MOS gas sensor technology for demand controlled ventilation

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SUMMARY

Due to increasing interest in indoor air quality and demand controlled ventilation in buildings aiming at energy and cost saving, as well as health and comfort aspects, the objective of our work has been the development of a reliable, low cost tool for demand ventilation control. Based on a single microelectromechanical (MEMS) metal oxide semiconductor (MOS) gas sensor VOC detection as close as possible to perceived air quality and additionally, a good correlation with measured CO_2 concentrations due to implementation of an empirical data evaluation algorithm has been achieved.

KEYWORDS

Indoor air quality, Volatile organic compounds, Demand controlled ventilation, Metal oxide semiconductor gas sensor.

INTRODUCTION

Since modern people spend ~ 90% of their lifetime indoors and ~ 40% of the total amount of energy in Europe is consumed in buildings especially for heating, cooling and ventilation (Clear-up, (2008)), there is an increasing interest in indoor air quality (IAQ) monitoring and demand controlled ventilation (DCV) in non-industrial buildings aiming at energy and cost saving as well as better comfort for occupants comprising improved perceived air quality, better productivity and less health problems (e.g. asthma or allergies (WHO, (2002)) caused by indoor air pollution.

IAQ refers to the condition of air as perceived by humans (Fanger, (1988)) dependent on the individual person as well as the composition of air. With heating ventilation air conditioning (HVAC) systems it is only possible to influence the composition of air in the room. Inadequate ventilation may cause accumulation of indoor air pollutants whereas they are diluted by ventilation in buildings equipped with HVAC systems which are generally operated on basis of fixed duty cycles without regarding the actual load condition. Uncontrolled preventive increase of ventilation results in an increment of overall energy consumption. More efficient use of HVAC systems in buildings applying DCV offering variable airflow rates adapted to the actual load conditions in a room is recommended to achieve considerable energy saving (Maripuu, (2009)).

DCV systems using sensors to control the composition of air (IAQ) have become of interest as a result of more strict hygienic ventilation requirements indoors. Standards (i.e. EN 15251, (2007)) that specify ventilation rates for keeping acceptable IAQ are well established for applying CO_2 as indicator for occupancy generated pollutants related to percentage of dissatisfied with the IAQ, since CO_2 is the most important biologically active agent whose production is proportional to the human metabolic rate and nearly proportional to the rate of other bio-effluent generation. Therefore, most attempts to implement DCV on IAQ control so far rely on the quantification of CO_2 based on optical absorption techniques (non-dispersive infrared sensors). However, due to their high price and their limited correlation to comfort and health complaints indoors their use in room-air control is still very rare.

Due to the fact, that there are also several other contaminants, especially volatile organic compounds (VOCs) which are produced by human metabolic processes, human activities, infiltration of outdoor air etc. present in indoor air and have superior impact on perceived air quality and well-being of occupants (Wolkoff and Nielsen, (2001)), they have become a criteria for IAQ control as well. In consideration of the fact, that it is still unknown which gases are the main responsible ones that should be controlled by DCV, broad-band sensing of metal oxide semiconductor (MOS) gas sensors can be advantageous for activity related DCV.

Since sensory pollution load from people is a mixture of a wide range of VOCs produced by human metabolism processes (bio-effluents), clothing and cosmetics (e.g. conditioner, deodorant) as well as certain activities (Burdack-Freitag and Mayer, (2007)) a study under various conditions in buildings has been carried out at the Fraunhofer Institute for Building Physics (IBP) that enabled identification and quantification of 8 anthropogenic VOCs occurring in an average concentration range from ~12 to ~600 [$\mu g/m^3$] as well as their correlation with perceived air quality. Based on these results the main focus of our work as member of the European clear-up project (Clear-up, (2008)) has been the development of an innovative, small, low cost and low power consuming tool based on a single MOS gas sensor that enables to monitor changes of IAQ from the presence of anthropogenic VOC as close as possible to perceived air quality with the functionality to correlate real CO_2 concentrations due to implementation of an empirical data evaluation algorithm.

