear to have potential as an overall IAQ indicator if used in alternating operation with a breather that periodically flushes the sampling chamber to automatically zero the sensor.

- High mixing rates in residential houses are preferable to zoning and can greatly reduce the ventilation requirements on a room by room basis. In an energy efficient home, the

ventilation requirements - not the heating load - should dominate the design specifications for air moving and distribution systems.

- DCV systems are particularly effective at reducing peak pollutants concentrations. This offers improved health and comfort, even if the mean level of pollutants are similar for systems without DCV.

- Further research, including theoretical work and chamber testing, is needed to develop a simple and reliable performance test capable of describing the effectiveness of fresh air distribution, and the response time of systems to fresh air demands. The development of these tests could greatly facilitate the evolution of ventilation systems and the incorporation of minimum standards within the building code.

- Inlets equipped with humidity controlled bladders were found to be particularly ineffective for DCV application, both in coastal climates and in central Canada.

- DCV system design can be simplified by defining the most common operating modes for the house, and configuring the air mixing and air change rates accordingly. Typical operating modes could be: standby (with timer activated intervals of operation); occupant arrival; high activity; odour control: and sleep.

- A potential exists for lowering the capital costs of sophisticated DCV systems by using a multipurpose home computer.

- Occupants should not be relied upon to optimize the operation of ventilation systems, although occupants must have the ability to interpret and override automatic controls

- DCV systems have the potential to become highly visible sales features in new homes, especially if occupants are provided with continuous feedback on their indoor and outdoor environments.

References:

1. Moffatt, P., Moffatt S., and Cooper, K., "Demand Controlled Ventilation", Final Report - March 1991, Canadian Mortgage and Housing Corporation, Ottawa, Canada.

3.6 A Demonstration of Low Cost DCV Technology on Five Canadian Houses

Contacts:

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T. Hamlin
CMHC
Research Div.
Ottawa, Ont.

The primary objective for the project was to determine if DCV can improve the way in which Canadian houses are ventilated, while lowering the operating or capital cost of ventilating systems. A further objective was to provide guidance for home builders and ventilation system designers on what DCV strategies might be most appropriate for near term applications.

The project was completed in five separate phases described in Table 1.

Table 1: Phases of CMHC Funded DCV Research

- Phase 1 Literature Survey
- Phase 2 Preparation of a Primer for Builders and Designers
- Phase 3 Field Research on Five Canadian Houses
- Phase 4 Computer Simulations of Ventilation Rates
- Phase 5 Economic Analysis of DCV

energy efficient
& low toxicity

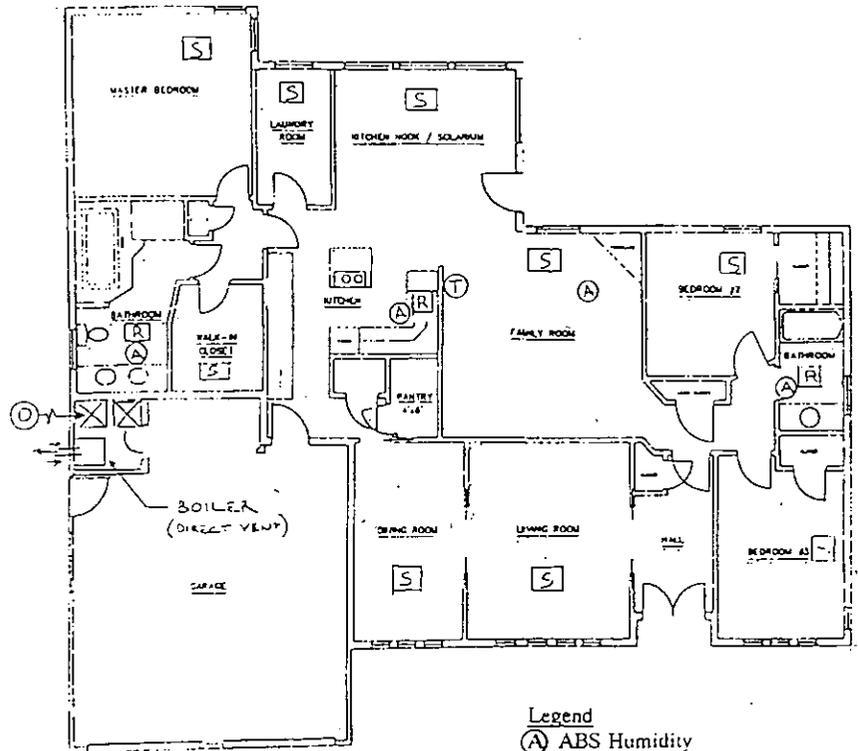
Field investigations were intentionally designed to test ventilation systems compatible with the new CSA F326 Ventilation Standard for Canadian houses. Four of the five research houses were energy efficient, low toxicity construction.

Site and Location

The houses were located in both coastal and interior climatic zones. The Sue, Smith, Jones, and Helma house were in the vicinity of Vancouver. The Morewood house was in Ottawa.

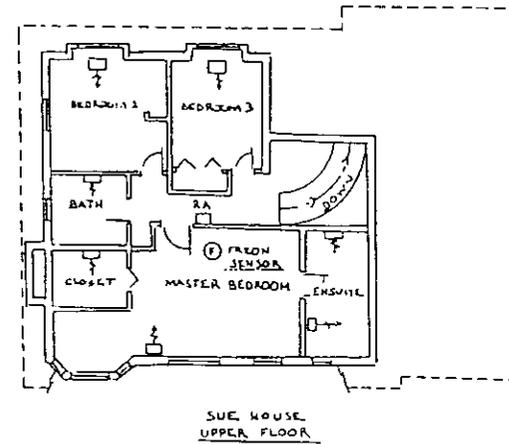
Ventilation Systems

The variety of systems was intended to reflect the most common approaches applied in new energy efficient Canadian housing.

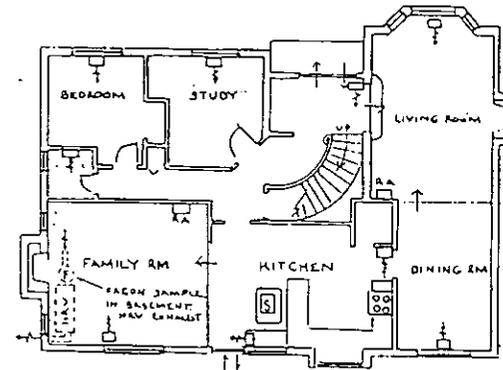


- Legend**
- (A) ABS Humidity
 - (T) Temperature
 - (R) Extractor
 - (S) Supply Air
 - (O) Outdoor Air

Smith House Floor Plan

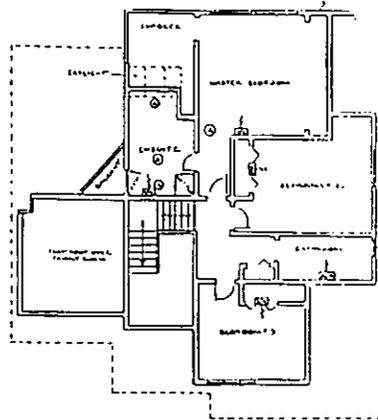
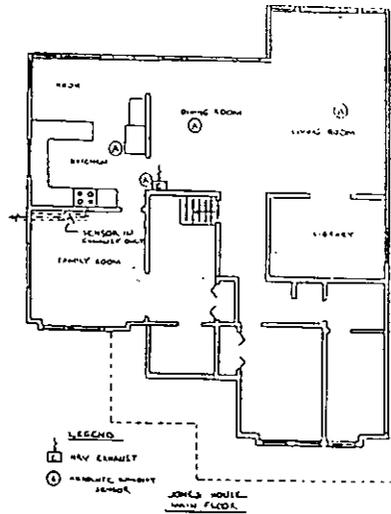


SUE HOUSE
UPPER FLOOR



- Legend**
- ☐ Supply Air
 - ☐ Exhaust
 - ☐ Return Air
 - ☐ Sampling Station

Sue House Floor Plan



Jones House Floor Plan

- Legend
- ⊙ ABS Humidity
 - ◻ Air Supply
 - ◻ Air Return

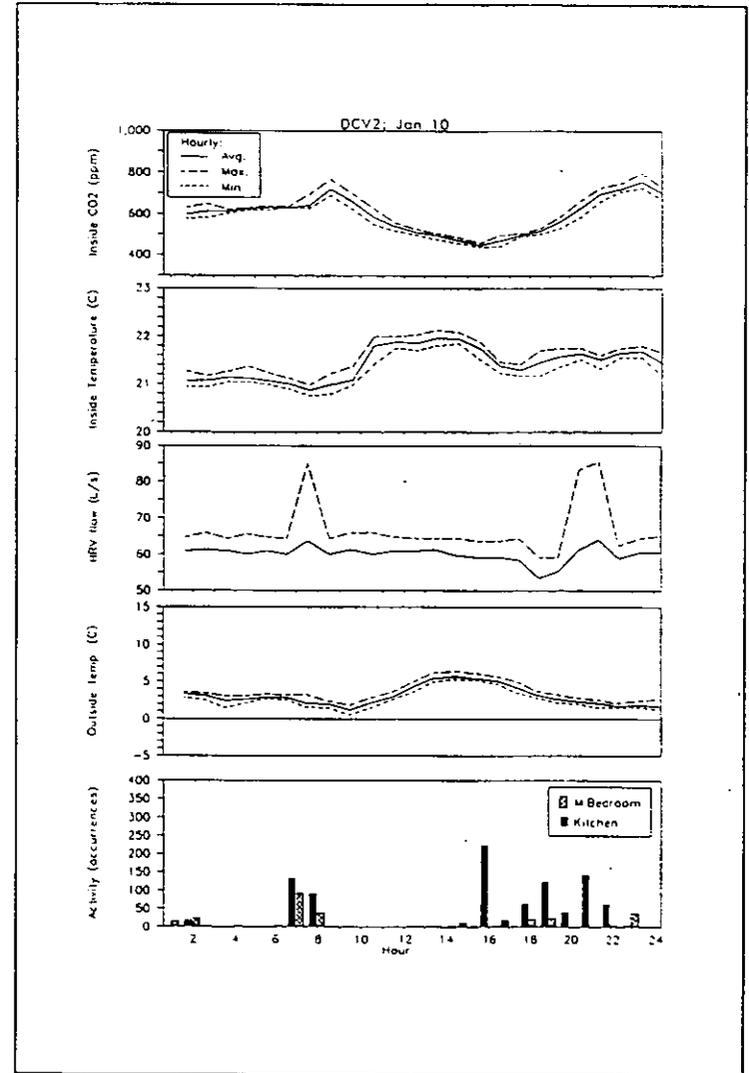


Figure 1: Jones house - Typical Working Day

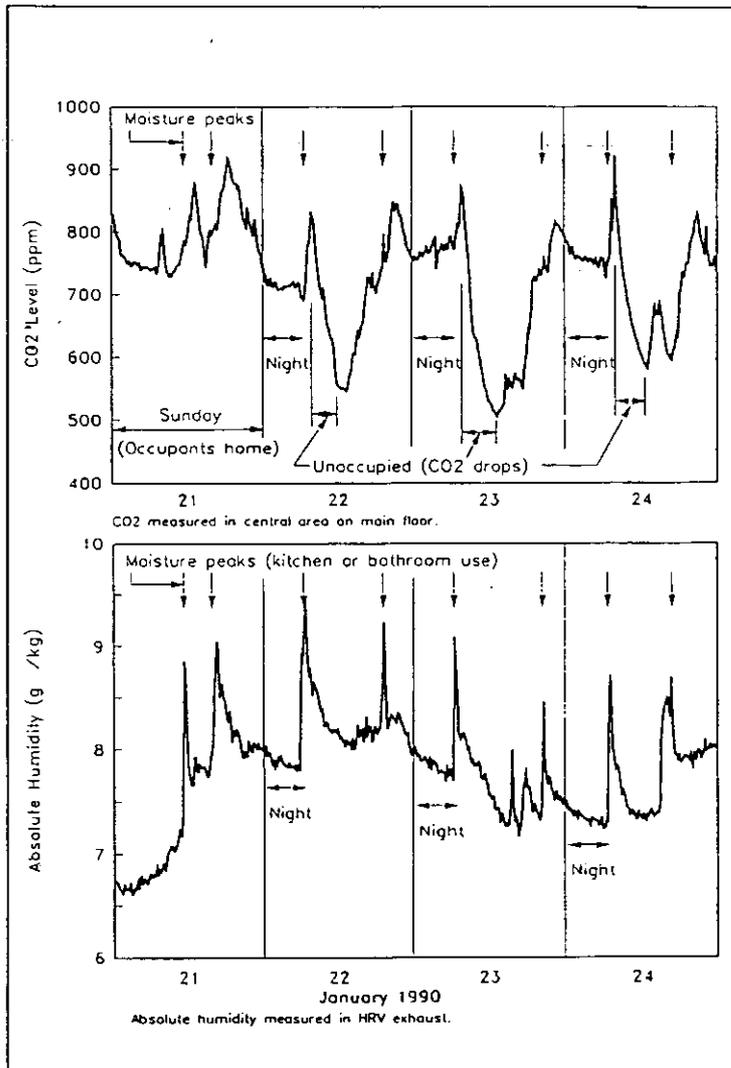


Figure 2: Evaluation of Absolute Humidity Sensor for DCV Control

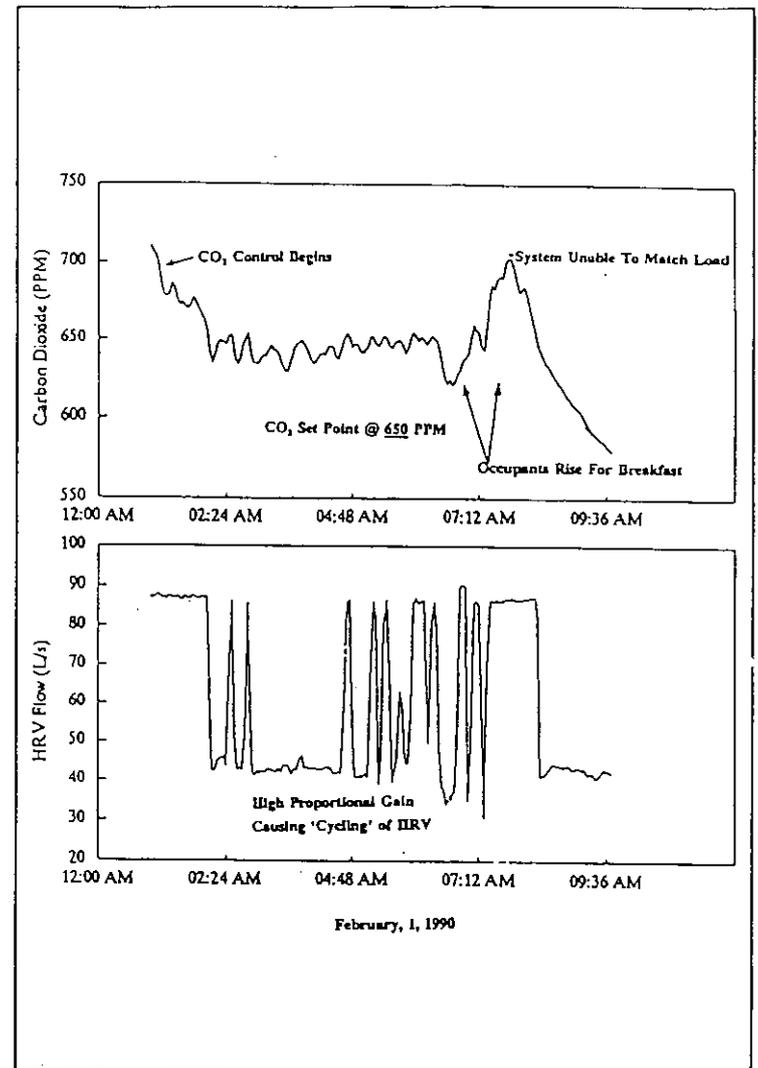


Figure 3: CO-Pilot CO₂ DCV Control

3.7 Advanced Humidity Controlled Ventilation

Summary

Based on research results of IEA-Annex 14 'Condensation and Energy' a new humidity controlled extract ventilation system was tested and improved. The characteristic feature of the controller is that it takes the special conditions for mould growth into account. The setpoint to activate the fan is not fixed, it is a function of the surface temperature at the critical location of a wall and the room air temperature. The system was tested in a bathroom with severe mould problems in an occupied dwelling. The aim was to find a control strategy which insures to avoid mould growth on one side and to be highly energy efficient on the other side. The different control strategies investigated gave valuable information about the design of such a system.

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W. Raatschen



Figure 1: Front view of the test dwelling in Friedrichshafen



Introduction

Humidity control in dwellings has only one reason: 'to avoid mould'. The demand for energy savings arises the need for a control strategy, which is directly oriented to the problem. And the problem is the growth of mould!

Common humidity controlled ventilating systems use a setpoint, which seems to be chosen quite arbitrarily. Almost always the setpoint is chosen to be constant throughout the year. Often it is chosen with regard to

good indoor climate for the occupants within a range of 60-70 % relative humidity (RH). Humans are not very sensitive to changes of the humidity level in indoor air, as long as the indoor relative humidity is not lower than 30%.

A problem oriented solution has to be adopted to the conditions, where mould growth becomes possible. Results of IEA-Annex 14 show that mould germination occurs when the mean water activity against/on a nutrient surface remains higher during a shorter or longer time than a threshold value 'a', a being a function of the mould species, the temperature, the substrate (nutrient)... Using the fact that in steady state, the water activity is nothing other than the RH, the condition for mould germination becomes $p \geq a \cdot p_s$.

Mould growth is a very slowly happening process. Unfavourable conditions may prevail throughout longer periods (days, weeks). A first order approximation has been established which says, that the RH against the surface on a monthly base should not be higher than a defined threshold value a, where a is a function of the lowest surface temperature in a room, usually a thermally weak spot in the building envelope, called a THERMAL BRIDGE.

Aim of the Project

The most effective way to avoid mould problems is to properly insulate the building and to choose the right materials especially in rooms with higher moisture loads. Assuming a quite well insulated house, an average occupant behaviour with regard to moisture emissions and ventilation rates, humidity control may not necessarily be controlled, as other pollutants may govern the ventilation rate. But in dwellings where moisture problems exist and where remedial measures on the building envelope insulation are not possible or wanted (due to economic reasons or others), advanced humidity control provides good means to solve the problem with minimum energy consumption.

This report tries to answer the following questions:

- is advanced humidity control able to avoid mould germination or not?
- down to which insulation quality (u-value, temperature ratio) is mould germination possible to avoid by advanced humidity controlled ventilation?
- does the a-value philosophy hold in practice?
- what energy consumption is associated with this control strategy?
- what maximum extraction rates are necessary?
- comparison of different control strategies
- investigate boundary conditions (moisture emission rates as a function of time); time period for the fan to run after the emission process.

Project Description

Year of construction: 1960

total living area: 177 m²

bathroom:

floor area 7.24 m²

height: 2.32 m

volume: 16.8 m³

flagged walls and floor

1 shower

1 bath-tub

2 sinks

window, double glazed

2 exterior walls

2 inner walls

gypsum plaster at ceiling

ratio of sorptive surface area to total surface area $R_{abs} = 0.18$

occupancy:

2 adults

3 children (age 1,5,7)

Important for this project was, that investigations were not made in a test house but in a commonly occupied building. Chosen was the bathroom of an old mansion in Friedrichshafen in the south of Germany. The house was situated only 100m away from the lake shore of Lake Constance, i.e. the local climate was more humid than in other parts of this region. The bathroom had a severe thermal bridge at the north-west corner where the insulation quality of the ceiling was very poor. Although windows in the past had been opened regularly after showering, mould germination appeared again and again after one or two months. The application of fungicides didn't cure the problem.

Preparation:

Mould spores at the ceiling and in between the tiles were 2 times washed off with a fungicide liquid. The ceiling was dried out for a day and then painted with usual wall paint.

Implementation of an Extract System:

Close to the shower and the bath-tub the extract grill was installed into the ceiling and connected to the fan by a flexible duct. To avoid any flow through the duct when the fan was off, a self-closing damper was interconnected. The extracted air was exhausted to the attic.



Figure 2: View into the interior of the bathroom

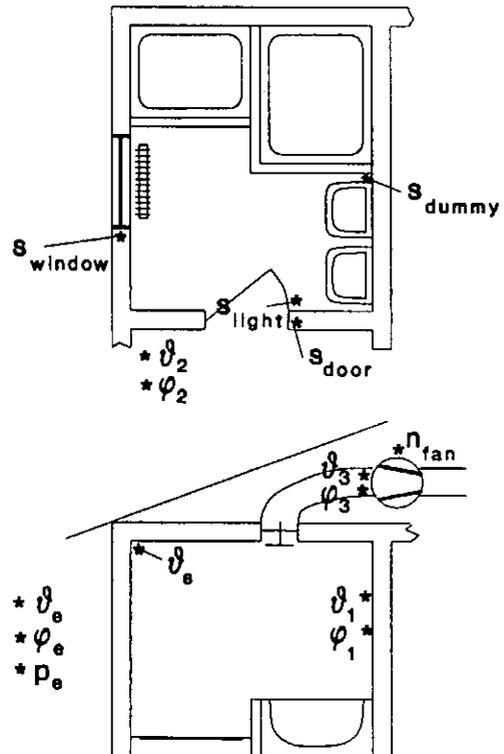


Figure 3: Schematic of the bathroom with measurement locations

Thermal Bridge:

To find the representative place, i.e. the weakest insulated spot in the room, to position the PT 100 resistance thermometer, local surface temperature measurements were made. The coldest spot was located on the tiles in the north-west corner just 0,5 cm below the ceiling.

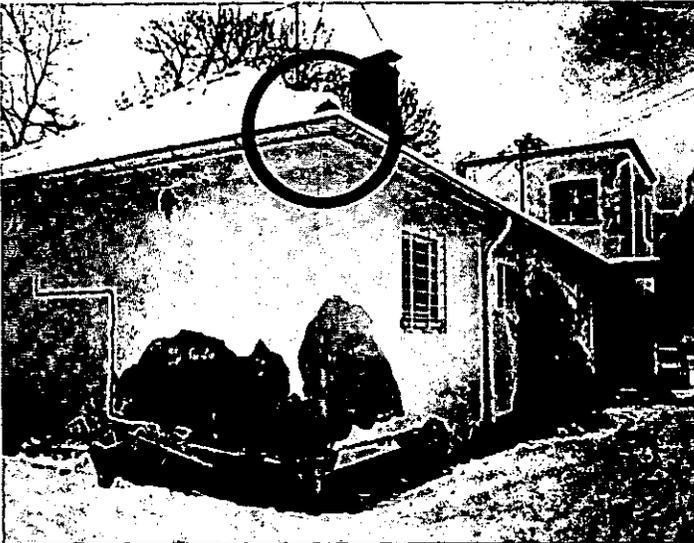


Figure 4: View at the north-west corner of the bathroom

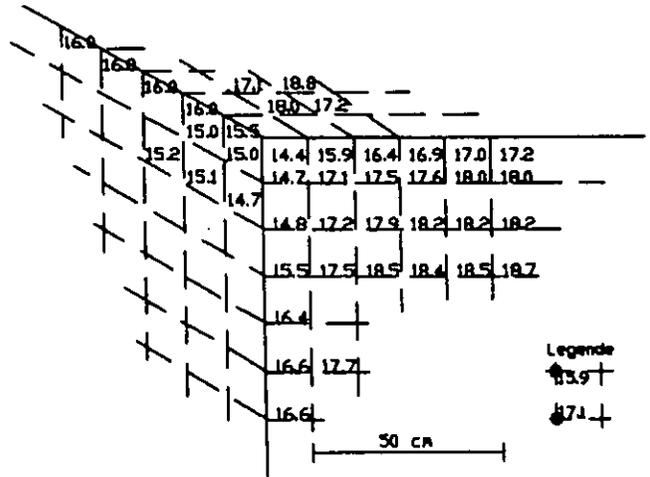


Figure 5: Distribution of surface temperatures in the north-west corner of the bathroom

Temperature Ratio:

$$\tau = \frac{\bar{\vartheta}_s - \bar{\vartheta}_e}{\bar{\vartheta}_1 - \bar{\vartheta}_e}$$

Indices:

- s - surface
- e - exterior
- 1 - room air

The bar indicates mean values.

A surface heat transfer coefficient of $h = 5W/m^2K$ gives a local thermal transmission coefficient of $u = 2.5W/m^2K$, where as the flat wall had a u-value of $u \approx 0.8W/m^2K$.

The temperature ratio 'τ' reflects the quality of a wall during steady state conditions and can be evaluated with monthly mean values of the ambient, the room air and the surface temperature. It is a parameter to characterize the insulation quality of a building. A temperature ratio of $\tau \geq 0.7$ is regarded as good. Our bathroom had a $\tau \approx 0.55$, what is very poor. However, it was intended to test the humidity controlled system in a house with severe mould problems to investigate whether mould germination can be stopped by adequate ventilation or not. Figure 5 shows the structure of the wall and roof design. The joints in the corner of interest could not be identified and are presumed.

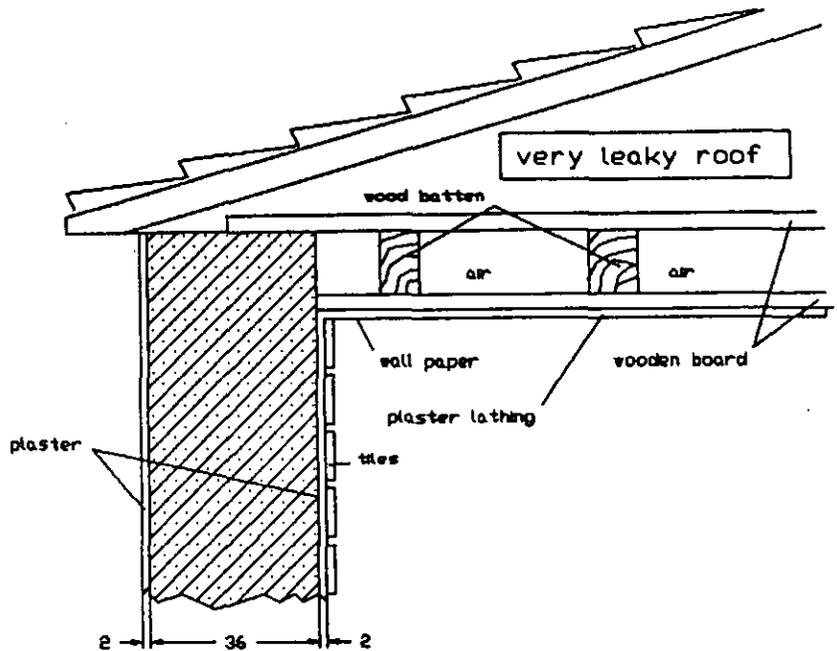


Figure 7: Schematic of the wall and roof design of the bathroom

Data Aquisition:

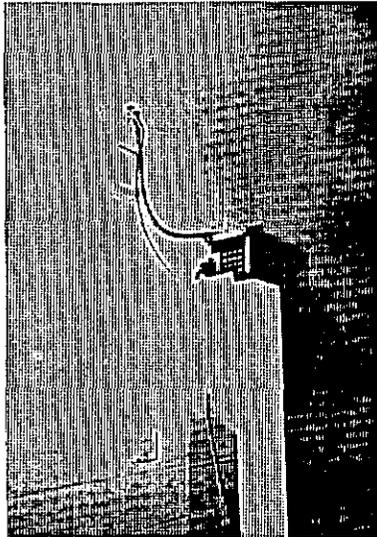


Figure 6: Temperature/humidity sensor, dummy switch, and data aquisition

The relative humidity and the air temperature was measured in the bathroom and in the floor at a height of 2 m, in the extract duct before the fan and in the ambient with capacitive humidity sensors and PT 100 thermometers from Rotronic. Also the total air pressure was measured. With reed-relais the opening condition of the window, the door and the light switch was detected. Also a dummy switch was installed; it was used manually by the occupants to fix the duration of emission during a showering or bathing process.

