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# Sensor-based Multi-Zone Demand-Controlled Ventilation

Marin Marinov, Todor Djamiykov, Borislav Ganev
Department of Electronics, Faculty of Electronic Engineering and Technologies
Technical University of Sofia
Sofia, Bulgaria

Volker Zerbe
Department Computer Engineering/Embedded Systems
Faculty of Engineering in Building and Computer Science
Erfurt University of Applied Sciences
Erfurt, Germay

*Abstract*— **With sensor-based demand controlled ventilation the ventilation rates are controlled through signals from indoor and outdoor air sensors and so better control of the indoor pollutant concentration and lower energy use can be achieved. Recently the successful use of renewable energy in the form of ground heat exchangers for fresh air preconditioning has served as the basis for the realization of innovative air conditioning systems. However, significant effects can be achieved only if considerable modifications in the systems architecture and especially, in the measurement and control technology are made. The paper elaborates on the design and the implementation of a cost effective multi-zone air conditioning system with a ground exchanger. For the implementation of dynamic demand-controlled ventilation strategies intelligent sensor nodes are used. Approaches for $CO_2$ sensor error correction are presented.**

***Keywords-*** ***Demand-controlled ventilation; energy saving; $CO_2$ sensors; $CO_2$ concentration control; energy saving***

## I. INTRODUCTION

In Europe more than 45% of the energy is consumed in buildings. More than 50% of this consumption is in non-residential areas where a lot of buildings are equipped with air conditioning systems. Buildings are becoming one of the fastest growing energy consuming sector and that is why its saving strategies are a global challenge. In this situation, sufficient indoor air quality must be guaranteed by cost effective heating, cooling and ventilation. Decentralized climate control operating separately in different zones and areas of the buildings provides opportunities to satisfy these demands. [1].

In recent decades new construction technologies and materials have been developed which have remarkably reduced energy losses from buildings. The role of measurement and control is becoming significant since they are directly related to the amount of the energy consumed in buildings. A great number of technologies have been developed to reduce energy consumption. Among the most successful and widely used one is the measurement of $CO_2$ concentration and the control of the ventilation systems on the basis of these data – the so called Demand-controlled ventilation (DCV). DCV based on carbon dioxide ($CO_2$) sensing is practically a combination of two technologies: $CO_2$ sensors that measure $CO_2$ levels in the indoor air, and an air-handling system that uses this data from the sensors to control the ventilation. Given a predictable activity level, as for example the one which might occur in an office, school, etc. people will also exhale $CO_2$ at a predictable level. Thus, $CO_2$ production in a space will very closely track the occupancy. Outside $CO_2$ levels are typically at low concentrations of around 400 - 450 ppm in urban areas [3]. So indoor $CO_2$ measurement can be used to control the amount of outside air with low $CO_2$ concentration that is introduced to dilute the $CO_2$ generated by the occupants of the building or by the building. The result is that ventilation rates can be measured and controlled to a specific $m^3$/person value based on actual occupancy. This is in contrast to the traditional method of ventilating at a fixed rate without taking into account the extent to which that particular place is occupied. [4].

In public places with big people flow and a number of visitors which varies widely, the manually set or following a fixed programme modes of operation of the ventilation systems make it possible to use the energy effectively only to a certain degree. The main reason for this is that the need for air renewal fluctuates significantly both within 24 hours and during the different days of the week. These fluctuations depend mainly on the number of visitors and the activities they are engaged in. Using demand-controlled ventilation (DCV) we can manage to adapt the supply of fresh air to the actual needs. Thus, energy costs can be reduced without compromising with the quality of the air in the premises.

From experience we know, however, that the actual number of occupants on the premises rarely corresponds to the number envisaged in the design stage of the system. Thus, during periods with smaller numbers of visitors, the ventilation system can reduce significantly the supply of fresh air and can even be switched off without impairing the quality of the air in the enclosed areas. In this way considerable quantities of energy, otherwise used for transport and conditioning of the air, can be saved.