METHODS

In order to point out the best sensitive MOS gas sensor material for IAQ monitoring regarding anthropogenic VOCs (metabolism or activity), measurements in laboratory investigating differently doped SnO_2 sensing layers, suitable operating conditions (e.g. operating temperature) and evaluation modes have been carried out. In cooperation with the IBP several real-life tests under various conditions in buildings (e.g. meeting rooms, bedrooms, kitchens, restrooms) have been realized using analytical instrumentation simultaneously in order to evaluate the sensitivity and efficiency of monitoring IAQ correlated to quantifiable anthropogenic VOCs in accordance with perceived air quality by means of our developed IAQ-module and to optimize the expressiveness of the implemented empirical data evaluation algorithm for CO_2 prediction.

Air samples trapped on TENAX TA® adsorber tubes (sampling time 20 min) have been taken sequentially starting with the room in an empty ventilated state to define a background level. VOCs released by humans and other ongoing activities (e.g.

cooking) have been identified and quantified by gas chromatography/mass spectrometry (GC/MS). In order to control the overall IAQ ambient temperature and relative humidity has been monitored as well. A commercially available non-dispersive infrared CO_2 sensor served to compare the effectiveness of the applied evaluation algorithm for CO_2 prediction (Herberger et al., (2009)). Observations of attendees have been used as a clue of perceived air quality.

The sensor component used for detection of relative changes in room air is MEMS MOS gas sensor. Data evaluation is based on a change in resistance R [Ω] in presence of VOCs, an automatic baseline correction (baseline initiated at defined outdoor CO_2 concentration) and transfer into prediction of CO_2/VOC equivalent units [ppm], that can be linked to specific air quality levels (AQLs) according to definite thresholds for CO_2 concentration in indoor air (output range: 350-2000 ppm). The calculated AQL can be used to control e.g. a fan or volume flow regulator. Detection of CO_2 is indirect via correlated VOC levels. Anthropogenic CO_2 is correlated to anthropogenic VOC (Herberger et al., (2009); AppliedSensor, (2009)).

RESULTS

Analytical approach - CO_2 vs. VOCs

In order to demonstrate the advantage of the MOS gas sensor based IAQ-module in real-life, where changes of CO_2 are too small to serve as indicator for bad air and to show data evaluation process as well as to emphasize correlation with specific VOCs quantified by PT-GC/MS, a cooking event performed in a kitchen (V_r=77 m^3) is given as an example. In a kitchen the air is mainly dominated by VOCs that affect perceived air quality rather than from CO_2. The sensors have been spotted in the middle of the room. Activities are labeled in Fig. 1 starting from the ventilated room.

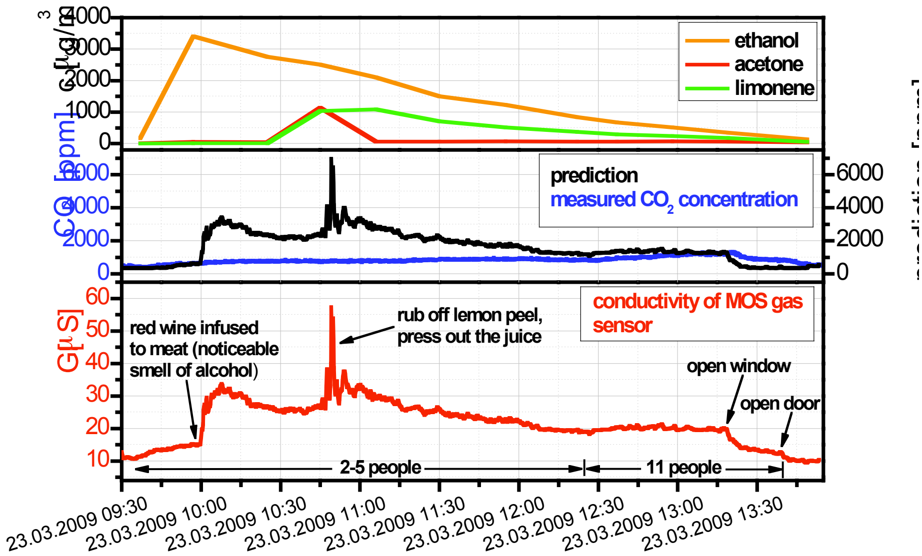

Figure 1: *Bottom*: Raw sensor signal (conductivity G [μS]) of MOS gas sensor. *Middle*: Correlation of predicted sensor signal (prediction of CO_2 equivalent units [ppm]) with measured CO_2 concentration [ppm] and ability to detect VOCs beyond CO_2. *Top*: Run of concentration [μg/m^3] of ethanol, acetone, and limonene during the event.

