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CONTROL

AIR QUALITY CONTROL — MEASUREMENTS AND EXPERIENCES

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SYNOPSIS

Too high a concentration of certain gases (*e.g.*, water vapour, carbon dioxide, tobacco smoke, alcohol, *etc.*) in public buildings can damage the health. Even low concentrations can cause discomfort and make the room air seem unpleasant. This paper describes this subjective perception of air quality.

It is shown that installation of an appropriate sensor can make substantial energy savings.

Introduction

The occupancy density and thus the hygienic load in, for example cinemas, department stores, conference rooms, and multi-purpose rooms can vary considerably. Air conditioning and ventilation systems with fixed minimum outside air change will supply too much outside air when the room is not fully occupied, *i.e.*, when the hygienic load is reduced. However, this additional outside air still has to be disturbed, heated, and possibly humidified during heating periods, or cooled and dehumidified during cooling periods.

Air quality control adjusts the outside air volume to changes in the room air hygiene load. The contamination of room air has many causes. For example, occupants emit water vapour and carbon dioxide by perspiration and breathing. They also produce body odours. Contamination is also caused by tobacco smoke, building materials, open fires, and evaporation of liquids (*e.g.*, alcohol in restaurants, chloride in swimming pools, household cleaning preparations, *etc.*).

Air Quality Measurement

Air quality is a complex concept which is determined by many factors. People judge air quality with their nose. Odours are noticed in particular when people enter a room. After they have been there for some time, they get accustomed to the poor air quality. The sensitivity threshold is increased. Since the various gases all have different effects on odour, it is not easy to measure air quality.

A good solution for air quality control is offered by the gas sensor developed on the Taguchi principle. This sensor consists basically of a heated element inside a semi-conductive tube (zinc dioxide). (See Figure 1.)

The semi-conductive material is porous and has a large surface area which is able to adsorb oxidisable gases. During this adsorption process electrons are released, which increases the conductivity of the semi-conductor. The process is reversible. If the gas concentration decreases, the gases are diffused from the semi-conductor. The sensor responds very quickly, *i.e.*, within a few seconds. It is not subject to wear, which means it will operate reliably for years. It responds with varying degrees of sensitivity to many different gases such as hydrogen, carbon monoxide, hydrocarbons, alcohols, esters, benzene, *etc.* The sensor also responds to water vapour.

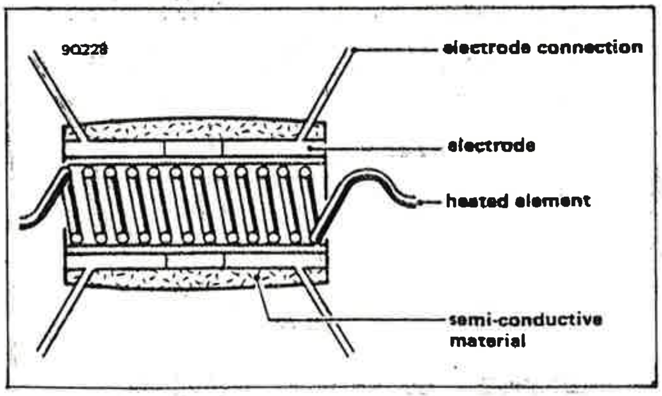

Figure 1: Schematic of gas sensor.

The gas sensor was used for measurements in various types of rooms: offices, theatres, gymnasia, multi-purpose halls, and lecture rooms. The purpose was to compare the gas sensor signal with the room air hygiene load caused by people, tobacco smoke, and other forms of contamination. The carbon dioxide content of the room air was measured at the same time.

Rooms without smokers

In rooms where smoking is prohibited and where occupants are the only source of contamination, the gas sensor responds to odours caused by breathing, perspiration, and flatulence. In the lecture room in the Zurich area, which we used for our measurements, the air is supplied directly at the seats, whereas the extraction grilles are located near the lighting in the false ceiling. The gas and CO_2 sensors were installed in this false ceiling. At first the correlation between room load and gas sensor signal was poor. The sensor scarcely responded at all to the changing room occupancy but it did respond to the air conditioning system switching on and off. The reason was that the air stream in the false ceiling overcooled the heated sensor and this temperature reduction caused the sensor sensitivity to change.

