AIR MOVEMENT & VENTILATION CONTROL WITHIN BUILDINGS

12th AIVC Conference, Ottawa, Canada
24-27 September, 1991

PAPER 9

DEMAND CONTROLLED VENTILATION - AN APPLICATION TO AUDITORIA

M. Zamboni, O. Berchtold, Ch. Filleux, J. Fehlmann*),
F. Drangsholt**)

Basler & Hofmann, Consulting Engineers, Forchstrasse 395,
8029 Zürich (CH)

*) Dept. of Hygiene and Applied Physiology, Fed. Institute of Technology, Zürich (CH)

**) SINTEF, VVS Divisjion, Trondheim (N)

1. SYNOPSIS

This paper is based on field measurements in auditoria which were carried out in Norway and in Switzerland. In both cases carbon dioxide (CO_2) was chosen as the relevant indicator to establish ventilation demand.

Investigations in Norway focus on the aspects of air flow patterns, ventilation efficiency and air quality. Intensive monitoring and numerical calculations with the computer code KAMELEON were performed.

The Swiss project puts more emphasis on impacts of demand control on energy consumtion and occupant response. The results of the field measurements, of the questioning of occupants as well as of simulations which were carried out with the simulation code TRNSYS are presented.

Results show that demand control with CO_2 as indicator for ventilating demand can maintain an acceptable indoor climate while allowing substantial energy savings.

These investigations were conducted as part of the IEA research programme "Annex 18: Demand Controlled Ventilating Systems".

2. INTRODUCTION

The principle aim of demand control of ventilating systems is to achieve energy savings by reducing operation time und air flow rate of the ventilating system without indangering an acceptable indoor climate. Ventilation demand can be caused by heat sources (e.g. persons, sun) or different pollutant sources within or outside the room.

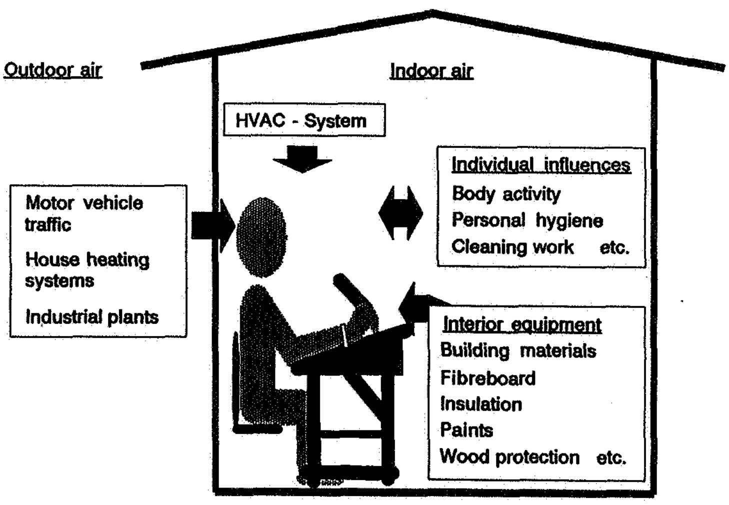

Fig. 1: Different sources of pollutants in auditoria

In auditoria, like in any other building, it is very important to eliminate or at least reduce pollutants caused by the interior equipment or the ventilating system.
Auditoria differ from other rooms in the way that all the remaining main influences on indoor climate are directly caused by the number of occupants. Usually auditoria are non-smoking areas.

Therefore only "pollutants" that are directly caused by the presence of people and correlate well with the perceived indoor climate can be used for demand control in auditoria.

The concentration of carbon dioxide (CO_2) in the room air is a good indicator for ventilation demand in auditoria since the CO_2 concentration in the room air correlates well with perceived indoor air quality and the occupants are the only relevant source of CO_2 ($C_{outside}$ = 360 ppm; C_{breath} = 40'000 ppm).

