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THE IAQ CONTROL

G.V. Fracastoro

Dipartimento di Energetica - Politecnico di Torino
Corso Duca degli Abruzzi, 24 - 10129 TORINO (Italy)

ABSTRACT

Traditionally, occupants have always been entrusted with the task of controlling IAQ, and this task was usually carried out by opening the windows, at the expense of heating (or cooling) energy. When mechanical ventilation started to be adopted as a common technique, the amount of fresh air was established according to design values, in their turn usually based on peak ventilation loads.

Only recently the concern for energy on one side, and the renovated interest for air quality on the other side, have given rise to a variety of applications of ventilation systems controlled by IAQ levels. This kind of systems has been termed by the International Energy Agency, which promoted a working group (Annex XVIII) under this heading, "Demand Controlled Ventilation" (DCV) systems, i e, systems which should be able to maintain always acceptable IAQ levels at the lowest possible energy costs.

A number of DCV systems are already commercially available. Their application ranges from natural to mechanical ventilation, from new buildings to existing ones, from dwellings to schools, or any other type of buildings and climate. A variety of different IAQ "indicators", and suitable sensors are also used. In order to avoid future disappointments, the choice of the right DCV system requires a careful analysis of the problem, which not always can be provided by installators, due to the novelty and intrinsic complexity of these systems.

After a general evaluation of DCV systems, related to their energy saving potential and IAQ improvement, a number of typical examples of applications are shown, derived from the preliminary results of IEA Annex XVIII, stressing the benefits which were achieved, but also the problems which were encountered. Areas for future research are also indicated (improved sensors, field and laboratory tests, etc.).

1. Introduction

The term "ventilation" of a building usually means the exchange of indoor air with outdoor air. By definition, we will assume that the sources of pollution are only indoors and therefore that indoor air is more polluted than outdoors (which is, by the way, not always true). Moreover, we will not consider ventilation as a mean to carry out a thermal function (air conditioning).

Under these assumptions the reasons for ventilating a building are merely related to hygienic matters. There are indoor sources of pollution in buildings which can produce stuffy air (odours), health risks (VOC, radon, formaldehyde, etc.), or damage to the building (moisture). Whenever these sources show a rather constant emission rate, an ordinary ventilation system may realize acceptable Indoor Air Quality (IAQ) indoors. When, on the opposite, the emission rate is strongly variable, the possibility of installing a Demand Controlled Ventilation (DCV) system should be taken into consideration.

According to the definition provided by IEA Annex XVIII "Demand Controlled Ventilating Systems" subtask A Report (Raatschen, ed., 1990), a DCV system may be defined as **"a ventilation system in which the air flow rate is governed by airborne contaminants"**, either by an automatic control device, or directly by the intervention of the user. We will consider in this context only automatic DCV systems.

This kind of ventilation systems are not widely spread, not even in those countries where mechanical ventilation is already a traditional technique. On the opposite, thermostat control of indoor climate is practised anywhere, and is often made compulsory by law.

Then, a question arises spontaneously: why is heat released according to the actual demand, while air flow rate provided by mechanical ventilation is usually constant ?

A tentative answer may be provided by the parallel between indoor climate control and IAQ control as shown in Table 1.

Table 1 - Parallel between Indoor Climate and IAQ control.

	Indoor Climate (IC)	IAQ
Reason to control	Subjective (thermal sensation) & objective: 1) Health related 2) Building related	Subjective (smell) & objective: 1) Hygiene related 2) Health related 3) Building related
Influencing factor	1) Outdoor factors (weather) 2) Indoor factors (people, equipment)	1) Indoor factors (human activity, building sources) 2) Outdoor fact. (infiltration)
Physical quantities (PhQ) defining IC/IAQ	1) Air temperature 2) Radiant temperature 3) Air humidity 4) Air speed	Concentration of VOC, H_2O, CO, smoke, Radon, Formaldehyde, etc.
Relationship between PhQ and perception	Exists and is well known (see, e g, Fanger equation)	Exists for some PhQ (see Fanger equation), does not exist for others.