## II. CALCULATIONS FOR MULTI-ZONE VARIABLE AIR VENTILATION

Equilibrium analysis is commonly used in the $CO_2$-based DCV for calculating the ventilation rates from indoor $CO_2$ concentration levels. This approach is based on the mass balance of $CO_2$ in a zone. For mechanically ventilated zones the following equation of mass balance, evaluation of the differences between $CO_2$ concentration in a specific zone ($C_Z$) and the $CO_2$ concentration of outdoor air ($C_0$) in a state of equilibrium can be used (it is accepted that the air which is supplied is well mixed and the effectiveness of air distribution in the zone is $E_Z = 1$). So the zone outdoor airflow (L/s) can be calculated by the equation:

$$V_{OZ} = N_Z / (C_Z - C_0), \tag{1}$$

where $N_Z$ is the coefficient of generating $CO_2$ and depends on the number of people ($N_Z = C \cdot P_Z$): where $P_Z$ is the zone population and C is a constant whose value is determined on the basis of the activities of the occupants, their health condition, etc. [8, 10, 11].

The ASHRAE 62.1 2010 standard [8] sets specific requirements in the calculation of multi-zone systems. Two ventilation rates have been introduced and the first one is related to the air pollution caused by the occupants in the zone and the second is related to the air pollution caused by the building itself.

The design outdoor airflow required in the breathing zone of the occupiable space in a zone, i.e. the breathing zone outdoor airflow ($V_{BZ}$), has to be determined in accordance with the equation:

$$V_{BZ} = R_P \cdot P_Z + R_A \cdot A_Z \tag{2}$$

where:

$R_P$ = outdoor airflow rate required per person, $P_Z$ = zone population: the largest number of people expected to occupy the zone, $R_A$ = outdoor airflow rate required per unit and $A_Z$= zone floor area: the occupiable floor area of the zone ($m^2$). The values of $R_P$ and $R_A$ are determined in accordance with a table for that specific occasion [8].

$$V_{OZ} = V_{BZ} / E_Z, \tag{3}$$

where $E_Z$ is the zone air distribution effectiveness.

Thus on the basis of (1) and (2) and for $E_Z = 1$ for $CO_2$ concentration in the zone we get:

$$C_Z = C_0 + \frac{N_Z}{V_{OZ}} = C_0 + \frac{C \cdot P_Z}{R_P \cdot P_Z + R_A \cdot A_Z}. \tag{4}$$

In order to ensure that the ventilation rate required by (2) is provided in that place, the measured $CO_2$ concentration, must be equal to (or smaller) than the value determined by (4). In the earlier versions of the established standards the product $R_A . A_Z$, which reflects the air pollution caused by the building itself, does not exist and allows parameter $P_Z$ (zone population) to be cut out, and thus for the difference $C_Z - C_0$ we get a constant value of $C/R_P$ In ASHRAE Standard 62.1 2004-2010, the product $R_A.A_Z$ requires dynamic evaluation or measurement of the difference $C_Z - C_0$ so that effective management of the ventilation system can be achieved [2, 7, 8].

The structure and the specifics of the proposed multi-zone ventilation system suggest as an effective solution the use of $CO_2$ concentration of the supply air $C_S$. Then for $V_{dz}$ (discharge air supplied to the zone) it can be written on the basis of the (1):

$$V_{dz} = N_Z / (C_Z - C_S). \tag{5}$$

Using (3) to get the needed concentration in the respective zone it is necessary to measure the CO2 concentration of the supply air Cs, which is determined in accordance with the following equation:

$$C_S = C_Z - \frac{N_Z}{V_{dz}} = C_0 - N_Z\left(\frac{1}{V_{OZ}} - \frac{1}{V_{dz}}\right). \tag{6}$$

It is necessary to calculate $C_{Si}$ for each zone and in order to ensure the CO2 levels in all zones it is necessary to determine the minimal value in accordance with equation:

$$C_S = \min(C_{Si}) = \min\left(C_{Zi} - \frac{N_{Zi}}{V_{dzi}}\right) = \min\left(C_0 - N_{Zi}\left(\frac{1}{V_{OZi}} - \frac{1}{V_{dzi}}\right)\right). \tag{7}$$

Practically the main problems in having an energy effective management of ventilation systems are related to a precise enough evaluation of the number of occupants in a particular zone and that is why we calculate $N_{Zi}$ and $V_{0Zi}$. In order to calculate these parameters we use data set out in the design stage which lead to considerable deviations in the evaluation and thus to a considerable reduction in the effectiveness of the ventilation systems.

The use of sensors for CO2 in each zone and determining the number of occupants of the zone on the basis of this is an alternative which has so far been dismissed as possible due to the high prices of the hardware.

