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A decipol Predictive Controller for VAV Systems

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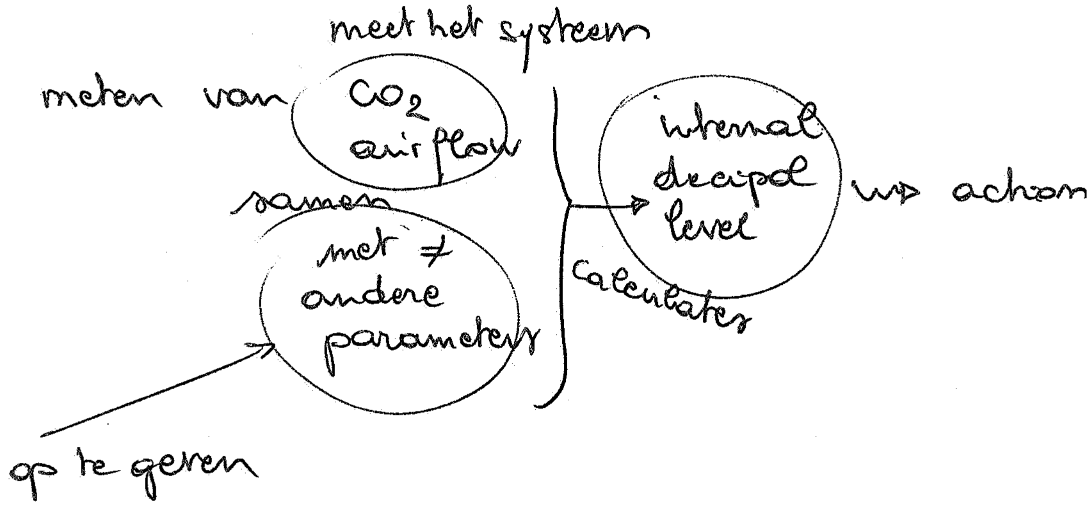

Synopsis

Due to the lack of proper sensors for odours, the odour concept, involving the units olf and decipol, is of very little practical use with respect to automatic control of VAV systems. However, the decipol level in a room may be predicted from the concentration of CO_2 and the amount of fresh air supplied. By using the CO_2 level as a decisive variable of the occupant load within the room, the actual air quality (decipol level) can be predicted. Once the decipol level is known, it is compared to a given set point, thus enabling the controller to alter the air flow rate accordingly. Eventually the room air quality should become equal to the specified set point. In this study, such a demand controlled ventilation algorithm is presented. The performance of the controller is visualized by simulation, and the results show that the approach to control the decipol level based on measurements of the CO_2 level could be advantageous compared to commercial CO_2 control.

1 Introduction

The olf and decipol units were introduced by Fanger in 1988 [2]. The basic idea was to find a method that related a quantitative measure of odours (olf) to a quality measure of odours (decipol), exactly the same way as any contaminant mass flow is related to a concentration within a space. A consequence of the lack of odour sensors, was that the results (the olf and decipol units) were based on the subjective perception of trained odour panels. One olf is defined as the emission rate of odours (bioeffluents) from a standard person and one decipol is the perceived air quality in a room hosting a standard person, ventilated with 10 litres/sec of fresh air. Olf emissions from other sources, such as building materials, are expressed in terms of the emission from one standard person (a one-olf source). The work by Fanger (see [2] and [3]) and the general acceptance of the units have led to new regulations and standards for determining minimum air flow rates for ventilation in many countries, for instance the new building regulations in Norway. Odour emission sources can roughly be categorized as follows:

1. From human occupancy
2. From non human occupancy, such as building materials and indoor processes
3. From external sources, such as the outdoor environment and depositions in the ventilation system.

The odour emission due to human occupancy depends mainly on the number of persons present and their physical activity levels. The emission rates from non human occupancy and external sources can in many cases be considered to be constant over time. Theoretically, the decipol level in a room can be used as the decisive control variable in a demand controlled ventilation (DCV) system. By measuring the actual decipol level and comparing it to a given set-point level, the required amount of fresh air to the room can be computed by the flow controller. The obvious obstacle for enabling such a control system in practice is that no reliable odour sensors exist. In efforts to overcome this problem, mixed-gas sensor arrays and VOC sensors in combination with CO_2 sensors have been introduced (e.g. as discussed in [4] and [5]), showing quite promising results. The intension of such sensors is to provide an overall measure of the air quality in a room. Unfortunately, there are practical limitations with respect to the number of substances which can be detected.

