DEVELOPMENT AND VALIDATION OF A VISUAL VENTILATION GUIDING DEVICE (VVGD) FOR USE IN DWELLINGS AND SCHOOLS

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ABSTRACT
Especially in northern European countries the insulation and the sealing of buildings increases in order to save energy. Thus the exchange between indoor and outdoor air is reduced. On the other hand, modern building materials often show considerable emissions of volatile organic compounds and thus may contribute to a decrease of indoor air quality, if there is no adequate ventilation of the rooms. An increasing indoor air humidity can be a possible consequence of insufficient air exchange rates, which may lead to an increased risk of mold growth. Within a research study, a visual ventilation guiding device (VVGD) for online-measurement of indoor air quality was developed. It contains sensors responding to volatile organic compounds, temperature and humidity and supports the users with an optical recommendation for free ventilation, i.e. opening or closing the windows. The VVGD was used and calibrated in dwellings, flats and schools supported by simultaneously performed “classical” analytical procedures.

INDEX TERMS
visual ventilation guiding device (VVGD), ventilation, gas sensor (GS), volatile organic compounds (VOC), total organic compounds (TOC), temperature, humidity

INTRODUCTION
Natural ventilation (ventilation through free joints, window ventilation and pit ventilation) depends strongly on varying driving forces (wind, temperature differences, etc.) as well as on the different need of ventilation. Without technical aid, a well adjusted ventilation (in quantity and duration) can be attained only coincidentally, because the human sensory organs are not reliable enough in order to judge the air quality necessary for human well-being or maintenance of the building materials. As long as the ventilation behavior itself depends not on the actual need, but on individual feeling of smells or temperatures, health risks or building materials damages can occur.

Ventilation, at least during the heating period, always implicates losses of heating energy, which should be minimized. Rooms are frequently ventilated too much because some of the conditions related to ventilation (like wind, temperature difference outside/inside...) may vary without being noticed. On the other hand, poor ventilation can lead to higher loads of indoor air with VOCs and humidity which may create risks to the inhabitants health or may lead to damages on building materials.

It is difficult to ventilate rooms manually in a well adjusted and appropriate manner. "As much ventilation as necessary, as little as possible", this should be the guiding principle. Since humans do not have a comprehensive sensorium, help - in this case the visual ventilation guiding device (VVGD) - is useful to the inhabitants to improve and adjust their ventilation behavior. The VVGD converts the signals of the gas sensor, of the temperature- and humidity sensor into an optical recommendation how to act.

The air quality sensor - as the heart of the VVGD - supplies a non-standardized and unit-free signal as a function of the quantity of oxidizable substances in the surrounding atmosphere. The goal of the development is a reliably working VVGD, which gives a scientifically based recommendation for ventilation which can be simply understood by the user.

METHODS
Checking of the air quality sensor
As sensor packages the SSM GS (Smart sensor module with gas sensor) for the air quality measurement and the

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SSM HT (for temperature and humidity) - as shown in figure 1 - are used. An external surface temperature sensor permits collect the external wall temperatures directly to evaluate to the local room air humidity. The heart of the SSM is a combustible gas sensor device (in the following named „gas sensor“) which consists of a heated semiconductor plate based on mixed metal oxides.

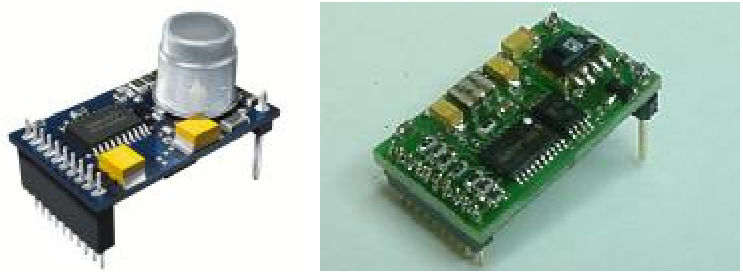

Figure 1. *Smart sensor module (GS, left) and HT, right (source: Co. ETR, Dortmund, Germany)*

By performing a test series with selected substances the signal output of the gas sensor was determined for different concentrations. These investigations took place in a test chamber. With far more than hundred different volatile organic substances (VOC) in interiors proven (Krause et al. 1991), it was impossible to examine each substance. Thus, for each substance group of the VOC a reference substance was used.

Simultaneously, pollutant investigations were accomplished with the photo-acoustic multi-gas monitor from INNOVA AirTech Instruments and - in the classical procedure - by thermal desorption gas chromatography and mass spectrometry (TD/GC MS). Data recording took place on-line via PC or by means of a data logger. A diagram of the test chamber measurements is shown in figure 2.