## III. MULTI-ZONE VARIABLE AIR VOLUME AIR CONDITIONING SYSTEM

### *A. The conventional air conditioning system*

Ventilation systems for big multi-zone spaces such as department stores, big office buildings, railway stations, airports and others are usually designed in such a way that the air handling units are located in the roof and sub roof area. The main conditioning of the outdoor air and the transportation of the exhaust air is carried out here. The conditioned air then passes through a complex system so that it finally gets to the zones and places which need to be ventilated.

The basic structure of a conventional air conditioning system is shown in Fig. 1.

Some of the main disadvantages of the conventional air conditioning system are:

- High energy consumption for conditioning the outdoor air in the roof area due to particularly unfavorable climatic conditions in this area. Here we usually have the highest temperatures in summer and the lowest in winter.
- The conditioned air in the air distribution system is transported over long distances to the air outlets and there are significant energy losses.
- The air from the supply air outlets has to be pressurized so that the underlying supply areas can actually be reached.

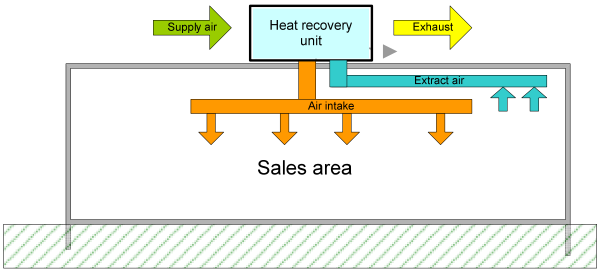

Figure 1. Basic structure of a conventional air conditioning system

### *B. The New Ventilation Concept with Variable Air Volume and Geothermal Heat Exchanger*

Over the last few years, as an alternative to the conventional ventilation systems, installations using renewable energy sources have increasingly being used. They employ, for example, a geothermal heat exchanger which partially performs the preconditioning of the outdoor air. It permits to move the basic components of the conditioning systems (air handling units) from the roof to climatically protected areas.

If the specifics of the construction permit it is possible to lay down the ventilation channels under the floor and air outlets at a level at which the occupants move. Thus, an additional reduction of the mechanical and thermal losses is achieved.

The incoming air is filtrated and through a flow controller the volume of zone primary airflow is controlled.

The needed air volume is adjusted by means of electromagnetic devices which regulate the valves of the air outlets. The data used to adjust the valves is provided by the central controller whose main task is to maintain the balance of the air volumes in the whole system. Thus, by using appropriate strategies of control a precise Variable Air Volume (VAV) control can be achieved.

The basic structure of the innovative ventilation system is presented in Fig. 2. The necessary air outlets are designed (e.g. with regulating valves, flaps, sensors and actuators), so that at any time a variable and adjusted air volume is possible. Thus, a situational optimization of the ventilation requirements can be achieved.

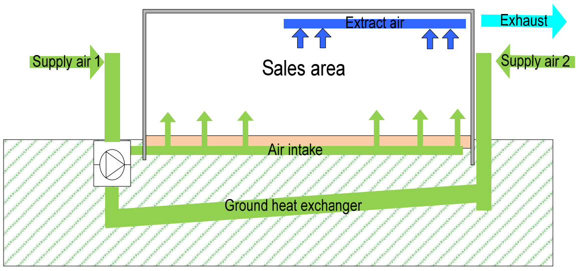

Figure 2. The proposed ventilation concept with geothermal heat exchanger and VAV control [19].

The distributed architecture of the proposed system requires also a new approach in the realization of both the overall control concept and the individual system components. It is necessary to "move" more intelligence in the sensor nodes (Fig.3). The intelligent sensor nodes pick up not only the variables to be measured; they also process the measured values and communicate these results.

## IV. THE INTELLIGENT SENSOR NODE

In particular, the proposed intelligent sensor node is composed of a main board and an expansion board. The common modules such as a processor, Ethernet circuits, power supply and memory are located in the main board. In this design a PIC18F86K22 microcontroller is used.

The other modules that are frequently changed according to the different application requirements are placed on the expansion board. The following sensors are connected to every sensor node: K-30 sensor module by SenseAir for the detection of carbon dioxide, ADT7311 by Analog Devices for temperature measurement, HIH-4000 by Honeywell for Relative Humidity (RH) measurement; MPXV-7002DP by Freescale for differential pressure measurement and MPX5100A (optional) for atmospheric pressure measurements and error correction purposes.