Two important matters are (1) which of the many present substances should be given most weight, and (2) the magnitudes of the set-points which are to be given to the controller. Accuracy, stability (instrumental drift), costs for calibration and price of the sensor should also be taken into account.

The decipol level in a room can be achieved indirectly, by measuring the CO_2 concentration level. The CO_2 level provides a measure of the number of persons present in a room, hence the CO_2 level may be recognized as a surrogate for human related odours. In the following section, a new control algorithm based on the measured CO_2 level and ventilation air flow rate is discussed. Simulations of a single zone VAV system is used to visualize the capability and performance of the controller.

2 Control algorithm

The block diagram shown in figure 1 gives an overview of a possible configuration of a single zone VAV system. A ventilation system with a fan, ducts, a coil and a terminal device provides fresh air to a room. The measured CO_2 room concentration combined with some given control parameters are converted to a measure of the occupancy.

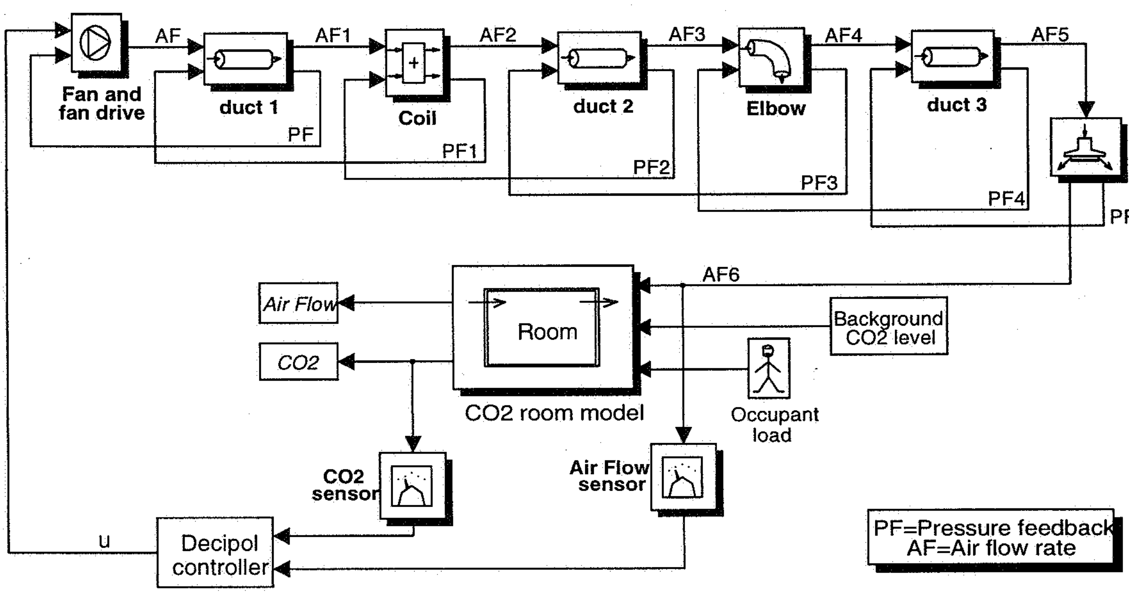

Figure 1: Block diagram of a odour controlled VAV system.

It has been assumed that the contaminants in the room (CO_2 and odours) is evenly distributed and that no infiltration air is present. These assumptions very much simplifies the room model, although it might be modified to take those effects into account.

The steady state CO_2 mass balance for a room with fully mixed conditions (and no infiltration present) can be written as:

$$C_s \cdot \rho_{CO_2} \cdot Q_a + S \cdot \rho_{CO_2} = C_r \cdot \rho_{CO_2} \cdot Q_a \tag{1}$$

C_s	:	Supply (background) CO_2 concentration $[m^3/m^3]$
C_r	:	Room CO_2 concentration $[m^3/m^3]$
S	:	Total CO_2 emission $[m^3/h]$
ρ_{CO_2}	:	Density of CO_2 $[kg/m^3]$
Q_a	:	Ventilated (fresh) air flow rate $[m^3/h]$

The CO_2 emission from n persons can be expressed as a function of their mean activity level M as follows:

$$S = k \cdot M \cdot n \quad [m^3/h] \tag{2}$$

The magnitude of the proportional factor k is determined by the respiratory quotient (RQ) times the amount of oxygen consumed by respiration. Hence, RQ is defined as the volumetric ratio of metabolic produced CO_2 to consumed O_2 [1]. RQ is found to be constant, independent of the level of physical activity, thus k must be a constant too. For a person having a normal diet mix of fat, carbohydrate and protein, RQ is equal to 0.83 [1]. At an activity level of 1.2 met, the O_2 consumption is about 0.0216 m^3/hour [1], and hence the value of k becomes $\frac{0.83 \cdot 0.0216}{1.2} = 0.015$ m^3/hour per person and met.