A folio PT 100 was glued onto the previously determined coldest surface spot of the wall. The fan speed was measured with a light barrier integrated into the fan. The energy consumption of the fan was measured with a conventional supply meter.

The data acquisition cycle time was approximately 5 sec. to scan all measuring points. During time intervals, where the relative humidity in the room was higher than the calculated setpoint, i.e., when the fan was in operation, minute mean values were recorded, so that the humidity history could be followed precisely. During all other times, where no vapour producing activities found place (fan turned off), hourly mean values were stored.

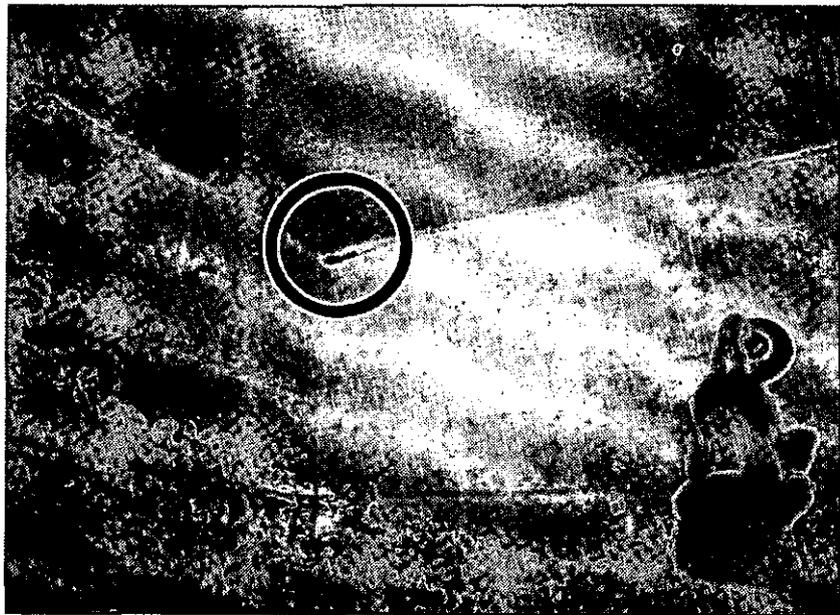


Figure 8: View to the north-west corner of the bathroom with PT100 glued against the coldest spot of the wall

Operation of the Fan

The fan speed could be controlled within 7 intervals. The micro-processor evaluated the actual RH setpoint with regard to the surface temperature measured at the wall. The difference of RH between 100% and the setpoint was divided into 7 intervals, i.e. the fan speed was linked to the moisture level in the bathroom (100% RH - max. speed).

Data Evaluation

Air Exchange Rates and Volume Flows

To answer the question, how much energy is associated with this kind of control strategy and how much vapour was produced, a mass balance of the air and the vapour in the room was established.

Air Exchange

During times, where the fan was turned off, the air exchange in the bathroom was governed by the positioning of the window and the interior door and the prevailing weather conditions. In this experiment it was not possible to use a tracer gas technique to monitor the actual air change rates continuously. Some spot measurements were taken, which indicate an air change rate of $n=0.2h^{-1}$ with window and door closed, no wind and outdoor temperatures around freezing. As the door was kept open for 80% of the time the mean air change rate of the bathroom was at approx. $n=0.12h^{-1}$.

Volume Flows

During all times, where the indoor RH exceeded the calculated setpoint, the fan was automatically turned on and operated in one of 7 modes determined by the humidity level in the bath. The extracted flow dominated the natural air exchange by far. The extracted flow rates were measured as a function of the fan speed and the positioning of the window and the door using tracer gas techniques. Results showed a substantial amount of background leakage.

The fan installed had at nominal speed of $n=2750\text{min}^{-1}$ and for $\Delta p=0\text{Pa}$ a max. flow rate of $325\text{m}^3/\text{h}$. Due to pressure losses of the duct, the inlet grill, and the self-closing damper the extracted flow rate at nominal speed decreased to $175\text{m}^3/\text{h}$ with door and window closed. At a nominal fan speed of 2750min^{-1} , door and window closed, the extracted flow rate was $174\text{m}^3/\text{h}$. 71% of the extracted air originated from outdoors and 29% entered the bathroom via the floor.

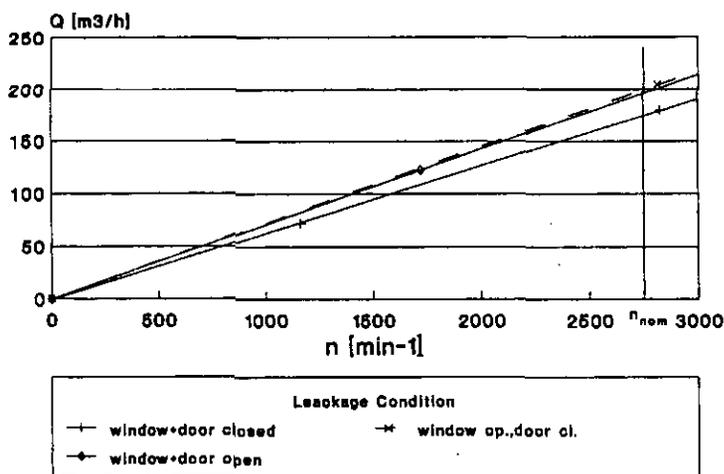


Figure 9:

Measured air flow of the fan as a function of speed and leakage conditions

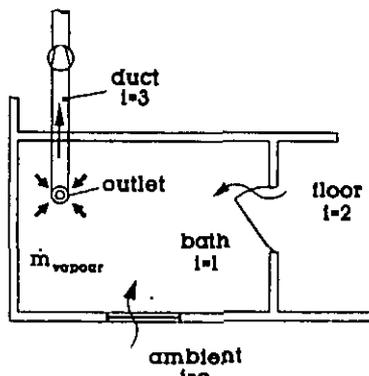
In addition to the tracer gas experiments the room with its extract system was simulated to obtain information about the room pressure and leakage characteristics of components. Leakage parameters were estimated according to tracer gas results. Window and background leakage were combined and represented by one power law element. The same expression was used for the closed door. The extract outlet, the flexible duct, the self-closing damper, and the resistance of the temperature/humidity sensor were also combined to one power law element.

At the nominal fan speed of 2750min^{-1} , door and window closed, and with an extracted flow rate was $174\text{m}^3/\text{h}$ the calculated underpressure in the bath was $\approx 42\text{Pa}$. Noise problems at the leakage paths at full speed were not encountered.

Vapour Emission Rates

Water vapour mass balance:

(fan on)



$$\dot{m}_{\text{vapour}}(t) = Q_3 \rho_3 x_3 - Q_2 \rho_2 x_2 - Q_e \rho_e x_e$$

\dot{m} - emitted mass flow rate of vapour

Q_i - volume flow rate of air at location i

ρ_i - density of air at location i

x_i - absolute humidity location i

Index i:

1 \equiv bathroom

2 \equiv floor

3 \equiv extract duct

The mass balance derived does not account for absorption/desorption effects, what means that the actual calculated rates of vapour emission at time t are not correct. But if one looks at longer time intervals, e.g. 12 or 24h, all absorbed vapour will be desorbed again and the accumulated vapour mass for this period will be quite accurate.

To obtain a reliable mass balance of the emitted water vapour, the supply flows from the ambient into the bath, from the floor into the bath, and the extracted flow by the fan and their humidities had to be known.

The water vapour mass balance gave the exhausted amount of vapour as a function of time and the accumulated vapour mass for a month. To compare the different months, all data were normalized to a month of 30 days. If there were gaps in the data because of malfunctioning of sensors and e.g. only data from 25 days exist, the information of the 25 days were also normalized to 30 days.

As it was not possible to measure air flows during times where the fan was off, calculated vapour production rates only represent those time intervals, where the fan was in operation and the volume flows known. Note, that due to the assumption of no absorption/desorption the momentary values may be off the real production rate.

Energy Consumption

The thermal energy consumption to warm up the mechanically ventilated air to bathroom temperature was calculated from September 14, where the building was heated. The readings of the supply meter gave the electric energy consumption of the fan.

Measurement Phase

The measurement phase could be divided into 4 parts:

1. Control strategy 1, the criterium for the evaluation of the setpoint is surface condensation, $\varphi_{\text{cr}} = 1.0$
Duration 12.05 - 02.11.1990
2. Control strategy 2; the criterium for the evaluation of the setpoint is surface condensation, $\varphi_{\text{cr}} = 1.0$.
Fan only operated in 2 speeds,
speed 1 = 85m³/h, speed 2 = 125m³/h.
Duration 05.11. - 14.11.90
3. Control strategy 3, the criterium for the evaluation of the setpoint was 95% RH against the surface, $\varphi_{\text{cr}} = 0.95$, fan operated in 2 speeds (see 2.)
Duration 15.11. - 30.11.90
4. Control strategy 4; the same as strategy 3, but fan operated in 7 modes
Duration 01.12. - 02.01.91

Control Strategy 1+2

The setpoint, φ_c , was determined in the way, that no surface condensation at the coldest surface spot of the wall should happen. The surface wall temperature, ϑ_s , the room air temperature, ϑ_1 , and the control criterium, φ_{cr} , was used to evaluate φ_c .

According to the example this means, that the fan was turned on as soon as the RH of the room air exceeded 57.5%. During a month there are now times, where φ_1 is higher and lower than φ_c . The condition for having no mould growth is fulfilled, if the monthly mean of the RH against the surface is lower than the a -value.

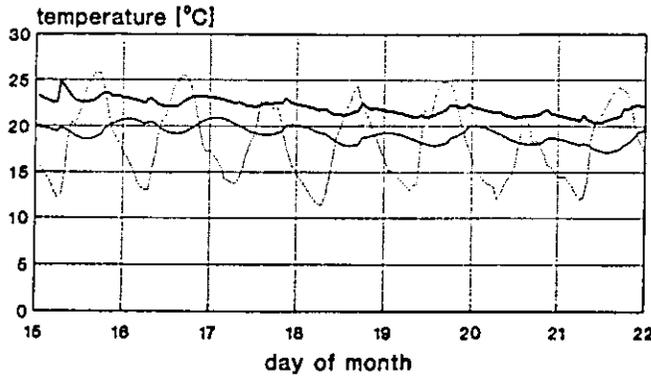
Data were recorded from May to November including hot and humid as well as cold and dry weather conditions. In July the light barrier in the fan broke, so that the fan operated well but the recorded fan speed was zero. The fan was repaired in September. Due to a change of the control software and a malfunctioning of the program only hourly mean values were recorded from July to November.

Control Strategy 3+4

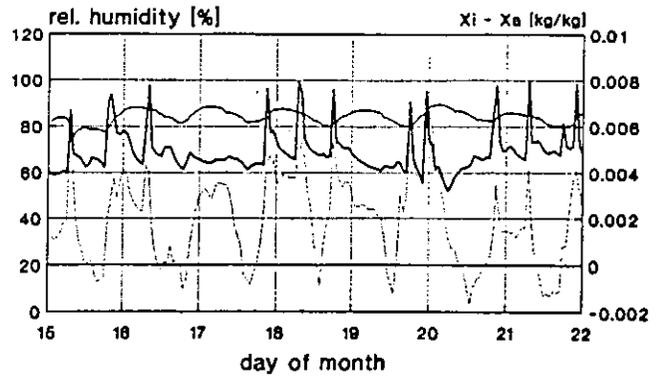
The setpoint φ_c was determined in such a way, that the fan was turned on, when the RH against the surface exceeded 95%, i.e. $\varphi_{cr}=0.95$.

Results

As the surface as well as the room air temperature (see figure 10) fluctuates, also the RH setpoint φ_c will change and adopt to the prevailing boundary conditions. E.g., during the 3rd week of may (see figure 11), φ_c oscillated between 78 and 90%. The peaks indicate emission processes. The fan operated during time intervals where φ_1 was higher than φ_c . The maximum extraction capacity of the fan of approx. 200m³/h assures that 100% RH in the room air is seldomly reached. The 3rd week of may was quite a humid week; every day had a period of 2-4 h during the afternoon where the absolute humidity outdoor was higher than indoor.



temperatures
 — surface ϑ_s — room air ϑ_1 — outdoor ϑ_e



rel.-abs. humidities
 — room air RH, φ_1 — control RH, φ_e — diff. abs. humidity

Figure 10: Measured temperatures during the 3rd week of May, 1990

Figure 11: Measured humidities during the 3rd week of May, 1990

'a' value

As mentioned before, one goal of the experiment was to find the correct criterium φ_{cr} , which assures that no favorite conditions for mould growth prevail for longer periods. Short moisture peaks are allowed (and can usually not be avoided due to limited extraction rates) as long as there is enough time for the surface to dry out again. I.e., the evaluation of the RH setpoint f_c , which is based on momentary data of the surface wall temperature and the room air temperature should guaranty, that the monthly mean RH against the surface is not higher than the mean a -value. Table 1 shows the a -value, calculated with the mean surface temperature and the corresponding mean RH against the surface from May to December.

- $\bar{\vartheta}_s$ ≡ m.m. surface temperature
- $\bar{\vartheta}_1$ ≡ m.m. room temperature
- $\bar{\vartheta}_e$ ≡ m.m. outdoor temperature
- $\bar{a}(\bar{\vartheta}_s)$ ≡ m.m. a -value
- $\bar{\varphi}_s$ ≡ m.m. RH against surface
- Δt_{fan} ≡ monthly running time of fan
- \bar{n} ≡ m.m. fan speed
- Q ≡ extracted air vol./month
- Δm_w ≡ extracted vapour/month
- P_{therm} ≡ therm. energy consumption/month

(m.m. - mean monthly)

Index *: not measured

X: if data are not complete, value is normalized for comparison to 30 days

	$\bar{\vartheta}_s$ [°C]	$\bar{\vartheta}_1$ [°C]	$\bar{\vartheta}_e$ [°C]	$\bar{a}(\bar{\vartheta}_s)$	$\bar{\varphi}_s$ [%]	Δt_{fan} [min]	\bar{n} [min ⁻¹]	QX [m ³ /h]	Δm_w [kg]	P_{therm} [kWh]
May	17.6	20.9	16.3	80	81.5	883	1350	1428	6.3	2.7
June	16.4	20.2	14.5	80.3	89.0	3408	948	3876	12.6	6.4
criterion July	20.1	22.7	19.8	79.2	78	*	366	*	*	*
$\varphi_{cr}=1.0$ Aug.	20.6	23.1	20.1	79.1	75.0	*	*	*	*	*
Sept.	15.9	20.1	14.0	80.5	90.7	*	*	*	*	*
Oct.	15.4	21.2	11.3	80.7	92.4	*	*	*	*	*
Nov.1	12.8	20.7	5.4	82.2	92.0	*	*	*	*	*
Nov.2	14.2	20.6	9.9	81.4	92.3	*	*	*	*	*
criterion Dec.1	10.4	20.5	1.3	83.9	88.9	6563	768	6207	17.7	36
$\varphi_{cr}=0.95$ Dec.2	11.6	20.0	2.9	83.0	88.0	9637	15.9	11890	39.0	56

Table 1: Monthly mean values of measurement campaign

For the warm months of May to August the control strategy 1 gives reasonable results. One conclusion is that if the evaluation of the RH setpoint is based on surface condensation, such a humidity controlled extract system is able to keep the RH so low that no critical conditions for mould growth prevail.

The results of the colder months from September to November indicate that a control criterium which is based on surface condensation is not able to keep the RH against the surface on a monthly base below the desired a -value. For December the control criterium was changed to $\varphi_{cr}=0.95$ RH against the surface. The results show that for December the difference between the measured RH against the surface and the a -value decreased to 5% (from 83.9 to 88.9 and from 83.0 to 88.0)

It can be assumed, that for this dwelling with its typic occupancy pattern a further reduction to $\varphi_{cr}=0.90$ RH would keep the mean RH against the surface close to the mean a -value.

Operating Time of the fan

Figure 12 is a plot of the air humidity in the room φ_1 , the set point or control humidity φ_c , and the fan speed n versus time for a warm day of May 26. At $t=1264$ min the shower started and lasted 8 minutes. At $t=1266$ min φ_1 exceeded φ_c and the fan was turned on. With some fluctuations the fan operated at full

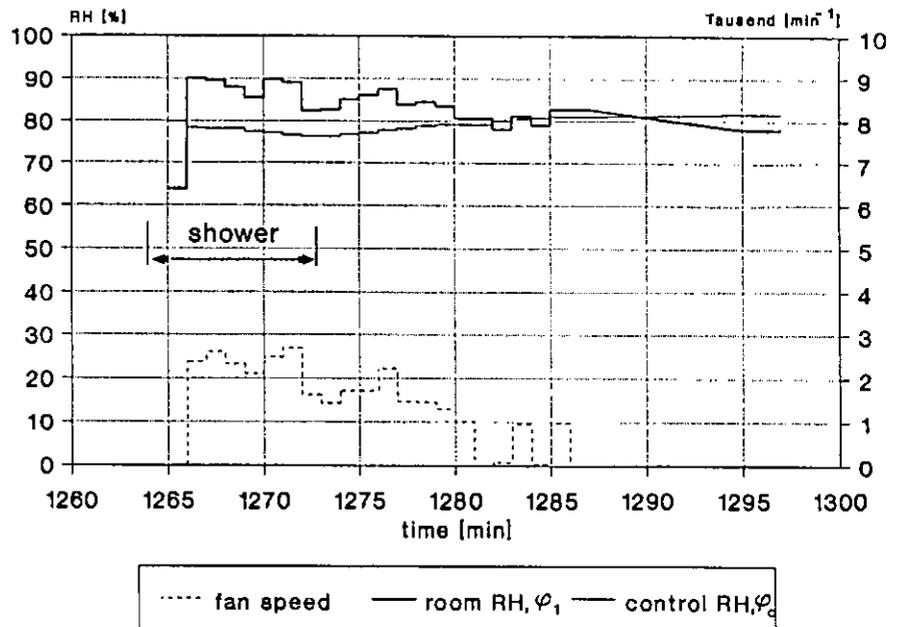


Figure 12: Room and control RH and fan speed during a shower process on May 26, 1990, bathroom door open

speed during the vapour emission process and needed another 13 minutes to bring the humidity in the room below the control value φ_c . At $t=1281$ min the RH φ_1 had fallen short of φ_c . Due to slow desorption of moisture from the walls and drying of wet towels the fan operated intermittently for another 5 minutes.

Figure 13 shows the fan performance during a cold day with a daily mean outdoor temperature of -4°C . One shower process of 10 minutes duration took the fan about 10h to bring the

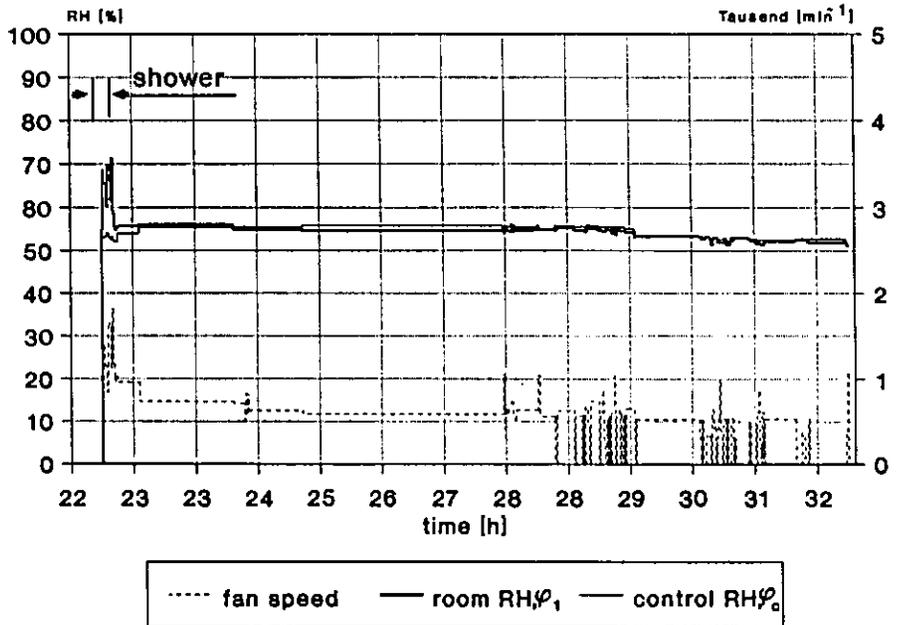


Figure 13: Room and control RH and fan speed during a shower process on Dec. 5, 1990, bathroom door closed

moisture level down to the set point φ_c . This is an extreme example. Although the bathroom door was closed for the whole time and the main supply flow came from outdoors ($x_e=0.0024$, $x_1 \approx x_2 \approx 0.0071$), it took so long. Also remarkable is, that during this shower process the peak RH didn't exceed 72% at a fan speed of 60%. During 8h the fan operated between stop and its lowest level. I.e. desorption is such a slow process, that a very low and constant extraction rate would be desirable for such a situation.

Figure 14 now shows the running time of the fan as a function of outdoor temperature. The scattering of points is high, what is

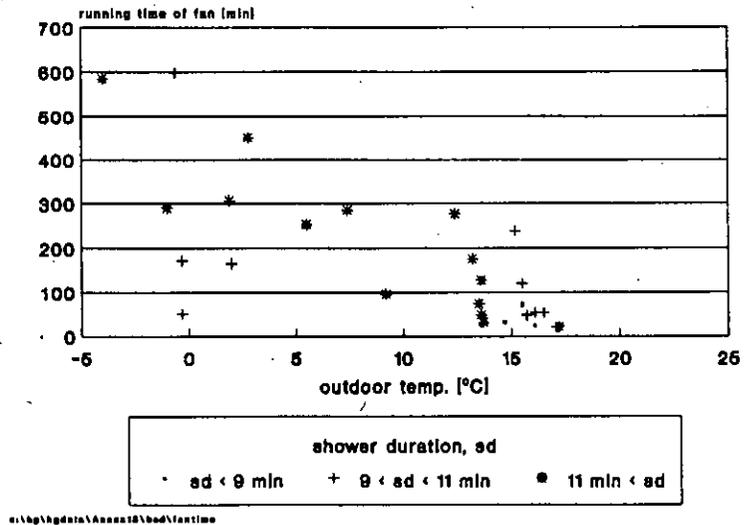


Figure 14: Operating time of fan as a function of outdoor temperature and shower duration (sd)

due to the diversity of emissions from the washing of hands, a short/long or cold/hot shower/bath from adults/children. Detailed examination of emission information lead to the following conclusions:

- the longer the emission process the longer the running time of the fan, what is obvious
- a bathing process leads to a shorter running time, as the peak emission rate is lower, the vapour is directly extracted and a smaller amount of vapour is absorbed, i.e. also desorption will be shorter
- during cold days also the washing of hands leads to an activation of the fan
- although the extraction rate of the fan with approx. 170-200m³/h was quite high, a shower process goes along with a significant amount of vapour being absorbed during colder days
- the colder the outdoor temperature, the longer the running time
- if the door is open and the greater part of supply air enters from the adjacent floor, the longer the running time. The RH data indicate, that the RH of the floor was on an average approx. 5% lower than in the bath, i.e. it was only slightly drier.

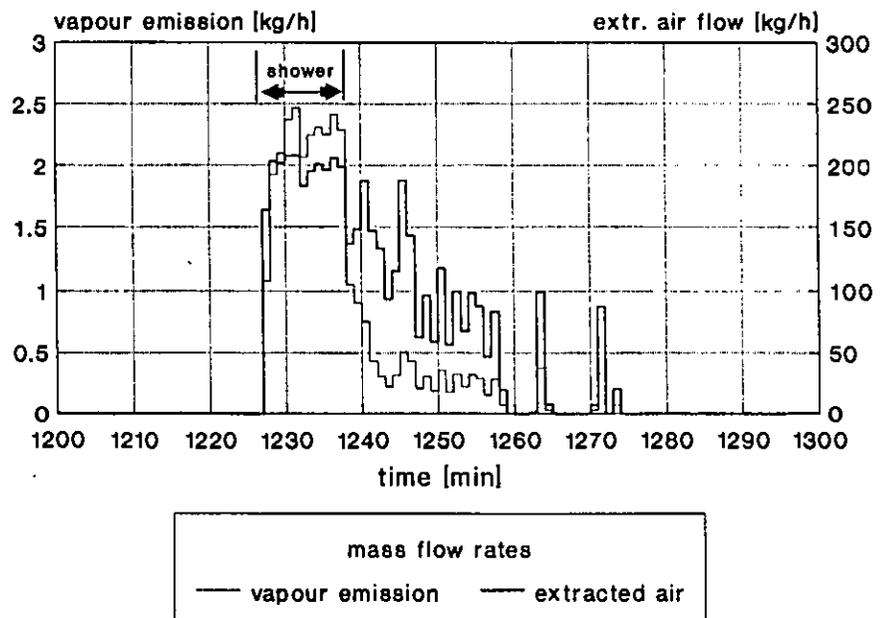
This last experience is worth to be emphasized, as it is contrary to arguments in previous research reports in this field /4,5/.

The argumentation was, that during winter time a smaller amount of supply air is needed to remove a fixed amount of water vapour produced as during summer time, because the cold air has a lower absolute humidity and will take up more moisture than the humid warm air in summer. Why do we experience the opposite?

- the first false conclusion is, that not all supply air entered the bathroom from outside. During most times the bathroom door was open and the major part of supply air originated from the floor and was only slightly drier (=5%) than the bathroom air. During shower processes, where the door was closed the predominant supply air originated from outside (79%). Here the operating time of the fan was significantly smaller.
- the second reason is that the RH setpoint in winter was around 55% and during summer around 80%. Therefore, during winter time the air humidity has to be reduced to a much lower level than in summer, what takes more running time of the fan.
- a wall in equilibrium with air of 50% RH can absorb much more moisture than a wall in summer in equilibrium with air of 80% RH. Therefore, also desorption can last longer.

