(2 to 14 $m^3/h \cdot m^2$), but due to extensive use of return air, the amount of fresh air was usually very low. Combined with poor ventilation effectiveness and poor HVAC-control, it was reasonable to blame the ventilation system.

In order to investigate this hypothesis, the ventilation system at school C was renovated in 1990. The supply air flowrate was adjusted to approximately 14 $m^3/n \cdot m^2$ (8 $l/s \cdot p$) and no return air allowed. No changes were done with respect to the use or the shape of the classrooms.

In the autumn of 1991 we repeated the questionnaire at school C. At the same time a technical survey was carried out in order to verify that the ventilating plant was still operating satisfactorily with respect to the amount of fresh air.

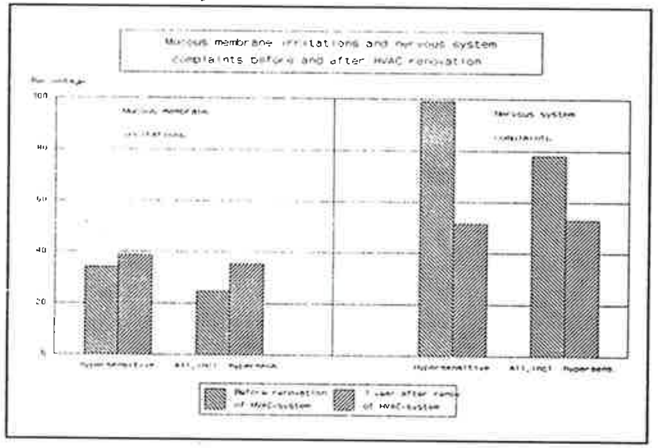

Fig. 4 Mucous membrane irritations and nervous system complaints, school C, before and after ventilation system renovation.

Figure 4 shows that the rate of nervous system complaints had dropped significantly while the mucous membrane irritations are at the same level as before. Although this result concerns only one building, it indicates that increased ventilation reduces general symptoms but not sensory reactions. Removal of fleecy factors, such as wall-to-wall carpets, open bookshelves and wall decorations (dust deposits) are probably equally important in order to reduce this kind of problems.

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# MIXED-GAS SENSORS - STRATEGIES IN NON-SPECIFIC CONTROL OF IAQ

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## ABSTRACT

While outdoors some known pollutants may be present in higher concentrations a wide spectrum of mainly unknown contaminants is typical for indoor air. The knowledge about combined and long term effects of volatile organic compounds and respirable suspended particles with high adsorptive load on gases and vapors on human health is still fragmentary. But the first step to healthy indoor air is to minimize emissions from sources as building materials, interior (furniture, equipments), HVAC systems, and only secondly by demand controlled ventilating (DCV) systems. DCV systems have to be controlled by sensors. While classical $CO_2$- and humidity-sensors detect above all human emissions mixed-gas sensors (MGS) are responsible for a large scale of pollutants. Up to now knowledge about mixed-gas sensors is very limited. Experimental studies with metal oxide sensors showed problems in stability, drift and reproducibility. An air mixture (n-Decan, Toluol, 1,1,1-Trichlorethan, α-Pinen, Ethylacetat) was used as standard pollutant. Concentrations were controlled by gaschromatography. High influence of humidity and non-systematic differences in sensitivity between the single compounds are the main dilemma for the practical use of MGS. For constant mixture ratio - the normal case in most of indoor environments - our experiments showed a good correlation with air quality, but simultaneous compensation of air humdity is essential.

## INTRODUCTION

In 1858 Max von Pettenkofer (1), a German hygienist, defined the $CO_2$-value for good indoor air quality. The reason for the use of this metabolic output as an index for all the other emissions of human beings: $CO_2$ was easy to measure. We are still using Pettenkofer's 0.1%value, but emissions have changed during the last decades. Field studies on perceived air quality (2,3) in several buildings of Copenhagen showed, that less than 1/5 of the pollution load came from occupants and the main emission sources are ventilation systems, building materials and interior. To find a new index for these non-human emissions Pettenkofer would be in a dilemma. Pattern of pollutants varied from room to room, from time to time, depending on temperature, humidity, cleaning procedures, building maintenance, habits, economy, etc.

Both groups of indoor air pollutants may warn man by sensory terms but a stay of some minutes in the room decreases this physiological function by adaptation. Longtime pollution load without sensory feedback mechanisms, as known for thermal and acoustic parameters, are the consequences. For a few pollutants the pathophysiological way to a Building-Related Illness is known, while most of the others may lead to effects, usually called Sick Building Syndrome.