### *A. The CO2 sensor selection*

The evaluation of the quality of the air by means of sensors is, at present, based on measuring the concentration of certain compounds or gas mixtures. In spite of the considerable advances in gas sensorics over the last few years, still there are no reliable sensors for broad spectrum measurement of a number of gas components and for their effect on people's health. For the purposes of DCV the types of sensors which are widely used are the selective sensors for measuring the $CO_2$ concentration and the VOC sensors which measure weighted influences of different types of gases which directly affect the quality of the air.

The established standards require that the error levels of the sensors be around ±75 ppm for a period of 5 years after the installation. That is why infrared sensorics is commonly used for measuring $CO_2$ concentration in enclosed areas for the purposes of DCV as it meets these requirements at reasonable costs [7, 8, 9].

The most common technology on the market for measuring $CO_2$ is the non-dispersive infrared (NDIR) technology. The main problem with this technology is that the required light source will lose its intensity over time. Most $CO_2$ sensor manufacturers offer an accuracy specification in the range of ±(50 – 100) ppm to certified calibration mixtures. When the uncertainty of calibration of gas mixtures (±2% usually) is added to the sensor accuracy the error rates in absolute measurements are considerably beyond those permitted by the standards ±75 ppm.

Due to these considerations a CO2 sensor is chosen and it is embedded in the sensor node. We have chosen a K-30 sensor module by SenseAir. This is an infrared, low-cost and maintenance free transmitter module with good measurement accuracy ±(3 % of measured value ± 30 ppm). The compact sized and low powered module is intended to be an add-on component to compliment other microprocessor-based controls and equipment.

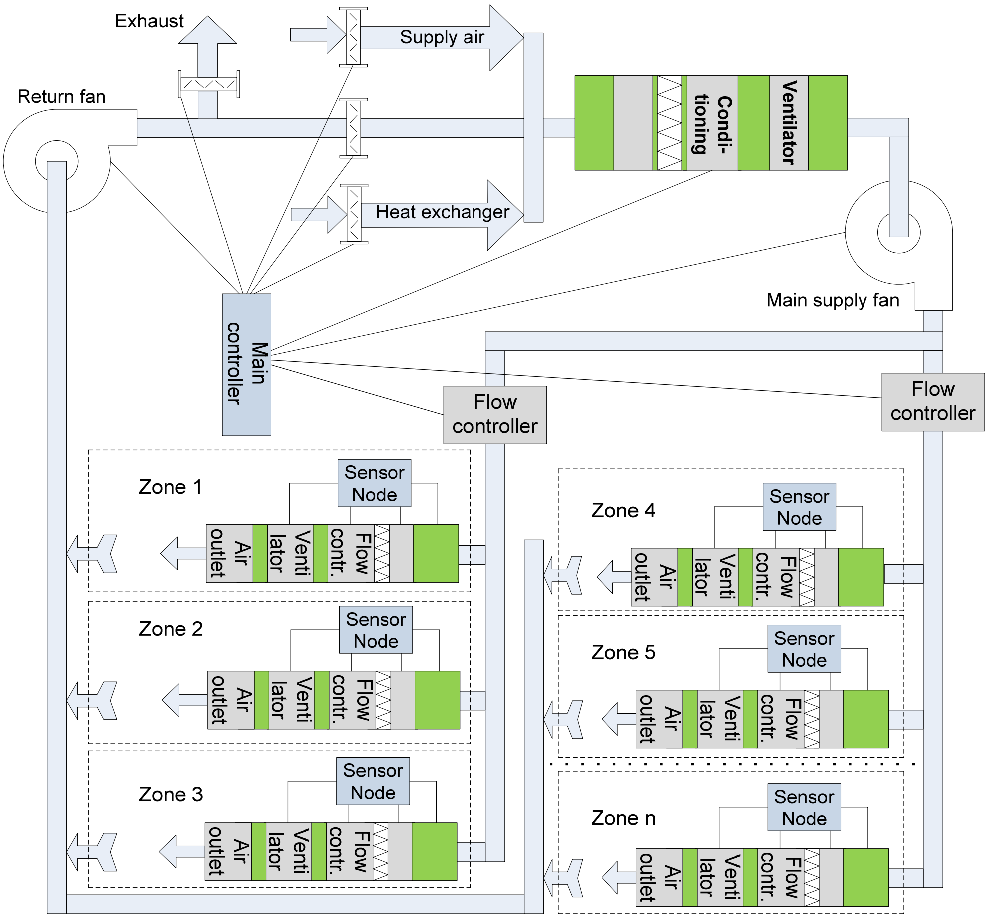

Figure 3. The distributed system architecture with intelligent sensor nodes.