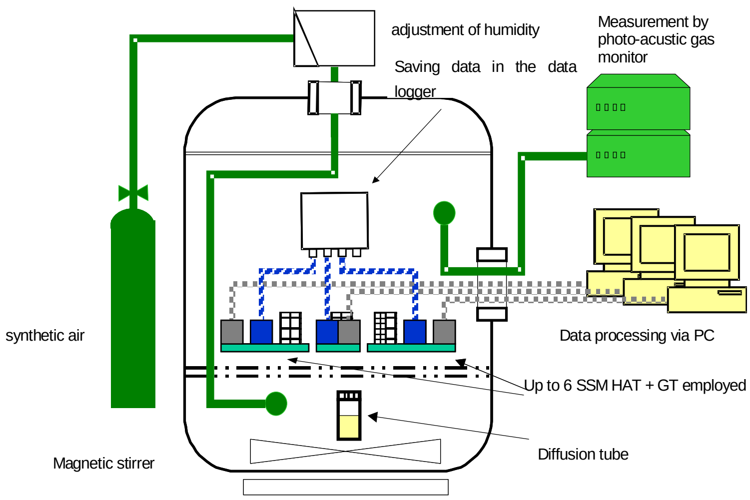

Figure 2. *Measurement setup for comparative measurement in the test chamber of the Environmental Institute of Bremen.*

During the field test, the gas sensors were exposed to the room atmosphere in order to test their response characteristics under typical conditions of room usage.

Choice of parameters measured and definition of the indicator values

A special software converts the signals of the sensors to electric signals being output on a LED display, so that a simply readable indicator is to the user’s disposal, similarly to a traffic light. The gas sensor signal corresponds directly to the content of oxidizable substances in indoor air. This content should not exceed a certain upper limit, which is set in relation to an average level of contamination in fresh outside air. Concentrations lower than a defined lower limit should be judged as “uncritical”. The VVGD should react immediately to steep rises of the gas sensor signal.

The indoor humidity must be evaluated in view to the danger of possible mould growth. Therefore, an upper limit for humidity should be defined at 80 % RH. With respect to the housing comfort, a minimum humidity level should be stated as well. It is crucial that the users react to strong rises of the humidity level rather fast.

Any energy consumption due to excess ventilation is to be minimized. Since the users usually are not able to react to the readout of the VVGD immediately, a delay in the users reaction to the recommendation "open windows" or "close windows" is likely to happen. Thus, the recommendation may be displayed slightly delayed, but with certainty.

As input signals, the air quality of the gas sensor, relative humidity rF_{HT} and temperature T_{HT} of the SSM HT are used. The external wall temperature T_{AW} is also recorded. It is read out from a building material surface which is likely to show the lowest temperature of all surfaces in the room. If the external wall temperature sensor is not connected to the VVGD, an external wall temperature based on a correction table is estimated. As the display unit of the VVGD, 2 scales with in each case 6 colored light emitting diodes (LED) were selected as bargraph display for the readout of air quality and humidity. Thus the user can distinguish whether a need of ventilation exists due to air pollutants or due to excessive humidity. Figure 3 shows the selected design.

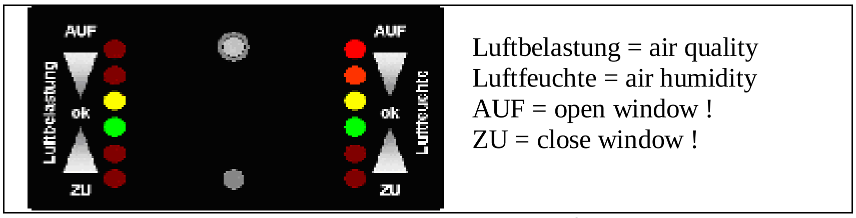

Figure 3. *Display unit and lettering of the VVGD*

Practice tests in dwellings and schools

A field test was accomplished in 15 dwellings and 5 class rooms. The housing units and class rooms were examined in a different manner: three dwellings and the class rooms were tested for a long period of time (4.5 months); 12 dwellings were examined during a short-term test (1.5 months).

Two dwellings were chosen for a long-term testing and equipped with one VVGD each. The VVGD should be set up for a defined period of time - like it is intended also for later practice - in one of the rooms, thus the inhabitants should „learn“ an adequate ventilation behavior. After this time the VVGD should be placed in another room.

The remaining 12 dwellings were examined for approx. 6 weeks intensively. They were equipped with a VVGD for each room.

The testing procedure in the class rooms essentially corresponds to that of the long-term testing. Due to the specific use of a class room the teachers were asked to record the user behavior (occupying of the room, closing/opening of doors and windows, etc.).