Air Mass Flow

With the fan speed measured and the positioning of the door and window known the extracted air mass could be calculated as a function of time. Figure 15 shows such a plot for a shower process of 12 minutes during May 28.



fig\hgdata\annex18\bed\m28may

Figure 15: Vapour emission rate and extracted air mass flow rate versus time

As soon as the water is turned on, the fan was switched to max. speed; with the water turned off, the vapour emission decreased rapidly, the RH in the room went down along with the fan speed. The fan kept on running for another 50 minutes. Figure 15 displays minute mean values. The zickzag behaviour between 402 and 425min indicate, that the fan operated in between zero speed and the minimum speed of approx. $75\text{m}^3/\text{h}$. I.e., due to desorption the fan went on but the extraction rate at minimum speed reduced the RH in the room immediately below the RH setpoint φ_c and the fan is turned off again. This intermittent operation of the fan was not favourable, a fan with a lower minimum speed would be better to take care of the slow and long lasting desorption process.

Vapour Emission Rate

With all air flows and humidities known, a mass balance was made to determine the evaporated mass of vapour for one shower process and as a total for a month. The thin line in figure 15 shows the vapour emission rate as function of time. The peak value is approx. $2400\text{g}/\text{h}$ what corresponds very well with emission rates in the literature [2+3].

Energy Consumption

Table 1 also shows the associated thermal energy consumption for the mechanically ventilated air to be warmed up to room temperature. The additional supply of air needs $\approx 100\text{kWh}$ energy for December. An estimate over the year amounts to $\approx 380\text{kWh}$ additional expenses for a higher energy consumption. Assuming $10\text{ct}/\text{kWh}_{\text{thermal}}$, additional operating costs are $\$38/\text{year}$. The total electric energy consumption was measured to 18kWh from May to Jan. 2, 1991. If we assume energy costs of $20\text{ct}/\text{kWh}_{\text{electric}}$, we get additional $\$3.6$. In total, it seems to be a reasonable strategy to cure the problem.

Mould

As it is shown in table 1 and mentioned in the chapter 'a-value', it was not possible at any time to keep the mean RH against the surface below the a-value. From September to November the setpoint criterium was not severe enough to make sure that favourite conditions for mould growth didn't prevail. However, the growth of mould seemed to have stopped at the ceiling; some mould spots were observed on silicon between tiles in October.

During the last day of the test campaign at January 2, 1991 a new careful examination of the ceiling was made; some small spots along the horizontal corner at the ceiling with a size of 2mm were observed, see figure 16.

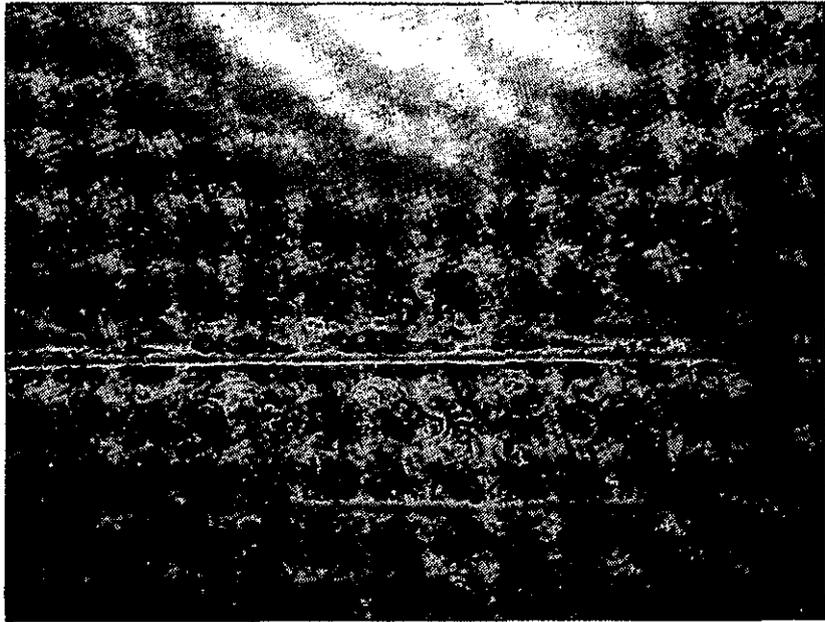


Figure 16: Picture of reappearing mould germination due to the too vage control criterium from Sept.- Nov., picture taken at January 2, 1991

User Behaviour and Acceptance

From the day the humidity controlled system was installed, occupants didn't open the window again. They were highly appreciated by the automatic system which was turned on and off automatically. The mirrors in the bath were free of condensation the whole time what increased the quality of living.

In August, when the fan was not installed, the occupants returned to their old habits and ventilated by using the window.

It was also appreciated that the extract system prevented the spread of vapour into other rooms of the building.

Discussion

To avoid the reappearance of mould only by proper ventilation in such a severe case like this bathroom with a thermal bridge, having a temperature ratio of 0.55, and where the wrong choice of materials (finishing layers) were used, leads to the certainty that a control strategy a little more severe as tested in December would completely prevent the reappearance of mould. This has to be assured in another field test.

The experience made so far leads to the conclusion that a temperature ratio of 0.55 will be almost at the limit, where mould growth can be avoided only by advanced ventilation. Because, lower temperature ratios will result in lower setpoint values. In such a case the humidity in the bath would have to be held on a lower level than the adjacent rooms with smaller emission rates.

The a -value philosophy seems to be a useful tool to tackle and solve problems with mould. A further field test has to finally verify it. However, the result of this case study is a very positive confirmation of this philosophy.

The energy consumption associated with advanced humidity control is less than expected. It should also be mentioned again, that just so much air is supplied to the room as necessary to avoid mould. This means, that the energy consumption can't be smaller.

During summer the control criterium with $\varphi_{cr}=1.0$ fulfills the a -value condition. With less outdoor temperature, φ_{cr} should be reduced to 0.9 at $t_e < 0^\circ \text{C}$.

Conclusions

A control strategy to avoid mould growths was tested with success. Germination of mould could not completely be avoided as the control conditions from September to November had not been severe enough. A reliable control algorithm could be found, which should be assessed also in other dwellings. The requirements for the exhaust fan are, that it can operate in 2 or better in 3 speeds. The lowest speed should take care of the low emission rates during desorption ($20\text{m}^3/\text{h}$), a moderate speed of $80\text{m}^3/\text{h}$ and a booster speed of min $150\text{m}^3/\text{h}$. The a -value philosophy turned out to be a very useful tool in practice. Temperature factors lower than 0.5 seems to define the limit, where moisture problems can be solved only by ventilation.

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4 School

4.1 Demand Controlled Ventilation in a School (Sweden)

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4.1 DEMAND-CONTROLLED VENTILATION IN A SCHOOL

Summary

The performance of a system for demand-controlled ventilation was investigated for a period of 1.5 years. Presence sensors of the passive infrared type are used to control the ventilation rate in each classroom. The signal from the presence sensors was recorded, as well as the CO₂ concentration in the classrooms.

One of the classrooms was equipped with displacement ventilation. A comparison was made between displacement and mixing ventilation to investigate the CO₂ concentration in the stay zone. A significantly lower CO₂ concentration was measured in the case of displacement ventilation.

Project description

In 1988, the rebuilding and renovation of an elementary school was planned in the Municipality of Nacka outside Stockholm, Sweden.



Fig 1. Järila school in Nacka

The most important part of the renovation project concerned an improvement of the ventilation in the school. One objective was to provide good air quality in the classrooms. A low energy consumption was also desired.

The purpose of this project was to demonstrate that it is possible to maintain better air quality in the classrooms by means of demand-controlled ventilation when the rooms are in use, and that this can be achieved at lower energy consumption, compared with the dimensioning of fresh air flows in accordance with current building codes.

Measurements and calculations also showed that this was a profitable measure.

Design and measurements have been carried out by Fläkt Indoor Climate AB, Stockholm.

The installation and test measurements were funded by the Swedish Council for Building Research (BFR).

Building form

The school consists of two buildings joined together by a common stairwell. The buildings were constructed at different times. The older section, which has four floors and contains six classrooms, a cafeteria and administrative offices, was built in the 1920s, while the newer building dates from the beginning of the 1940s and has three floors and six classrooms.

The classrooms face the south and southeast. The height from floor to ceiling is approximately 360 cm in the older section, and 310 cm in the newer section. The floor measures 9 m x 6.5 m in the classrooms.

Building services.

Heating and ventilation before renovation.

The school has a radiator system for heating that is connected to the Nacka district heating system. When the school was renovated, the

radiators were equipped with thermostat valves. Before the renovation, the ventilation system consisted of a natural draft system in the older section of the school. The new building had a mechanical exhaust air system, in which the fan operated 24 hours a day.

Before the renovation, tests were conducted to test the tightness of the buildings and the air change situation. In the building with the natural draft system, as well as in the section with mechanical exhaust air ventilation, carbon dioxide measurements were conducted in the classrooms to determine how the air was changed. At the end of a lesson, the CO₂ concentration was between 2000 and 3000 ppm.

In the newer section of the school, the CO₂ concentration normally stayed below 2000 ppm, provided that windows were opened during recesses.

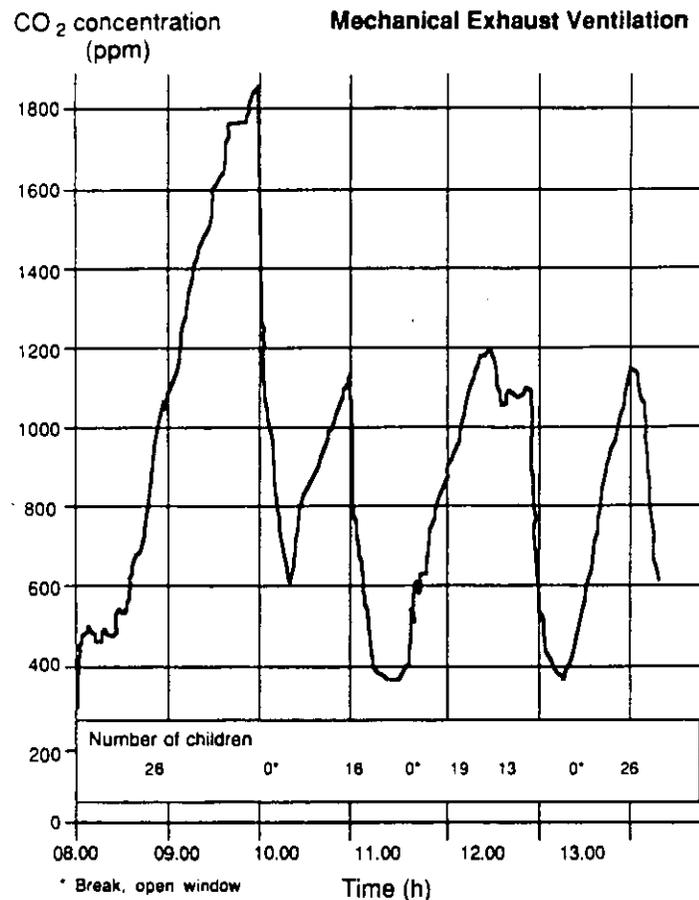


Fig 2. CO₂-concentration in a classroom before renovation

Air flow tests indicated air changes corresponding to a fresh air flow of approximately 2 l/s per student. Thus, earlier complaints about the ventilation system were justified.

Heating and ventilation after renovation

The existing radiator system was kept. The radiators were equipped with thermostat valves. When the school was renovated, the six classrooms in the older section were equipped with a supply and exhaust air system that was dimensioned in compliance with existing building codes (5 l/s of fresh air per student).

The six classrooms in the newer wing were equipped with a demand-controlled ventilation system connected to a separate AHU, as shown in Fig. 3. The objective was to prevent the carbon dioxide concentration from exceeding 1000 ppm in the stay zone.

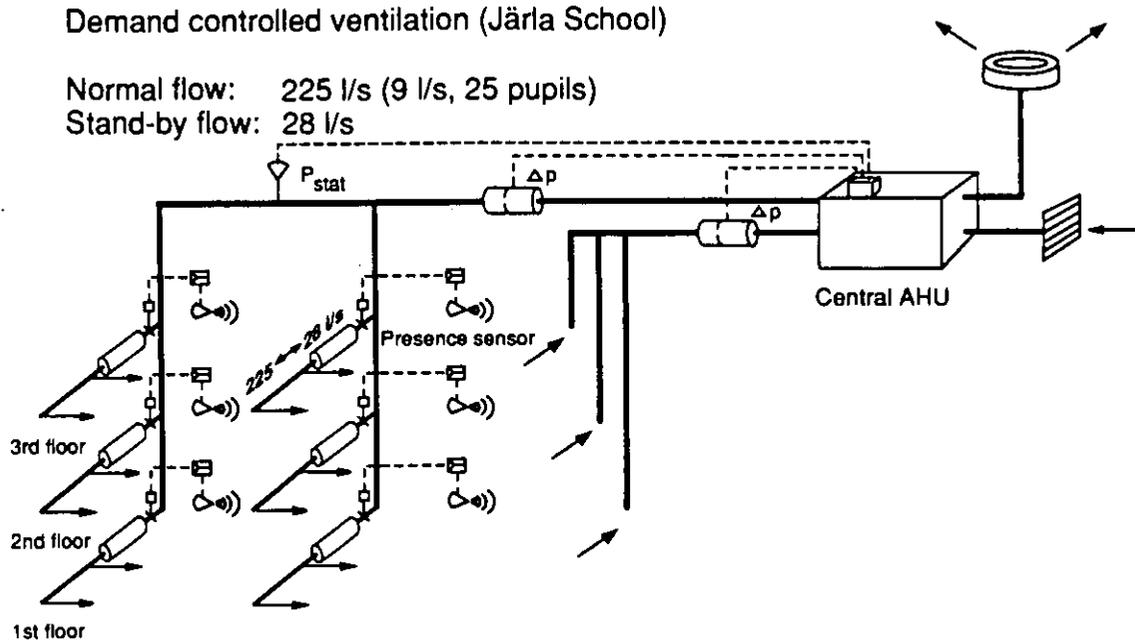


Fig 3. System principle

The system functions as follows:

- Each classroom is equipped with a presence sensor of the passive infrared type. When the device senses that someone is in the classroom, a supply air damper opens and closes ten minutes after the presence sensor picks up the last movement in the room.
- When the damper opens, the supply air to the classroom increases from approximately 28 l/s to about 225 l/s. This corresponds to 7.5 l/s per student, with 30 students in the class (grades 4-6), or 9 l/s per student, with 25 students in the classroom (grades 1-3).
- The general ventilation (basic flow) system operates 24 hours a day.
- Air exhausted into the corridor outside the classrooms is evacuated through exhaust air devices on each floor.
- The central air handling unit for supply and exhaust air is equipped with fans with guide vane control. The supply air is controlled by maintaining a constant pressure in the supply air duct system. The exhaust air follows the supply air flow.
- The AHU is equipped with a plate heat exchanger for heat recovery, as well as a microprocessor-based controller that makes it possible to easily monitor the AHU's function. No air is recirculated.
- Five classrooms have traditional mixing air distribution with air being supplied at the front end of the ceiling. One room has displacement ventilation, with the supply air terminals positioned at floor level at the two corners in the front of the classroom. The supply air temperature is 18°C.

Measurements after the renovation



Fig 4. Classroom (306) with displacement ventilation

Measurements were conducted in three classrooms after the renovation was completed. One classroom had displacement ventilation and five had mixing air distribution.

The following measurements were made during 1990-91.

- The CO₂ concentration was recorded on a continuous basis for about two months.
- The signals (supply air flow) from the presence sensors were recorded in conjunction with the CO₂ measurements.

- Fresh air and exhaust air temperatures were recorded.
- Detailed measurements were made of horizontal and vertical CO₂ gradients in two classrooms over a period of several days.
- The supply air flow was measured when the detailed measurements were made. During these periods, teachers or students recorded how many persons were present in the room.
- The variation in the supply air in the central air handling unit was recorded.

Results of the measurements

Function of the ventilation system.

Room function.

During the 1.5 years the system has been in operation, the measurements have shown that the demand-controlled system has functioned as planned. An example of this is shown in Fig. 5.

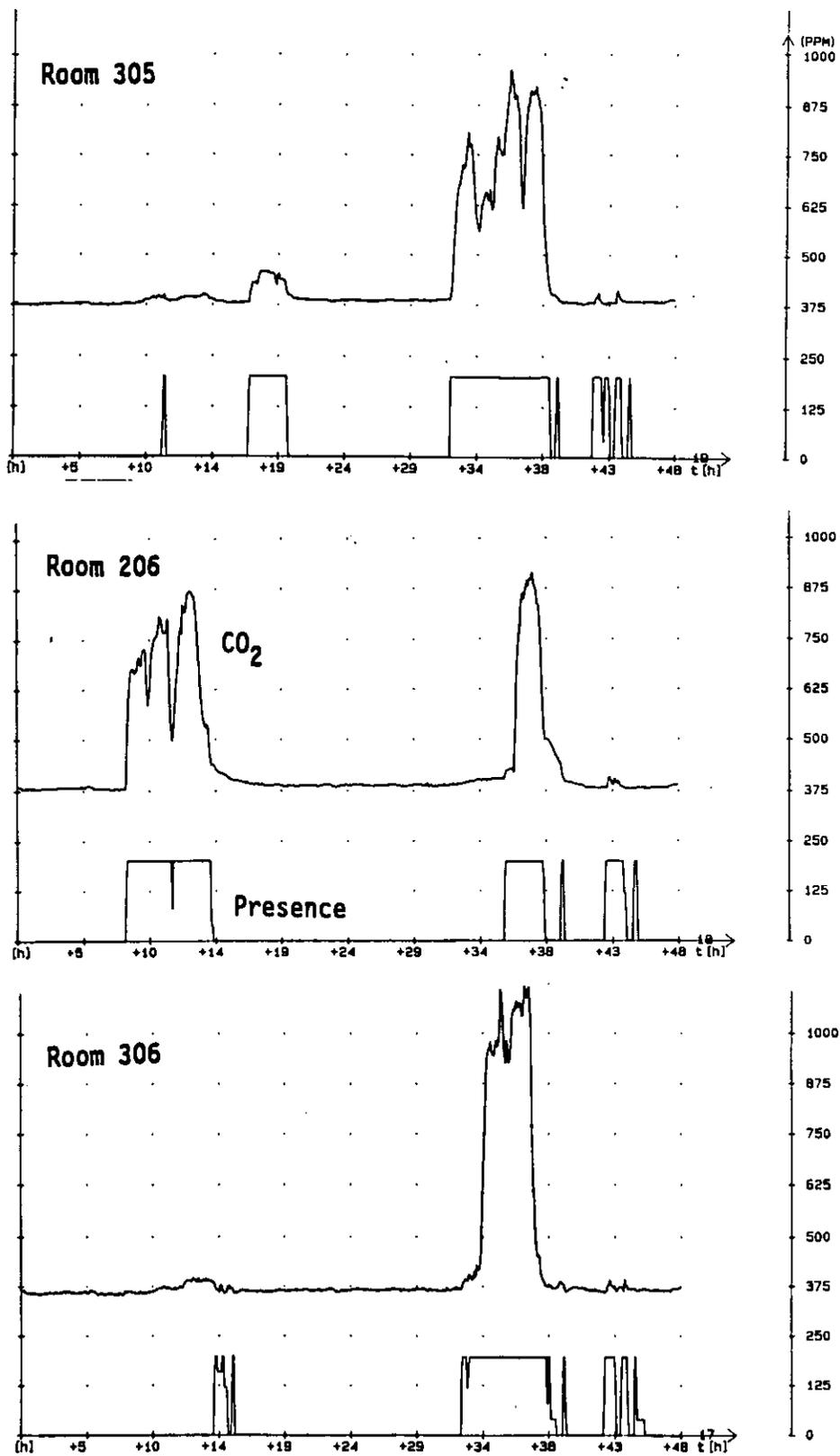


Fig 5. Presence and CO₂-concentration Monday and Tuesday, May 14th and 15th 1990

Here the carbon dioxide concentration and signal from the presence sensor have been measured for the three classrooms over a 48-hour period. The figure shows

- that only one of the three classrooms was in normal use on Monday, May 14, 1990.
- that in the other classrooms, some one entered the rooms to get books or other materials on a few occasions.
- that a small class meeting was probably held one evening in one of the classrooms.
- that the classrooms were cleaned on Tuesday evening.

The fact that two of the classrooms were not used on Monday was not in agreement with the ordinary schedule. In general, the signal of the presence sensor followed the respective class schedules closely.

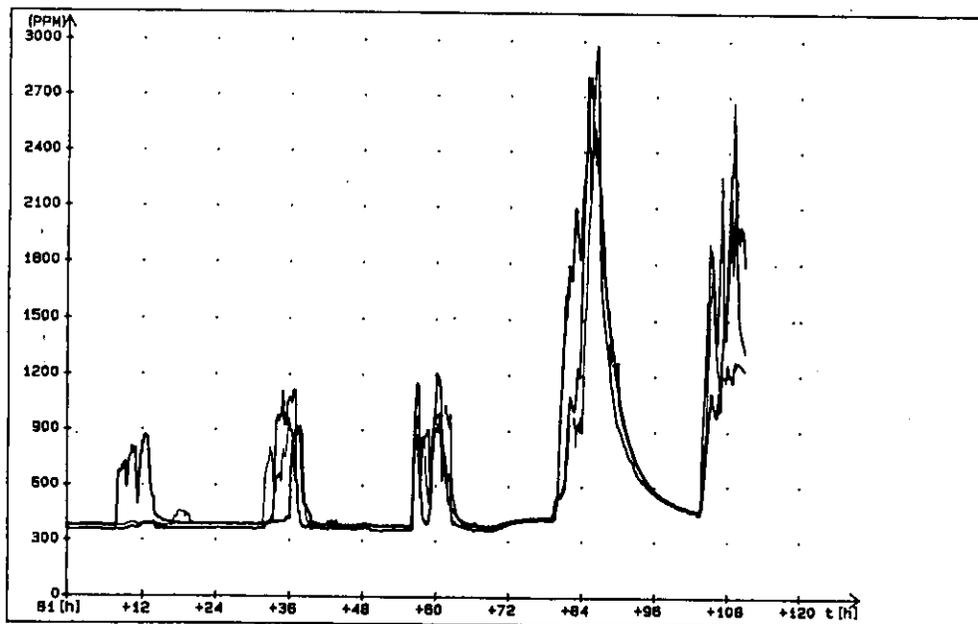


Fig 6. Power supply cut off

During the same week referred to above, the operation of the ventilation system was disturbed at the end of the week, due to the ongoing renovation work in the school. On Thursday and Friday the power was cut off completely to the AHU. The consequences of this disturbance are shown in Fig. 6.

Central Air Handling Unit

The following was recorded in the central air handling unit:

- the control signal to the guide vanes for supply air: 100% = full flow.
- the static pressure in the duct system (supply air): set value 310 Pa.
- the control signal for the air heater: 100% = open valve.
- the supply air temperature: set value = 18°C.

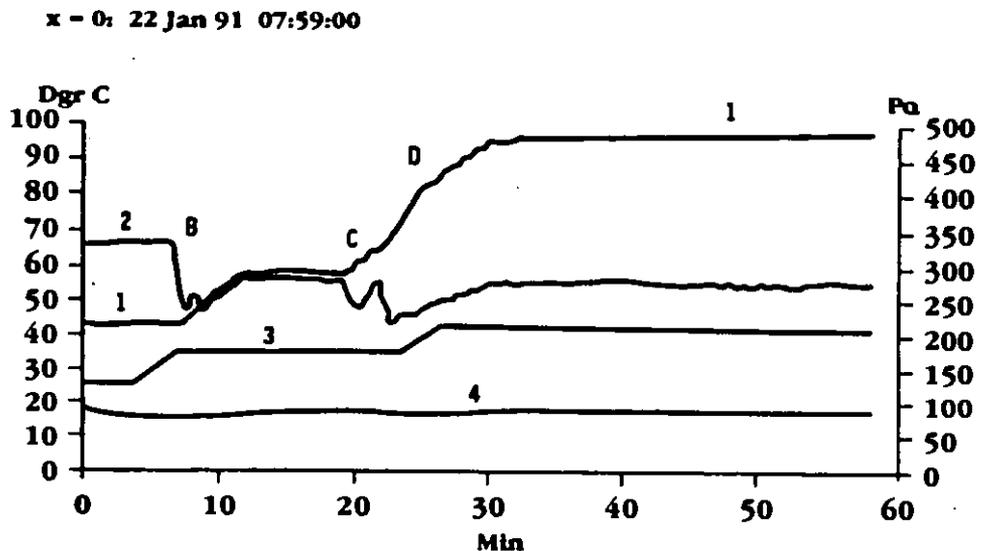


Fig 7. Measured values in central AHU

Fig. 7 shows how the air flow increases as the classroom is used. Only about 50% of the total air flow in the AHU is affected by demand control, since the remaining 50% is supplied to two workshops and to teacher rooms.

It is possible to see that:

- at 8.00 a.m. students arrive at one of the classrooms.
- the presence sensor in the classroom opens a damper.
- the pressure decreases. Guide vane B compensates the pressure drop.
- another classroom starts to be used, C and D, and the signal to the guide vane increases.
- at 100% all classrooms are being used.

Air quality

During the longer measurement periods, the CO₂ concentration was recorded in the exhaust air from the three classrooms.

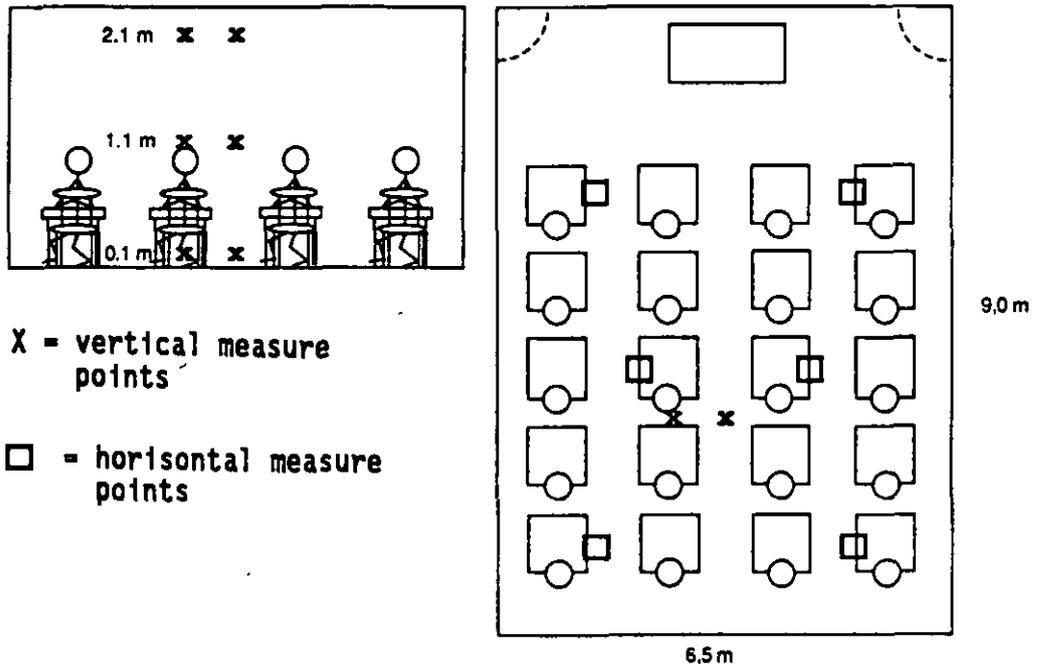
The goal to keep the CO₂ concentration below 1000 ppm in the stay zone was achieved. This could be expected, considering the actual supply air flows being used.