A combination of the equations 1 and 2, reveals the following expression for the occupant load:

$$n = \frac{200 \cdot Q_a}{3 \cdot M} \cdot (C_r - C_s) \tag{3}$$

If the supply concentration varies significant over time, for instance due to heavily traffic outdoor or due to recirculation of air, this concentration should be measured as well. However, it has been assumed that no recirculation of air is present and that variations to the background level is negligible. Thus C_s is constant.

Now, establishing a similar balance for odours in the room:

$$G_s \cdot Q_a + 36 \cdot F = G_r \cdot Q_a \tag{4}$$

G_s	:	Supply (background) decipol level
G_r	:	Room decipol level
F	:	Total olf emission to the room

The background decipol level is in the range 0 (clean air) to 0.5 decipol (low AQ in cities). The scaling of the olf emission term $(36 \cdot F)$ of equation 4 comes from the definition of the decipol unit (1 olf ventilated with 10 litres/sec or 36 m^3/h of fresh air). The total olf production in the room (F) is the sum of occupant related odours (F_o) and building related odours (F_b). F_b emits from materials and processes within the room.

$$F = F_o + F_b \quad [olf] \tag{5}$$

F_o will of course vary by the occupant load, and the contribution to F_o from a single person is very much dependent on the level of activity. Also, a major influence is caused by tobacco smoking, if smoking is present. F_o can be written as:

$$F_o = f_o \cdot n \quad [olf] \tag{6}$$

where f_o is the olf emission from one person in the room. The magnitude of f_o as a function of the activity level can be found in various literature, for instance from Fanger [3]. A standard person conducting sedentary work , i.e. having an activity level of 1-1.2 met, emits 1.0 olf to the room air. f_o increases dramatically with the percentage number of occupants smoking.

The emission from non occupant sources (F_b) can be written as:

$$F_b = f_b \cdot A + F_p \quad [olf] \tag{7}$$

where f_b is the olf emission from building materials per. square meter floor area A, and where F_p represents the emissions from processes within the room. The first term of equation 7 (f_b) will often decrease slowly, during a relatively long period of time. Fanger [3] found that the mean value of f_b for offices and schools was 0.3 olf/m^2. Although it is possible to take into account any variations of f_b, it is here, however, considered to be constant.

The combination of the equations 4 and 5 gives the following expression of the actual decipol level in the room:

$$G_r = \frac{36}{Q_a} \cdot (f_o \cdot n + f_b \cdot A + F_p) + G_s \ [decipol] \tag{8}$$

The following algorithm should be implemented to the controller [6], [7]:

If	$G_r < G_{r,\min}$
then	Decrease the controller output signal (decrease the fan speed)
elseif	$G_r > G_{r,\max}$
then	Increase the controller output signal (increase the fan speed)
else	Do nothing

$G_{r,\min}$ and $G_{r,\max}$ refer to the lower and upper control limits of the room decipol level, respectively. The controller ensures that the room level is kept within these limits. For instance, one might want to allow an occupant dissatisfaction of maximum 20% in the room, meaning that the upper decipol level should be kept below 1.4 decipol, Fanger [3]. The lower limit, which also must be given as a control parameter, should be specified, for instance 0.1 to 0.2 decipol below the upper limit.

In figure 2, a block diagram of the controller model is shown. The blocks are named in accordance with the nomenclature used above. The controller has two inlets and a single outlet. The inlets are the measured CO_2 level (C_r) and the air flow rate (Q_a), and the outlet is the controller signal (u). Five different parameters have to be specified to the controller; the metabolism (M), the background CO_2 level (C_s), the olf emission from building materials per square meter floor area (f_b), the floor area (A) and the background decipol level (G_s). Two multiplexers are used to vectorize the different parameters and variables used by the equation blocks (Eq. 3 and Eq. 8). A relay modulates the controller output sign according to the computed decipol level (G_r), and a rate limiter ensures that the rate of changes to the output signal is not too high (or too low), causing possible problems of instability.