During the field test, a total of 35 VVGDs were installed with 19 test users. During the first 2 weeks the VVGDs were set up with covered displays in the “measuring mode”, in order to take up the unimpaired weekday room utilization (logger period). Thereafter the display was opened and the users were asked to act according to the recommendations of the VVGD (indocator period). Figure 4 shows the temporal operational sequence of the short-term test:

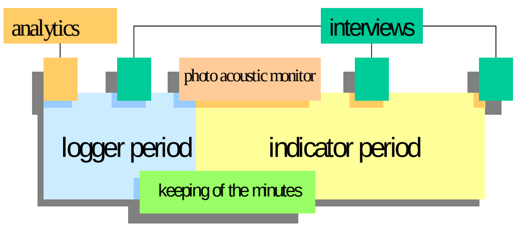

Figure 4. *Temporal sequence of the short-term test*

The analytics, which were accomplished during the logger period in each examined room, were always the same. At first, investigations of certain pollutants under worse case conditions took place (VOC, formaldehyde, if necessary PCB, PAH, PCP and moulds). Simultaneously to the data collecting, minutes were kept and interviews were held. Altogether 220 samples were taken and analyzed. With the photo-acoustic monitor, extensive data concerning CO_2 levels, air humidity and the TOC content (TOC = total organic compounds) of the indoor air in the investigated rooms were at disposal. Data was collected during the "logger and displaying" stage. Every 3 to 5 minutes the measure values were taken simultaneously in up to 6 rooms per dwelling.

RESULTS AND DISCUSSION

Examination of the gas sensor

As the result it was determined that the sensitivity of the gas sensor is depending on the different substances. For example, the sensor reacts very sensitively to combustible substances with small molecules such as acetone or carbon monoxide. For substances with bigger molecules without reactive groups e.g. the n-alkanes or n-hexane, the sensor sensitivity is partly several times lower. This shows clearly the different response character of the sensors. The sensor does not react to CO_2 (which is already fully oxidized). Therefore, CO_2 is not important to evaluate the sensor sensitivity.

In relation to health implications, precarious concentrations of some pollutants with a low volatility such as PAH or PCB are very small compared to those of the air pollutants described above. Thus they cannot be detected with the gas sensor directly. The sensor is not suitable for and thus it is not planned to apply it for the examination of low volatile pollutants.

During the field tests the gas sensors are exposed to indoor air atmospheres and not to a single substance. Already now some characteristic load lines (see figure 5) from typical dwellings could be pointed out.

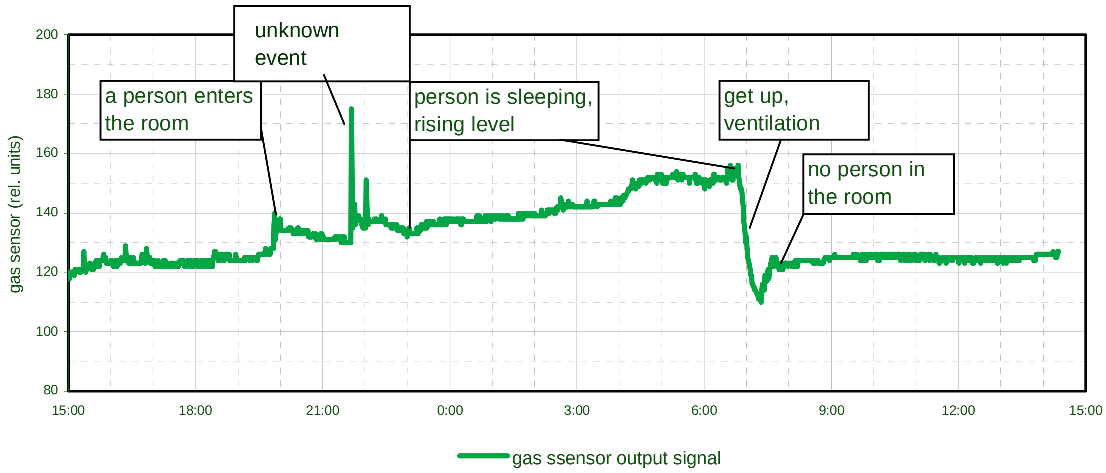

Figure 5. *Typical gas sensor output course in a sleep room with windows closed at night*

Pollutant measurements for status collection during the practice tests

The investigations under worse case conditions were accomplished without regard to complaints or health impairments of the inhabitants. Nevertheless, in some dwellings and schools high TVOC loads and high loads with single VOC were determined (M∅lhave et al. 1996; Scholz 1998; Plieninger. et. al. 1999). These could be partly attributed to certain sources of emission.

All measured formaldehyde concentrations in the dwellings are considered to be small loads, under which only inhabitants with excessive sensitivity should suffer any health-implications.