Proceeding further in the comparison we will refer to control systems, as shown in Table 2.

Table 2. Main features of Indoor Climate and IAQ control systems.

	Indoor Climate (IC)	IAQ
Type of control possibilities	1) Feed-forward 2) Feed-back	Feed-back only
Control variable for feed-back control	Air temperature	VOC, H_2O, CO_2, ...
Relationship between control variable & IC/IAQ	Very close	Depends ...
Typical time constant of control variable dynamics	hours	seconds
Space distribution of control variable	rather uniform	widely variable
Control feasibility	easy	difficult
Control sensitivity	$1^{o}C \Rightarrow 10\%$ PPD	100 ppm CO2 $\Rightarrow 2\%$ PD
Potential energy savings	$1^{o}C \Rightarrow 5\text{-}10\%$ of total losses	100 ppm $\Rightarrow 15\%$ of ventilation losses

The conclusion which may be drawn from the Table above is that controlling IAQ is much more difficult than controlling Indoor Climate. If one adds that a large part of the perceived poor air quality is not due to bioeffluents and people related activities, but to materials in ventilation systems themselves (Fanger, 1989), the picture becomes even more fuzzy...

2. Suitability of DCV systems

Despite the difficulties in realizing a well designed DCV system, the possibility to adopt one of these systems should be (carefully) considered according to the following fundamental factors:

i) The characteristics of contaminant production within the building

ii) The building features

iii) The HVAC installations

iv) The climate

2.1 Characteristics of contaminant production within the building

There are many pollutants produced within the building, each one requiring a certain level of ventilation rate. They may be considered as belonging to three categories:

a - **building pollution sources**, showing a rather steady source strength,

b - **event related sources**, and

c - occupant related sources

One of these pollutants should be chosen to drive a DCV system: this will be called the **driving (or dominant) contaminant**, and it will be the contaminant, the level of which is such as to require the highest ventilation rate, as an average. Moreover, the driving contaminant should have an emission rate, which is

i) high enough as to require the installation of additional (natural or mechanically assisted) ventilation in addition to that provided by natural infiltration

ii) strongly variable in time (variations of at least 100 % should be considered)

iii) unpredictable as to time and location of the source.

It is obvious that none of pollutants of categories a and b show all above properties. Building related pollutants do not owe properties ii) and iii). Event related pollution usually do not owe property iii). They should be rather reduced by exhausting them at the source: if the time when a strong increase of pollutant emission rate (PER) will take place is known in advance, a simple clock-control system may be adopted. If, on the other hand, the location of pollutant emission is well known and localized in a small area within the conditioned space, it may be preferable to adopt local exhaust systems (e.g., hoods), which are much more efficient in the removal of contaminants than are even well designed central systems.

A decision diagram taking into account these factors is shown in Figure 1.

2.2 Building-related factors

There are at least three major building- related factors which may be relevant for the adoption of a DCV system:

a - the air tightness of the envelope of the building

b - the building use and destination

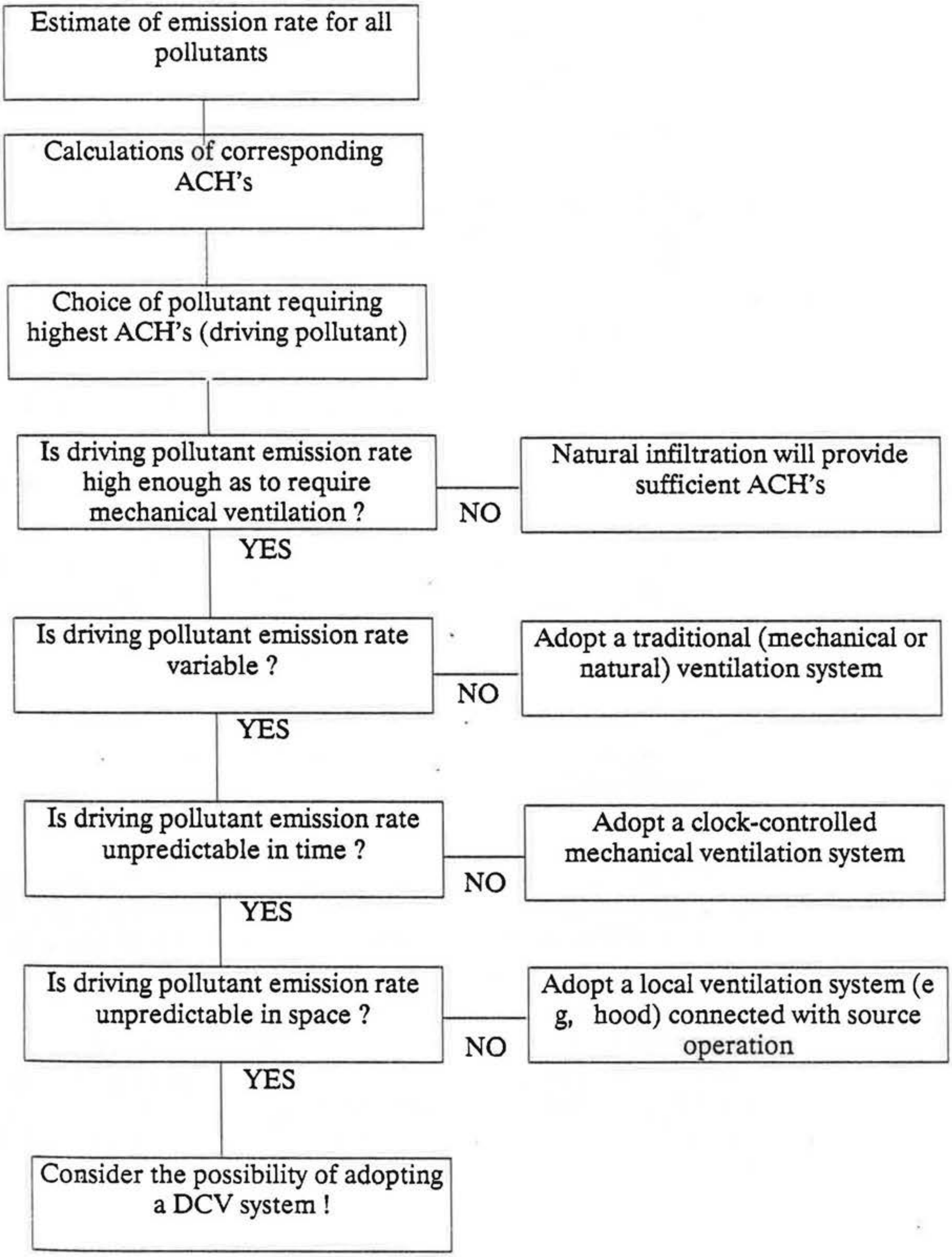
c - emission and absorption of pollutants by building materials

a) Air tightness

If a building is so leaky that natural infiltration generally provides sufficient ventilation, then a DCV system is clearly not applicable. The tighter the building, the more efficient the control of ventilation by the DCV system, and the greater the energy savings will be. As a rule of thumb, if normally more than 50 % of outdoor air comes from uncotrolled natural infiltration, the performance of DCV systems will be rather ineffective.

However, where a mechanical system is already installed, even in leaky buildings the installation of DCV systems will result in some energy savings, because it will "sense" the effect of natural infiltration in terms of IAQ improvement.

Figure 1 - Decision diagram for choosing a DCV system according to Pollutant Emisssion Rate characteristics



- IAQ levels (i e concentrations)
- Ventilation loads

Once the total energy losses are calculated, these will be compared to ventilation energy losses induced by competing systems (e g constant flow rate ventilation systems). The energy savings and the extra costs for DCV will have to be compared in order to evaluate the return on investment, profitability or Life Cycle Cost.

5. Experiences with DCV systems

Experience with DCV is still very limited, and cannot bring to definitive conclusions.

In general, IAQ improvements are always observed when DCV is compared to natural ventilation. In some cases, incorrect positioning of sensors may lead to underventilation of certain areas of the building.