The air quality was also considered good by students and teachers, despite the fact that measurements were made during the outgassing period, when solvents were being emitted by new building materials. The interior of the school was also painted and fitted with an acoustic ceiling.

Comparison between mixing and displacement air distribution

In two classrooms, one with displacement air distribution (306), and one with mixing air distribution (206), detailed measurements were made of the CO₂ concentration vertically. In room 306 (displacement ventilation), the CO₂ concentration was also measured horizontally at floor level.

When measuring the CO₂ gradient vertically, two measuring bars with sensors were used at 0.1, 1.1 and 2.1 m above the floor. The bars were placed about 2 m from the rear wall of the classroom as shown in Fig. 8. Thus, measurements were made at six points in all.



During the measurements, activity was normal in the classroom, meaning that students moved between their desks and the blackboard, and between groups.

The results from the two *vertical* measurements are shown in Fig. 9. After a recess, the measurements were carried out over a double lesson (about 90 minutes in length).

Depending on the actual number of students in the classrooms, the fresh air flow corresponded to 8.0 l/s per student in the room with

displacement ventilation, and 9.2 l/s per student in the room with mixing ventilation. If the measurement values are corrected to take this into account, the measured concentration at the 2.1 m level coincides in both classrooms, which, theoretically, should be the case.

As can be seen from the diagrams, the CO₂ concentration in the mixing air distribution case (206) is largely the same at all measurement points. But in the classroom (306) with displacement air distribution, a clear difference can be seen between the CO₂ concentration at the three different levels.

Here, the mean concentration in the breathing zone (1.1 m) is approximately 750 ppm, while the concentration at 2.1 m is about 1000 ppm.

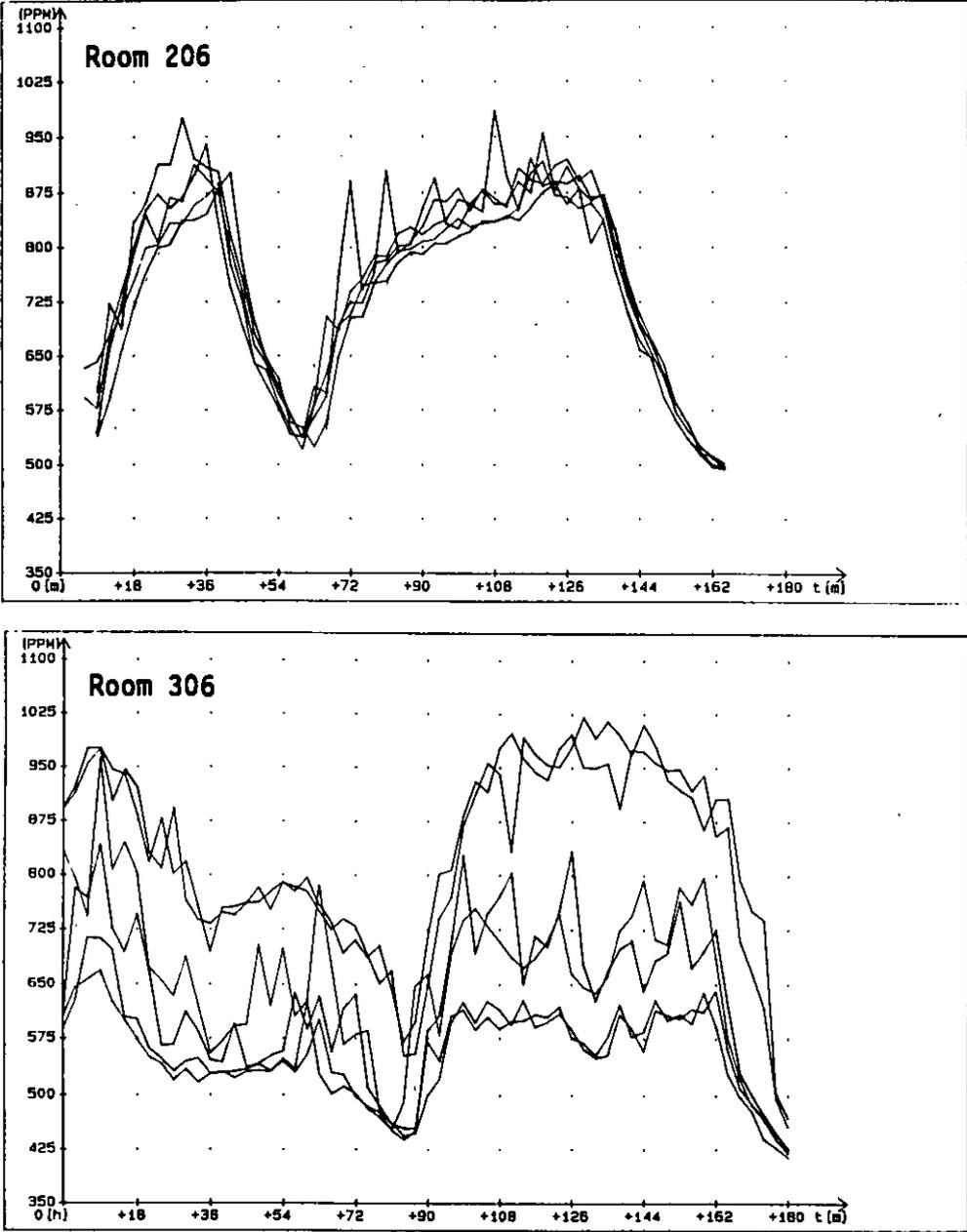


Fig 9. Mixing vs displacement ventilation

Thus in classrooms, displacement air distribution improves air quality in the breathing zone corresponding to about 250 ppm of CO₂, compared with mixing air distribution and a similar air flow.

It can also be stated that, with displacement air distribution, it is possible to decrease the fresh air flow, and thereby lower the energy requirement for heating air, by about 25 percent, and still retain air quality.

In general, it can be noted that the measured concentrations (206) indicate that the children (ages 7-13) exhale about 18 l of CO₂ per hour. This is otherwise a value considered typical for adults performing office work.

The *horizontal* measurements were also made at six points at floor level (0.1 m).

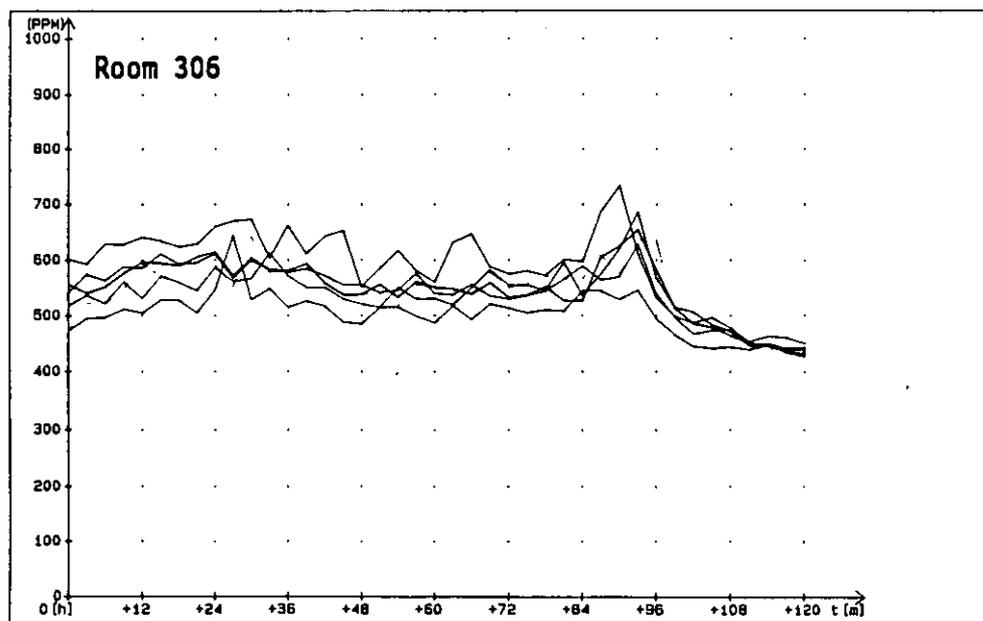


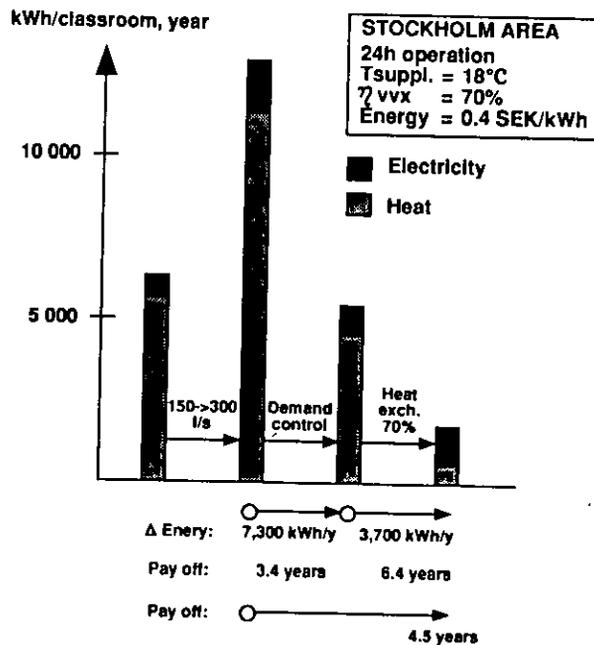
Fig 10. CO₂-concentration in 6 points at 0.1 m level

The measuring points and results are shown in Fig. 10. As indicated by the results, the supply air, which was cooler than the

room air temperature, was distributed effectively throughout the classroom. The radiators were not on when the measurements were made.

Energy performance

The measurements confirmed that the air flow to the classrooms met the requirements shown on the respective schedules. Based on the schedule for the six classrooms with demand-controlled ventilation, the system's function and energy requirement for heating can be simulated. Climate data were used for Stockholm.



As shown in Fig. 11, increasing the fresh air flow specified in the existing building code (5 l/s per student, 150 l per class) to a fresh air floor guaranteeing good air quality – for example, a maximum of 800 ppm of CO_2 (10 l/s per student, 300 l per class), doubles the energy requirement for air handling.

By using demand-controlled ventilation, however, the energy requirement is reduced by more than half. The use of heat recovery further decreases the amount of energy required. Based on the

demand-controlled ventilation and heat recovery system used in this project, the payoff period has been estimated at about 4.5 years for both measures.

Conclusions

When the air flow is 8-9 l/s per student, the student feel the air quality is sufficient during those months of the year when the room temperature is at an acceptable level.

In the autumn and spring, an increase in the fresh air flow, using air cooler than room air, is desirable to keep the room temperature down. It is not always possible to open windows to air out the classrooms because of noise, or because of pollen, for example. A high room temperature is one of the main reasons why the students feel the air is dry and of "poor" quality.

In a VAV system controlled on the basis of air quality, the air flow can vary between 100-10% at any time of the year.

This places special demands on the control of the heating coil in the central air handling unit.

The classroom ventilation system controlled by presence sensors has functioned reliably. The estimated energy savings were confirmed. In a centralized ventilation system, equivalent savings can almost be achieved by using a more efficient heat recovery system. This should be a more profitable solution in systems with short operating times, such as in schools.

5 Auditoriums

- 5.1 Lecture Hall at NTH Trondheim (Norway)**
- 5.2 CO₂ Controlled Ventilation in an Auditorium (Switzerland)**

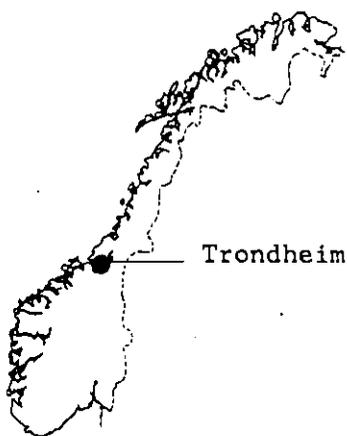
5.1 Lecture Hall at NTH Trondheim

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Researcher :

Finn Drangsholt



Demand Controlled Ventilation (DCV) has been tested in an auditorium with displacement ventilation at the University of Trondheim (fig.1). Based on full scale trials and numerical simulations, this project gives guidelines for sensor location, initial settings of the controller and expected savings.

The study has shown that the sensor may be located in or close to the exhaust only if the ventilation system is operated with a steady state basic ventilation rate covering situations with small occupant load. If the air flow is allowed to vary widely (zero to maximum), a sensor location at the exhaust will not give acceptable controller performance.

A PID controller tuned to be stable when the room is half full has shown good performance when a steady state basic ventilation rate of 1/3 of the maximum is used.

Energy savings were affected by the outdoor climate, the utilization of the room, the heat exchanger efficiency and controller reference. Greatest savings are achieved when the climate is cold, the controller reference is conservative, occupancy of the room is small and the heat exchanger efficiency is low.

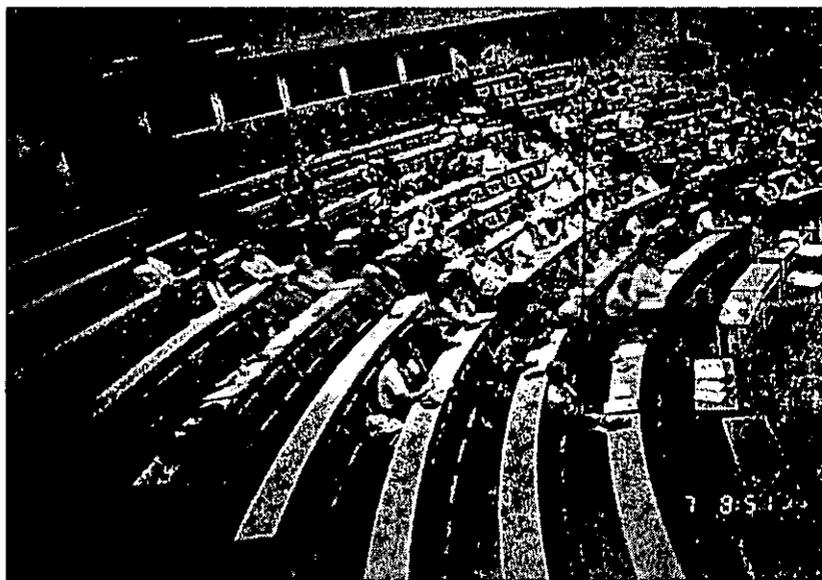


Fig. 1. View of the auditorium EL5 - Trondheim.

Introduction

Ventilation of living rooms is close connected to the human beings requirement of comfort and well being.

Besides supplying the human with oxygen, the ventilation provides acceptable indoor air quality and thermal comfort by removing contaminants, embarrassing odors and surplus energy.

Normally auditoria are ventilated mechanically with balanced supply and exhaust. The ventilation rate is steady state and based on maximum load.

Ventilating by demand means that the air flow rate is adjusted to meet the actual need situation, either manually or by a sensor and a controller. The intention of this principle is to save energy and to keep the thermal and atmospherical environment at an acceptable level.

Project Description

Aim of project

The object of this project has been to verify the energy savings potential and the controllability of the DCV principle used in auditoria.

Auditoria are characterized by high occupant loads, meaning that the indoor environment is strongly influenced by the users. The utilization of these rooms may vary greatly from class to class. This should make these type of rooms well fitted for demand control.

Based on results from full scale trials and numerical simulations, this report addresses the following questions:

controllability :

- where should the sensor be located?
- which controller structure gives sufficient response and stability?
- how does room design, ventilating principle and location of occupants affect the control ability?

energy savings :

- what is the relation between room utilization and energy savings?
- how do other energy measures affect the benefit of the

DCV system?

Building construction

Full scale trials with demand controlled ventilation have been carried out in an auditorium (EL5) at the Norwegian Institute of Technology (NTH).

Year of constr. : 1986
Capacity : 320 stud.
Floor area : 340 m²
Room vol. : 1600 m³

The auditorium is located inside an older building. It is surrounded by rooms and corridors at three sides, and an atrium glazing at the fourth side. The heat transfer losses to the surrounding areas are small. Fig. 2 shows the ground level plan.

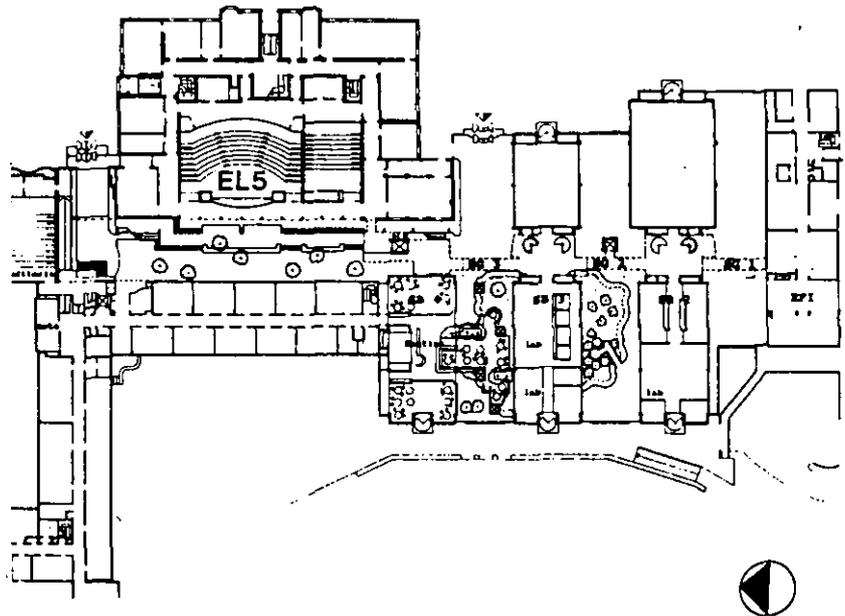


Fig. 2. Ground level.

The walls are made of light concrete. Floor, furnishing and intermediate ceiling are made of wood. Part of the front wall facing the atrium glazing is made of glass.

The auditorium is ventilated by displacement ventilation, with inlet devices under the seats and exhaust devices in the ceiling. There is no heating system inside the auditorium.

Ventilation system

Max airflow : 10000 m³/h
Exch. eff. : 70%

The ventilation system is located in the basement under the auditorium. The system is mechanically balanced and equipped with a heat recovery unit and a heating coil. Inlet

temperature is fixed at 18°C. The rotating heat exchanger has an efficiency of 70% and is interlocked with the heating coil. Control functions are handled by decentralized direct digital control (DDDC).

Implementation of DCV system

Frequency convert :

Voltage : 380 v
 Load : 20 kW
 Frequency : 0 - 50 c/s
 Input : 0 - 20 ma

A frequency converter was temporary installed to control the speed of the fans. The output from the converter could be adjusted manually or by signals from a controller. The air flow rate was variable from 0 to 10.000 m³/h. Max. and min. flow could be adjusted on the converter.

A PID controller was used with the DDDC equipment to handle the DCV operations. Carbon dioxide was chosen as relevant indicator of indoor air quality, while temperature was used as indicator of thermal comfort. The controller algorithm was arranged to handle the most conservative conditions from these indicators. Fig. 3 shows a sketch of the DCV system.

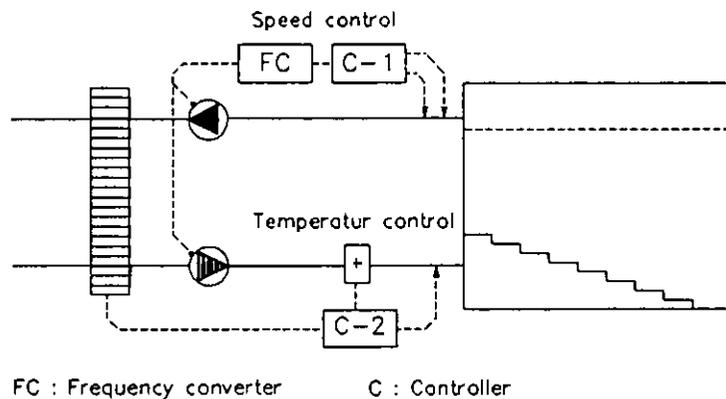


Fig. 3. DCV principle.

As carbon dioxide indicator chosen was an infrared analyzer. The analyzer was continuously fed with samples via a plastic tube and a pump. This arrangement made easy to sample from anywhere in the room.

CO2 analyzer:

Range : 0-2500 ppm
 Output : 0-20 ma

The temperature indicator chosen used a PT-100 element. The sensor was fixed at the front wall of the auditorium.

Data acquisition

The data acquisition system used a micro computer with analog/digital inputs and digital outputs. The system

controlled a mechanical multiplexer with 30 channels for gas samples, 30 analog inputs (0-20 mA), for humidity, temperature, gas analyzers etc., 30 channels for thermocouple and 16 channels for sensors with pulse output.

The development of the equipment started early in the eighties and was completed during this project. Fig. 4 shows a sketch of the data acquisition system and the sensor arrangement.

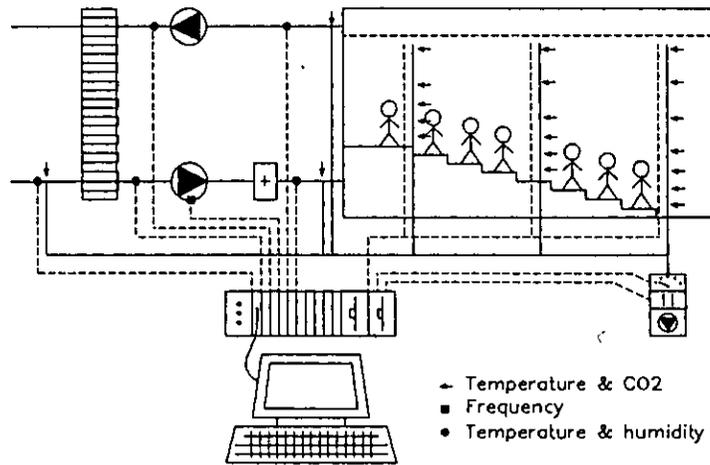


Fig. 4. Data acquisition system and sensor arrangement.

Inside the auditorium there are three measurement columns containing 19 spots for gas and temperature measurements. Column 1 is at lower left side of the auditorium, column 2 is in the middle of the room, and column 3 is at the upper left side. Further three spots for gas and temperature are located at the wall. Table 1 provides a more detailed description of the sensor arrangement.

Tab. 1 Location of temp. and gas spots

spot nr.	location	temp	CO2	hum	vel	c/s
1-8	column 1	*	*			
9-15	column 2	*	*			
16-19	column 3	*	*			
20-22	side wall	*	*			
23	outdoor	*	*	*		
24	vent. sup.	*	*	*	*	
25	vent. exh.	*	*	*	*	
26	freq. con.					*

The measuring columns covered the room condition, while the spots on the wall covered the boundary conditions. In addition 16 spots covered the operation of the DCV system.

Data Evaluation

Performance of DCV system

Knowing the system, and the components function and response to various loads is important when the DCV principle is evaluated.

A critical part of this study was to verify the performance of the ventilation system and the ventilation principle. The performance study included verification of air leakage and short circuiting, calculation of ventilation efficiency and indexes, air flow measurements, measurements of the heat recovery unit efficiency and studies of the air inlet temperature control.

Air flow measurements

During DCV operation the air flow could vary from zero to maximum. The actual air flow rate was controlled by the number of occupants and the CO₂ level inside the auditorium.

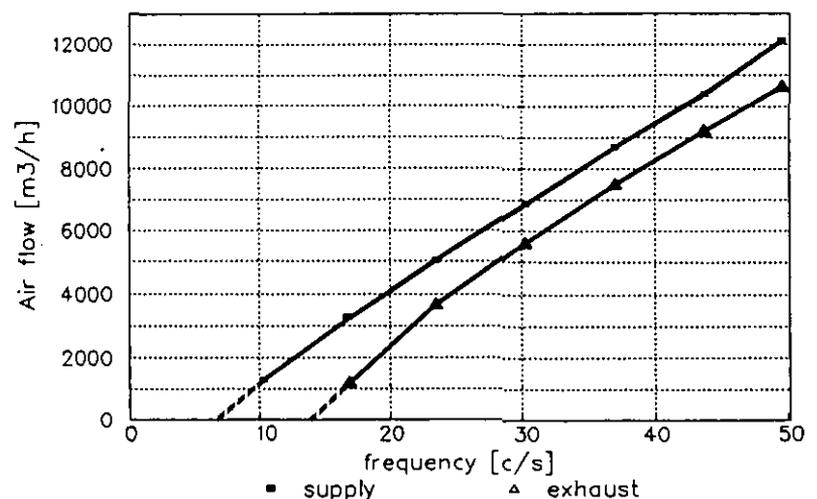


Fig. 5. Air flow rate as a function frequency output.

Since the energy consumption for heating and transportation of air is associated with the air flow rate, it was important that flow rate was recorded during the trials. In this case study, the output from the frequency converter was recorded as a substitute. Fig. 5 shows the relationship between the output from the frequency converter and the air flow rate in the ventilation ducts.

As we can see from this figure, the air flow in the supply and exhaust duct changed direction when the frequency output decreased below 7 c/s and 14 c/s respectively. This situation occurred because several ventilation plants were connected to a common exhaust and fresh air duct arrangement.

This arrangement also affected the relation between fan speed and energy consumption. While expecting that the energy consumption should follow the power law, measurements showed a more linear connection between speed and load. Fig. 6 shows this relationship.