The evaluation of the load distribution of TVOC resulted in the following. From altogether 69 sampled rooms we found:

- 43 % of the rooms showed a small air load (TVOC < 300 µg/m³)
- 43 % of the rooms showed a plain air load (TVOC 300 to 1,000 µg/m³)
- 12 % of the rooms showed a high load (TVOC 1,000 µg/m³ to 3,000 µg/m³).
- < 1 % showed a very high load (TVOC > 3.000 µg/m³)

In some cases, the indoor air in the examined rooms was also analyzed for wood preservatives, mould spores and polychlorinated biphenyls (PCB). However, no considerable loads of such pollutants were determined in the rooms which were subject to the field tests.

Discussion and evaluation of the complete results of measurements for single VOC (Scholz 1998) substances from all dwellings and schools are published separately [interim report 4].

Correlation of the gas sensor's TOC with the VVGD measurement

In order to determine whether TOC values and gas sensor values correlate to each other, the results of the measurements recorded simultaneously by the photo-acoustic monitor and the VVCD were compared to each another.

The obtained data showed that the gas sensor values correlate quite well to the TOC values. During increasing TOC loads usually rising gas sensor values are measured. Both shape and course of the value pattern correspond well to each other. However, there is no fixed correlation between TOC and gas sensor value. It fluctuates in a certain range, which can amount up to 2 mg/m³ of the TOC in extreme cases.

Change of the indoor air load situation by the employment of the VVGD

One of this study's most important questions was to proof an improvement of indoor air quality due to the operation of a VVGD. The air quality was improved most impressively in one of the dwellings where an increased indoor air load was documented in the logger phase, as the TOC of 17,22 mg/m³ (90 percentile value of all measurements) in the one of the rooms shows. More than 70 % of the high loads in this dwelling caused a ventilation recommendation. This led to a reduction of the air load of 32,8 % (see figure 6).

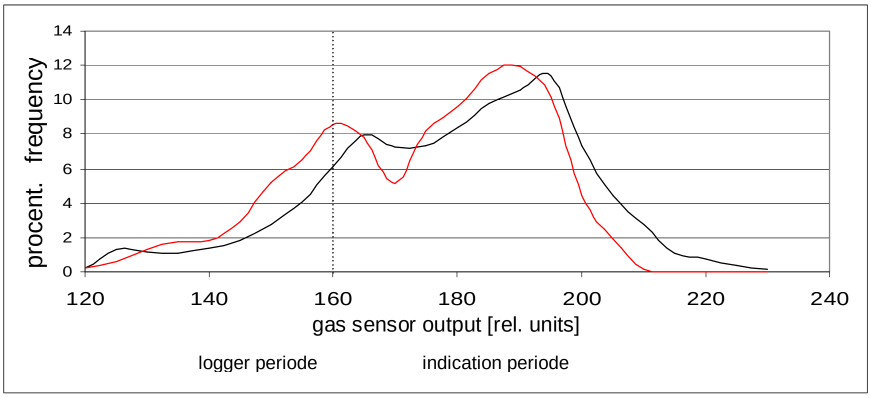

Figure 6. *Comparison of the gas sensor values in logger and indicator period in one of the dwellings shown as sum curve*

A further method for describing a change of the indoor air loads during the field test is to represent the statistic distribution of both periods by the comparison of the gas sensor measured values in the logger period and the indicator period. In one dwelling with high air loads it turned out that the load of interior air decreases with the VVGD in use. This is an other example for reducing the indoor air load by usage of the VVGD.

Correlation of the CO_2 concentrations with the gas sensor values of the VVGD

The gas sensor is not able to react directly to CO_2. Nevertheless, by experiences in handling the air quality sensors it actually worked out that an indirect coherence between CO_2- and gas sensor signal could be found. This coherence may be caused by other, detectable substances which are emitted from humans and appear synchronously to CO_2 in indoor air

CONCLUSION AND IMPLICATIONS

With the VVGD a simple device was developed, which shall help housing users to perform a sensible ventilation behavior based on reliable sensor data. A well adjusted ventilation is useful in saving heating energy and also important with regard to hygienic aspects or aspects of building materials maintenance. The sensors controlled via a newly developed software output their signals to a display unit similar to a traffic light. The user learns an optimal ventilation behavior with time, i.e. to open windows at poor air quality and, in addition, to close them again in time to prevent excess loss of energy. The results from the field tests show improvement of the acceptance of the device in practice, both in private dwellings, flats and in schools. Further development work should concentrate on improvement of the acceptance. So should the display unit of the VVGD be designed to make the given recommendation clearer. A clearer statement about changes in the behavior of the users due to using the VVGD and its acceptance requires a broader field test with at least 250 participants. In addition the VVGD should be revised according to the results gained from this research project. The former version should be used over at least a whole heating season and supported by adapted investigations.

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