3 A brief description of the simulation system

The simulation system is built from different component models. The system contains models for ducts (straight and elbow), a fan, a terminal device and a coil (see [6] for further details). In addition, a simple room model is used to predict the CO_2 conditions. Based on turbulent flow conditions, implicit, nonlinear relations are employed to determine the pressure loss through the components. The pressure loss output from a model is fed backwards through the system, while the corresponding air flow output is fed forward (for an overview, see figure 1). The simulation system shown in figure 1, has the following properties:

- The fan model (fan motor included) has two inlets; (1) the controller output signal and (2) the total pressure loss. Ideal fan laws are employed to determine the corresponding air flow output from the fan.

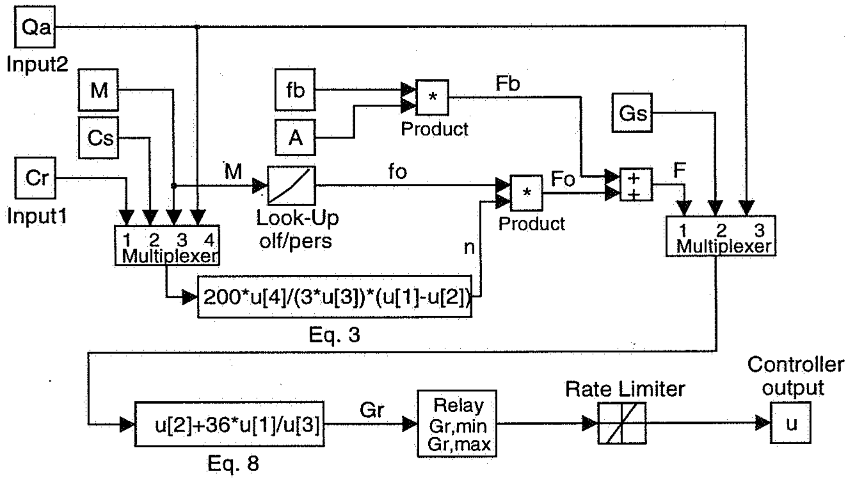

Figure 2: Block diagram of the controller.

- Both the duct and the elbow model account for pressure loss by friction. In addition, the elbow model has a table look up for single losses.
- The pressure losses in the coil and the terminal device are considered to be quadratically proportional to the air flow (i.e. fully turbulent flow).

4 Simulation case

In most cases a dynamic simulation system has a large number of parameters which must be specified, hence the number of possible simulation cases are almost infinite. In this study, only influences of the major load of the system have been investigated, i.e. the room occupancy.

The chosen room for the simulation case was typically a meeting room where the occupant density was expected to be high. The floor area was 40 m^2 and the ceiling height 2.5 m, giving a room volume of 100 m^3. Olf emission from building materials was expected to be 0.15 olf/m^2. The supply air quality was assumed to be around 0.05 decipol, constant over time, and no internal odour emitting processes were present. The ventilation system was able to keep the room decipol level below 1.4 with occupant loads up to 29 persons. Maximum air flow to the room was 925 m^3/h. Based on the olf emission from building materials, the flow controller determined a minimum air flow rate of 160 m^3/h.

5 Simulation results

The system was simulated for different occupant loads over a time period of six hours, using the RK45 numerical integration method with a simulation time step of 2 seconds. Figure 3 shows the occupant loads during the simulation. The actual load present in the room is represented by the dashed, stairs shaped line. The other line shown is the estimated number of occupants. As one might notice, the size of the inertia of the room model is important for the estimation to become accurate. If the occupant load was varying rapidly over time, the estimated load would probably not reach its steady state value, hence giving an inaccurate estimate of the actual load. In such cases, however, the actual decipol level would not reach its steady state level either. For this reason, a poor load estimate due to large room inertia is not critical. Because of the low pass filter effect of the occupant load estimation, the controlled state amplitudes get more attenuated. One should have in mind though, that the system being simulated is dynamic and that the control algorithm is based on steady state formulas.