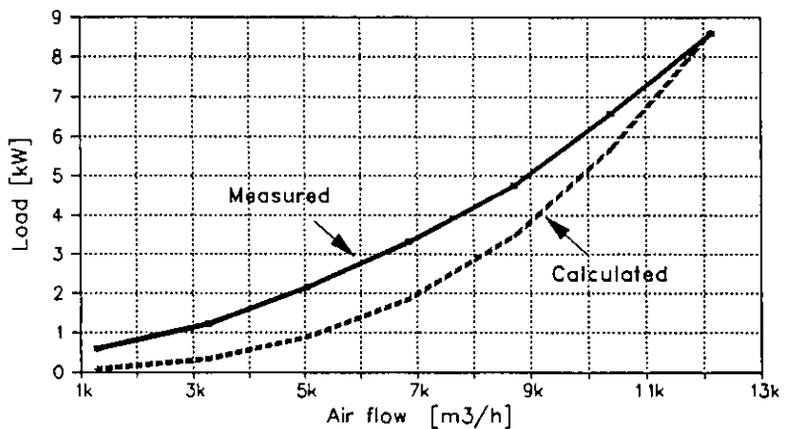


Fig. 6. Relationship between fan speed and electric load.

Heat exchanger efficiency

It is important when evaluating the saving aspect of the DCV system, to know the performance of other energy saving measures that may affect the results.

In the EL5 full scale trial, the ventilation plant was equipped with a rotating heat exchanger. The exchanger had a stated efficiency of 70% when the air flow is balanced at 12:000 m³/h. Verification studies based on temperature measurements and air flow measurement confirmed this efficiency.

Also of interest when calculating the energy consumption, is how the efficiency varies with the variable air flow. Fig. 7 gives this relation. The curve is based upon empirical formulas given in DANVAC /1/.

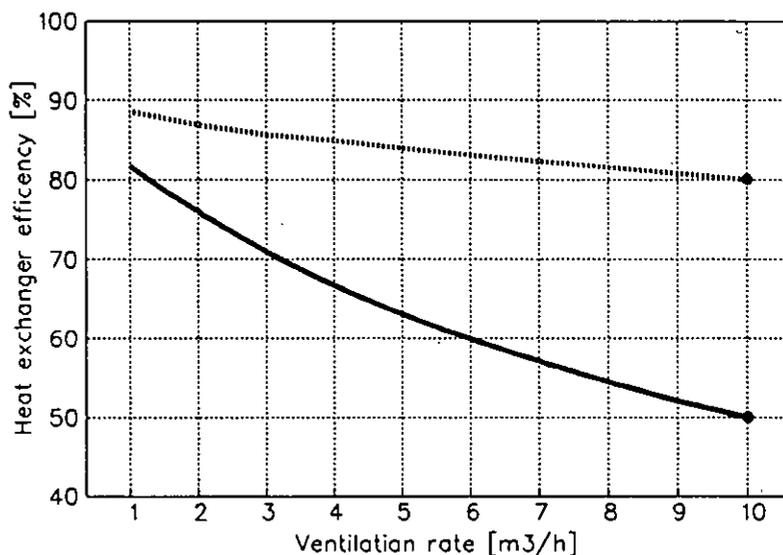


Fig. 7. Relation between the heat exchanger efficiency and the air flow.

Leakage and short circuiting

Leakages and short circuiting through components, ducts, inside the room and outside the building may also affect the results. Using tracer gas techniques, the ventilation plant, the ducts and the room were examined. During examinations, all doors leading to the auditorium were closed.

Short circuiting through the heat exchanger was measured at 1500 m³/h. That means that 15% of the total flow was recirculated through this component. Positioning the exhaust fan at the opposite side of the exchanger probably would have reduced this.

Leakage from the pressurized plenum chamber to the surrounding corridor was caused by poor trading. Slots and holes have been revealed by smoke tests.

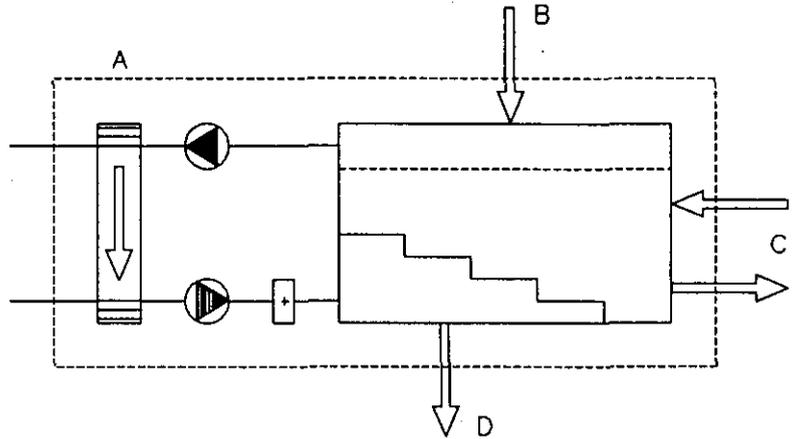
The leakage from outdoor to the return air duct is caused by leaky sealing and breakages of the sky light. The sky light is not in use after the rehabilitation of the building, but it represents parts of the outer roof construction. Fig. 8 shows the results from this investigation.

Leakages :

Heat exchanger : 15%

Plenum chamber : 15%

Sky light : 5%



A : Leakage through heat exchanger (1500 – 2000 m3/h)

B : Leakage through sky light (500 m3/h)

C : Infiltration/exfiltration (not measured)

D : Leakage from plenum chamber (2000 m3/h)

Fig. 8. Leakages and short circuiting

Air flow pattern inside the auditorium

Measurements

As mentioned in the introduction, one reason for ventilating is that we want to maintain an acceptable thermal and atmospherical environment inside the room. How efficient surplus energy and contaminants are removed from the occupied zone is closely connected to the air flow pattern.

Using different tracer gas techniques it is possible to classify the air flow pattern in terms of air exchange efficiency, local air change index, ventilation effectiveness and local ventilation index. This gives us useful information about the fresh air distribution inside a room, and the contaminant currents from the sources to the exhaust.

Air change efficiency :

$$\epsilon_a = \frac{\tau_n}{\langle \tau_r \rangle}$$

Local air change index :

$$\epsilon_p = \frac{\tau_n}{\tau_p}$$

τ_n : nominal time const.

τ_r : air change time

τ_t : local mean age

The air change efficiency (ϵ_a) expresses how well the fresh air is distributed in the room. It gives the relation between the mean age of the air in the exhaust duct and the mean age for all the air in the room.

The local air change index (ϵ_p) shows the relation between the mean age of the air in the exhaust duct and the local mean age at any specific point inside the room. An $\epsilon_p > 1.0$ indicates that this point is better ventilated than if the room air was complete mixed.

The ventilation effectiveness ($\langle \epsilon_v \rangle$) express how efficiently contaminants generated in the room are removed. It gives the relation between the concentration of contaminants in the

exhaust air and the mean concentration in the room.

Ventilation effectiveness :

$$\langle \epsilon_v \rangle = \frac{C_e(\infty)}{\langle C_p(\infty) \rangle}$$

Ventilation index :

$$\epsilon_v = \frac{C_e(\infty) - C_s(\infty)}{C_p(\infty) - C_s(\infty)}$$

$C_e(\infty)$: cons. in exhaust

$C_s(\infty)$: cons. in supply

$C_p(\infty)$: cons. at a specific point

< > : mean value of all points

The local ventilation index (ϵ_v) shows the relation between the concentration of contaminants in the exhaust air, and the concentration at any spot in the room. The mean of this index in all points of the room equals the ventilation effectiveness.

The technique used for these evaluations is based on injection of tracer gas. Air distribution is studied by step injection of tracer gas (N_2O) in the supply air. The capability to remove contaminants is studied by step injection of tracer gas at the contaminant sources. In this study the CO_2 dissipation from the occupants was used.

Since constant concentration is not obtained during a lesson, mathematical regression analysis was used to "predict" the final concentration cycle. Several situations with different initial settings have been examined. Different occupancy have been combined with different air inlet temperature and ventilation rate. Table 2 shows the air exchange efficiency and the local air exchange index at different locations (see table 1) as a function of occupancy and ventilation rate.

Table 2. Air change efficiency and local air change index

Ventilation rate	5.000 m ³ /h			12.000 m ³ /h		
Nr. of occupants	0	130	220	0	150	240
ϵ_a	0.63	0.65	0.63	0.62	0.57	0.59
ϵ_p at spot 3	1.77	0.83	1.01	1.18	0.96	0.88
at spot 4	0.86	0.69	0.84	1.13	1.00	0.85
at spot 11	1.61	1.00	1.41	1.65	1.54	1.28
at spot 12	1.47	0.85	1.09	1.64	1.22	1.29
at spot 18	0.63	0.67	0.94	0.74	1.02	0.85
at spot 19	0.69	0.91	1.06	0.92	1.42	1.01

The air change efficiency (ϵ_a) in tab. 2 tells us that the air distribution in the auditorium takes place by displacement ($\epsilon_a > 0.5$). Further we can read that the air distribution within the tested ranges, is little affected by the variation of air flow and occupancy. The observed variations may likely be imputed to the accuracy of the tracer gas method.

Getting any trend from the local air change indexes is difficult. These results are influenced by the students sits, the air inlet temperature and the temperature on all surfaces.

From pictures taken during the tracer gas experiments we can see that the seating pattern varies from lesson to lesson, even if the number of students is almost the same. Still one conclusion may be drawn. The air distribution to the middle of the room (spot 11 and 12) is somewhat better than the air distributions to the corners (spot 3,4,18 and 19).

The local ventilation indexes however are more significant. Fig. 9 shows a situation with the auditorium fully occupied, and the ventilation running at full speed.

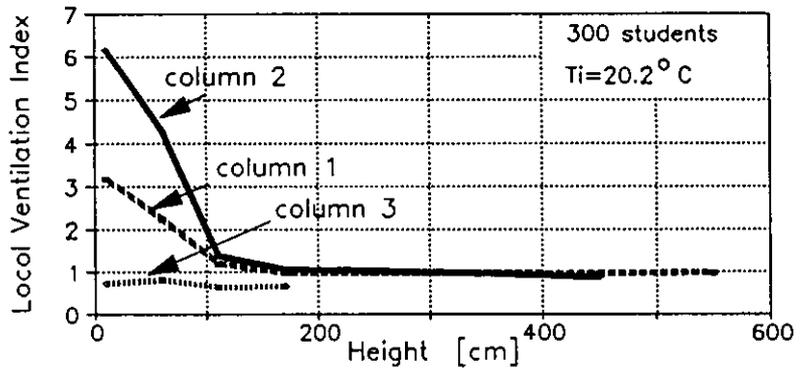


Fig. 9. Local ventilation indexes.

From this diagram we can see that at the upper left zone (column nr. 3) of the auditorium, contaminants are removed less efficiently than contaminants from other places in the room.

Using CO₂ dissipation from the occupants to calculate the ventilation effectiveness was tested. The method based on step injection, however failed. The main reason for this is that the students are not arriving the auditorium simultaneously, but over a period 15 to 20 minutes. Fig. 10 shows the students entry to the auditorium.

An alternative method of calculating the ventilation effectiveness is by making an average of all measured indexes. This gives us an ventilation effectiveness ($\langle \epsilon_v \rangle$) of 2.1. Comparative to ventilation based on complete mixing which gives an $\langle \epsilon_v \rangle$ of 1.0, this means that contaminants are removed more efficiently.

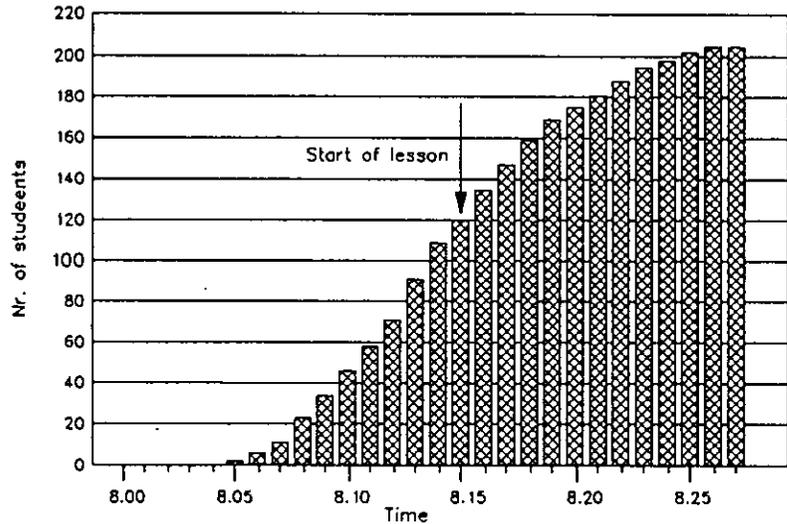


Fig. 10. Students entry to the auditorium

Numerical Simulations

Tracer gas measurements gives us an idea of the efficiency of the ventilation principle. An exact picture of the air flow pattern involves a large and impractical number of measuring spots. By supplement of numerical calculations solving the continuity equation, the momentum equation (Navier-Stokes), the energy equation and the ideal gas law, it is possible to compute more information about the air flow pattern.

By using the Computer Fluid Dynamics (CFD) technique, the temperature, velocity and mass fraction field for the auditorium EL5 have been calculated. These studies have been carried out with the computer code KAMELON developed at SINTEF applied thermodynamics.

The auditorium was modelled in three dimension, using cartesian coordinates. Half of the auditorium was represented by 29184 blocks. The calculations are executed on a CRAY X-MP, and the cpu time for one calculation is about 4000 seconds.

The results from these calculations are presented graphically as horizontal and vertical sections in the auditorium. The velocity field is represented by the size and the direction of arrows. The representation of mass fraction and temperature are built upon iso contours filled with colors or gray shading.

Fig. 11 shows an example from these computer simulations. The results presented are from the vertical section yz19. The section is parallel to the side walls. Measurements from the

auditorium are used to define the boundary conditions. The pictures illustrates a situation with the auditorium fully occupied and the ventilation system running steady state.

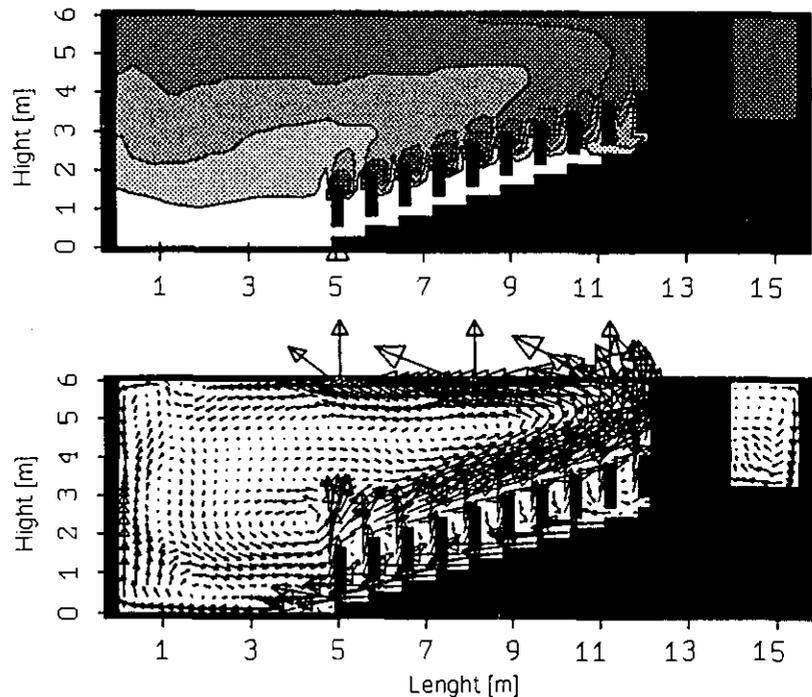


Fig. 11. Mass fraction (CO_2/Air) and velocity field at section yz19.

A number of situations were simulated, indicating that the air flow pattern is affected by several factors including room geometry, capacity and location of heat source, furnishing, aspects of building materials and construction, ventilation principle, air inlet temperature and leakages.

The numerical simulations also confirmed the conclusions from the referred tracer gas experiments. As observed, the air quality and the thermal comfort in the occupied zone was not uniform. Some zones had stratified temperature and contaminants, while other zones were well mixed. Where these zones occurred depended on the number and distribution of occupants.

Sensor location

To attain acceptable thermal and air quality environment during demand control, it was crucial that the sensors in the control loop gave representative information about the conditions in the occupied zone.

The full scale trials and the CFD calculations showed that the air flow pattern inside the auditorium was quite complex.

Poorly ventilated zones which occurred when the room was fully occupied, might have been well ventilated when the load was reduced. The fluctuations and the inconsistency caused by the variable occupant load, the ventilation principle and the room geometry therefor made it difficult to recommend sensor locations inside the room.

Presuming steady state conditions and no short circuiting, means that the concentration of contaminants in the exhaust equals that which we would get if the air flow pattern was completely mixed. A sensor located in the exhaust will give a good indication of occupancy, but will not reflect poor ventilated zones.

Steady state conditions, however will not occur during a single class. In addition short circuiting between the supply and exhaust devices may occur on sunny days (the front wall is heated) and when the room is moderately utilized after several fully occupied lessons (all walls are heated by the heavy load).

As we can see there is no ideal location for the sensor, so we have to compromise. In our study we found that the short circuiting between supply and exhaust appeared infrequently and was of moderate size. We also observed that the inconsistency in the air flow pattern were not critical. Our further experiments with the DCV principle was therefore based mainly on sensors located in the exhaust air.

System regulating ability

The controller settings and the regulating ability were examined using of the process reaction method (Ziegler and Nichols) and dynamic simulations. The systems were tested with various occupant load, various controller algorithms (P, Pi, PID) and various controller references.

The process response is given by the lags, delays, time constant and gain factors. Parameters that affected the process were room volume, maximum air flow rate, ventilation principle, occupant distribution, sensor location and surface temperatures.

Step response analyses showed that the delays and time constants varied widely. The delay was small (< 60 sec.) when the auditorium was fully occupied and the air flow rate was high. Together with the ventilation rate, the convective flow caused by the heat dissipation from the occupants dominated the situation.

Fig. 12 shows an example of process reaction carried out on a fully occupied auditorium. The responses shown are based on full scale trials and mathematical simulation.

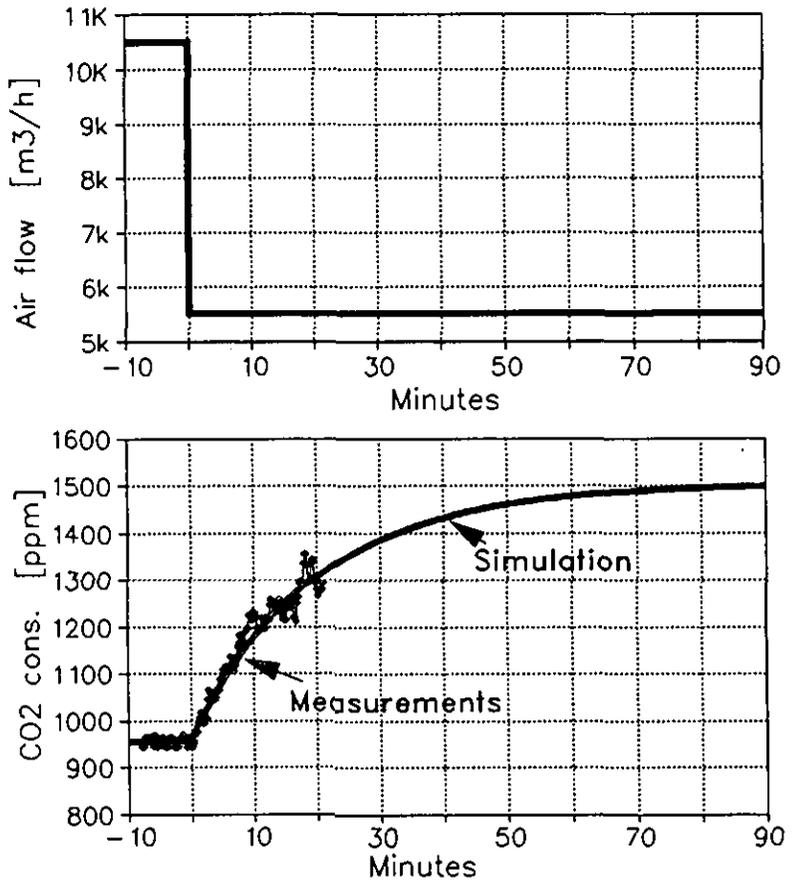


Fig. 12. Step response in the exhaust duct (measurements and computer simulations)

When there were few people in the auditorium the convective flows were minimal. The time delay was then given by the ventilation rate, the flow area and the students distribution.

Theoretically the air flow pattern inside the auditorium may vary from completely mixed to piston flow. This unique situation is caused by the terraced construction of the auditorium and the ventilating principle (displacement).

The analyses have shown that the process contains several essential nonlinearities. This makes it difficult to find a controller which is stable when the occupant load is small and not too sluggish when the room is fully occupied.

Fig. 13 illustrates the different process responses as a function of air flow patterns.

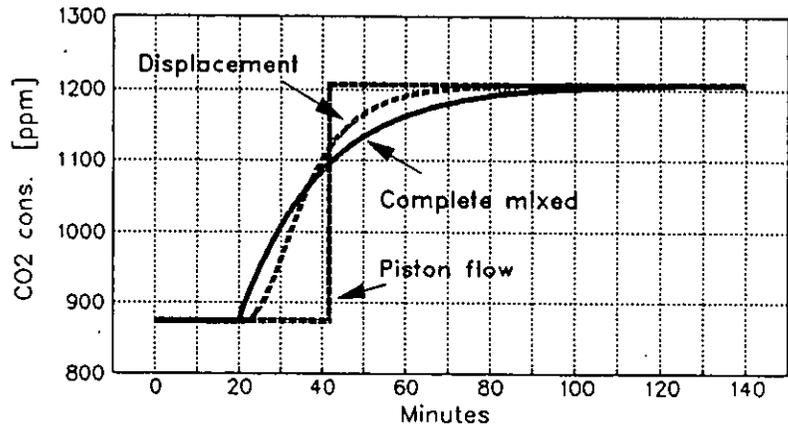


Fig. 13. Process response as a function of air flow pattern

One way of avoiding the wide range of time delay, is to operate the system with a steady state basic ventilating rate when the occupancy is small and the convective flows are negligible. This situation is handled by a basic ventilation rate, and the DCV principle takes control when the convective flows from the occupant load dominate the air flow pattern.

Fig. 14 shows how a PI and PID controller can handle this controlling strategy.

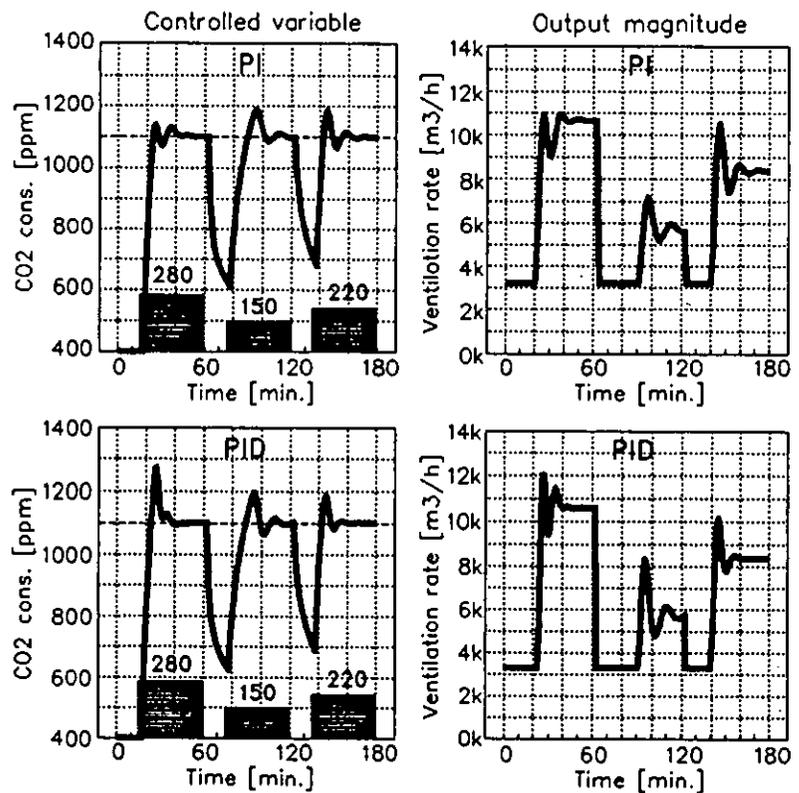


Fig. 14. Controller performance.

Three cases with different numbers of students, the one following the other were simulated. The first class had a occupant load of 280 students, the second class had 150 students and the third class had 220 students. The basic ventilation rate was set to cover an occupancy load of 100 students. As fig. 14 shows both controllers reach the set point fairly quickly and perform acceptable stability. The difference between the controllers is small. Activating the derivative element did not improved the controller performance significantly.

Energy Savings

The energy savings related to the DCV principle are affected by the occupancy of the auditorium, the outdoor climate and the air inlet temperature, the capacity and pressure drop in the ventilation system, the heat recovery efficiency, the room volume, the thermal mass and the set point of temperature and contaminants. These quantities which are all used as inputs into the computer analysis of the energy saving potential in EL5.

The computer code developed for this purpose takes into consideration the thermal and atmospheric dynamics of the auditorium. The heat exchanger was modelled in a way that account for the flow dependent efficiency. The time step for these computations was set to 5 minutes, and the outdoor temperature was derived from meteorological observations.

Occupancy of the auditorium

During our full scale trial with ventilation by demand, all human activity was recorded by photography. A camera connected to a timer and a clock relay automatically took pictures at the end of each lesson.

The usage of the room was monitored from spring 89 to autumn 91. Based on these pictures, the utilization of the auditorium was calculated for 6 education terms. The results are presented in Table 3.

Table 3. Utilization of the Auditorium.

Spring 89	Autumn 89	Spring 90	Autumn 90	Spring 91	Autumn 91
37%	51%	34%	45%	22%	37%

At the University of Trondheim autumn term last from 1. of September to 10. of December. Spring term last from 1. of February to 10. of May.

Another relation that may affect the energy savings, is how the use of the auditorium varies during the working day. The room temperature is influenced by the internal heat load (the occupants), the ventilation rate and the heat capacity of walls and furnishing. This means that an alternating between fully occupied classes and empty classes may give another result, than if the room were fully occupied continuously half the day. Fig. 15 gives an example of the variation of occupancy during day time.

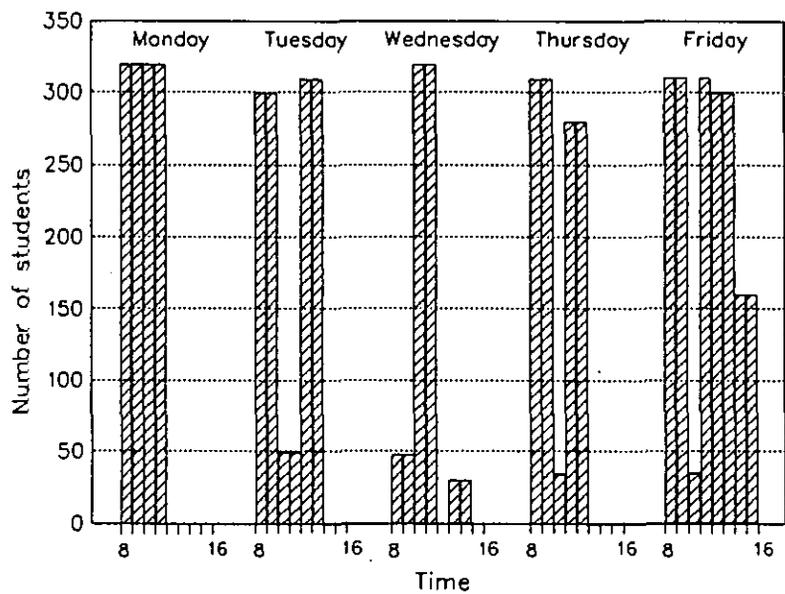


Fig. 15. Occupancy variations during day time.