A good correlation was achieved after a specially designed sensor model for duct installation, which was unaffected by air flow, had been installed.

Figure 2 shows the measured results. The lecture room was fully occupied with approximately 300 people in the morning and afternoon. The gas sensor signal increased when the students entered the room at approximately 09.30 hours.

During the short break at approximately 11.00 hours, the occupants left the lecture room for 15 minutes. This short break was clearly detected by the sensor. The air quality improved during the lunch-break. After the lunch-break the sensor responded again to the re-contamination of the air. The measured results with the CO_2 sensor were similar.

In the lecture hall at Trondheim University the signals of

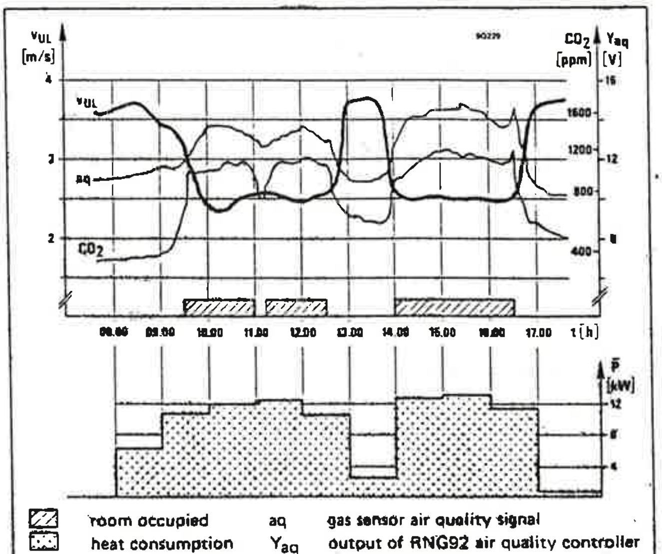

Figure 2: Sensor signals, return air velocity, and energy consumption: lecture room, Zurich.

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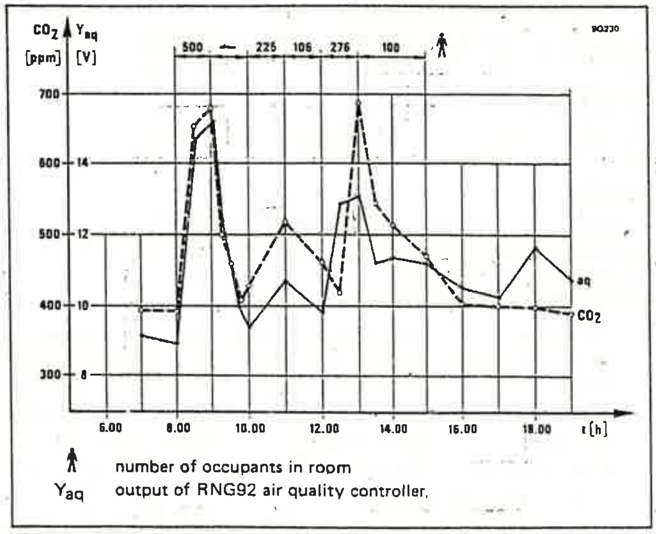

Figure 3: Lecture room at Trondheim University: comparative results.

several CO_2 and gas sensors were compared with each other. Smoking was not permitted. A precise count of the occupants was made whilst the measurement was carried out. Figure 3 shows the measured value curves for comparative measurements in the extract air duct. Both sensors responded very quickly to changes in occupancy. These measurements likewise show a good correlation between the two sensor types.

In sports halls, body odours due to perspiration cause a relatively large room air hygiene load. Both sensor types responded to this hygiene load. The measured value curves clearly indicate the high emission of CO_2 and body odours. The gas sensor responded with a delay of approximately 30 minutes, presumably because the body odour was first absorbed by the clean clothing before being emitted to the air.