The graph at the bottom of Fig. 1 shows the MOS sensor raw data (conductivity data G [μS]) that is used as input for the subsequent calculations according to the evaluation algorithm. The graph in the middle of Fig. 1 therefore shows the predicted sensor signal (prediction of CO_2 equivalent units [ppm] with baseline initiated at CO_2 concentration of 350 ppm) after applying the evaluation algorithm compared to the measured CO_2 concentration in the room using a non-dispersive infrared CO_2 sensor. The graph at the top of Fig. 1 shows the good correlation of the sensor data with the run of the concentration [$\mu g/m^3$] of three significant VOCs (ethanol, acetone and limonene) identified and quantified by GC/MS, indicating times during the cooking event (at ~ 10:00 and 10:50 p.m.) where most of the VOCs and odorous compounds affecting perceived air quality are produced. As can be seen from Fig. 1 a rise in the concentration of these VOCs can be attributed to cooking activities. The accumulated appearance of the quantified VOCs correlates with the hedonic impression of an unpleasant air quality which is in good accordance with the sensor data.

The superior functionality of the IAQ-module for IAQ control closer to perceived air quality compared to quantification of CO_2 is obviously shown. Since the CO_2 sensor is only able to measure the CO_2 emission produced by the human metabolism and therefore only correlates with the number of attendees, the MOS gas sensor is able to detect in real-time VOC related changes in indoor air originating from human metabolism and ongoing cooking activities (i.e. the sum as well as point source VOCs) beyond CO_2. The main signal caused by cooking activities corresponding to approximately 7000 ppm of CO_2 can not be seen in the CO_2 signal. Due to the applied evaluation algorithm, there is a direct, reliable correlation with CO_2 levels in the room. One further important advantage compared to other analytical methods for IAQ control is also obvious, i.e. the fast response and real-time capability when there are changes in IAQ. As soon as the red wine is infused to the meat, a change in the conductivity of the MOS gas sensor indicating produced VOCs can be achieved. The sampling time for GC/MS analysis on the other hand takes 20 minutes.

Application in real-life

In order to emphasize the intended application in real-life, i.e. DCV based on VOC detection the performance of the IAQ-module installed in a HVAC system in a gym is shown in Fig. 2. The predicted sensor signal (calculated AQL) is used as control system for IAQ and trigger for turning on the supply air flow of the ventilation system. The graph at the bottom of Fig. 2 shows the predicted sensor signals of one sensor module installed inside plus one reference module fixed outside the ventilation system (operated at two different output signal types) compared to the measured CO_2 concentration. The predicted and measured CO_2 concentrations are consistent, with the further ability of the IAQ-module to detect odor events beyond CO_2. The performance of the supply air flow of the ventilation system in accordance with the predicted sensor signal can be taken from the graph at the top of Fig. 2. The prediction of CO_2 equivalent units of the sensor module used in the ventilation system is limited to a value of 2000 ppm, this means that the HVAC system should run 100%. Contrary to time or presence controlled systems the IAQ-module ventilates a room only if the air is deteriorated. Energy conservation up to 60% could be reached by DCV using the IAQ-module as control system compared to time-controlled ventilation.