Other indicators could also be used to establish ventilation demand but have serious disadvantages:
- *presence, motion*: does not indicate the number of occupants, therefore the needed air flow can not be established; could be used to cut off superfluous operating time
- *humidity*: wide range of comfort inside which only a weak correlation with perceived indoor climate can be observed
- *temperature*: important to be held within certain limits; dynamic behavior (and thus correlation with perceived air quality) is strongly dependent on building construction; can be combined with CO_2 control
- *volatile organic compounds*: still uncertainties about which substances can/should be measured; poorly defined comfort range; better suited for smoking areas

3. CASE STUDY IN TRONDHEIM

3.1 Object description

The auditorium EL5 is located at the University of Trondheim, NTH. It has a floor area of 340 m^2 and a seating capacity of 320 persons. The room volume is about 1'600 m^3. The height-difference between the seats in front of the room and those at the back is about 3 m.

Back and side walls are made of light concrete. Front wall, floor and intermediate ceiling are made of wood. Since the auditorium is placed within the building and doesn't have any direct contact to the outside it has no transmission losses.

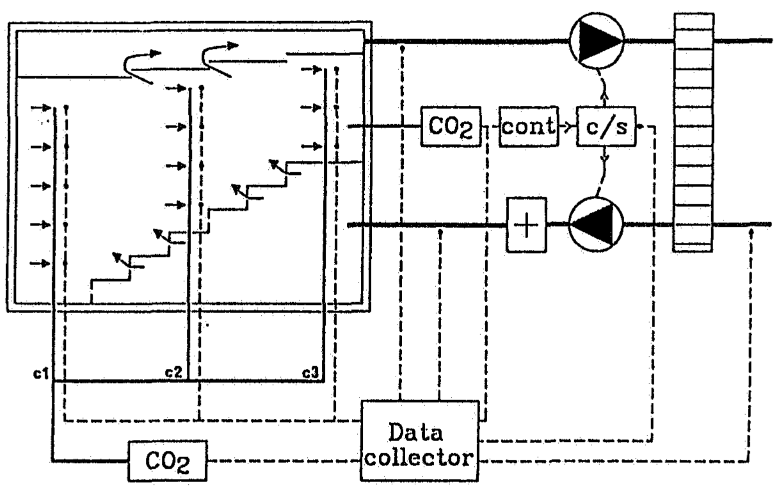

Fig. 2: Sketch of the ventilating system with placement of sensors (column 1 - column 3) and data aquisition

The auditorium is ventilated by displacement ventilation with inlets under the seats and outlets in the ceiling. For this field study rpm controlled fans were installed. The air flow may vary between 0 and 10'000 m^3/h. The air flow can be adjusted manually or controlled with a sensor.

3.2 Monitoring programme

Investigated control strategies

a) Time control
Before activating the demand control CO_2 measurements were carried out with constant air flow. The air flow was set to 10'000 m^3/h which is equivalent to an air change rate of 6.25 h^{-1} or 30 m^3/h and person.

b) Demand control according to CO_2 concentration
During operation with demand control a basic ventilation rate of about 2'600 m^3/h was adopted. Dependant on CO_2 production due to occupancy the air flow could be raised to a maximum of 10'000 m^3/h. The set point for CO_2 concentration was set to 1'000 ppm and the controlling CO_2 sensor was placed on column 2 (mid-height of the room) at 1.1 m from the floor level.

Monitoring periods

Monitoring and tests have been carried out at different person loads during selected periods through 1990 and winter 1990/91.

Monitored parameters

The data aquisition system was built around a micro computer which handles a mechanical multiplexer with 30 channels for gas samples, 30 analog inputs for humidity, temperature and gas sensors, 30 channels for thermocouples and 16 channels for sensors with pulse output (velocity).

Inside the auditorium the sensors were placed on three measuring columns which were situated on three different levels (see also Fig. 2). Three measuring spots located at the side walls cover the boundary conditions. Every measuring spot includes sensors for CO_2, temperature and relative humidity.

column	channel	location in cm above floor level
column 1	1-8	10, 60, 110, 170, 250, 350, 450, 550
column 2	9-15	10, 60, 110, 170, 250, 350, 450
column 3	16-19	10, 60, 110, 170
	20-22	left wall
	24	outside conditions
	25	supply air
	26	exhaust air

Tab. 1: Location of sensors

With this set up of the measuring equipment temperature, relative humidity and CO_2 concentration cannot be measured simultaneously.