Rooms with smokers

Tobacco smoke represents a very heavy room air hygiene load. It has been shown to contain more than 2000 different components.* This demonstrates the complexity of the term air quality. The gas sensor is very sensitive to tobacco smoke, as measurements in an office equipped with a VAV system show. Figure 4 shows the measured value curves of both sensors. The gas sensor responds very quickly and sharply to cigarette smoke in the room. The CO_2 content however increases by only a negligible amount in a smoky atmosphere. It cannot therefore be taken as criterion for air quality in this case.

Other sources of air contamination

Formaldehyde which is released from some building materials can cause irritation of the eyes and respiratory tracts. Tests with the gas sensor show that it registers this form of contamination but it is not sufficiently sensitive to register the low concentrations at which some discomfort can start.

Air Quality Control

As already mentioned, air quality control adjusts the outside air volume to the actual demand, *i.e.*, the hygienic load of the room. The upper limit of this air volume is defined by the size of the equipment and air ducts. The lower limit can be adjusted by incremental or proportional control of fan speed or by return air mixing in return air systems.

Control system in the Concert Hall, Oslo

The small auditorium in the Concert Hall, Oslo, has 200 seats. An air conditioning system supplys 9000 m³ hour⁻¹ air. Before the control system was modified, the outside air dampers had the following minimum positions:

— during performances:	50% open
— day mode:	10% open
— night mode:	0% open (100% return air)

The three positions were controlled by a clock. By measuring the air volume, it was determined that the outside air volume did not change proportionally to the damper positions. When the dampers were 10% open, 18% outside air was supplied: when the dampers were 50% open, 90% outside air was supplied.

After air quality control (with the Taguchi sensor and the Staefa Control System RNG92 proportional controller) had been installed, the outside air volume could be controlled precisely in accordance with the actual demand. For this, the controller P-band and the setpoint had to be adjusted accurately during commissioning.

When the auditorium is not used during the day (Figure 5, Section I) no outside air demand is signalled. The demand only starts, when preparations for the performance of a dance group are made in the auditorium (II). The outside air volume increases during the performance (III). On the following day the situation was found to be similar.

However, the choir rehearsing in the auditorium needs only a little outside air in comparison with the dance group.

With fixed damper position — *i.e.* before the control system was modified — too much outside air was supplied due to the fact that the damper positions were not linear. Air quality control corrects these positions when the outside air volume exceeds the actual demand.

Air quality control in a lecture room

The outside air volume in the Zurich lecture room mentioned earlier is also controlled by a gas sensor signal. The partial air conditioning system has a capacity of 16 000 m³ hour⁻¹ and is only switched on when the hall is occupied. A room supply air cascade controls the heating coil, the dampers, and the cooling coil in sequence. During heating operation or at outside temperatures above 22°C, the minimum outside air proportion defined by the system design is 33%. This percentage is reduced by the air quality control. The effect of air quality control was determined by measuring the return air volume. Figure 2 illustrates the gas sensor signals Y_{aq}, and the measured air velocity values, v_{UL}. As the air quality deteriorates, the return air volume is reduced because more outside air is demanded. As the quality of the room air improves during the lunch-break, a lower outside air volume is required and the return air volume is increased accordingly. The air quality in a fully occupied room depends on the minimum outside air volume required per person. Air quality control does not influence this value. During partial occupancy, the outside air volume is appropriately reduced by air quality control but only in cases where handling the outside air would mean unnecessary energy consumption. The P-band offset of this control means that even if the room air load is low, there is nevertheless some improvement in air quality.

Energy Calculations

The instantaneous heat balance of a room can be used to determine the heating or cooling output which is necessary to maintain the temperature at a desired level. For our purposes, we shall examine a heating and cooling coil without humidification with fixed load. The output P_Z which has to be provided is as follows (not allowing for the heat exchange with adjoining rooms):

$$P_Z = P_{TR} + P_L - P_S - P_i \quad (kW) \qquad (1)$$

P_{TR} = transmission losses.

$$= \frac{1}{1000} \sum_i k_i \cdot A_i \cdot \Delta T \quad (kW)$$

where:

k_i = thermal conductance of walls (W m⁻² K).
A_i = surface of walls (m²).
ΔT = differential outside temperature (T_a) − room temperature (T_i) (K).
P_L = ventilation losses = $\rho \cdot c \cdot \dot{V} \cdot \Delta T$ (kW).