Outdoor Climate

Another parameter that affects the savings is the outdoor temperature. In our study of energy savings with demand control, meteorological observations recorded by the Meteorological Institute were used. These records contain daily observations of temperature made at 07:00, 13:00 and 19:00. The records also include daily maximum and minimum temperature.

By comparing the number of degree day from several years, a year with typical climatic data has been selected. In this case climate data from Trondheim in 1973 are used as input for the computer simulations. Fig. 16 shows the daily mean temperature for Trondheim in 1973.

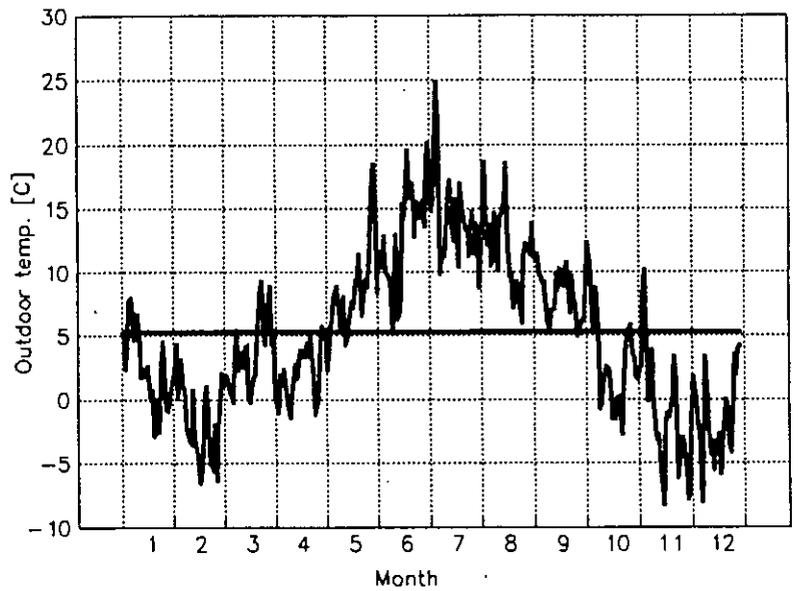


Fig. 16. Daily mean temperature - Trondheim 1973.

Computer simulations

Computer simulations of the energy savings were conducted for various personal loads and three different level of CO₂ concentrations. Inputs to the computer program were based on information from the full scale trial and climate data are representing typical weather.

Each DCV simulation was compared to a steadily operating system. The steady state system was designed to keep the CO₂ level at the reference when the auditorium was fully occupied. Table 4 shows the plant capacity as a function of maximum acceptable CO₂ level.

Table 4. Plant capacity as a function of CO₂ reference.

max CO ₂ level [ppm] :	800	1000	1200
Plant capacity [m ³ /h] :	16.800	11.400	8.400
Fan load [kW] :	14.7	10	7.4

During DCV operation, the minimum air flow rate was set at 3000 m³/h. Hours of operating were from 7 AM to 4 PM. Holidays and weekends were treated as if the ventilation system was shut down. Accumulated contaminants from the furniture and building construction were removed by running the ventilation system at full speed from 7 AM to 8 AM.

Fig. 17 shows the results from these simulations. The savings are separated in two graphs. One represents the fans and the other represents the heating coil.

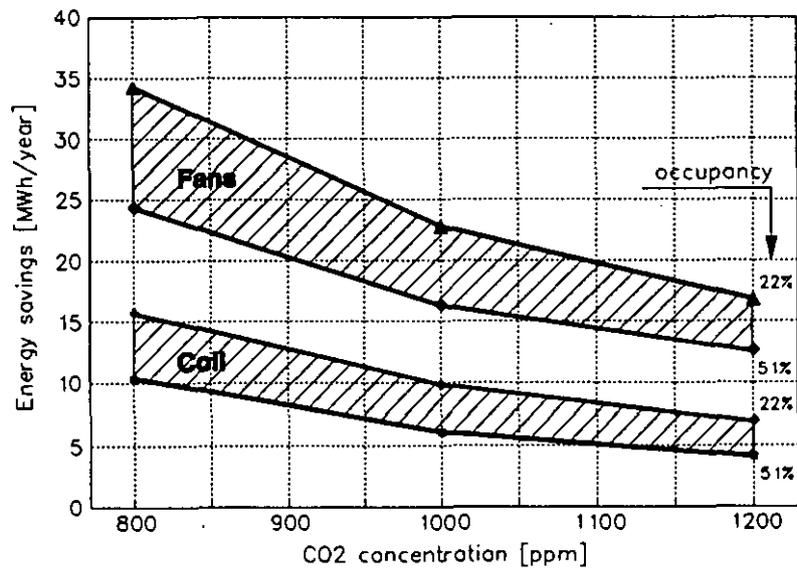


Fig. 17. Energy savings in EL5 auditorium

As we can see from this graphical illustration, the total energy savings may vary from 17,000 kWh/year to 50,000 kWh/year depending on occupancy and the CO₂ level.

Conclusions and Recommendations

This study has shown that auditoria may be an excellent application for the demand controlled ventilating principle.

The regulating ability and the location of the sensor are strongly affected by the ventilation principle and the room geometry.

While room based on complete mixing are easy to control, care must be taken when the ventilation principle is based on displacement and the room is terraced. Location of the sensor in the exhaust demands that a steady state basic ventilation rate be used in situations with limited occupancy. Otherwise the sensor must be moved closer to the occupied zone. Unfortunately the occupied zone is not easily defined when the number of students is few and they are free to sit anywhere.

The energy savings are strongly affected by the occupancy of the room, the heat exchanger efficiency, the outdoor climate and the controller set point.

Whether the principle is cost effective or not has not been evaluated in this study. Several components used in this study were prototypes and their cost would not give a realistic base for an economical analysis.

References

- /1/ Danvak
Varme og klimateknikk - Grundbok

5.2 CO₂ Controlled Ventilation in an Auditorium

Project description

Introduction

Research Institutions:

- Basler & Hofmann;
Consulting Engineers,
Zurich
- Institut für Hygiene und
Arbeitsphysiologie; Swiss
Federal Institute of Tech-
nology (ETH), Zurich
- Laboratoire d'énergie
solaire et physique du
bâtiment; ETH, Lausanne

Contact person:

Marco Zamboni
Basler & Hofmann
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CH - 8029 Zurich

The choice of the appropriate strategy for demand control has to be based on the activities in the concerned rooms. The investigations of this project are restricted to rooms where the main source of air pollution is represented by the occupants (e.g. breathing, odours). In these cases the concentration of carbon dioxide may be used as an indicator to assess ventilating demand.

One example of rooms which have these characteristics are auditoria: high concentration of occupants, no other pollutant activities, low emission of contaminants by other sources (e.g. furniture). Ventilating demand can therefore be considered to be depending exclusively on the presence of people.

Objectives

Energy savings through demand control

The main objective of this study is to determine the energy savings that can be achieved with the use of demand control. Simultaneously an acceptable quality of environment (temperature, air quality, etc.) has to be maintained. The main work focuses on the comparison between clock control and control strategies based on the use of CO₂-sensors. As far as possible competitive strategies such as motion-sensor control and VOC-sensor control are also considered.

The results are based on short-time monitoring during system operation. Computer simulations provide results for:

- the comparison of annual performance and for
- different conditions of operation.

Tracer gas measurements provide information about the air flow patterns within the room and about the recommended sensor locations.

Building and Site

Climate of Zurich:

Heating Degree Days
(20/12 °C): 3'600

Annual average
temperature 5.6 °C

The field measurements were carried out in an auditorium of the Swiss Federal Institute of Technology (ETH) in Zurich.

Zurich is situated near a lake in the northern part of Switzerland. The climate is moderately cold in winter and quite warm in summer.

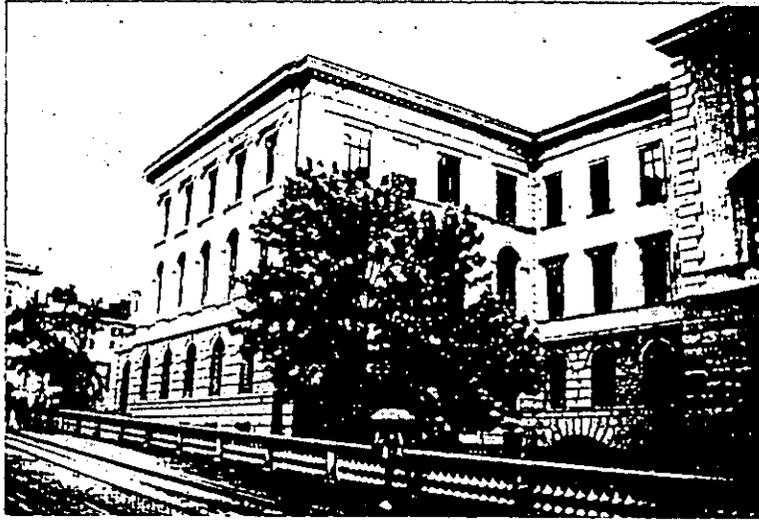


Figure 1: Main building of the Swiss Federal Institute of Technology

Investigated zone

Room

Area : 120 m²

Volume: 440 m³

Capacity: 80 persons

The investigated room (auditorium HG D 16.2) is one of the smaller auditoria with an area of about 120 m². It has a capacity of 80 persons.

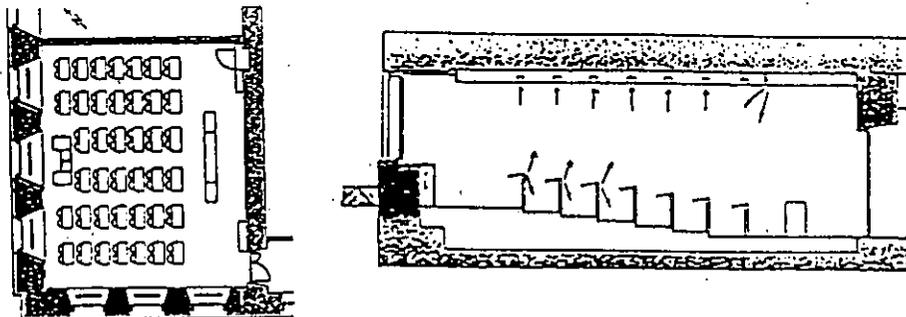


Figure 2: Ground-plan and sectional view of the auditorium HG D 16.2

The auditorium is situated in a corner of the main building and has windows on one side and at the rear. Because of the near traffic these windows have to be kept closed at all times.

Construction: heavy walls with poor insulation

Frequency of use: 6 days per week

The walls of the auditorium are extremely heavily built (up to 1.2 m thick) but poorly insulated. Floor and ceiling consist of lightweight constructions (metal, wood). The floor of the auditorium rises towards the back of the room but the elevation is not significant (about 1 m).

The use of the auditorium is subject to great fluctuations. The main building is open on 6 days per week (monday through saturday) from 7:00 to 22:00. The investigated auditorium could also be used during this range of time.

Heating and ventilating system

Heating: convectors below the windows

Convectors with thermostatic valves are placed below every window and keep the room temperature at an almost constant level.

Ventilation: Balanced system with heat recovery

The auditorium is equipped with a balanced ventilating system with a heat recovery wheel. The ventilating system supplies air only to this room. The supply air can be heated or cooled and enters the room at the desks (85%) and through ceiling diffusers above the front desk (15%). The exhaust air is removed through ceiling slots.

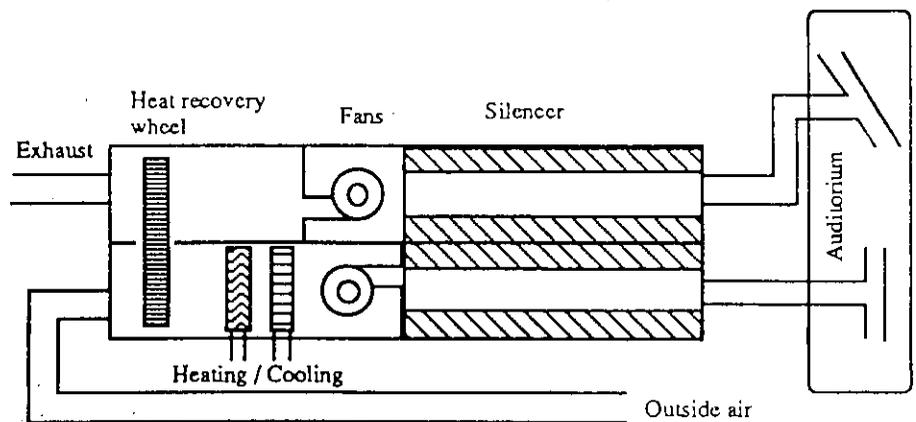


Figure 3: System sketch of the ventilating system

Both fans have two speeds but since no adequate control parameter is available both fans are always run on speed 2.

Monitoring programme

Control strategies

Clock control

All the heating and ventilating systems of the main building are connected to a centralized control and monitoring system. In the investigated room this system controls room and supply air temperature and operating time. Room and supply air temperature are controlled according to the outside temperature. The running time could be programmed according to the expected occupancy of the room but usually the ventilating system is running on speed 2 from 7:00 until 19:00.

Demand control according to CO₂ concentration

The temperature control of room and supply air was left unchanged. Only running time and speed choice are now controlled by a CO₂-sensor.

Every morning before people arrive the auditorium is ventilated for half an hour at maximum air flow (clock control: 7:30 - 8:00). At 8:00 CO₂-sensor control takes over until 22:00 when the whole system is turned off. For comfort reasons the ventilating system would also be turned on if the room air temperature rose above a certain level (27°C).

Table 1: Threshold values for CO₂ concentration or room air temperature

CO ₂ concentration	room air temperature	operation
> 750 ppm	> 27 °C	speed 1 on
< 600 ppm	< 26 °C	speed 1 off
> 1'300 ppm	> 28 °C	speed 2 on
> 1'100 ppm	< 27 °C	speed 2 off

These threshold values were chosen according to the following criterias:

- a minimum operation time should be guaranteed
- CO₂ concentration should never exceed 1'500 ppm (comfort level while in the room)
- CO₂ concentration should fall under 1'000 ppm within 10 min. after people leave the room (comfort level when entering the room)

Monitoring periods

Summer: June 1990
Winter: January 1991

The system was monitored during two short periods of about one month in summer and one month in winter. During both monitoring periods the system was operated alternatively with one of the control strategies described above. The evaluation of the acquired data is based on the period of one week during summer/winter and clock control/CO₂ control respectively.

Monitored parameters

Questioning of occupants

During the monitoring periods all users of the auditorium HG D 16.2 were questioned about their perception of indoor climate. The questions were concerned with perceived temperatures, air quality and draught. The occupants were asked to answer the questions both when entering and before leaving the room.

Monitoring

The monitoring focused on the parameters which are relevant for the assessment of:

- energy consumption of the system
- indoor climate in the auditorium.

Energy consumption

The first aspect (energy) concentrated on measurements within the ventilating system: air and water temperatures, mass flow in heating and cooling coils, etc.

Indoor climate

The second aspect (indoor climate) led to the monitoring of the following parameters inside the auditorium: air temperatures, CO₂, air quality, humidity. The sensors were placed near the front desk, near the projection desk at the back of the auditorium and on one seat in the middle of the room.

Used sensors

Table 2: Monitored parameters and used sensors

Parameter	Sensor	Application	Measuring range / Output signal
CO ₂	Leybold, BINOS 100 NDIR	room air	0 - 5'000 ppm
	Sauter, EGQ 10 F001	room air	0 - 2'000 ppm
	Sauter, EGQ 10 F003	exhaust and supply air	0 - 2'000 ppm
	Aritron, AROX 425A	room air	0 - 2'000 ppm
IAQ	Stäfa control systems, FRA-Q1	room air	10 - 0 V
	Sauter, EGQ 1	room air	0 - 10 V
Motion	Stäfa Control systems, FRA-B2	room	0 / 10 V
Humidity	Rotronic, YA-100	room air	0 - 1 V
Temperatures	Resistance thermometers, PT 100		

To avoid problems of accuracy caused by commercial CO₂-sensors the BINOS 100 NDIR gas-analyzer was used for system control. The values of the commercial CO₂-sensors were monitored for comparison.

Further investigations

Computer simulations

The short monitoring periods lead to a comparison of energy consumption based on one week's operation in summer and one week's operation in winter. They strongly depend on the choice of the single week and on the actual occupancy of the auditorium. Computer simulations can provide results both for annual performance comparisons and for different conditions of operation.

Simulation code

The computer simulations were performed with the simulation code TRNSYS, which was developed by the University of Madison. Thanks to the modular structure of TRNSYS the integration of new system components is very easy. Since the CO₂ concentration is of great importance for demand control a new TRNSYS module was developed [4]. This module is based on mass balance and dilution. The effect of imperfect mixing of supply air with room air is expressed by the introduction of a mixing factor γ ($\gamma = 1$ implies perfect mixing).

Mapping of the age of the air

Tracer gas measurements

The location of the sensors is very important for the concept of demand control. The "right" location is strongly dependent on the air flow pattern within the room. The local distribution of the age of the air can provide some information about flow patterns and sensor location.

The age of the air will be measured using two tracer gases and simultaneously analyzing the concentrations at 10 different locations within the room. More details about the applied method are found in [1].

Results

Preliminary measurements

Air change rates:

Speed 1: 3.3 h⁻¹

Speed 2: 5.3 h⁻¹

No recirculation of exhaust air was planned. Tracer gas measurements [2] showed a recirculation through the heat exchanger of almost 40 %.

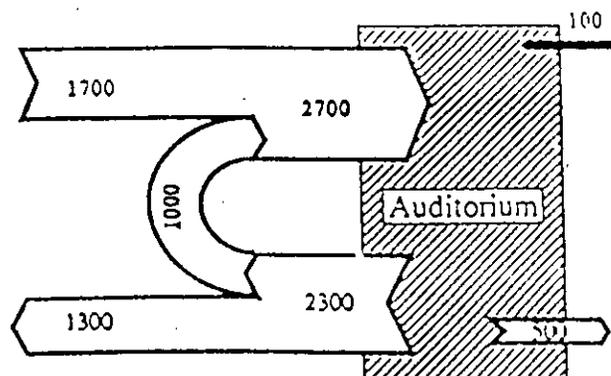


Figure 4: Air flows during system operation on speed 2 [kg/h]

This serious recirculation is caused by the position of the fans in respect to the recovery-wheel. Since the space in the installation room is very restricted the normal positioning of the fans (both fans on the suction side) was not possible.

Monitored period

General remarks

During both monitoring periods the auditorium was often occupied but very seldom there were more than 20 persons present. Unsolved problems with temperature control in combination with both clock control and CO₂ control caused different unexpected effects (e.g. heating of supply air up to 35°C for a few hours in summer)

Energy consumption

In both monitoring periods (summer and winter) the consumption of electricity could be reduced by about 80 % due to demand control. These large energy savings are due to the fact that the room was poorly occupied and therefore the operation time of the system could be remarkably reduced. Speed 2 was never used during demand control operation. The following diagram shows the different operation times for a day with similar occupancy.

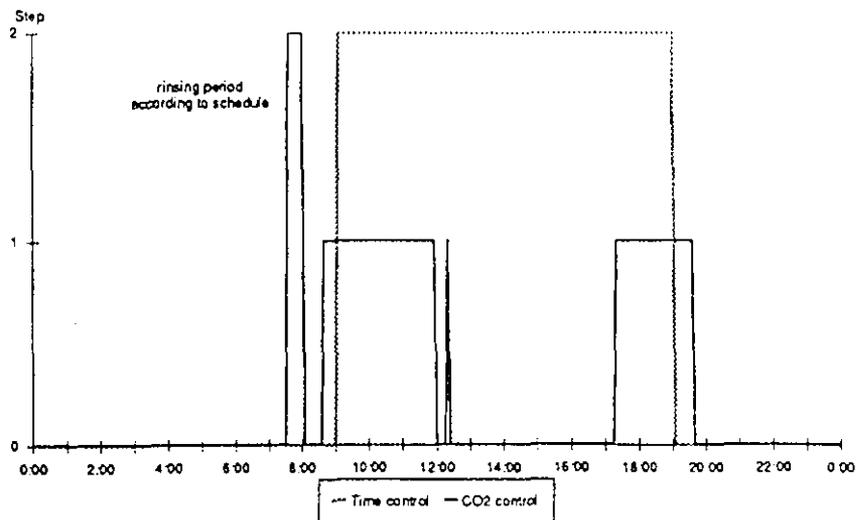


Figure 5: Operation of the ventilating system with clock control and CO₂ control. (same weekday; occupancy: 15 - 20 persons)

Even in summer the room air temperature never rose above the threshold value of 27 °C, which means that in practice the operation of the ventilating system was only controlled by the CO₂-sensor.

Cooling energy consumption in summer could be reduced by 75%. Heating energy consumption was reduced by 15% although during the week with CO₂ control the average outside temperature was 4.5 K lower.

Energy savings are strongly dependent on room occupancy and chosen threshold values for CO₂ control. Computer simulations help to provide information about energy savings under different operating conditions.

Indoor climate

The perception of draught and the acceptance of air temperature is directly connected with the operation time of the system. Since the operation time and the average air change rate was much lower with CO₂ control the perceived thermal comfort was definitely higher with CO₂ control (less draught).

On the other hand during the first monitoring period in summer air quality was considered to be slightly worse for system operation with CO₂ control. Figure 6a shows a clear tendency towards greater annoyance by odours.

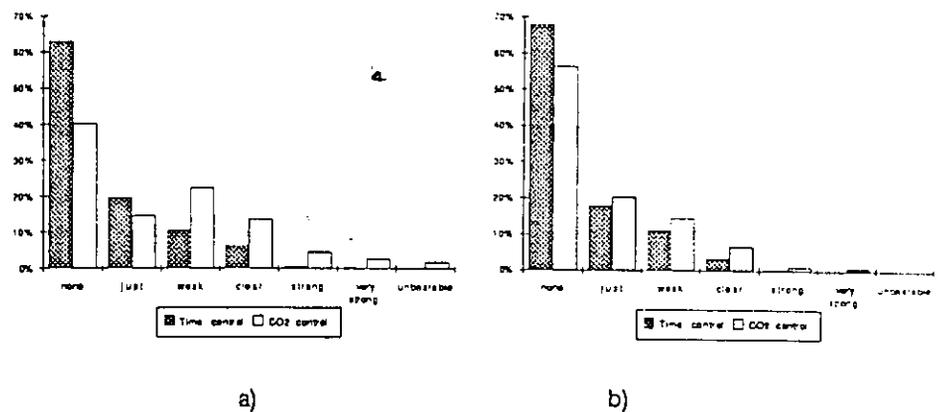


Figure 6: Perceived odours during system operation with clock control and CO₂ control. (left: summer, right: winter)

Further questioning of the occupants showed that the source of odours were not the occupants themselves but bad smelling cleaning fluids which were used for the cleaning of the blackboard. The evaluation of the winter period when these cleaning fluids were avoided shows much better results for odour perception (Figure 6b).

Simulations

Operating conditions as monitored (threshold values, occupancy) were simulated on a yearly basis and showed important energy savings.

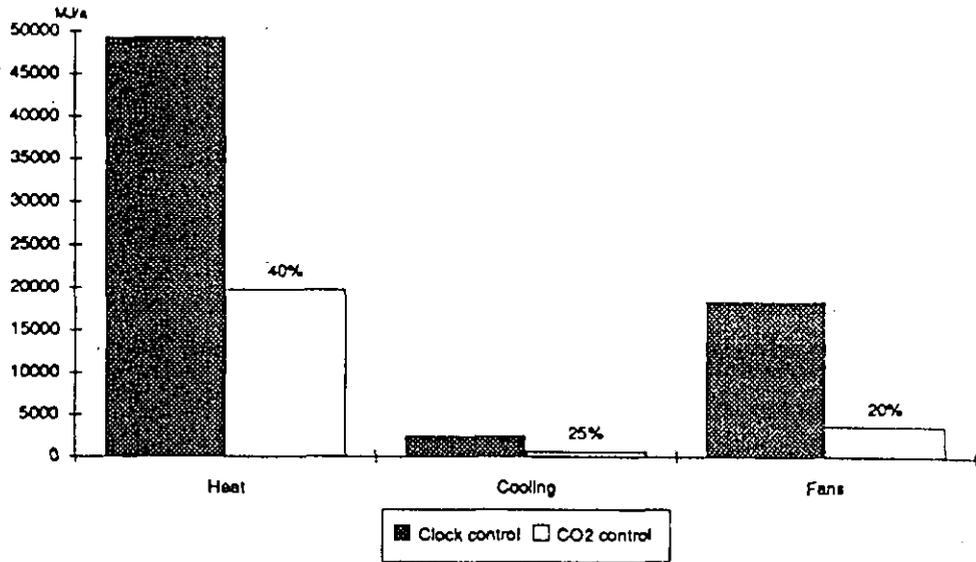


Figure 7: Calculated energy consumption for monitored operating conditions

Since energy consumption is strongly influenced by the choice of threshold values for speed control and occupancy of the room these two parameters have been varied.

Figure 8 shows the calculated heat energy consumption for system operation with demand control compared to system operation with clock control. With known average occupancy of the auditorium and desired comfort level (threshold values) possible energy savings can be estimated.

- 100% occupancy corresponds to the presence of 80 persons between 8:00-12:00 and 13:00-18:00 (720 person hours / day).
- 100% threshold values means that speed 1 is activated at 1'000 ppm, speed 2 is activated at 1'500 ppm. 1'000 ppm is considered to be the comfort level for people entering the room, while 1'500 ppm is considered to be the comfort level for people who are already sitting in the room. Simulations were performed for threshold values at 100%, 80% and 60% of these comfort levels.
- 100% energy consumption is equal to the energy consumption with clock control, the same occupancy and the same max. air flow.