Theoretical evaluation of energy savings may induce optimistic conclusions, and cannot be generalized. As an example, a calculation performed in a classroom (Raatschen, 1990) showed that the installation of DCV would lead to a reduction from 1.19 ach to 0.64 ach with a maximum carbon dioxide level of 1,400, and from 1.92 to 1.05 ach when the CO_2 set-point was lowered to 1,000 ppm. In both cases the ventilation load reduction was 46 %.

Measured savings were in the range of 8 % in a Bank (Gabel, 1986) up to 17 % in a Cinema (Anon, 1986) of the total fuel consumption.

Respect to ventilation load, 20 % savings were estimated in a theatre (Warren, 1982), and 40% in an office building (Södergren and Punttila, 1983). Payback times from less than one year in an entertainement building (Lyons, 1983) to more than 6 years in a library (Smith et al., 1984) were reported.

6. Need for further research and conclusions

As this technology is rather new, many items should need further research both in the field and in the laboratory:

a) Control strategy

Differently from indoor climate feedback control, in which the controlled quantity and the controlling (driving) quantity is the same, i e air temperature, IAQ control may make use of as many driving quantities as there are pollutants in the air, none of which is completely reliable in all situations.

Moreover, some investigations show that a large part of perceived pollution is not due to the occupant-generated pollutants (smoke + bioeffluents + CO_2 + humidity), but to those emitted by the building, the furniture or by the ventilation system itself (Fanger, 1989). Therefore it is not clear which should the best quantity to be monitored in order to keep an agreeable IAQ. CO_2 is often considered to be the best indicator of bioeffluents, but this is no longer valid when smoking is allowed.

condensation on walls surfaces (a rather frequent case for residential buildings in humid winter climate regions).

3. Types of DCV systems

Most DCV systems are designed in order to keep under control:

- air quality (in general)
- odours
- tobacco smoke
- humidity

This can be accomplished adopting monitorable indicators as:

a - water vapour

b - carbon dioxide

c - mixed gases (volatile organic compounds - VOC)

The cross-correlation matrix between controlled quantities and their indicators is shown in Table 3.

Table 3 - Controlled quantity and indicator

Controlled quantity	VOC	CO_2	Water vapour
Air quality	x	x	(x)
Odours	x	x	(x)
Tobacco smoke	(x)	(x)	-
Relative humidity	-	-	x

3.1 Humidity controlled ventilation (HCV) systems

This type of DCV is generally adopted in residences, where large and sudden increases of RH are often observed, causing moisture problems to the building fabric.

Particularly interesting appear those HCV systems making use of self-regulating grilles, whose opening section varies according to the dwelling humidity. These systems may be adopted either with mechanical ventilation or with natural ventilation ducts ("shunt" system). The rationale behind these systems is shortly described below.

Because there is always a certain amount of water vapour in outdoor air, the amount of this air required to keep indoor air relative humidity (RH) below limit values will vary according to outdoor air moisture content. The theoretical number of ach, derived from the general equation of continuity under the hypotheses of perfect mixing, steady-state, taking into account absorption/desorption phenomena, will be:

$$n = \frac{P + B \cdot S \cdot (x_{\max} - x_i)}{\rho \cdot V \cdot (x_i - x_o)}$$

where

P = moisture production rate (kg/h)

x_i = moisture content in indoor air

x_{max} = maximum moisture content on the surface (kg/kg), corresponding to saturation conditions at the surface temperature

x_o = outdoor moisture content (kg/kg), varying with temperature and RH of outdoor air

B = moisture absorption or desorption resistance (kg/m^{2}h), equal to zero when x_i x_{max} and no condensation is left on the surfaces

S = Surface area of walls and furniture (m^2)

When the goal is to maintain a constant indoor RH (e.g. 50 % RH at 20 °C, corresponding to 7 g of water per kg of dry air) x_o tends to diminish with decreasing outdoor temperature and therefore the amount of outdoor air needed to maintain a constant indoor RH will also diminish (Fantozzi et al, 1990), thus tending to compensate for the increase of ventilation loads with increasing temperature difference (see Figure 2).