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* See Spengler & Sexton, Bibliography.

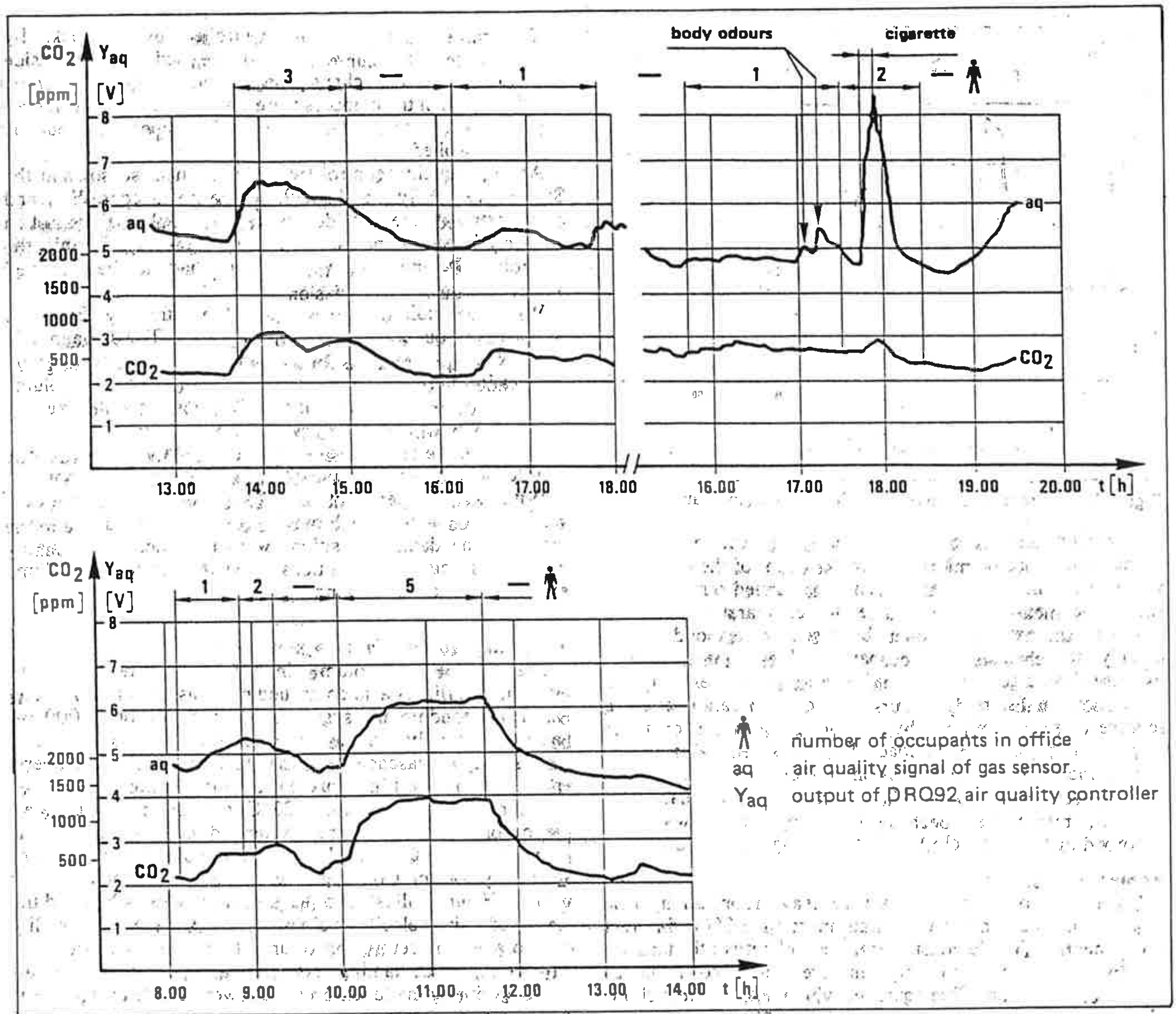

Figure 4: Comparative measurement between CO_2 content and gas sensor in an office.