The default sensor OEM unit is maintenance free in normal environments thanks to the built-in self-correcting ABC algorithm. This method takes advantage of the fact that in every building or zone there are periods of time without any activity. Then the $CO_2$ concentration on the premises reaches a minimum which is almost identical with certain concentrations in the outside air. That information can be used for automatic periodic recalibration of the sensor. The algorithm embedded in the K-30 sensor module constantly keeps track of the sensor's lowest reading over a 7.5 days interval and slowly corrects any detected long-term drift.. The system contains complete self-diagnostic procedures. A full system test is executed automatically every time the power is turned on. In addition, constantly during operation, the sensor probes are checked against failure by checking the valid dynamic measurement ranges [6, 15].

### B. *Error compensation of the CO2 sensor*

The infrared gas sensors generate a signal proportional to the molecular density (molecules/volume of gas), even though the reading is expressed in parts per million. The changes of pressure and temperature also change the molecular density of the gas according to the ideal gas law.

Temperature changes of about 15K lead to a measurement error of 5%. Similar errors cause pressure differences of about 50 hPa. The ideal gas law can be used to calculate the molecular density of a gas at a given temperature and pressure, when the gas density at standard conditions is known. For the error correction purposes the following equation can be used:

$$\rho(\vartheta, p) = \rho(25°\mathrm{C}, 1013{,}25\mathrm{hPa}) \cdot \frac{p}{1013{,}25} \cdot \frac{298{,}15}{273{,}15 + t} \cdot \qquad (8)$$

Where $\rho$ is the gas volume concentration in ppm, $p$ = ambient pressure in hPa, $\vartheta$ = ambient temperature in °C.

So with the temperature sensor, built in the sensor node, and with an additional pressure sensor significant error compensation can be made.

The influence of water vapor on $CO_2$ sensor readings can be estimated based on Dalton's law of partial pressure, which states that the total pressure of a gas mixture is the sum of the partial pressures of all the component gases in the mixture. So based on the humidity sensor readings, the sensor node can perform additional error compensation.

### *C. The additional sensors*

The ADT7311 is a high accuracy digital temperature sensor that uses a 16-bit ADC to monitor and digitize the temperature to 0.0078°C of resolution. The ADC resolution, by default, is set to 13 bits (0.0625K). An internal temperature sensor generates a voltage proportional to the absolute temperature, which is compared to an internal voltage reference and input into a precision digital modulator. The internal temperature sensor has high accuracy and linearity over the entire rated temperature range without needing correction or calibration by the user.

The HIH-4000 Relative Humidity Sensor is a laser trimmed, polymer capacitive sensing element with on-chip integrated signal conditioning. It has a typical current draw of only 200 µA, whereby it is ideally suited for low drain, battery operated systems [16].

The sensor MPXV7002DP is chosen for differential pressure measurement and filter monitoring. Appropriate signal conditioning is included in an integrated circuit form, providing a DC voltage linearly proportional to the pressure difference over a specified range. The output voltage generated by a selected integrated sensor is given in [17]. The MPX5100A sensor is chosen for atmospheric pressure measurement and $CO_2$ readings correction [18].

## CONCLUSION

The sensor-based DCV seems to be an increasingly attractive option for controlling indoor air quality while reducing energy loses and costs. The lead tasks for the realization of the indoor air monitoring and control system are to maintain a healthy climate and an optimized thermal comfort. As, in practice, it is difficult to asses the exact number of occupants in each zone, the multi-zone ventilation concepts are mostly based on design occupancy profiles instead of on dynamic measurement methods, which lead to over ventilation of the zones and consequently to waste of energy.

The proposed new ventilation concept with variable air volume and geothermal heat exchanger offers more advantages than conventional systems. The distributed architecture of the proposed system requires also a new approach in the realization of both the overall control concept and the individual system components. The core of the system presented here are the intelligent sensor nodes which enable the continuously precise measurement of the indoor and, outdoor air quality and other significant parameters at acceptable price and thus permit the easy implementation of energy effective management strategies.

The next research steps are aimed at improving the long-term stability and robustness against influences of temperature, pressure and humidity.

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