So occupants cannot be responsible for good air quality. Primary healthy indoor air has to be guaranteed by prevention: Minimize the emission sources. That looks to be a hard work for scientists and politicians for the next decades.

Simultaneously a second way has to be gone: As at the time of Pettenkofer sufficient ventilation leads to healthy air, which ASHREA defines *'air in which there are no known contaminants at harmful concentrations'*. To make ventilation sufficient without energy deficit demand control is required. But control of ventilation works only with suitable sensors, $CO_2$- or humidity-sensors for the Pettenkofer-case and 'all-over-integrating'sensors for emissions by materials. To develop sensors for non-human pollutants may be one of the most effective modes to avoid sick buildings now.

Table 1. Guidelines for the application of air quality sensors (following (5)).

| room | dominant emission | | sensor | |
|---|---|---|---|---|
| | anthropogen | VOC, smell | $CO_2$ | MGS |
| school | ■ | | ■ | |
| office | | ■ | | ■ |
| conference | ■ | | ■ | |
| theatre | ■ | | ■ | |
| cinema | | ■ | | ■ |
| hotel | ■ | | ■ | |
| restaurant | | ■ | | ■ |
| shop | | ■ | | ■ |
| housing | | ■ | | ■ |

Raatschen (4) analyzed with his state-of-the-art review the present sensor market. He found that at this time knowledge about the performance of mixed gas sensors is very limited. Main problems are long term experience, drift, stability, reproducibility, calibration, cross sensitivities to humidity, etc. Recommendations for the application of the two basic groups of sensors are given in (5) (see Table 1).
Air quality sensors have some advantages: they are able to substitute to some extent the human nose without any adaptation, and they can record even such pollutants which man does not smell.
Considering the pros and cons of MGS some pilot investigations from the view of experimental hygiene were made, to gain experience of possibilities and circumstances for the use of air quality sensors.

## MATERIALS AND METHODS

The investigations are subdivided into three parts:

α) Pilot study in life buildings - comparison of the air quality measured with the MGS and by the method of perceived IAQ (Fanger et al.(6)) in decipol.
ß) Influence of smells - laboratory comparison of MGS and perceived air quality.
γ) Test chamber investigations on single VOCs and on a mixture, modelling indoor air pollution under gaschromatographic control.



Metal oxide sensors in thin-layer technology were used for all experiments. During the chamber studies simultaneously two sensors with different temperatures of the active layer and slight chemical distinctions were applicated.

To compare MGS-output and decipol in life buildings, during a field study on perceived air quality in danish office buildings (3) the mixed gas sensor was applied for recording air quality. Simultaneously a trained panel (n=11) was voting directly in decipol. As a second objective method TVOC concentrations were measured by a photoacoustic device.

To correlate GMS and decipol under extreme conditions, odorous substances (see Table 2) were used as emission sources. Members of a trained panel (n=7) were exposed to ventilated jars as described by Bluyssen and Fanger (7). Subjective voting of the perceived air quality and simultaneous MGS measurements were carried out under clean room conditions.

Table 2. List of odorous substances used for GMS-decipol comparison.

| SUBSTANCE | FORMULA |
|---|---|
| Thymol | $C_{10}H_{14}O$ |
| Terpineol | $C_{10}H_{18}O$ |
| Eucalyptol | $C_{10}H_{18}O$ |
| Menthol | $C_{10}H_{20}O$ |
| Borneol | $C_{10}H_{18}O$ |
| Fenchol | $C_{10}H_{18}O$ |
| Campher | $C_{10}H_{16}O$ |
| Menthylacetat | $C_{12}H_{22}O_2$ |
| Diphenylether | $C_{12}H_{10}O$ |
| Diphenylmethan | $C_{13}H_{12}$ |

Table 3. List of single chemicals used for chamber experiments.

| SUBSTANCE | FORMULA |
|---|---|
| n-Decan | $C_{10}H_{22}$ |
| Toluol | $C_7H_8$ |
| 1,1,1-TCE | $C_2H_3Cl_3$ |
| α-Pinen | $C_{10}H_{16}$ |
| Ethylacetat | $C_4H_8O_2$ |
| Aceton | $C_3H_6O$ |
| Benzol | $C_6H_6$ |
| n-Octan | $C_8H_{18}$ |
| n-Nonan | $C_9H_{20}$ |
| ß-Pinen | $C_{10}H_{16}$ |
| n-Undecan | $C_{11}H_{24}$ |
| n-Dodecan | $C_{12}H_{26}$ |

The response of air quality sensors to single VOCs and mixtures was investigated in a test chamber. An exsiccator tower was ventilated from a closed system. To control air quality in the system, bypasses with heat exchanger and absorbers were installed. Injection of VOC's and sampling for GC injection were made through a silicon membrane. Sensor response and chamber air temperature were measured continuously, and stored on a PC.