3.3 Results

Performance of the ventilating system

The capability to bring fresh air to and to remove contaminants from the occupied zone is of great importance when evaluating the performance of the ventilating system. Tracer gas technique was used to establish ventilation effectiveness ($<\varepsilon_v>$), local ventilation indexes (ε_v), air change efficiency ($<\varepsilon_a>$) and local air change indexes (ε_i).
Ventilation efficiency and local ventilation index were measured using CO_2 dissipation from the occupants as tracer gas. Air change efficiency and local air change indexes were measured by step injection of tracer gas (N_2O) into the supply air duct.

Ventilation rate	5'000 m^3/h			12'000 m^3/h		
Nr. of occupants	0	130	220	0	150	240
$<\varepsilon_a>$	0.63	0.65	0.63	0.62	0.57	0.59
ε_i at column 1/1.1m	1.77	0.83	1.01	1.18	0.96	0.88
ε_i at column 1/1.7m	0.86	0.69	0.84	1.13	1.00	0.85
ε_i at column 2/1.1m	1.61	1.00	1.41	1.65	1.54	1.28
ε_i at column 2/1.7m	1.47	0.85	1.09	1.64	1.22	1.29
ε_i at column 3/1.1m	0.63	0.67	0.94	0.74	1.02	0.85
ε_i at column 3/1.7m	0.69	0.91	1.06	0.92	1.42	1.01

Tab. 2: Air change efficiency $<\varepsilon_a>$ and local air change indexes (ε_i) at 1.1 m and 1.7 m from floor level

The results for the air change efficiency show that the air distribution is better than the ideal value for complete mixing ($<\varepsilon_a>=0.5$). It is difficult to get a trend from the measurements of local air change indexes since these results are influenced by by the seats chosen by the occupants even if the number of persons is the same.

Indoor climate

As expected for a displacement ventilation system the highest CO_2 concentrations were registered at the top of the auditorium (column 3). Figure 3 shows that while the system was operated based on demand control CO_2 concentrations between 1'000 and 1'500 ppm were registered in the middle of the auditorium (column 2).

The comparison of the values for temperature, relative humidity and CO_2 which were monitored under similar operating conditions shows that also temperature and humidity can be used as an indicator for occupancy. But since changes are quite small compared to the comfort range these parameters are not equally suited for demand control as CO_2.