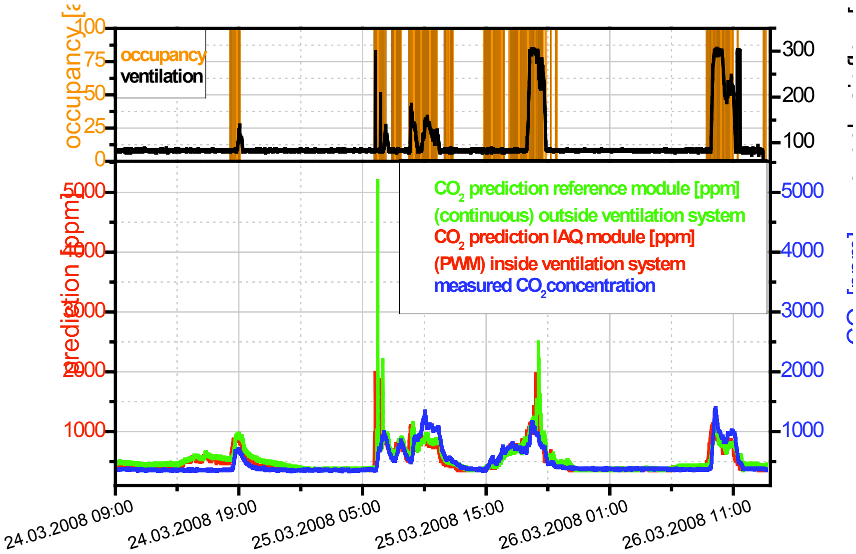

Figure 2: *Bottom*: Correlation of predicted sensor signals (prediction of CO_2 equivalent units [ppm]) of two IAQ modules, one installed in the ventilation system and one reference module fixed outside (operated at two different output signal types), with the measured CO_2 concentration. *Top*: Performance of supply air flow of HVAC system in accordance with predicted sensor signal and correlation with grade of occupancy (use of occupancy sensor) in the gym.

DISCUSSION

Due to the fact that the CO_2 concentration in a room can solely be considered as an indicator of indoor air pollution linked to the grade of occupancy but does not correlate with perceived air quality or consider health aspects we developed a module equipped with one single MEMS MOS gas sensor for IAQ monitoring as close as possible to perceived air quality in real-time. Based on the results from IBP concerning anthropogenic VOCs we optimized the MOS gas sensor material and adequate working conditions for detection of occupancy related indoor air pollution. Field tests using analytical instrumentation simultaneously in order to elucidate the sensitivity and efficiency of monitoring IAQ in accordance with human effluents, perceived air quality and CO_2 prediction have been performed. Finally installation of the IAQ-module in a commercially available ventilation system has been carried out in order to make a statement on energy saving.

All data obtained from real-life tests show the good correlation between the IAQ-module and anthropogenic VOCs (> 300 $\mu g/m^3$) but very low relative sensitivity to office furniture etc., which is advantageous for their application for activity related DCV. A direct, reliable correlation of anthropogenic VOCs with CO_2 levels in a room could be achieved due to implementation of an empirical evaluation algorithm.

The developed module offers a solution based on a single controlling component for DCV in real-time and is not limited to applications in premises where pollution loads that vary in time are only activity related (kitchen, restrooms) or dependent on other sources but also where people are the main pollution source (e.g. meeting rooms, schools). This has been achieved due to correlation of anthropogenic VOCs/CO_2.

Due to its functionality in a temperature range from 0°C to +60°C and the possibility to detect significant changes in humidity indicating bad air there might be additional functionality where humidity changes are of interest. Often the emission from outdoor air (vehicle traffic, industries and related combustion) can cause the problems of IAQ. Even if the CO_2 outdoor concentration varies little in time the outdoor conditions might be checked with the IAQ-module, since VOCs like benzene and toluene will be detected by means of MOS gas sensors. Also other health related gases like CO can be detected and potentially serve as control parameter for DCV.

CONCLUSION

Our developed IAQ-module based on a single MOS gas sensor, combines both, VOC detection and prediction of CO_2 equivalent units due to implementation of an empirical evaluation algorithm. Real-time IAQ control more precisely and closer to perceived air quality than using CO_2 as indicator for DCV has been achieved. The technological process of MEMS MOS gas sensors in terms of stability and reproducibility has promoted the technology for mass market particularly where small size, low power and low cost is a demand. The evaluation algorithm avoids false events, sensor drifts and therefore recalibration of the module. An expected lifetime of at least 10 years without any maintenance facilitates installation in a variety of applications. In order to ensure the efficiency of the module and to estimate the energy saving potential, specific operation modes, long-term stability tests and field tests taking into account also ambient air have been investigated. Tests using CO as control parameter for safety applications/ventilation has been started.

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