Table 3 lists all single substances investigated in the chamber. The following chemicals were used as mixture, modelling typical indoor air pollutants: n-Decan (as part of cleaning agents), Toluol (glue, felt tips), Trichlorethan (dry cleaning, furniture and shoe polish), α-Pinen (wood, washing-up and cleaning agents) and Ethylacetat (glue, solvent in many cleaning and care products).

The conditions for all experiments: air temperature near the sensors = 22° ... 24°C, dry and clean air at the beginning of each measuring cycle, cleaning up after each experiment and negative control by gaschromatography (FID and ECD).

## RESULTS

### ad α) Comparison of MGS and decipol

The MGS signal in all of the 9 investigated office buildings varied between 15% and 85%, while decipol values were found from 2 to 7. There was no significant correlation, but a slight trend was found by linear regression:

$$C_i = 2 \cdot MGS/100 + 3 \quad (1)$$

where $C_i$ = the perceived air quality, judged by a trained panel (n=11) and MGS = the sensor output in %.

### ad ß) Influence of smells on MGS/decipol comparison

Figure 1 correlates sensor output and subjective voting for the odorous substances listed in Table 2. Comparing equation (1) with the regression line (Fig. 1) man perceives smells ten times more sensitive then the air quality sensor.

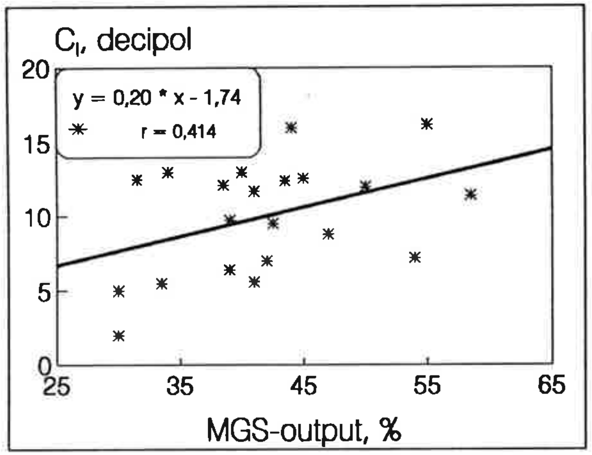


Fig. 1. Relation between perceived air quality in decipol and the signal of the mixed gas sensor for odorous substances as pollution source.

The comparison of the concentration equivalents, measured by MGS and photoacoustics showed a good correlation:

$$PA = 1.27 \cdot MGS - 15.2 \quad (r = 0.905) \quad (2)$$

where PA = TVOC concentration equivalent, measured by photoacoustics.



### ad γ) Chamber investigations

First experiments were made on the influence of water vapor on MGS signal. Equation (3) shows, that moisture effects the MGS output intensively:

$$MGS = 1.4 \cdot RH + 8 \quad (r = 0.991) \quad (3)$$

where RH = relative humidity in %.

The humidity effect on mixed gas sensors is overlapped by a second mechanism: increasing humidity leads to higher TVOC concentrations because of desorption from the surfaces of the closed system as GC controlled measurements under water injection showed. In consequence of these findings all chamber experiments were done with dry air.

Figure 2 shows the response of the two sensors to a model mixture. Good reproducibility over 3 experiments and corresponding curves were found. Sensor II reacted with a more homogeneous course while MGS I was more sensitive in the central field of concentrations.

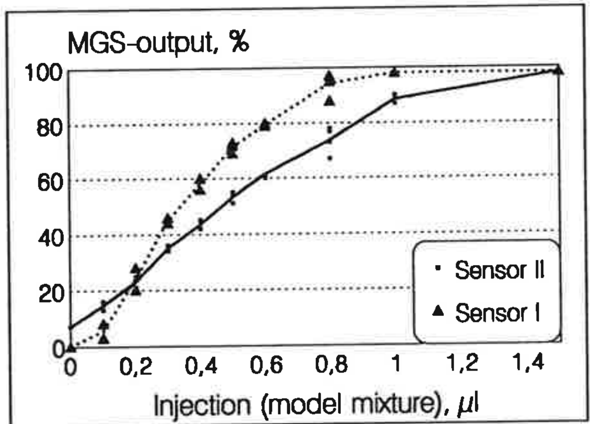


Fig. 2. Concentration curve of both sensors for the model mixture.