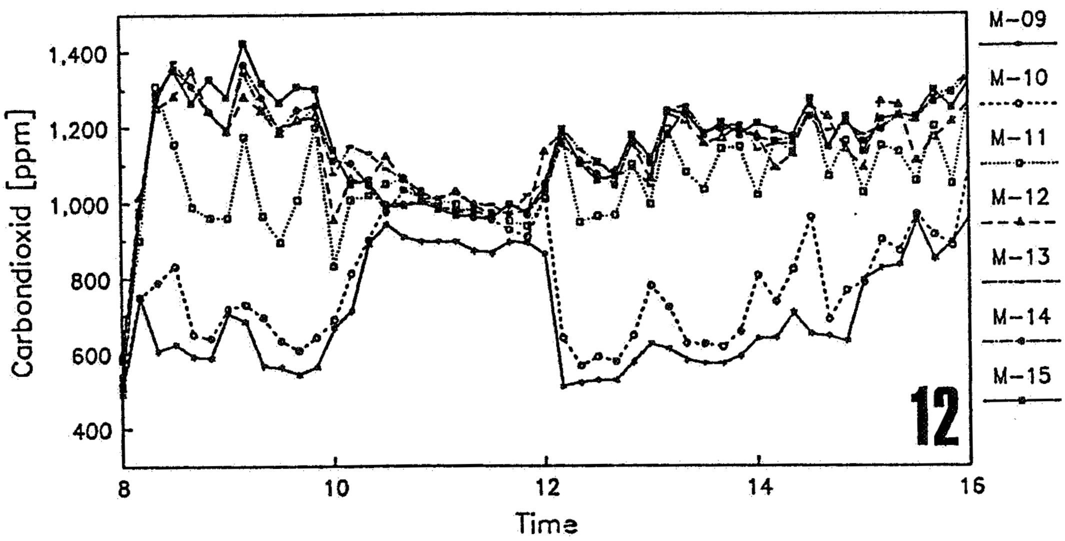

Fig. 3: CO_2 concentrations under CO_2 control (column 2 in the middle of the auditorium)

Measurements of dust concentration in the exhaust air showed that it is the movement of the arriving and leaving students that raises the dust.

Computer simulations

Temperature, velocity and mass fraction fields were calculated using the computer code KAMELEON which was developed at SINTEF. Figure 4 shows the mass fraction field for CO_2 in a vertical section.

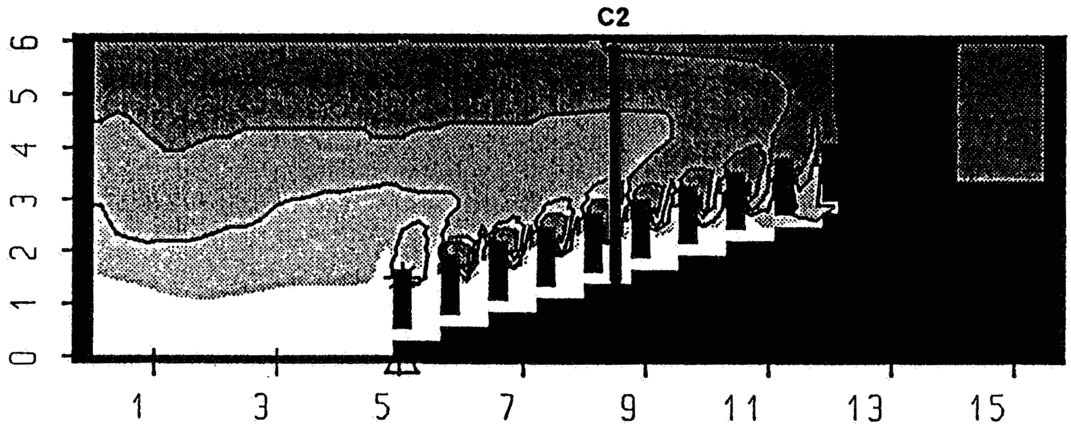

Fig. 4: Mass fraction field for CO_2 including column 2 (room fully occupied)

Measurements and numerical fluid dynamics techniques show that the air flow pattern in the auditorium is very complex. Due to this fact air quality and thermal comfort in the occupied zone are not uniform. Depending on occupancy and distribution some zones have stratification of pollutants and temperature while others are mixed.

4. CASE STUDY IN ZÜRICH

4.1 Object description

The investigated room is one of the smaller auditoria at the Swiss Federal Institute of Technology in Zürich. It has an area of about 120 m^2 and a capacity of 80 persons. 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.

The occupancy of the auditorium is subject to large fluctuations. The room is often used but usually not more than 20 persons are present.

