Intelligent Sensor System for Air Quality Monitoring

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Abstract - **In the presence of persons in energy-saving and thereby air-tight sealed rooms, the concentration of anthropogenically and building materials generated substances quickly reaches inadmissible values. Air ventilation leads to energy losses and hence must be demand-driven. The admissible limits of air with acceptable are defined in regulations, but cannot be completely monitored due to large efforts. Therefore, the range of substances to be monitored must be limited by scenarios with sufficient probability and the definition of lead substances. The values needed for the operation of air ventilation systems must be measurable with low cost, sufficient accuracy and long-term stability. For this goal, intelligent sensor systems are needed with properties adjusted to the special requirements**

Keywords – **intelligent sensors, air quality monitoring, home automation.**

I. Introduction

Today, intelligent offices and administrative buildings and building management systems (BMS) comprise bright range of technologies used in commercial, industrial, public and residential buildings, such as energy management and building automation. The functionality of BMS is based on the concept of intelligent buildings: they monitor and optimize systems in buildings such as lighting, heating, security access, video surveillance and alarms, audio and visual, ventilation, air filtering and air conditioning etc.

The application of modern and intelligent control technology can tap significant potentials for saving energy - especially in commercial buildings. When doing this, e.g. classic control algorithms are replaced with innovative, highly-efficient and energy-saving solutions. New methods not only help attain maximum energy efficiency while optimally fulfilling the demand for convenience, but also prolong the lifetime of systems and extend maintenance cycles. Savings of up to 15%, for example, can be achieved by optimizing the control parameters. The following article describes the essential influential factors for saving energy which can be achieved by the use of intelligent sensor systems for air quality monitoring by the control of ventilation systems.

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II. HVAC Systems and Indoor Air Quality

A. The New Standards for Air Quality

Standards are usually applied when ventilation systems are designed. In particular, the amount of fresh air is a design criterion which determines the size of the systems.

European EN1946 part 2 and American ASHRAE 62-1989 still calculate the fresh air volume by area and a fixed number of occupants. The new European standard EN 13779, based on the Energy Performance of Buildings Directive (EPBD), already includes the option to design the fresh air supply with the air quality as a controlled variable and proposes that air quality is the best input for an economically operated air conditioning system [1, 2, 4].

HVAC (heating, ventilation, and air conditioning) can be considered the most important item in a modern building.

The composition of indoor air is complex and has a high impact on the comfort of inhabitants because the normal citizen spends more than 90% of his life in interior rooms [12]. A minimum of air exchange is necessary to achieve comfort of the inhabitants and avoidance of damage to the building material, etc. In older buildings, leakage through wooden windows, etc., assures this minimum air change, whereas in new energy-saving houses controlled ventilation is necessary. HVAC systems assure a minimum change of air per hour. This air exchange should be kept to the minimum to preserve energy (heating energy in winter, cooling energy in summer). Time humidity-and temperature-controlled ventilation is best suited to save energy, because incomplete data about the other constituents of air force a minimum air exchange [3].

Therefore, an air quality strategy needs air quality sensors to achieve a further reduction of air exchange with the same comfort. Table 1 gives an overview of the expected values of the energy-saving potential.

TABLE 1. EXPECTED ENERGY-SAVING POTENTIAL WITH SENSOR-CONTROLLED AIR CONDITIONS [3]

Location	Energy-saving potential (%)
Lecture hall	20 - 50
Large offices: ~50% inhabitants present	20-30
Hotel lobby, public halls, booking halls	20 - 60

B. Factors Influencing the Indoor Air Quality

In recent decades, new construction techniques and insulating materials have been developed which remarkably reduce the heat loss of buildings, enabling high energy savings at the cost of a diminished natural air exchange. In this situation, sufficient indoor air quality must be guaranteed by appropriate heating and ventilation of rooms. Demand-driven control of heating, ventilation and air conditioning (HVAC) systems helps to establish a comfortable climate in rooms along with reduced energy consumption [1, 2, 3, 12].