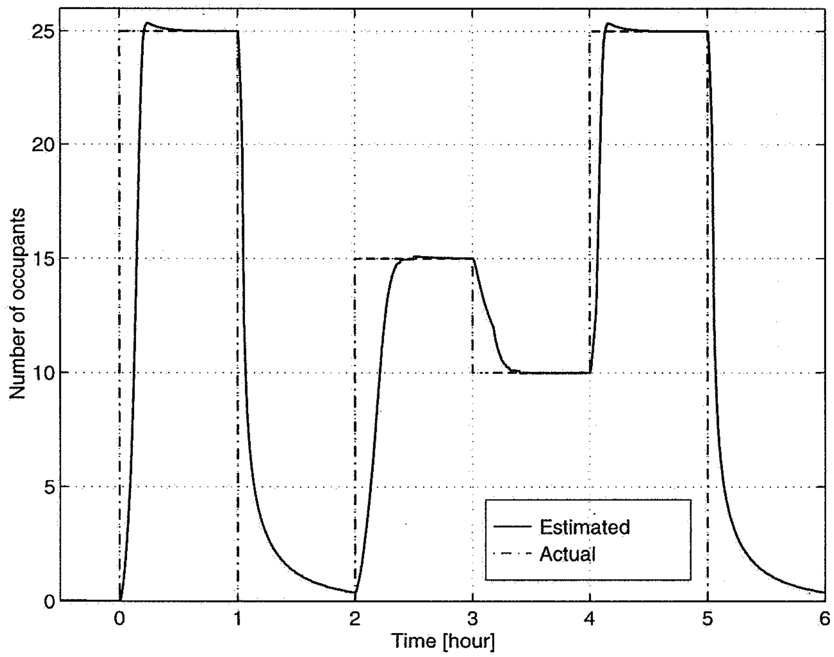

Figure 3: Actual and estimated occupant load in the room.

Now, focus on the controlled decipol level in the room (shown in figure 4). The control limits has been fixed to 1.4 and 1.2 decipol, upper and lower respectively. As 25 persons enter the room at time 0 hour, the room air quality deteriorates quickly. At a level of 1.4 decipol ($G_{r,\max}$), the controller begins to work, and the room decipol level is forced below the upper control limit. Most of the time between 0 and 1 hours, the room level stays between the control limits, and hence no control action is taken. At time 1 hour all the occupants leave the room. The room air quality improves very fast, down to a decipol value of 1.2 (the lower control limit, $G_{r,\min}$). When the lower limit is reached, the fan speed is reduced, forcing the air quality to stay around 1.2 decipol. The increasing, oscillating amplitude of the response just above the lower control limit stabilizes eventually between the control limits (a simulation period of one hour is to short to visualize this). As the simulation proceeds, the occupants enter and leave the room as shown in figure 3 and 4. The controlled state is kept within its limits, hence giving the desired room air quality.

In figure 5, the corresponding CO_2 responses from the simulation is shown. Starting with a background level of 350 ppm at time 0 hours, the concentration is rising rapidly as 25 persons enter the room. The maximum concentration during the simulation is below 900 ppm. If no occupants are present in the room, the CO_2 concentration drops towards the background level. The supply air flow rate, controlled by the decipol level in the room, is at this point 160 m^3/h.