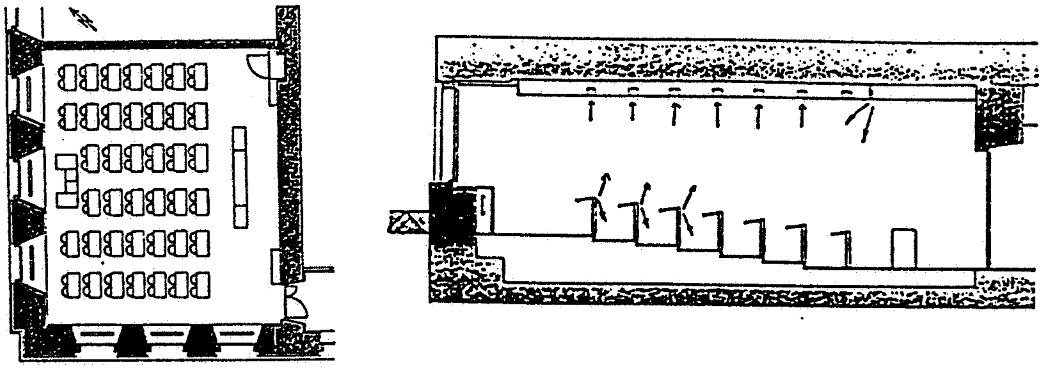

Fig. 5: Ground-plan and sectional view of the auditorium HG D 16.2

The walls of the auditorium are heavily built but poorly insulated. Floor and ceiling consist of lightweight constructions. The floor of the auditorium rises towards the back of the room but the elevation is not significant (1 m).

The auditorium is equipped with a balanced ventilating system with 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 over the catheder (15%). The exhaust air is removed through ceiling slots.

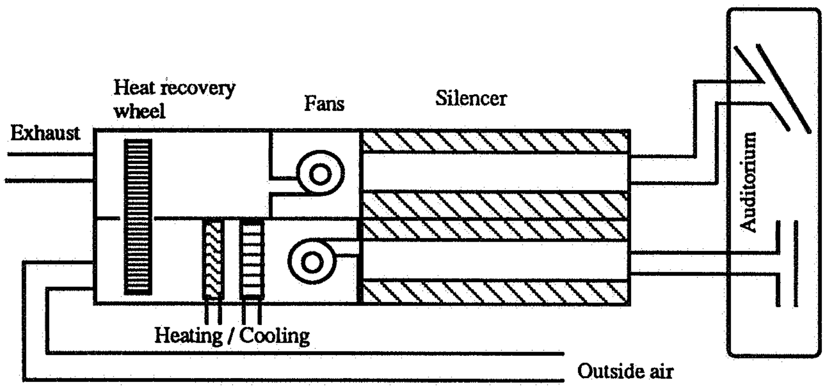

Fig. 6: Sketch of the ventilating system

Both fans have two steps but since no adequate control parameter was available the system was always operated on step 2.

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

4.2 Monitoring programme

Investigated control strategies

a) Time 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 und supply air temperature and running time. Room and supply air temperature are controlled according to the outside temperature. The running time can be programmed according to the expected occupancy of the room but usually the ventilating system is running on step 2 from 7:00 until 19:00.

b) Demand control according to CO_2 concentration
The temperature control of room und supply air was left unchanged. Only running time and step choice are now controlled by a CO_2 sensor.
Every morning before people arrive the auditorium is ventilated for half an hour at maximum air flow (time clock control: 7:30 - 8:00). At 8:00 CO_2 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 rises above a certain level (27°C).

During demand controlled operation the fans are turned on / off according to the following values for CO_2 concentration or room air temperature:

CO_2 concentration	room air temperature	operation
> 750 ppm	> 27 °C	step 1 on
< 600 ppm	< 26 °C	step 1 off
> 1'300 ppm	> 28 °C	step 2 on
> 1'100 ppm	< 27 °C	step 2 off

Tab. 3: Treshold values for step control

Monitoring periods

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 mentioned above. The evaluation of the aquired data is based on the period of one week during summer/winter and time control/CO_2 control respectively.

Monitored parameters

The monitoring focused on the parameters which are relevant for the assessment of:
- energy consumption of the system
- indoor climate in the auditorium

During the monitoring periods all users of the auditorium were questioned about their perception of indoor climate. The questions focused on perceived temperatures, air quality and draft. The room occupants were asked to answer the questions both when entering and before leaving the room.

The first aspect (energy) concentrated on measurements within the ventilating system: air and water temperatures, mass flow in heating and cooling coils, etc..
The second aspect (indoor climate) lead to the monitoring of the following parameters inside the auditorium: air temperatures, CO_2, 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

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		

Tab.4: Used sensors

To avoid problems of accuracy caused by commercial CO_2 sensors the BINOS 100 NDIR gas-analyzer was used for system control. The values of the commercial CO_2 sensors were monitored for comparison.