The main constituents of indoor air are oxygen, nitrogen, humidity, carbon dioxide, and an immense number of different hydrocarbons from various sources. Normally, the concentration of nitrogen and oxygen does not vary significantly. Equipment to control the humidity concentration is widespread and the control of relative humidity is normally no problem for air conditioners. Carbon dioxide is a significant gas for human indoor air pollution. In clean air the carbon dioxide concentration ranges from about 0,035 vol. % in rural regions up to 0,07 vol.% in cities. Carbon dioxide concentrations below 0,1-0,15 vol.% are comfortable and 0,5 vol.% is the threshold limit value (TLV). High concentrations of carbon dioxide are toxic. In addition one may find more than 10000 different gases in a room, most of them different hydrocarbons (volatile organic compounds, VOCs) at very low concentrations.

In general, there exist two sources of emission: the inhabitants of the room, which are a changing source of emissions, and fixed building materials such as carpets, wallpaper, electronic devices, etc., which give a constant emission rate. A selective measurement of toxic or carcinogenic substances with sensor methods seems unnecessary for normal indoor air quality, because in the case of an effect on human health the source of the emission should be identified and removed.

B. The Fanger methodmodel for estimating air quality

The requirements on air quality measuremnt are to enhance the comfort of the inhabitants and to remove odors and toxic substances. An empirical measure of indoor air quality is the contentedness of the inhabitants, which is estimated following [6]. Fanger defines an emission unit „olf": 1 olf is the odor and $C0_2$ emission of a normal man (0,7 showers per day, daily fresh underwear), which is now widely used. The corresponding immission rate is a decipol: in a room where 15% of the test persons are uncontent, there is an immission rate of 1 decipol. A simple calculation gives an immission of 1 decipol for a room occupied with one standard person and a ventilation rate of 101/s.

The Fanger method for estimating air quality is based on a statistical measure. The conventional experimental setup for measurement following the Fanger method is that a panel of carefully selected persons compares the strength of a probe with a certain standard. A panel of about 10 persons results in a good quality of decipol measurement. This leads immediately to a classification of indoor air quality (Table 2).

TABLE 2. CLASSIFICATION OF AIR QUALITY AFTER FANGER [6]

High	0,7 decipol	< 10% discontented people
Medium	1,4 decipol	< 20% discontented people
Low	2,5 decipol	< 30% discontented people

The immission unit decipol leads to an equation to calculate the actual ventilation rate:

$$\nu = 10 \frac{G}{(C_i - C_0)\varepsilon_v} . \tag{1}$$

ν - ventilation rate (L/s), G - indoor emission (olf), C_i - expected indoor air quality (decipol), C_0 - outdoor air quality (decipol), and ε - ventilation efficiency.

This equation includes the outside pollution, which can be assumed to be 0,1 decipol in cities with high air quality, 0,2 decipol in normal cities and 0,5 decipol in polluted areas. Equation (1) leads to a scheme for an additional air quality control module on an existing HVAC system, shown in Figure 1 [3].

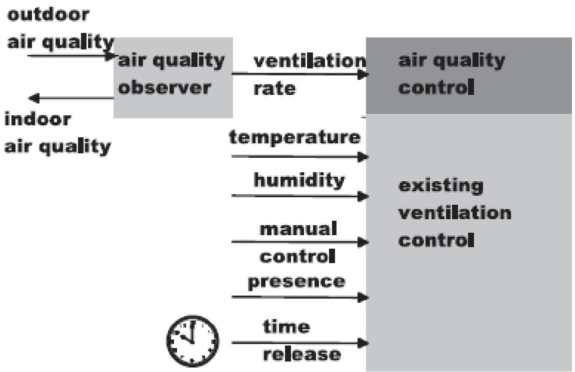

Figure 1. Addition of an air quality module to an existing HVAC unit.

Following the VDMA 24772/73 [1, 2] recommendations it is not necessary to analyze all these constituents to achieve an acceptable indoor air quality. The important task is to find a cheap and reliable sensor system which covers most of the demands of air quality measurement.

The VDMA 24772 gives the recommendations in Table 3 for indoor air quality sensors.