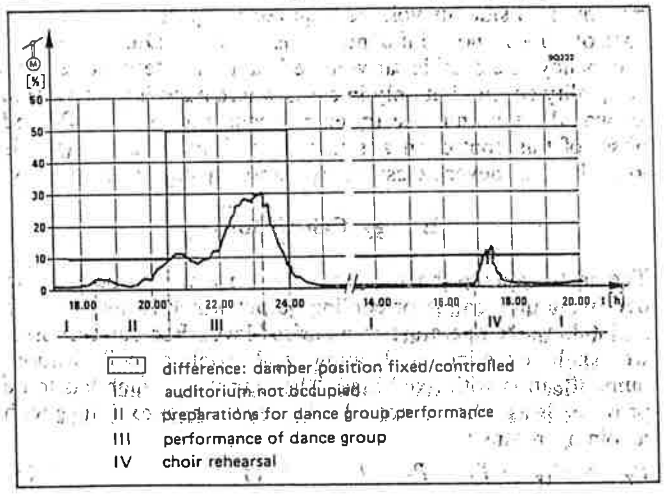

Figure 5: Damper positions in the system installed in Oslo concert hall.

ρ = density of air (kg m^{-3}).
c = specific heat of air (kJ kg^{-1} K^{-1}).
V = outside air rate (m^3 s^{-1}).
P_S = solar radiation (kW).
P_i = internal heat production = $P_p + P_B + P_M$ (kW).
P_p = heat gain from people (kW).
P_B = heat gain from lighting (kW).
P_M = heat gain from equipment (kW).

At a certain outside temperature (defined in the following as the heating limit) the internal heat gain is equal to the heat loss. Above the heating limit, the temperature in the room will increase or the extra load will have to be cooled. Below the heating limit when occupancy varies, heating energy can be saved by reducing the outside air volume.

EXAMPLE

A conference room with 40 seats and a ventilation system (heating operation only) has an average occupancy level of 20 people. The conditions are given in Table 1.

Table 1: Conditions of 40-seat Conference Room.

Operating times:	Monday — Friday 08.00 — 17.00hrs.
Room temperature:	20°C during operating time. 18°C outside operating time.
Outside air rate:	1200 m^3 hour^{-1} (during operating time)
Outside wall area:	135 m^2
Average *U*-value:	1 W m^{-2} K^{-1}
Internal heat gain:	1.8 kW (20 people) + 1.4 kW (lighting) = 3.2 kW
Solar radiation:	none

First the heating limit during the occupancy time is calculated. The heating limit is derived from the following condition: Load supplied equals 0. Equation (1) is consequently:

$$P_{TR} + P_L - P_S - P_i = 0$$

If ρ = 12 kg m^{-3} and c = 1 kJ kg^{-1} K^{-1} the result is:

$$\Delta T = 6K$$

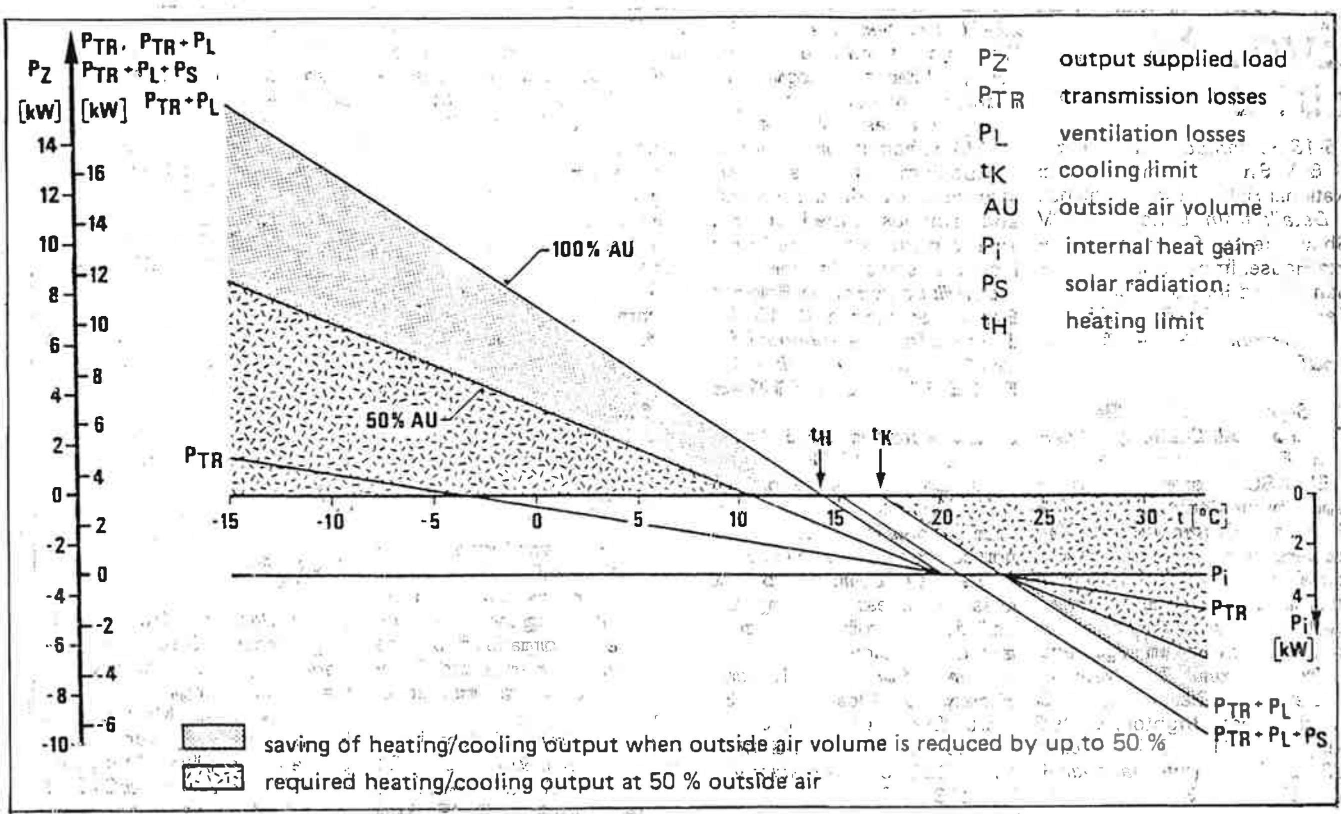

Figure 6: Heating and cooling output for conference room as a function of the outside temperature during operating time.

The heating limit is therefore at 20-6 = 14°C.

Figure 6 illustrates this calculation in graph form (line defined as 100% AU = outside air). If the outside air volume is reduced to 50%, which is possible with partial occupancy, the line becomes flatter and will intersect the horizontal axis at 10.5°C. This represents the corresponding heating limit. The same result is achieved with the equation (1) if V is 600 m³ hour⁻¹ ($\Delta T = 9.5$K).

The area between the two lines on the graph (100% AU and 50% outside air) shows the energy saving at various outside temperature.

A similar calculation is possible for the required cooling output: however the situation is much more complex due to the varying solar radiation. A reduction in ventilation results in lower cooling output if the outside temperature is higher than the room temperature (in Figure 6, room temperature = 23°C during cooling operation).