4.3 Results

Preliminary measurements

No recirculation of exhaust air was planned. Tracer gas measurements [1] showed a recirculation through the heat exchanger of almost 40 %.

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 correct positioning of the fans (both fans on the suction side) was not possible.

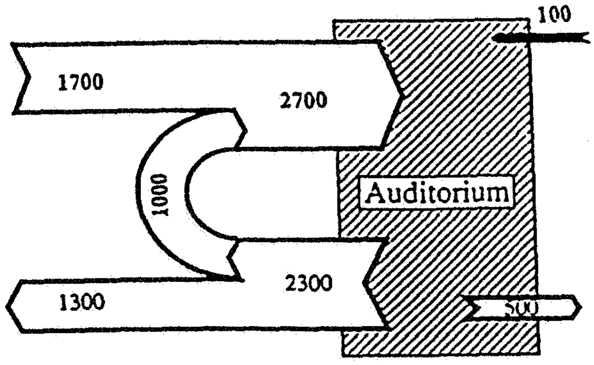

Fig. 7: Air flows during system operation on step 2 [kg/h]

Energy consumption

In both monitoring periods (summer and winter) the consumption of electricity could be reduced by 70 - 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. Step 2 was never used during demand control operation.
Even in summer the room air temperature never rose above the treshold value of 27 °C, which means that in practice the operation of the ventilating system was only controlled by the CO_2 sensor. Cooling energy consumption in summer could be reduced by 75%. Heating energy consumption was reduced by 15% although during the week with CO_2 control the average outside temperature was 6 K lower.

The following diagram shows the different operation times for two days with similar occupancy but different control strategies.

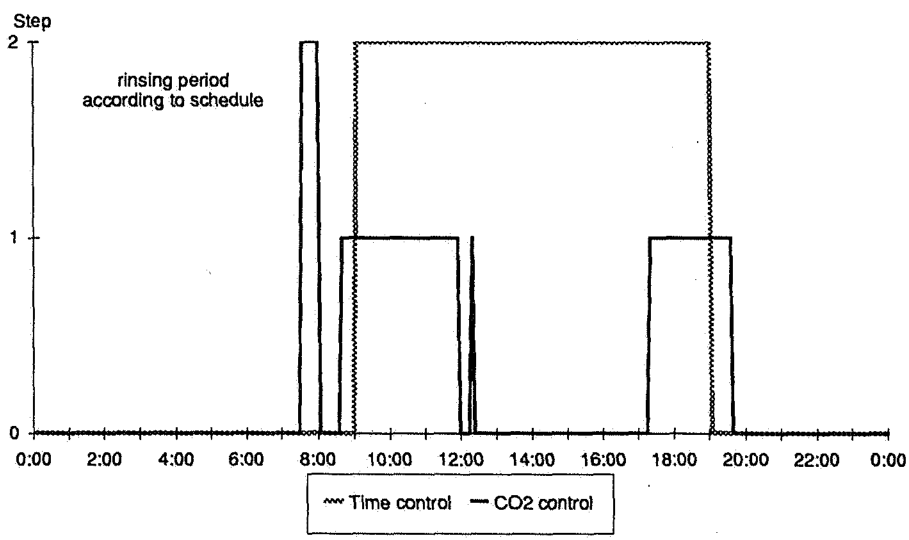

Fig. 8: Operation of the ventilating system with time control and CO_2 control (same weekday)

Indoor climate

The perception of draft and the acceptance of air temperature is directly connected with the operation time of the system. Since the operation time and the air change rate was much lower with CO_2 control (less draft) the perceived thermal comfort was definitely higher with CO_2 control.

On the other hand during the first monitoring period in summer air quality was considered to be slightly worse for system operation with CO_2 control. Figure 9a shows a clear tendency towards greater annoyance by odours.
Further questionning 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 9b).