TABLE 3. TECHNICAL PARAMETERS FOR INDOOR AIR QUALITY SENSORS [1]

Technical specifications	CO_2 sensor	VOC sensor
Measurement range	0–2000 ppm	Choice of manufacturer
Measurement accuracy	±10% at 1000 ppm	± 20%
Influence of other gases	Selective (<5%)	Non-selective (100%)
Rise time	<5 min	< 5 min
Lower detection limit	<0.5% of range	< 0.5% of range
Reproducibility	<1.0% of range	< 1.0% of range
Long-term stability	<5% of range/year	< 5% of range/year
Influence of relative humidity (RH)	<0.1%/1% RH	< 0.3%/1% RH
Humidity (operation)	30–70% RH	30–70% RH

In view of the large amount of possible substances in indoor air, the use of selective gas sensors is not meaningful because the composition of air changes from one location to another. The present state of sensor techniques leads to a measurement of carbon dioxide and a summary measurement of volatile organic compounds.

Carbon dioxide is well known as a guiding gas for indoor air quality. Available sensors for carbon dioxide include infrared (IR) sensors and electrochemical cells. The IR measurement technique is based on the extinction of an IR beam with small bandwidths which depend on the $C0_2$ concentration following the Lambert-Beer law. Compared with most other sensors, IR measurement units have excellent stability, depending on the quality of the electronic components.

On the other hand, $C0_2$ sensors have a reasonable energy consumption (IR source) and sensor types for low concentrations and/or high resolution must have a minimum optical length, which limits the miniaturization.

Electrochemical cells to measure $C0_2$ are also on the market with a shorter lifetime and lower stability than IR sensors. Electrochemical cells work similarly to a battery and have low energy consumption and a small size. On the other hand, the baseline drift necessitates regular calibration. But in recent years there are many new developments of electrochemical sensors with improved characteristics.

One of the best choices for measuring a summary signal for VOCs is metal oxide sensors. These sensors are based on semiconducting metal oxides. Triggered via a chemical conversion (oxidation or reduction) on the surface of the metal oxide at higher temperatures (ca 200-800 °C), the equilibrium concentration of oxygen at the surface is influenced by the concentration of several gases in the surrounding air. It is well known that this oxygen concentration has a large impact on the conductivity of the semiconductor and can be easily measured. The selectivity is controlled from the temperature and the doping of the metal oxide with metals and covers many VOCs. Some preparations of the metal oxide are especially recommended for air quality measurements. In general, the sensitivity of metal oxide sensors towards $C0_2$ is low and they are not suitable for indoor air quality measurements [3, 14].

A large number of VOCs can be measured with metal oxide sensors, but the sensitivity has no decipol scale, because the human recognition of odor is different from the measurement principle of the sensor. Unfortunately, the humidity concentration as OH groups on the sensor's surface also has an important influence on the sensor signal. Therefore, it is not easy to distinguish between changes in the humidity or oxidizing and reducing gases.

III. THE INTELLIGENT SENSOR SYSTEM FOR INDOOR AIR QUALITY

A. Choice of sensors

On the basis of the above considerations can be summarized that the main factors that influence the indoor air quality include:

- High CO_2 concentration due to inadequate supply of fresh air,
- Contaminations arising from sources within the building (e.g., combustion products, tobacco smoke and other particles; volatile organic compounds (VOCs) from building materials, fabric furnishings, carpet, adhesives, new paneling, and cleaning products).

Other important factors that influence the air quality are:

- Contamination from outside the building (e.g., ozone, carbon monoxide, and particulate matter) through air intakes, infiltration, open doors, and windows,
- Microbiological contamination of ventilation systems or building interiors.

With the intelligent sensor system, the following air parameters are measured:

Indoor:

- concentration of carbon dioxide (CO_2),
- concentration of volatile organic compounds (VOCs);

Outdoor:

- concentration of volatile organic compounds (VOCs),
- concentration of ozone (O_3) and NO_X.

The air composition in the room may vary considerably; therefore the use of broadband electrochemical gas sensor is preferred over selective gas sensors. In Table 4 the basic gases relevant for indoor and outdoor air quality together with typical trigger thresholds and the used sensors are given.