The annual consumption can be calculated as follows: If the heat losses ($P_{TR} + P_L$) are higher than the internal heat gain, heating is necessary. The annual heating energy demand E_H is:

$$E_H = (\rho \,.\, c \,.\, V + 0.001 \,.\, \Sigma k \,.\, A_i) \,.\, Gr_x \quad \text{(kW)} \qquad \ldots(2)$$

where:

Gr_x = degree hours in relation to heating limit.
T_x = sum of hourly temperature differential between heating limit and outside temperature.
$\sum_k (T_x - T_a)\, k\ [Kh]\ T_x$ = heating limit

In Holland (de Bildt Utrecht Province) the degree hours for a reference year have been calculated.* Using these figures in relation to the conference room described in the above example the results of Table 2 are obtained.

With controlled outside air volume the annual energy saving relating to the total heat requirement of heating and ventilation systems is thus 28%.

The heating energy required for the lecture room in the Zurich area when the outside air volume is controlled was measured in the air ducts. For this, four PT 100 temperature sensors were used on both the inlet and outlet side of each supply air device. A velocity sensor controlled the supply air volume. A computer used the measured data to calculate the energy consumption every 45 seconds. Figure 2 illustrates the average heat output, P, for every hour over a working day at an outside temperature of 6°C and a room temperature of 22°C. At full occupancy and an outside air rate of approximately 5300 m³ per hour the output was approximately 12 kW. When the outside air volume was reduced during the lunch break and after the lecture, the output immediately decreased.

Table 2: Calculation of Annual Fuel Consumption.

100% outside air:
Gr 14°C = 10 990 Kh (Mon — Fri: 08.00-17.00 hours)

50% outside air:
Gr 10.5°C = 6 680 Kh (Mon — Fri: 08.00-17.00 hours)

Depression period:
Gr 18°C = 53 290 Kh

By using equation (2) for calculating the heating energy demand we arrive at the following:

	Fixed outside air volume	*Controlled outside air volume*
During operating time:	5 880	2 240
outside operating time:	7 190	7 190
TOTAL	13 070 kWh per year	9 430 kWh per year

The achievable energy savings depend very greatly on the particular situation. As shown in Figure 6, the saving potential decreases as the internal heat gain increases. Large savings can be achieved in rooms with high outside air volume per person (rooms with smokers) and low occupancy. In order to make reliable predictions a calculation must be made for each particular case. The measurements with the gas sensor produced the results given in Table 3 in respect of savings and pay-back for the additional equipment installed. It can be seen that in the auditorium and the sports hall the percentage energy saving is less than in the concert hall due to the larger internal heat gain. The pay-back period was calculated on the basis of

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* See Thys, Bibliography.

Events

1986

16-18 September: **9th London H & V Show.** Olympia 2 and National Hall London, England.
Details from: London H & V Show, Trenton Group Ltd, Trenton House, Imperial Way, Croydon, United Kingdom CR9 4RR. *Telephone:* 01-680 7525; (*International:* + 44 1 680 7525).

19 September: **Acid Rain — The Political Challenge.** London, England. This is a joint IEEP/NSCA conference sponsored by the Commission of the European Communities. The conference is intended for decision makers in government and industry, including those with responsibility for energy and environmental management.
Details from: The National Society for Clean Air, 136 North Street, Brighton, United Kingdom BN1 1RG. *Telephone:* 0273 26313. (*International:* + 44 273 26313).

29 September-2 October: **7th AIC Conference 'Occupant Interaction with Ventilation Systems'.** Stratford-upon-Avon, England.
Details from: Jenny Elmer, Air Infiltration Centre, Old Bracknell Lane West, Bracknell, United Kingdom RG12 4AH. *Telephone:* 0344 53123. (*International:* + 44 344 53123). *Telex:* 848288.

22-26 October: **SAIE '86—** (The International Building Industry Exhibition). Bologna, Italy. Highlights include a meeting of the general assembly of the RILEM which is organising a symposium **'Materials and structure: trends in research and demands of the industry'.** This is mainly concerned with industrial standardization.
Details from: Fiere Di Bologna, Piazza Costituzione, 6, 40128 Bologna, Italy. *Telephone:* 051 282111. (*International:* + 39 51 282111). *Telex:* 511248.