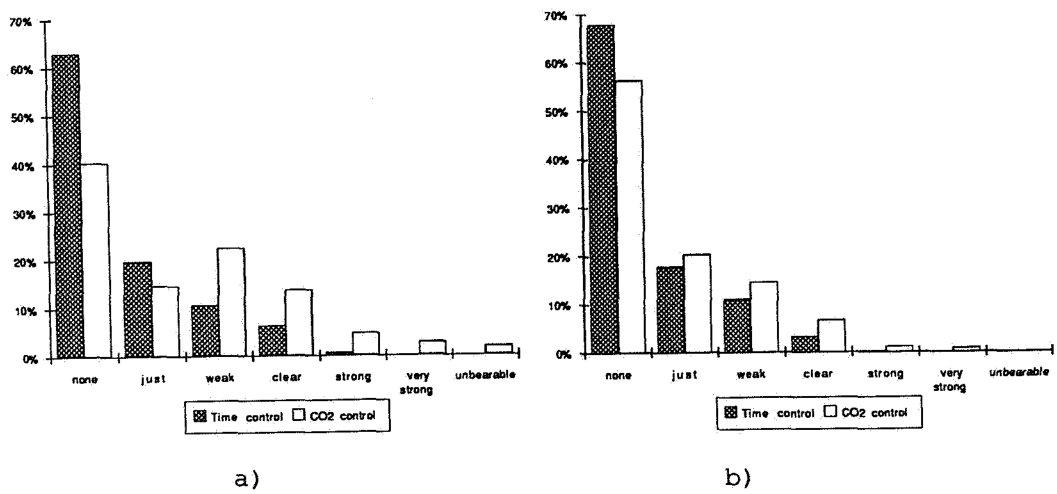

Fig. 9: Perceived odours during system operation with time control and CO_2 control (left: summer; right: winter)

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. This comparison strongly depends on the choice of the single week and and on the actual occupancy of the auditorium. Computer simulations can provide results both for
- annual performance comparisons (Fig. 10) and for
- different conditions of operation.(Fig. 11)

The computer simulations were performed with the simulation code TRNSYS. Thanks to the modular structure of TRNSYS a new module for the calculation of CO_2 concentration was easily integrated. 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 (γ = 1 implies perfect mixing).

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

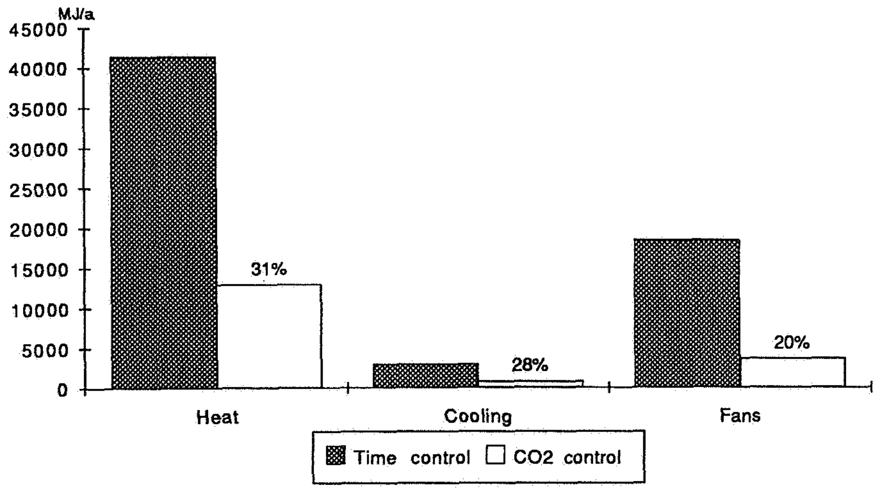

Fig.10: Calculated energy consumption for monitored operating conditions

Since energy consumption is strongly influenced by the choice of treshold values for step control and occupancy of the room these two parameters have been varied. Figure 11 shows the results of this parameters study.