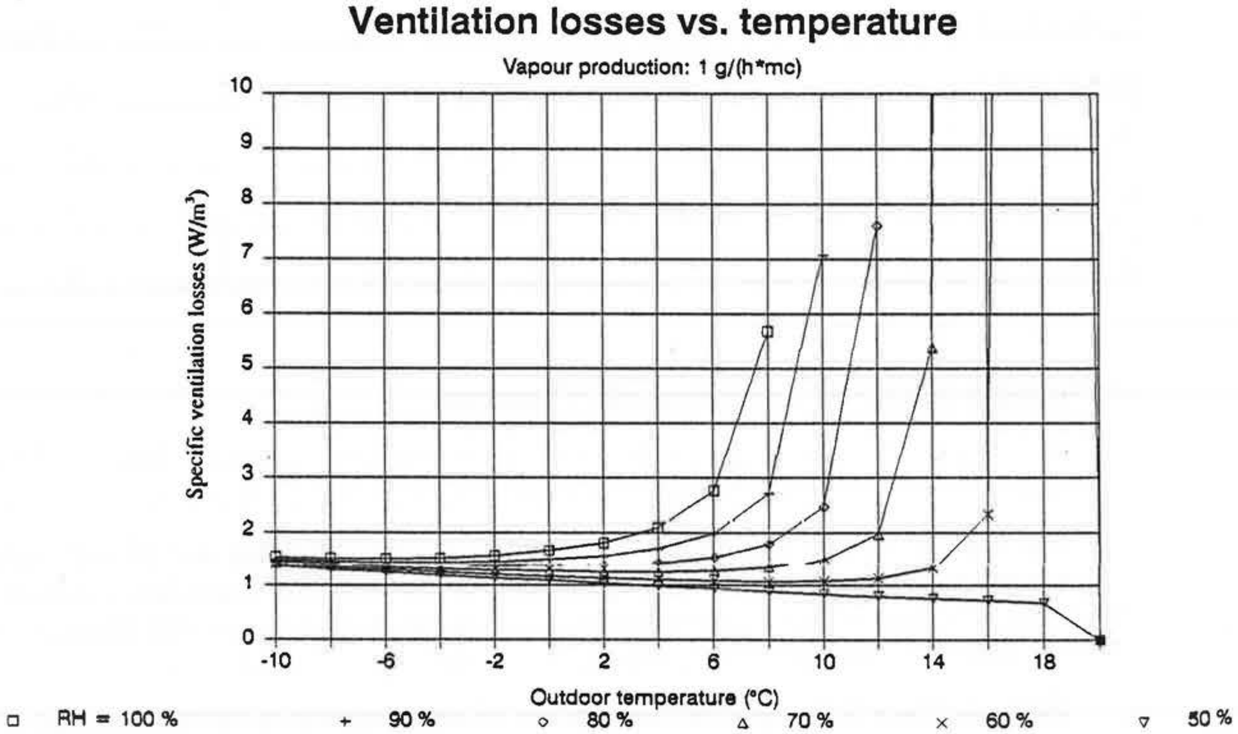


Figure 2. Ventilation losses versus temperature. Vapour production: 1 g/(h.m3). Indoor air conditions 20 °C, 50 % RH.

However, if the aim is to maintain the dew-point temperature of the air below the surface temperature of the coldest spots in the walls, the maximum allowable moisture content indoors will also decrease with decreasing outdoor temperature, partially counterbalancing the above effect.

In extremely cold climates these systems may have problems such as freezing of the grille tissue with chilly air and snow entering pushed by strong winds. Moreover, if the air inlet grilles are not correctly sized, they may induce such a large air flow that, in extreme conditions, indoor air temperature will decrease, leading to an increase of indoor RH, with a dramatically divergent result.

3.2 CO_2 controlled ventilation systems

Carbon dioxide seems to be a rather trustworthy driving contaminant for schools, offices, auditoria, where the main pollution problem is related to occupants, and the occupant load shows strongly variable trends.