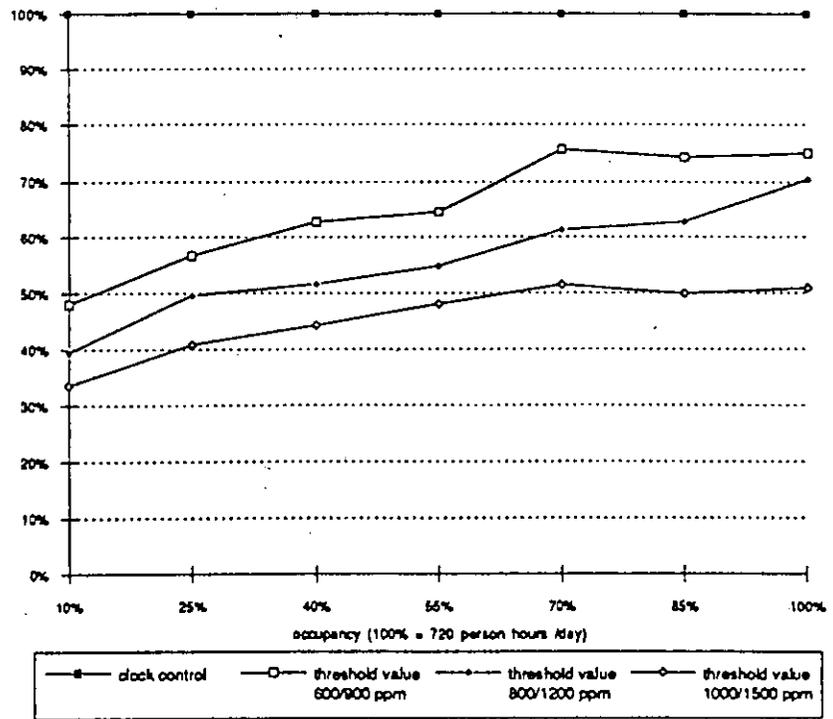


Figure 8: Annual heat energy demand for different control strategies and different occupancy

Similar savings were also achieved for cooling energy and electricity. The choice of threshold values is of great importance for the achieved energy savings and has to be adapted according to the comfort needs of the occupants. High comfort standards lead to lower energy savings.

Age of the air

Age of the air

The local mean age of the air was measured at 10 different locations at different height in the room. Pulse, step-up and decay technique has been used.

Table 3: Local mean age of the air for speed 1
(italics: desk level; bold: close to the ceiling; rest: about 2m over floor level)

	Right	Center	Left	Average
Back	31	25	28	28
Center	26	33 and 32	29	29
Front	28	34	29	30
Average	28	28	29	

The measured ages show no significant difference between the different locations. This means that a good mixing of the room air is achieved and the choice of the sensor location is not very important.

Air change efficiency

Measurements performed in the exhaust duct resulted in an air change efficiency of 66 %.

Conclusions

Demand control of ventilating systems in auditoria based on CO₂ concentration is a very valuable method to reduce energy consumption. The achievable energy savings are strongly dependent upon chosen threshold values and room occupancy but will very often be in the range of 50 % or more.

Before a demand control strategy can be adopted all other contaminant sources except human beings must be reduced to a minimum (e.g. furniture, cleaning fluids, ...). If this is the case an acceptable indoor climate (thermal comfort and indoor air quality) can be maintained.

The occupancy of auditoria is often subject to unpredictable changes. It would imply a great effort from the operating staff to keep track of all these changes. Our experience with this case study is that this continuous adaptation of operating time is seldom done. Demand control can thus reduce personnel costs while avoiding unacceptable air quality in unforeseen occupancy periods.

A combination of CO₂ control and temperature control is recommended for comfort reasons. For heavyweight constructions the influence of this combination will be small.

Today's quality of commercially available sensors is sufficient for a widespread application. A small security margin (e.g. 100 ppm) is recommended when choosing the threshold values.

Publications

- [1]: C.A. Roulet, R. Compagnon, M. Jakob; Planning of Experiments to measure Ventilation Efficiencies; LESO-EPFL; May 1990
- [2]: R. Compagnon, J.-M. Furbringer, M. Jakob, C.A. Roulet; A simple Method to identify the Main Air and Contaminant Paths within a Room; 11th AIVC Conference, Belgirate; September 1990
- [3]: R. Compagnon, M. Jakob, C.A. Roulet; Applications de méthodes à gaz traceurs aux mesures aéroliques dans les bâtiments et les systèmes de ventilation; 6. KWH-Status-Seminar, Zürich; September 1990
- [4]: M. Zamboni, O. Berchtold; The Concentration of Carbon Dioxide in Indoor Air - A TRNSYS Subroutine; Basler & Hofmann; September 1990
- [5]: M. Zamboni; IEA Annex 16 - Bedarfsgeregelte Lüftung in einem Hörsaal; 4. ERL Status-Seminar, Bern; November 1990
- [6]: M. Zamboni, O. Berchtold, Ch. Filleux, J. Fehlmann, F. Drangsholt; Demand Controlled Ventilation - An Application to Auditoria; 12th AIVC Conference, Ottawa; September 1991
- [7]: C.A. Roulet; Measurements of the Age of the Air in an Auditorium; LESO-EPFL; December 1991
- [8]: Bedarfsabhängige Lüftung in einem Hörsaal (final report of the national project); Basler & Hofmann, Zürich; to be published in spring 1992

6 Offices

- 6.1 Demand Controlled Ventilation in a boardroom
(Canada)**
- 6.2 Demand Controlled Ventilation in an Office Building
in Jönköping (Sweden)**
- 6.3 Demand Controlled Ventilation - Full scale tests in
a Conference Room (Sweden)**

6.1 Demand Controlled Ventilation in a boardroom

Project Description

Introduction

Research
Institution:

Public Works Canada

The practicality of using DCV strategies to control ventilation in boardrooms or other similar areas of highly variable occupancy was investigated. costs.

Contact Person:

Bob Davidge,
Public Works Canada,
Sir Charles Tupper
Building,
Riverside Drive,
Ottawa, Ontario,
K1A 0M2,
Canada.

Field trials included ventilation control by: the occupant, timers, infrared movement sensors and carbon dioxide levels.

Temperature and CO2 levels were monitored. In addition, a questionnaire was issued to determine the users' preferences.

The room's users preferred the CO2 controlled ventilation strategy. The manual control system was found to be more cost-effective.

Objectives

The objectives of this study were:

feasibility

a) to determine if DCV systems were feasible in a boardroom,

environment

b) to determine if they resulted in equal or improved environmental control,

occupant preference

c) to determine if the occupant had any preference in control strategy, and

energy savings

d) to determine if energy savings would result.

Boardroom Description

Area: 27.6m²
Volume: 77.3m³
Occupancy: 10

The board room was 4.6 by 6 by 2.8 m high. It had two entrances on opposite long walls and is often used by up to 10 people.

The boardroom was situated within a large office building within an urban area.

Ventilation Strategy

Building:

Constant fresh air:

10 l/s/person
0.66 l/s/m²

The building as a whole has a constant fresh air ventilation rate equivalent to about 10 liters per second per person or 0.66 liters per second per square meter of floor area. The building's ventilation system is energized at least two hours before the first occupants arrive in the morning and runs for at least one hour after the majority of occupants have left.

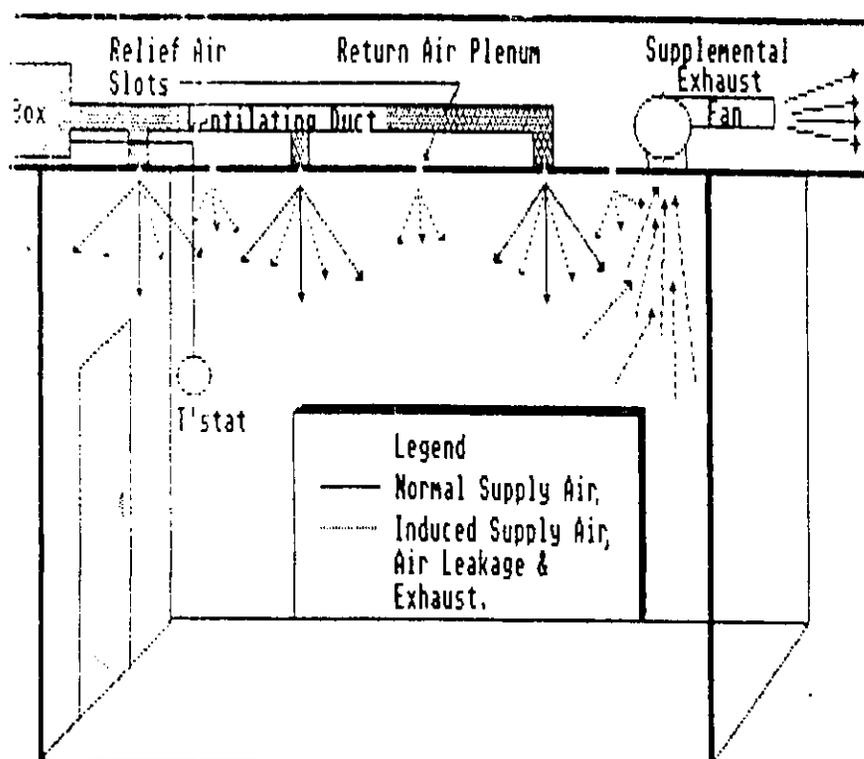
Boardroom:

supplemental exhaust fan

The board room was ventilated at the same rate as the rest of the building by the building's central ventilation system. This provided the boardroom's base ventilation rate.

The boardroom was also equipped with a supplemental exhaust fan. When this fan was on, it tended to induce more air to enter the room from the building's central ventilation system. In addition, air would be drawn from the surrounding area.

The boardroom ventilation system is illustrated in figure 1.



DCV Control

The study examined five control strategies:

Always on

Week 1: The fan was run continuously regardless of switch position.

Off-on switch

Week 2: The on/off switch controlling the supplemental fan was operated by the occupants.

Infra-red sensor

Week 3: The fan was controlled by an infra-red occupancy detector. Occupants could not control the fan although the switch was left in place and the light on the switch would still illuminate as if the occupants were controlling the fan.

CO2 control

Week 4: The fan was controlled by a CO2 sensor. The fan was turned on when the CO2 concentration reached 800 ppm and turned off when the level was reduced to 600 ppm.

Always off

Week 5: Unknown to occupants, the fan intake was rerouted away from the board room. The users could use the fan switch in the normal manner, the fan would be energized, but it would not provide additional ventilation.

Data Collection

Room use,
Occupancy,
Perception,
CO2,
Temperature,
Relative Humidity.

The room usage was monitored through the room booking log. During this period occupants were encouraged to fill out a questionnaire. The fan usage was monitored with a data acquisition system. In addition, CO2 levels were monitored using a Fuji Electric Type ZFP5 Portable Infrared CO2 gas analyzer. A "Stickon" temperature/relative humidity sensor/data recorder was used.

The questionnaire used was developed by PWC to assess building interior environmental performance. In all cases, the performance is rated on a scale of 1 to 5 where 1 is poor and 5 is good. Using the results from over 4,000 responses, norms have been developed for this questionnaire. These are presented

Questionnaire Norms

below:

thermal comfort	2.8
air quality	2.3

Results

CO2 control preferred

Week	Temp. (C)		RH (%)		CO2 ppm Max	Occupant Rating Temp IAQ	
	Max	Min	Max	Min		Temp	IAQ
1	21.5	19.5	39	34.5	1050	3.9	3.8
2	21.5	19.5	34.5	19	1100	2.9	4.0
3	22.5	19.5	25.5	18.5	850	3.2	3.6
4	23	20.5	31	25.5	775	3.0	4.9
5	22	19	31.5	25.5	1350	2.5	3.6

Observations

During week 2, the occupants never turned the fan on, even they knew that they could.

During week 4, higher CO2 levels were achieved, but no questionnaire data was available for these periods.

Maximum CO2 levels were very likely driven more by the CO2 levels in the supply air and the occupancy of the boardroom than by the style of DCV chosen. Unfortunately, this was not tested.

Thermally, the occupants seemed to prefer a well ventilated environment.

The occupants also seemed to prefer the CO2 driven DCV system. It should be cautioned, however, that they may have been responding to the maximum CO2 levels attained. It is equally likely that they may have been responding to the rate of change which occurred when the controller energized the fan at 800ppm CO2.

Energy Efficiency

Off-on switch most efficient

There are two ways that a DCV system in a boardroom may achieve energy efficiency. First, by allowing complaints to be avoided, the building operator will not be pressured into overventilating the rest of the building in order to improve the boardrooms. Secondly, the DCV system will allow the additional ventilation to be supplied to the boardroom only when it is needed.

In a sense, the manually controlled fan was the most energy efficient since it was never turned on and it provided the occupants with the means of improving their ventilation if they so desired.

Savings small

The fan which was always on was the least efficient. The fan only drew 130 watts so the energy penalty would be equivalent to not having a light switch for a small office.

Motion sensor annoying

The motion sensor and the CO2 sensor were somewhere in between with the motion sensor being less effective. It tended to turn the fan on even if the room was only occupied by one or two people. Also, it had the annoying tendency to turn the fan off in the middle of a meeting if little physical action was taking place.

Conclusions

DCV a practical alternative

DCV systems were found to be feasible in a boardroom application.

Environment improved

Thermal control and IAQ were found to be at least equal and sometimes better than the base boardroom system.

CO2 preferred

The occupant seemed to prefer the CO2 control strategy.

Off-on switch recommended

Energy savings would result from the use of a DCV system. It would not currently be cost effective to install anything more complex than a motion sensor or a manual off-on switch. Of these, the off-on switch is recommended.

6.2

Demand controlled ventilation in an office building in Jönköping, Sweden

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Fläkt AB

Project description

The air quality and energy consumption in a conference room with demand controlled ventilation and in two offices with temperature control have been investigated during an 18 month period. Carbon dioxide concentrations, supply air flows and supply and room temperatures were recorded in the test program. Further, the reliability of the control system for the conference room was studied.

Site and location

The office building is located in the town of Jönköping in central Sweden.

Building form

The office building has four storeys and it is about 18 m wide and 60 m long.

Building services

The building is heated by means of water radiators. Both the outer and inner zones of the building are ventilated by means of Variable Air Volume (VAV) systems.

Building or zone investigated

The tests of the demand controlled ventilation system were carried out in a conference room on the second floor. This conference room has a floor area of 33 m² and a volume of 90 m³. It is designed for an occupant load of 15 persons.

Measurements were also made in two offices adjacent to the conference room. Each of these offices has a floor area of about 180 m². The two offices, as well as the conference room, are located in the inner zone of the building.

Local ventilation systems

In the conference room, the ventilation air is supplied by one air diffuser located in the centre of the ceiling and exhausted by exhaust devices located on one of the walls and close to the ceiling, see Figure 1. Both the supply and exhaust air devices for the two offices are located in the ceiling. One central air handling unit supplies the air to the conference room, the two offices and all other rooms on the second floor.

Demand control strategy

Before the tests were started in the conference room, the ventilation system was changed from a conventional temperature-controlled VAV system to a VAV system with combined temperature and carbon dioxide control. In this system, both the carbon dioxide and temperature sensors are connected to the control unit originally supplied with the VAV system, see Figure 2. The sensor controlling the outdoor air flow rate at any given time is dependent on the prevailing occupant load and the temperature conditions in the room.

The carbon dioxide sensor used for control of the supply air flow to the conference room is of type Aritron AROX 425 A and operates on the photo-acoustic principle. This type of sensor is well suited for measuring the carbon dioxide concentration present in indoor air, primarily levels ranging between 300 and 2 000 ppm. It is located in vicinity of one of the exhaust devices in the room. The control system is preset in such a manner that the output signal from the carbon dioxide sensor begins to control the air flow when the concentration of carbon dioxide has exceeded 600 ppm.

For the tests in the two offices (designated Z1 and Z2), no changes of the temperature-controlled VAV system were made, but one carbon dioxide sensor (AROX 425 A) was installed in each office for measurement of the carbon dioxide concentration.

Monitoring

The supply air flow rate, the supply air temperature, the room air temperature and the concentration of carbon dioxide were recorded both in the conference room and in the two offices during an 18 month test period (October 1989 – March 1991). Also, the outdoor air temperature at the inlet of the air handling unit and the temperature of the supply air at the outlet of the air handling unit were recorded. Thus, a total of 14 parameters were recorded.

Measurements of the various parameters were made every minute, but only the mean values of five measurements were normally stored by the data logger, whereas all measured values were stored during one week in the middle of each month. When analysing the results, mainly the values measured during these weeks of more intense recording were utilized. Several separate tests were also made during the test period to check the stability of the sensors and the control systems.

As mentioned above, the carbon dioxide concentrations were measured by means of AROX 425 A sensors. The supply air flows to the conference room and the offices were measured in the terminal units for these premises by means of orifice plates and differential pressure sensors. For measurements of the various air temperatures, thermo-couples were used.

Results

Performance of building and ventilation systems

The system for demand controlled ventilation installed in the conference room is very similar to a ventilation system installed in an auditorium about a year before (1). In both cases the reliability of the systems has turned out to be very good. Also the stability of the carbon dioxide and air flow sensors can be regarded as satisfactory (see below).

In Figure 3, the measured values of room temperature, carbon dioxide concentration and supply air flow are shown for a working day during which the occupant load in the conference room varied widely. The temperature of the supply air to the room was maintained virtually constant throughout at around 17.5 °C, while the outdoor temperature varied between 7 and 11 °C during the period when the ventilation system was in operation, i.e. between 06.30 and 18.00 hours.

As shown in Figure 3, the rate of air flow supplied to the room increased substantially as soon as the carbon dioxide concentration exceeded 600 ppm. As a result, the maximum carbon dioxide concentration is restricted to around 800 ppm, which is only about 450 ppm higher than the concentration in outdoor air. At maximum occupant load in the room, the supply air flow is about 210 l/s. However, the mean value of the supply air flow during the 11.5 hours of operation of the ventilation system was only 60 l/s.

If a Constant Air Volume (CAV) system had been selected instead of a VAV system for ventilating the conference room, it would probably have been rated for a supply air flow of 10 l/s per person, i.e. a total of 150 l/s. The average energy consumption for heating the ventilation air would thus have been higher. In addition, the carbon dioxide concentration at the highest

occupant load would have been higher, since the supply air flow to the room would have been restricted to 150 l/s, which is only 71 % of the flow supplied by the VAV system. A VAV system controlled by the carbon dioxide concentration in the indoor air can thus be beneficial both to energy consumption and to the quality of the indoor air.

To maintain a good performance of the control system, it is important that the carbon dioxide sensor is stable and reliable. The stability of the carbon dioxide sensor over the whole 18 month measuring period was investigated by measuring the carbon dioxide concentration in the conference room during weekends, when the concentration should be close to the value prevailing in the outdoor air. In Figure 4, the average values of the concentration measured on Sunday mornings (average values for an 8 hour period) are given.

If the carbon dioxide concentration in the outdoor air is regarded as constant during the measuring period, this investigation indicates that the sensitivity decrease of the sensor corresponds to about 50 ppm at a background level of 350 ppm. Also the sensors used for monitoring in the two offices show the same tendencies, i.e. a decrease in sensitivity corresponding to 40 – 60 ppm. When the sensitivity of the sensor in the conference room was checked with a newly calibrated instrument, similar results were obtained also at higher carbon dioxide concentrations.

A further prerequisite for a good performance of a demand controlled VAV system is that the sensor utilized for measuring the supply air flow is stable. Calibrations of the flow sensors in the conference room and in the two offices indicate that the sensibility changes are small after 18 months of operation. Typically, the deviations from the original flow values are less than 5 % in most of the flow range. Similar results have also been obtained at long-term tests in an auditorium, extending up to 3 years (4).

Indoor air climate and occupant response

The carbon dioxide concentration in the conference room was relatively low during the whole measuring period. Usually this means that also the intensity of body odour should be low, as well as the percentage of persons dissatisfied with the indoor air quality (2). As the room temperature has been rather stable over the whole period, in most cases between 21 and 24 °C, there should be few complaints also about the thermal comfort in the room, which is in accordance with the experience of the operating staff of the building.

It may be interesting to study how well the measured carbon dioxide concentration agrees with that calculated at a certain occupancy level. An example for the case that 14 persons occupy the

conference room is given in Figure 5. After about 3 hours, both the carbon dioxide level and the supply air flow were rather stable at about 840 ppm and 145 l/s, respectively.

The calculated carbon dioxide concentration for an air flow of 145 l/s is $350 + 14 \cdot 5\,000/145 = 833$ ppm, which is in agreement with the measured value. It is then assumed that the concentration in the outdoor air is 350 ppm and that an adult person produces 18 l/h of carbon dioxide at an activity level of 1.2 met units (3).

To investigate the air quality in the conference room, air samples were also taken by means of Tenax tubes and the content of Total Volatile Organic Compounds (TVOC) was determined with a flame ionization detector calibrated against hexane. A value of the TVOC content of $0,19 \text{ mg/m}^3$ was found in this way. In an office building which is about 4 years old, as in this case, such a low TVOC content can be regarded as typical. Most of the substances identified (by a mass spectrometer) were hydrocarbons common in modern buildings.

Energy performance

The occupant load in the conference room has been varying considerably during the 18 test months. In Table 1, the average supply air flow measured during working hours (06.30 – 18.00) are given for the test periods in each month. For determination of the average values, only the flow values measured during weeks with intense measurements were normally utilized. According to Table 1, the average air flows are much lower than if the room had been ventilated by means of a CAV system. Such a system would probably have been rated for 150 l/s, as mentioned above.

The power demand and the energy consumption for heating and cooling of the ventilation air to the conference room can also be calculated from the measured values. For the intense measuring periods, the power demand and the energy consumption during working hours have been calculated with knowledge of the air flow and the difference between the outdoor air temperature and the supply air temperature at the outlet from the air handling unit. In Table 1, the calculated average values are given of the power demand and of the relative energy consumption, compared to a ventilation system with a constant air flow of 150 l/s. It should be noted that a considerable part of the energy used in this building for heating of the supply air is recovered from the exhaust air by a liquid-coupled heat recovery system and a heat pump.

In the two offices the supply air flow rates, the supply and room air temperatures and the carbon dioxide concentrations were recorded in the same way as in the conference room. However, the carbon dioxide sensors were only used for monitoring – not for control of the supply air flow to

the offices. During the whole test, the occupant loads in both offices have been much lower than expected when the measurement program started. Therefore, the carbon dioxide concentrations have been low, usually below 600 ppm, during most of the working hours. Also, the cooling demands have been lower than expected.

The measured values of the room temperature, the carbon dioxide concentration and the supply air flow in one of the offices (Z1) are shown in Figure 6 for a day in February 1990 when the outdoor temperature was about + 9 °C. According to the measurements during the test period, October 1989 – March 1991, it seems possible to decrease the supply air flow to the offices during the whole year at the present occupant loads. This means that the energy consumption for heating, cooling and distribution of the ventilation air can be reduced.

Costs

The conference room was originally equipped with a temperature-controlled VAV system. As pointed out above, such a system can very simply be modified to a system that works as a combined temperature and air quality controlled system. Only an air quality sensor, in this case a carbon dioxide sensor, has to be added to the control system, and no changes in the ventilation system or in the building are necessary. It is therefore possible to limit the costs for modifying the temperature-controlled system to a demand controlled system to about 1 000 – 2 000 USD.

Conclusions and recommendations

The measurement program in the conference room has demonstrated that demand controlled ventilation based on carbon dioxide control can provide major benefits in premises in which the occupant load varies unpredictably.

It is also obvious that temperature-controlled VAV ventilation systems easily can be supplemented with carbon dioxide control.

According to the tests, which extend up to 18 months, the reliability of the control system seems to be very good. However, it is recommended that the carbon dioxide sensor of the type in question should be recalibrated every second year. On the other hand, the air flow sensor utilized for measuring the supply air flow does not seem to need recalibration, even after a period of 3 years of operation.

References

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2. Iwashita, G., et al. Field study on indoor air quality of body odor in classrooms. *Proc. of the Second World Congress, CLIMA 2000*, Aug. 27 - Sept. 1, 1989, Sarajevo.
3. ASHRAE Standard 62 - 1989, Ventilation for acceptable indoor air quality. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1989.
4. Strindehag, O., Norell, L., Long-term experience of demand controlled ventilation systems. *Proc. of the conf. Healthy Buildings - IAQ 91*, Sept. 4 - 8, 1991, Washington.

Test period	Supply air flow (l/s)	Power demand (kW)	Rel. energy cons. (%)
Oct 89	53.5	0.21	35.8
Nov 89	39.3	0.50	26.7
Dec 89	179.9*	4.51*	120.4*
Jan 90	32.6	0.38	22.0
Feb 90	71.1	0.66	46.7
Mar 90	62.1	0.59	41.7
Apr 90	63.1	0.58	39.0
May 90	42.5	0.21	27.2
Jun 90	46.0	0.16	28.0
Jul 90	40.0	0.07	28.3
Aug 90	132.2	0.35	86.7
Sep 90	47.4	0.25	29.4
Oct 90	51.9	0.27	33.6
Nov 90	46.8	0.53	30.6
Dec 90	41.9	0.83	27.9
Jan 91	49.7	1.16	33.0
Feb 91	40.8	1.09	27.3
Mar 91	21.3	0.43	14.2

Table 1. Measured average values of the supply air flow, power demand and relative energy consumption in the conference room during working hours. When calculating the relative energy consumption for heating and cooling of the supply air, the measured consumption is compared with the estimated consumption for a ventilation system with a constant air flow of 150 l/s.

* The high values in December 1989 are due to an incorrect thermostat setting in the control system for the air handling unit.

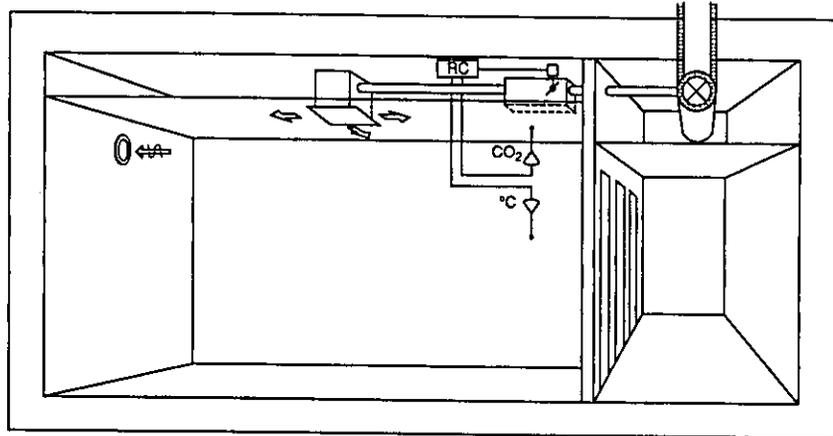


Figure 1. Principle design of the VAV system with combined carbon dioxide and temperature control for the conference room.