TABLE 4. RELEVANT GASES FOR INDOOR AND OUTDOOR AIR QUALITY MEASUREMENT AND TYPICAL THRESHOLDS

	Gases	Activity thresholds	Used sensor
Indoor air quality	CO_2	1000ppm	Figaro 4161
	VOC	30ppm	GGS 3470 T
Outdoor air quality	VOC	30ppm	GGS 3470 T
	O_3	20ppb	GGS 5470 T
	NO_X	20ppb	GGS 5470 T

Electrochemical gas sensors are available for a large variety of gases.TGS4161 is a new solid electrolyte CO_2 sensor which offers miniaturization and low power consumption. A range of 350 ~ 10,000 ppm of carbon dioxide can be detected by TGS4161, making it very suitable for indoor air control applications.

The CO_2 sensitive element consists of a solid electrolyte formed between two electrodes, together with a printed heater substrate. By monitoring the change in electromotive force generated between the two electrodes, it is possible to measure CO_2 gas concentration. Electromotive force (EMF) of the sensor is measured using a high impedance (>100 GΩ) operational amplifier with low bias current (< 1pA) [14].

The GGS series 3xxx and 5xxx sensor elements are produced in hybrid technology. The main response of the sensor is based on the changes in conductivity of the sensitive semi conductor layer when exposed to gases. The gas sensor element consists of an Al_2O_3 substrate with a structured Pt-film, which in turn consists of heater channels and contact electrodes covered by an insulating and a sensitive semiconducting layer.

The sensors require two voltage inputs: heater voltage and circuit voltage. The heater voltage is applied to the integrated heater in order to maintain the sensing element at a specific temperature which is optimal for sensing. Circuit voltage is applied to allow measurement of voltage across a load resistor which is connected in series with the sensor.

A well-known problem of semiconductor gas sensors are temperature and humidity influences and a considerable baseline drift. To overcome this limitation for practical use, air temperature, relative humidity measurement and correction algorithms are needed.

As temperature sensor serve a conventional Pt1000 Platinum resistance sensor (FMS 2000 [13]). For humidity measurement a HIH-3610 integrated humidity sensor is used [16].

B. Choice Hardware Platform and Communication Interfaces

The standard model of a building automation system can be divided into three levels - field level including measurement of parameters, level of automation and management level. Modern building automation systems are increasingly presented with models, divided into two levels. This is due to increasing functionality offered by modern intelligent devices. A part of the functions from the automation level goes to the field level.

The modern trend is to use open hardware solutions that support various communication standards and thus allow the integration into different environments. For the specific implementation is selected. The necessary signal processing and communication is carried out with the WAGO-I/O-IPC. The I/O-IPC is an industrial PC that combines the functionalities of a PC and a programmable logic control (PLC). I/O modules and fieldbuses can be connected. The fieldbus connections depend on the version of the IPC. All versions have two 10/100BASE-TX Ethernet interfaces. If using the I/O-IPC as a PLC, it is possible to control all or some of the I/O modules locally by using WAGO-I/O-PRO CAA (CoDeSys). WAGO-I/OPRO CAA is an IEC 61131-3 compliant programming tool for programming and configuring the I/O-IPC.

IV. CONCLUSION

Energy loss estimations in residential buildings show that automated room climate control working separately different areas has the potential to reduce the over-all energy consumption in “intelligent buildings”. The lead tasks for the realization of the indoor air monitoring system are to maintain a healthy climate and an optimized thermal comfort.

The air quality assessment and the thermal comfort sensation depend on numerous variables which are difficult to measure precisely at low cost. The core of the sensor system presented here is a comprehensive monitoring system which continuously measures the indoor and outdoor air quality. The conditions for indoor air quality control and the assessment of subjective thermal comfort are sometimes contradicting. If the CO_2 concentration exceeds a certain level (commonly 1000 ppm), the air quality control must have priority over the adjustment of thermal comfort.

Next research steps are aimed at improving the long-term stability and robustness against influences of temperature and humidity.

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