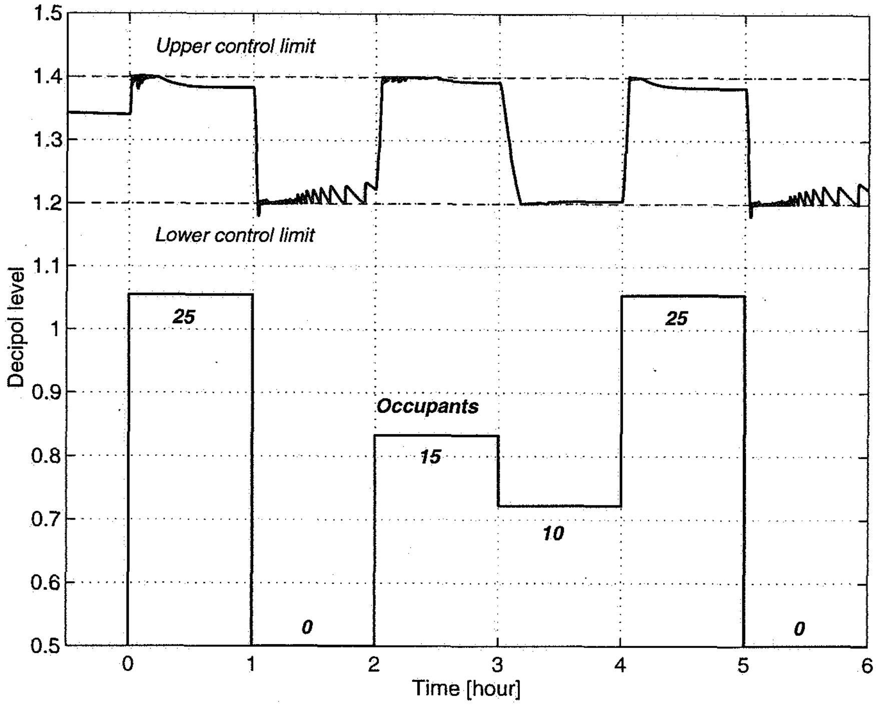

Figure 4: Simulated decipol level in the room. Upper and lower control limits are 1.4 and 1.2 decipol respectively.

6 Conclusions

A new control algorithm which enables predictive control of the air quality in a room has been presented. The control algorithm is based on measurements of the CO_2 level and ventilation air flow rate, giving an estimate of the occupant load in the room. The occupant load is then used to determine the air quality (represented by the decipol level) in the room. The algorithm is able to account for all odour sources in the room, for instance emissions from building materials. This ensures that the controller will provide a minimum ventilation air flow rate to the room at any time. However, the mean activity level of the occupants, the expected percentage of smokers (optional) and the emissions from non human sources have to be given as parameters to the algorithm. The predicted decipol level in the room is then compared to a given set point level, imposing the air flow to change properly. The following events should also be handled by the controller:

- Decreasing building odour emission rates over time
- Scheduling internal odour emitting processes
- Variations due to external sources

Simulations has been used to outline the controller performance, and the results show that the decipol level in the room can be kept within specified control limits, providing the desired room air quality. At this time, no efforts for a practical implementation of the algorithm have been conducted. Although the algorithm is functioning well for the ideal simulation case, this may not be the truth in reality. Some factors which may affect the performance are variable air quality background level, rapidly changes to any disturbance,

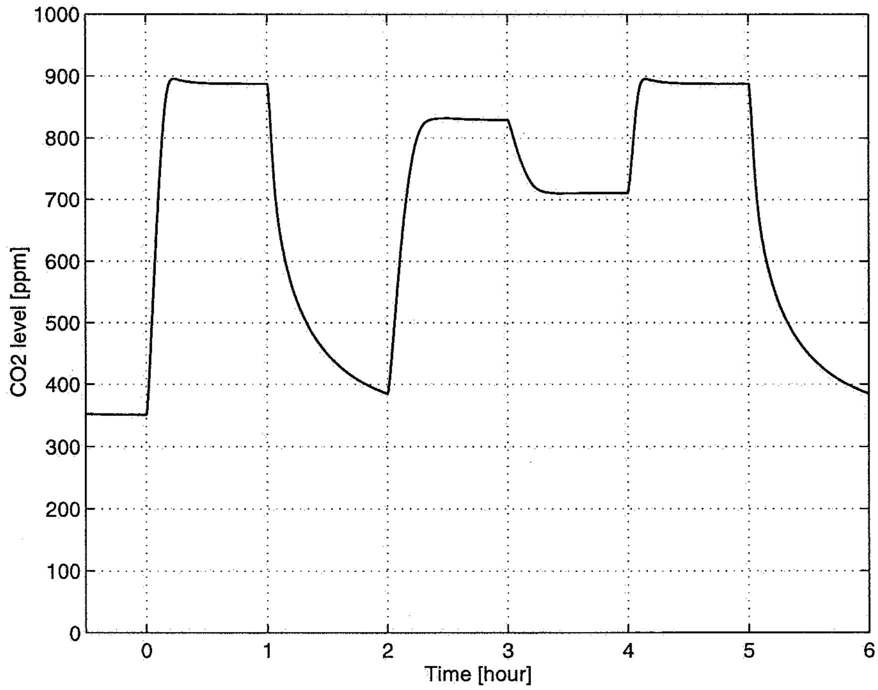

Figure 5: Simulated CO_2 response

placement of sensors, air flow patterns in the room, infiltration, recirculation and so on. The promising performance of the algorithm, shown by the simulations, has to be investigated further in practice.

References

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