It should be borne in mind that CO_2 in no way represents a harmful contaminant. It is, on the opposite, a good indicator of IAQ, when this is mainly put at risk by bioeffluents.

CO_2 sensors are usually sufficiently accurate to carry out their task. As CO_2 is usually emitted together with heat it is recommendable that the exhaust terminal are placed at a high level, and the sensors are placed in the exhausts.

3.3 VOC controlled ventilation systems

Volatile Organic Compounds are also good indicators of IAQ, but the sensors available on the market (often termed "mixed gas sensors", or "IAQ sensors") are not as reliable as CO_2 sensors, due to their weak stability and accuracy. Furthermore, "there is no direct relationship between the sensitivity of the sensor to a certain gas and the effect of this gas on IAQ" (Fahlén, 1991).

4. Evaluation of potential energy savings

Pre-evaluation of energy savings is needed to make a cost-benefit analysis upon deciding on the application of DCV. This will require the use of simulation techniques.

In order make a cost-benefit analysis the system performance will have to be analysed under typical (and not design) climatic conditions. The following data are needed to predict the operation of the system:

- meteorological data
- PER data
- features of the mechanical ventilation system
- geometrical and technical characteristics of the building
- absorption and desorption features of building walls and furniture

The following quantities will be calculated as a function of time:

- Air flow rate

- IAQ levels (i e concentrations)
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b) Sensors

Sensors are a key point for the good performance of DCV. The following crucial features have to be considered (Fahlén, 1991):

- low cross-sensitivity

- good stability

- immunity to climatic, mechanical and electro-magnetic interference

Some "special features", such as e g the possibility to display the measured signal may well help to improve the acceptability of DCV.

Another important matter is the correct positioning of sensors. It is maybe difficult to provide practical "rules-of-the-thumb" of general validity; improvement of DCV design should have recourse to simulation techniques, for example, to determine the correct position of sensors, grilles or extraction hoods. This can be accomplished by using rather sophisticated Computer Fluid Dynamics (CFD) models, simultaneously solving the three-dimensional equation of continuity and momentum for each room. Many of the CFD programmes available on the market, such as PHOENIX, FLOVENT, FLUENT, FIDEP, and others, are listed in an AIVC paper by Liddament (1991).

REFERENCES

Anon; Ventilation control by meas. of carbon dioxide levels in public entertainement buildings, ECD Partnership, Final Report ED/85/172, ETSU, Harvell, 1986.

Fahlén, P., Private communication, 1991.

Fanger, P.O., The new comfort equation for indoor air quality, IAQ '89, ASHRAE, 1989.

Fantozzi, Fracastoro G V, and Masoero M, "Assessing the performance of passive humidity controlled ventilation systems", XI AIVC , Belgirate (Italy), 1990.

Gabel, S.D., Janssen, J.E., et al., Carbon dioxide based ventilation control system demonstration, DOE, Bonneville Power Administration, Engineering Branch, Division of Resources Engineering, 1986.

Goodfellow, H.D. (Ed.), Advanced Design of Ventilation Systems for Contaminant Control. Elsevier, Amsterdam, 1985.

Liddament, M. W., A Review of Building Air Flow Simulation, AIVC Technical Note 33. March 1991.

Lyons, M., The Breathaliser Test, Energy Manager, Vol. 6, No. 10, p. 59-61, 1983.

Raatschen, W. (Ed.), Demand Controlled Ventilating Systems - State of the Art Review, International Energy Agency. Published by Byggforskningsrådet, D9:1990, Stockholm, Sweden, 1990.

Smith, B. E., Prowse, R.W., Owen, C.J., Development of occupancy-related control for Brunel University Library, Proc. of 5th AIC Conference, Reno, Nevada, 1984.

Södergren, D., Punttila, A., A CO_2 controlled ventilation system. Pilot study. Swedish Council for Building Research Document D7:1983.

Warren, B.F., Energy saving in buildings by control of ventilation .., Building Services Engineering and Technology, 1982, Vol. 3, No. 1.