To determine the quota of each of the compounds and to find out how the sensors will react if intramixture concentrations are changing, all compounds (see Table 3) were separately investigated. Figure 3 gives the results of these measurements: MGS-signal after injection of 0.5 µl of the 12 chemicals. The substances are in order of increasing boiling points. Immense differences are noticeable between the two sensors. MGS II shows a steady output for all pollutants except those with a higher boiling point. MGS I is very sensitive for 5 substances and nearly non-sensitive for the other ones.

A first raw conclusion is: MGS II-like sensors may be used to determine TVOC load in a room while MGS I-sensors may be able to sniff. But today both sensors can only be used for steady state conditions in the inter-mixture ration, otherwise paradox results will occur. But a good chance to describe air quality realistically can be the linking of more sensors with different characteristic if a logical connection can be established.

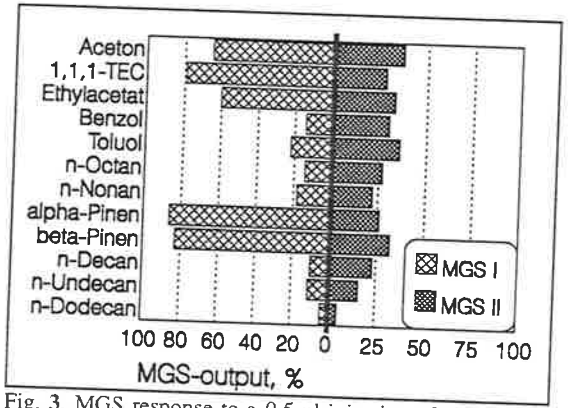


Fig. 3. MGS response to a 0.5 µl injection of single substances.

## CONCLUSIONS

Pilot studies on metal oxide sensors from the view of experimental hygiene have shown

- It is still impossible to determine air quality by sensors of the present generation **in analogy** to IAQ perceived by man.

- Concentrations of single pollutants and mixtures of them with constant mixture ratio can be measured and controlled by MGS.

- Regulation of air quality in spaces with sporadic changing of some of the pollutants by air quality sensors may occur hyper/hypo-ventilation. But development and adaptation of non-selective sensors are a feasible way for a healthy environment indoors.

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# INDOOR AIR QUALITY AND ENERGY CONSUMPTION WITH DEMAND CONTROLLED VENTILATION IN AN AUDITORIUM

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## ABSTRACT

The ventilation system of an auditorium was regulated in response to continiously measured $CO_2$ concentrations in the room, or according to the time-table of the occupancy. The running time, the energy consumption and several climatic parameters as well as the $CO_2$ concentrations were measured under winter and summer conditions. Furthermore, the occupants' judgement of the indoor air quality was surveyed with a questionnaire. It was shown that during the monitored periods the ventilation controlled by measured $CO_2$ concentrations consumes 80% less energy during summer and 30% less during winter than the ventilation operating on a fixed time-schedule. If all the avoidable sources of odour in the room would be eliminated, the indoor quality would still remain within an acceptable range.

## INTRODUCTION

Over the last few years, various attempts to run Demand Controlled Ventilation (DCV) Systems have been conducted at international levels (1). However, only in a few of these trials have the possible energy savings of DCV systems been calculated or measured, compared to conventional systems recording **simultaneously** the users' judgement of the indoor climatic parameters and the indoor air quality. Feedback is therefore missing concerning the user acceptance of the possibly altered DCV system conditions. As our own investigations had shown (2) that user perception of indoor air quality correlates well with the $CO_2$ content of indoor air (correlation coefficient: 0.77), corresponding trials were run using a $CO_2$ controlled DCV system. The experimental set-up was as follows:

- Installation and operation of a $CO_2$ controlled DCV system in an auditorium.
- Measurement of the electrical, heating and cooling energy saved in comparison to the normal operating mode (time control) of the ventilation system.
- Measurement of the indoor air quality and of the most important indoor climatic parameters at different locations of the auditorium during both control conditions.
- Surveying of the room occupants regarding indoor air quality during both conditions.

## MATERIALS AND METHODS

The trials were undertaken in an auditorium of the Swiss Federal Institute of Technology in Zurich. The auditorium has a surface area of 120 $m^2$, a volume of 440 $m^3$, and a seating capacity of 80 persons. The room features two external walls, each with three sound