27-30 October: **53rd International Clean Air Conference.** Blackpool, England. Topics to be covered in seven sessions include: new initiatives in pollution control; combined heat and power; air pollution of the diesel engines; planning and pollution control; noise; ozone and carbon dioxide.
Details from: The National Society for Clean Air, 136 North Street, Brighton, United Kingdom BN1 1RG. *Telephone:* 0273 26313. (*International:* + 44 273 26313).

3-7 November: **Expoclima, The European fair for refrigeration, heating, ventilation, air conditioning, vacuum cleaning and drying.** Brussels, Belgium.
Details from: Brussels International Trade Fair, Place de Belgique, 1020 Brussels, Belgium. *Telephone:* 02/478.48.60. (*International:* + 32 2 478 48.60). *Telex:* 23.643.

25-27 November: **Power Electronics and Variable Speed Drives Conference** in association with the **Drives, Motors and Controls Exhibition.** National Exhibition Centre, Birmingham, England. Conference organised by The Institution of Electrical Engineers and originally scheduled for London in June.
Details from: Evan Steadman Communications Group, The Hub, Emson Close, Saffron Walden, Essex, United Kingdom CB10 1HL. *Telephone:* 0799 26699. (*International:* + 44 799 26699). *Telex:* 81653.

1987

25-26 February: **Instrumentation '87** and conference on **'Trends in Instrumentation'.** Harrogate, England. The conference is organised by the Instrument Science and Technology Group of the Institute of Physics.
Details from: Trident International Exhibitions Ltd, 21 Plymouth Road, Tavistock, United Kingdom, PL19 8AU. *Telephone:* 0822 4671. (*International:* + 44 822 4671). *Telex:* 265871.

14-18 September: **Weldex 87.** National Exhibition Centre, Birmingham. The exhibition is sponsored by the Welding Manufacturers Association BEAMA, and the Welding Institute with the support of British Compressed Gases Association, Association of Welding Distributors, and British Association for Brazing and Soldering.
Details from: Weldex 87, Industrial and Trade Fairs Limited, Radcliffe House, Blenheim Court, Solihull, United Kingdom B91 2BG. *Telephone:* 021-705 6707. (*International:* + 44 21 705 6707). *Telex:* 337073.

27-29 October: **10th London H & V Show.** London, England.
Details from: Trenton Group Ltd, Trenton House, Imperial Way, Croydon, United Kingdom CR9 4RR. *Telephone:* 01-680 7525. (*International:* + 44 1 680 7525).

1988

18-21 January: **The British Engineering Supplies and Technology Exhibition.** Olympia, London, England.
Details from: Mack-Brooks Exhibitions Ltd, Forum Place, Hatfield, Herts, United Kingdom AL10 0RN. *Telephone:* 07072 75641. (*International:* + 44 7072 75641). *Telex:* 266350.

September: **Conference on Heat Transfer.** London, England. Date and venue to be finalised.
Details from: The Institution of Mechanical Engineers, 1 Birdcage Walk, London, United Kingdom, SW1H 9JJ. *Telephone:* 01-222 7899. (*International:* + 44 1 222 7899). *Telex:* 917944.

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Table 3: Savings Achieved and Pay-back Time After Installation of Additional Equipment.

	Savings	**Pay-back**	
	(%)	(kWh per year)	(Years)
Concert hall Oslo	40	500 000	1
Auditorium Trondheim	12	23 000	1.5
Tranbyhallen Oslo (Sports hall)	10	33 000	4.3

the absolute saving and the costs of carrying out the measurements and delivering and commissioning the air quality control plus in the first example some modifications to the system.

Conclusion

The Taguchi gas sensor is capable of measuring the degree of air contamination. The sensor signal acts on the fan speed or on a mixing air damper *via* a proportional controller. This makes it possible to reduce the minimum outside air volume required during full occupancy on the basis of the effective air quality, thus saving heating and cooling energy expended on handling and distributing the outside air. The extent of the saving depends heavily on the internal heat gain, the outside air rate per person and the room occupancy. To be able to make a reliable prediction of savings and payback on the additional equipment required, a separate energy calculation therefore needs to be made in each case.

Acknowledgement

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