- 100% occupancy corresponds to the presence of 80 persons between 8:00-12:00 and 13:00-18:00 (720 person hours / day)
- 100% treshold values means that step 1 is activated at 1'000 ppm, step 2 is activated at 1'500 ppm
- 100% energy consumption is equal to the energy consumption with time control, the same occupancy and the same max. air flow

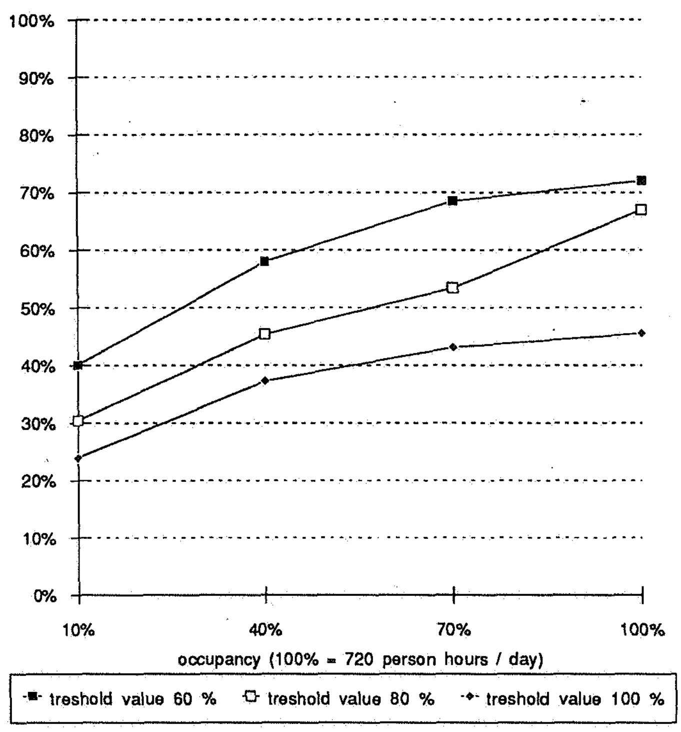

Fig.11: Annual heat energy demand for different control strategies and different occupancy

Similar savings were also achieved for cooling energy and electricity. The choice of treshold 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.
The energy savings for monitored conditions as shown in Fig. 10 correspond to an occupancy of 10% and chosen treshold values of approximatively 80%.

5. CONCLUSIONS

The results of the field measurements and simulations lead to the following conclusions:

- The experience from the case studies shows that CO_2 is very well suited for demand control of ventilating systems in auditoria.
- Important energy savings are possible without serious drawbacks for indoor climate.
- The effective energy savings depend strongly on occupancy and chosen comfort level but are very often in the range of at least 50 %. The highest energy savings were observed for heating energy.
- A combination of CO_2 control and temperature control is recommended for comfort reasons but doesn't have a strong impact on energy consumption
- The elimination of other pollutant sources (e.g. cleaning fluids) is very important for the concept of demand control
- Today's quality of commercially available CO_2 sensors is sufficient for a widespread application. A small security margin is recommended when choosing the treshold values. This margin has only a small influence on energy consumption.
- The choice of control strategy has to be in accordance with the planned ventilating system:

a) *Displacement ventilation with variable air volume*: a minimum ventilation rate should be guaranteed to remove the remaining pollution from building materials etc.; the ventilation rate can then be raised according to the presence of people (measured CO_2 concentration); the CO_2 sensor can be placed in the exhaust duct.

b) *Mixing ventilation with steps*: a periodical rinsing of the room (e.g. every morning) should be adopted to remove the remaining pollution from building materials etc.; the step control of the system is based on the measured CO_2 concentration; CO_2 sensor should be placed in the room.

6. ACKNOLEDGEMENTS

The Norwegian contribution was supported by the Royal Norwegian Council for Scientific and Industrial Research (NTNF).
The Swiss contribution was supported by the Swiss Federal Office of Energy (BEW).

7. REFERENCES

1. ROULET C.-A., COMPAGNON R., JAKOB M.
"Planning of experiments to measure ventilation efficiencies"; Laboratoire d'énergie solaire et physique du bâtiment; Lausanne; 1990