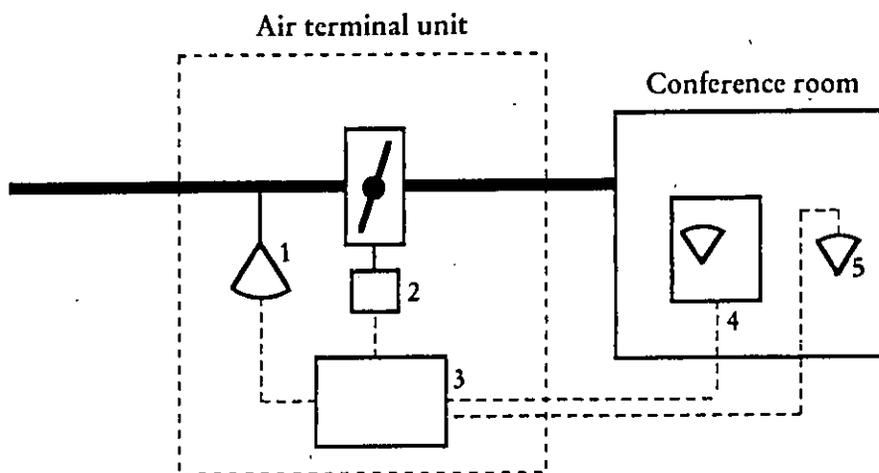


Figure 2. Diagrammatic arrangement of the control system for the conference room: 1) air flow sensor, 2) damper, 3) control unit, 4) room temperature sensor and set point selector, 5) carbon dioxide sensor.

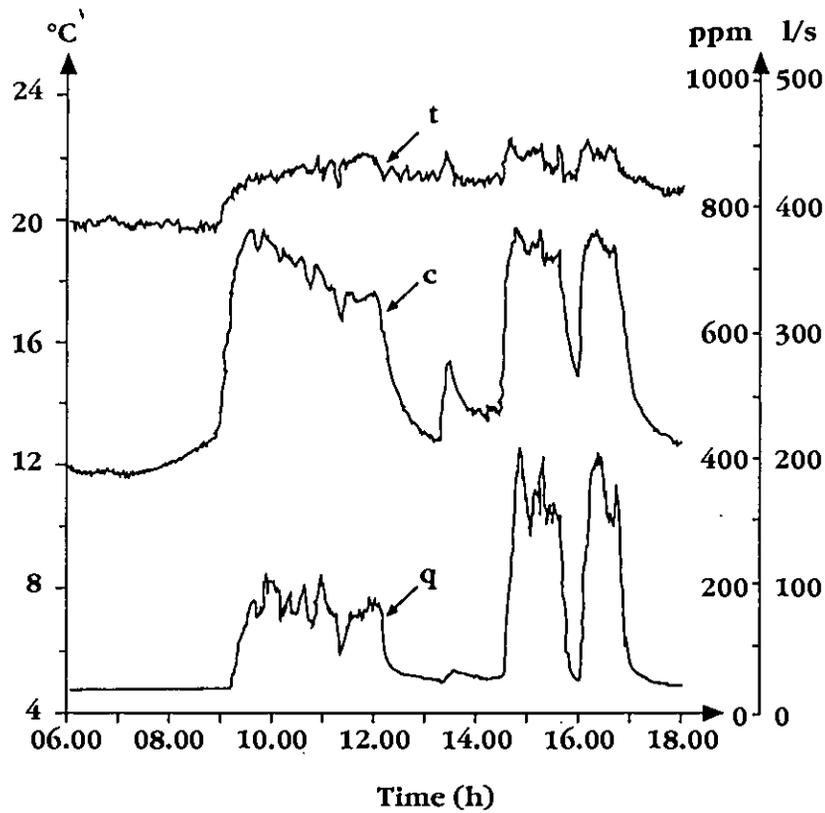


Figure 3. Measured values of room temperature (t), carbon dioxide concentration (c) and supply air flow (q) in the conference room for a working day during which the occupant load varied widely.

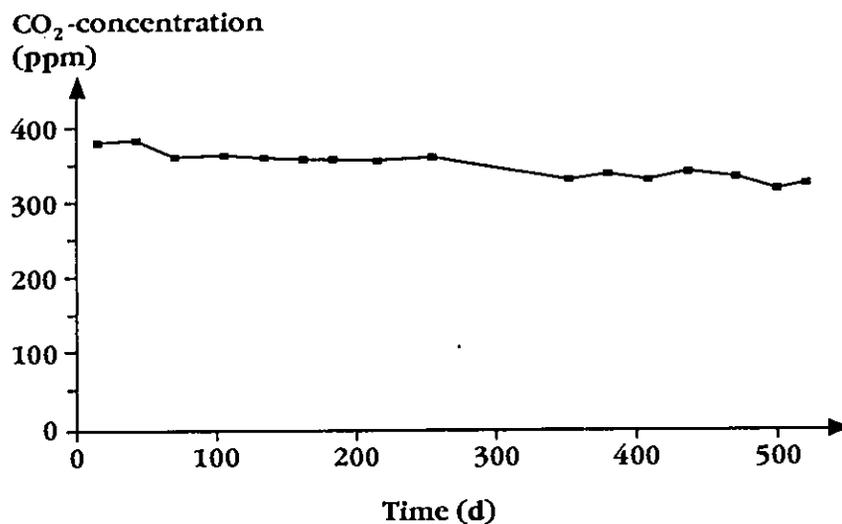


Figure 4. Background carbon dioxide concentrations, according to measurements with the sensor used for control of the supply air flow to the conference room. The values given are average values for an 8 hour period during Sunday mornings when the room was unoccupied.

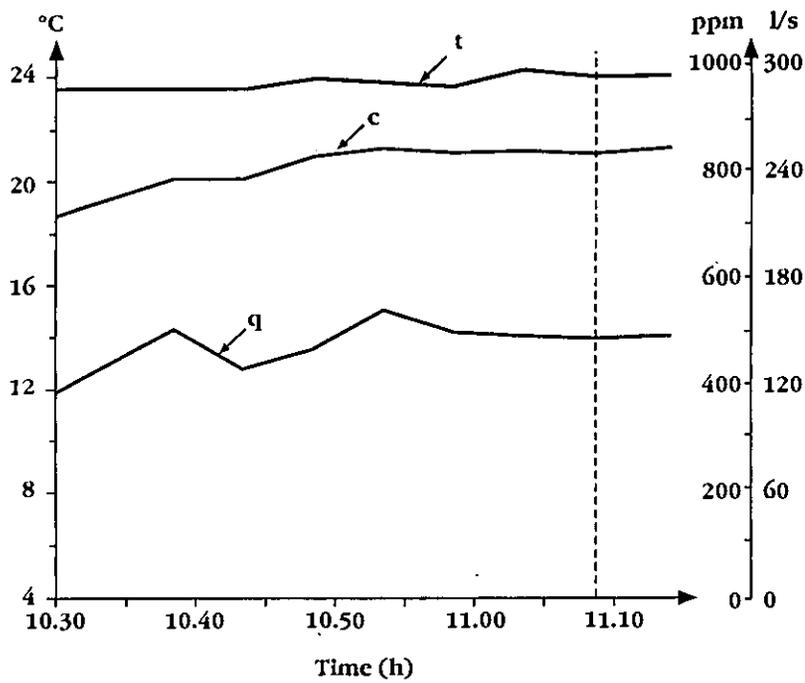


Figure 5. Measured values of room temperature (t), carbon dioxide concentration (c) and supply air flow (q) when 14 persons occupied the conference room.

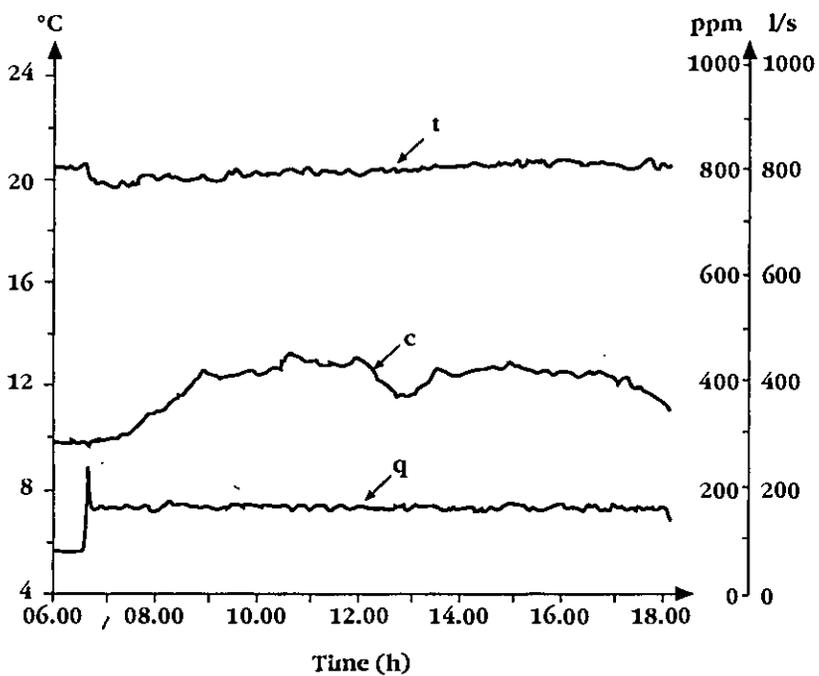


Figure 6. Measured values of room temperature (t), carbon dioxide concentration (c) and supply air flow (q) in one of the offices ventilated by a temperature-controlled VAV system.

6.3 DEMAND CONTROLLED VENTILATION - Full scale tests in a conference room

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Introduction

A conference room has been converted to temperature and carbon dioxide controlled ventilation. It can be considered as quite representative for a lot of smaller conference rooms. The room has been in use for about eight years. All furniture and other inventories are of about the same age. The room has no boundaries in direct contact with the outdoor environment and no windows. This means that there should not be any large exchange of energy with the surrounding environment. Because no daylight is available, there is a lot of electric lighting installed. The energy consumption of the lighting can vary from 160 to 1200 W, which is about equal to the sensible heat from 2-16 persons. The room has a mixed ventilation system designed for a maximum of about 20 persons. A new HVAC-system, separated from the rest of the building, was installed during 1990. The system is equipped with devices for heating, cooling and heat recovery. It has been especially designed to give a larger than usual span between maximum and minimum air flow rate. To regulate the air flow rate, the system is equipped with sensors for both temperature and CO₂. It is normally temperature controlled, but when the CO₂ concentration exceeds 800 ppm the system is CO₂ controlled.

Characteristic measures for the room:

Area: 43 m²
Volume: 115 m³
Air flow span: 170-1000 m³/h (1,5 - 8,7 ach)
 η_v : 80-100% (900 m³/h), 140-160% (300 m³/h)
(inlet temperature 5 °C below room temperature)

The room has also been acting as a reference field test installation for a simultaneously ongoing test program for DCV-sensors. CO₂-sensors, RH-sensors and VOC-sensors have therefore been installed in a chamber connected to the exhaust air duct. It was planned to control the system with some of these sensors as well, but due to problems in getting a stable base level to regulate against these plans had to be abandoned. The RH- and CO₂-sensors have been calibrated in the beginning and at the end of the project. The VOC-sensors have only been checked functionally. The latter all gave an output signal between 0 and 10 volts, which we in the following will refer to as an indicated AQ of 0-100%.

The main purpose has been to evaluate the ability of a DCV-system to maintain a good indoor AQ. Measurements have only been made on the temperature and CO₂ controlled system, but from simultaneous measurements on sensors for RH and VOC, conclusions have also been drawn as to how suitable these sensors are for the purpose of DCV.

Calculations on energy savings are very much dependent on other system components than those of the DCV itself and also how often the system is in use. We have chosen to calculate the mean consumption of purchased energy for the actual system during two test periods, assuming two different outdoor temperatures and three different temperature efficiencies for the heat exchanger. Assuming the loads during the actual tests to be the same, we have also calculated the consumption of purchased energy for several simulated system solutions.

Full scale tests

The conference room is not used very frequently. Most of the time it is empty and when in use, very seldom more than 10 persons are present. Because of this the threshold level for CO₂-control is rarely exceeded. Instead of making long term measurements we have therefore concentrated our measurements to shorter periods of 6-12 hours. A test programme consisting of 14 full scale tests has been carried out. The tests are tabulated together with short comments in table 1 below.

Table1; Full scale tests carried out in the conference room.

test No	date	comments
1	1991-03-05	lighting is the only load, chosen temperature is varied
2	1991-03-12	low load (two meetings with 4-5 persons)
3	1991-03-12	medium load (9 persons), fixed air flow rate (650 m ³ /h)
4	1991-04-07	Smoke test (6-7 persons), 3 fixed air flow rates (low - high)
5	1991-04-09	lighting is the only load, 3 fixed air flow rates (low - high)
6	1991-04-16	temperature load simulated with a electric heater (1400 W)
7	1991-04-18	low to medium load (3-8 persons)
8	1991-04-18	medium load (8-10 persons), CO ₂ -control nearly activated
9	1991-04-21	electric heater and lighting (2400 W)
10	1991-05-02	2 meetings with 24 persons (lunch break between)
11	1991-05-03	2 meetings with 24 persons (lunch break between)
12	1991-05-13	meeting with 14-18 persons + meeting with 7-13 persons
13	1991-06-15	CO ₂ -declination, fixed high air flow rate
14	1991-06-16	CO ₂ -declination, fixed low air flow rate

Test No.11, that is shown in the figure 1 on the next page, is a good example of how the system is working . When the measurement starts the room is empty, but people have been in the room for a very short while about half an hour before. This can be seen on the CO₂ concentration which is a little bit higher than the background level (335 ppm according to the sensor) and slowly declining. Half the lighting (600W) is also turned on. After 1 hour and 30 minutes the full lighting (1200 W) is turned on and 24 persons enter the room attending a meeting for 1 hour and 45 minutes. Then there is a lunch break for 1 hour, followed by a second meeting with the same people, going on for 1 hour and 15 minutes. The room is then left empty for the rest of the day. 45 minutes after the second meeting, the lighting is turned down from full to half. The above described load conditions are also shown in figure 3.2 below (note 1). Both the air quality and the thermal comfort were by the persons present considered as good.

For details concerning measurements on humidity- and VOC-sensors we refer to the main report from this study.

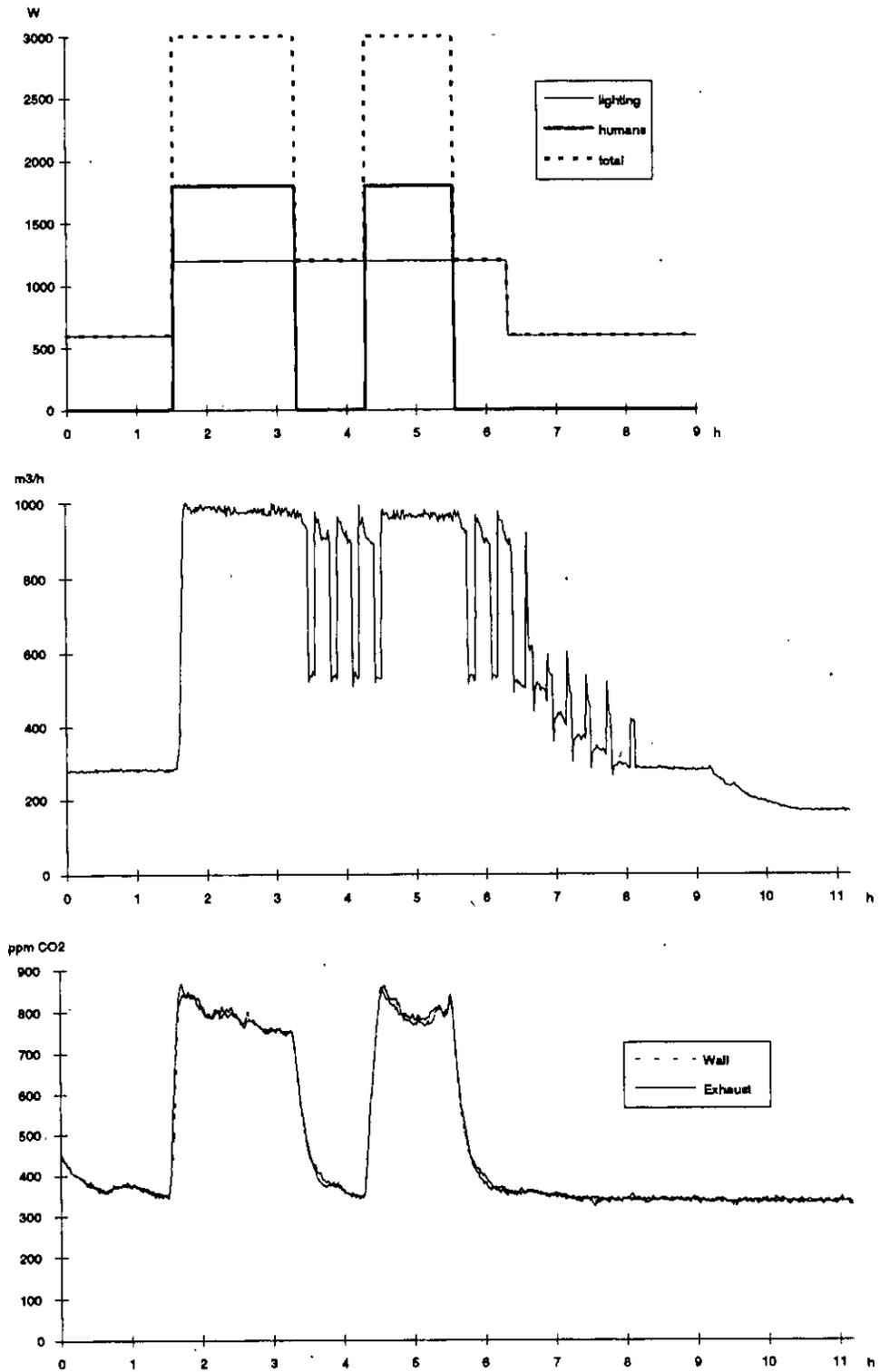


Figure 1; Load, air flow rate and CO₂-concentration during test No 11.

Calculations

Knowing the measured values of air flow rate, the inlet and exhaust air temperature and how the loads have varied in time, calculations have been made for the mean purchased power consumption during the actual tests No 11 and 12. The mean purchased power consumption for the actual system when nobody is in the room, but with or without lighting, has also been calculated. Some assumptions and simplifications have been made. These are the use of an ideal air to air heat exchanger with three different temperature efficiencies, two different and time independent outdoor air temperatures, a constant heat load per person etc.

To make conclusions about how good (or bad) the calculated values for the actual system are, calculations have also been made for several simulated ideal systems, from a simple CAV system to a sophisticated VAV system with combined temperature, CO₂ and occupancy sensor control.

To be able to estimate how the CO₂ concentration would vary for these simulated systems, a simulation function for the CO₂ concentration assuming a constant CO₂ production per person is also introduced.

The values calculated for the case when nobody is in the room are steady state values. All other values of mean purchased power consumption are calculated for nine hours and with the room in use either as in test No 11 or as in test No 12.

In table 2 below the mean purchased energy consumption for the actual system when no person is present, but with or without lighting, has been calculated. As mentioned before, the lighting is such a large heat source that it on it's own will cause a considerable increase in air flow rate.

Table 2; Actual system when people are not present.

η_t (%)	0	0	60	60	80	80	Air flow
t_{outdoor} (°C)	0	10	0	10	0	10	rate (m ³ /h)
$P_{\text{pur, mean}}$ (kW), no lighting	1,38	0,74	0,55	0,30	0,28	0,15	191
$P_{\text{pur, mean}}$ (kW), 0,6 kW lighting	2,04	1,10	0,81	0,55	0,55	0,55	281
$P_{\text{pur, mean}}$ (kW), 1,2 kW lighting	3,08	1,66	1,23	0,95	0,95	0,95	420

It is obvious that the lighting in this case gives a large contribution to the total purchased power consumption, especially when there is no heat recovery ($\eta_t = 0\%$). On the other hand, even when one has a heat exchanger with a very high temperature efficiency only a little part of the energy consumed by the lighting can be transmitted to the surrounding environment. The rest will be lost in the ventilation system.

During test No 11 the mean energy consumption by the lighting was 510 W and during test No 12 it was 502 W. In both cases this corresponds very well with a minimum possible purchased power consumption of about 0,5 kW due to the lighting.

In table 3 below, the mean purchased power consumption for the actual system during tests No 11 have been calculated assuming three different temperature efficiencies for the heat exchanger and two different outdoor air temperatures. Below the table some characteristic values, that are independent of the above mentioned variables, are also given. These are the maximum and mean exhaust air temperature, the minimum inlet air temperature, the maximum, mean and minimum air flow rates and the maximum, mean and minimum CO₂ concentrations. (The values for test No 12 are similar).

Table 3; Actual system, test No 11.

η_t (%)	0	0	60	60	80	80
t_{outdoor} (°C)	0	10	0	10	0	10
$P_{\text{pur, mean}}$ (kW)	4,02	1,89	1,25	0,61	0,59	0,51

$t_{\text{exhaust max}} = 23,0 \text{ °C}$ $t_{\text{exhaust mean}} = 21,6 \text{ °C}$ $t_{\text{inlet min}} = 15,2 \text{ °C}$

$q_{\text{max}} = 1002 \text{ m}^3/\text{h}$ $q_{\text{mean}} = 638 \text{ m}^3/\text{h}$ $q_{\text{min}} = 265 \text{ m}^3/\text{h}$

$C_{\text{max}} = 868 \text{ ppm}$ $C_{\text{mean}} = 510 \text{ ppm}$ $C_{\text{min}} = 321 \text{ ppm}$

The calculations for test No 11 (actual and simulated systems) can be summarized by diagrams figure 2 below, where the mean purchased power consumption (at 0 °C outdoor air temperature) for the different system solutions has been plotted as a function of the temperature efficiency of the heatexchanger.

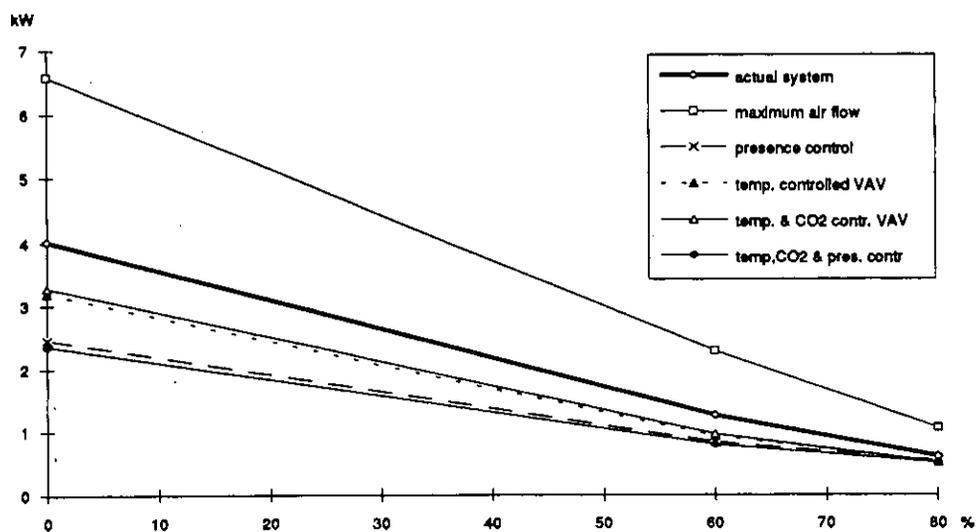


Figure 2; Mean purchased power consumption (at 0 °C) as a function of the temperature efficiency, test No 11.

Here one can see that only the simplest system has a higher mean purchased power consumption than the actual system. The actual system is, on the other hand, closer to best system than to the worst. However the results indicate that the actual system could be further improved.

In test No 11 the relatively simple occupancy controlled system is very close to the best (and most sophisticated) system. This is because in this case we have only two levels of occupancy, either very high or none at all, and in both cases the air flow rate given by the occupancy control is close to the optimum. In test No 12 there are instead four different levels of occupancy, making the two-speed occupancy controlled system move further away from the optimum.

Having no heat recovery at all there are quite large differences (2,2-6,8 kW) between the systems. On the other hand, having a heat exchanger with a high temperature efficiency (80%) all systems but the simplest converge almost to the same low level (0,5-0,6 kW). The simplest system would use about twice this figure (1,0-1,1 kW), but this is still only half of what the most sophisticated system would use if one had no heat recovery at all. Our conclusion is therefore that the most effective way to save a lot of thermal energy is to invest in a heat exchanger with a high temperature efficiency and that a highly sophisticated control system would then be superfluous. On the other hand, a well designed DCV-system can save a lot of electric energy input to the fans.

Conclusions

A simple system with only temperature controlled air flow rate can in many cases be sufficient to achieve a well functioning demand controlled ventilation. Especially if there are large heat loads in addition to the sensible heat produced by the persons.

The carbon dioxide control works very well and the output from the sensor has a very distinct and good correlation with the number of persons present in the room. The measured background/outdoor level is quite stable and the sensors do not show any great sensitivity to changes in humidity or to any other contamination in the air. The carbon dioxide control is only activated for shorter periods of time in order to keep down peak values of the carbon dioxide concentration. Most of the time the system is only temperature controlled, due to large heat loads from the lighting.

Calculations of the mean purchased power consumption indicates that the actual system could be further improved. In some cases a very simple system, with maximum air flow rate when people are present and minimum when not, can be superior to the actual system. Another conclusion from the calculations is that if one has an air to air heat exchanger with a high temperature efficiency, then the consumption of purchased energy gets very low and quite independent of which control system one uses.

The relative humidity sensors are quite accurate and seem to be very suitable for humidity control, but as their output is only slightly increased even for a large number of persons present and as the background/outdoor level can vary substantially and rapidly, they do not seem suitable for this type of demand controlled ventilation.

The sensors for volatile organic compounds are quite sensitive to the presence of persons, tobacco smoke and other contaminations produced in the room, but they are also very sensitive to changes in temperature/humidity and to changes in the contamination level in the outdoor air. Different sensors also have quite different outputs for the same air. The sensors seem to have a potential for demand controlled ventilation, especially when the main load is something else than heat sources and human related production of carbon dioxide, but further development of sensors and/or control system software is needed.

Appendix: Annex 18 National Representatives

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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.

This report contains summaries of 15 case studies which have been carried out in the participating countries. The case studies have been analysed both in national groups and in the international group.

DCV has been applied on various building types and different strategies have been used. In a laboratory in Sweden the sensor locations have been studied when used in mixing and displacement ventilation.

DCV in dwellings has been tested in Italy, Belgium, The Netherlands, Germany, and Canada. The sensors used are indicating Relative Humidity, CO₂, and Air Quality.

In offices DCV-systems for CO₂- and time control have been applied on board-rooms and meeting rooms. Tests have been carried out in Canada and Sweden.

Auditoriums have been tested in Norway and Switzerland. They showed the best savings potential in tests on CO₂- and time control.

A DCV system with presence control has been applied on a school in Sweden. Both mixing and displacement ventilation principles were tested.

All these parallel studies give a great number of good examples on the implementation of DCV systems. It has been shown that they work well, save energy, and offer an acceptable air quality.



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