

CO₂-BASED OCCUPANCY DETECTION FOR ON-LINE DEMAND CONTROLLED VENTILATION SYSTEMS

J Sowa*

Institute of Heating and Ventilation, Warsaw University of Technology, Warsaw, Poland

ABSTRACT

The paper presents part of the outcomes from the preliminary stage of the project set up by Polish Committee for Scientific Research and devoted to development of the recommended control strategies for DCV systems in Poland. The performance of three CO₂-based occupancy detection algorithms for on-line demand controlled ventilation systems has been studied. Additionally, the analysis covers three different procedures of adjusting ventilation rates according to the following ventilation standards: ASHRAE 62-2001, CEN CR 1752 and Polish standard PN -83/B-03430. Computer simulation was used to present the accuracy of analyzed algorithms.

INDEX TERMS

Occupancy detection, Demand controlled ventilation, Computer simulation, Ventilation standards

INTRODUCTION

The purpose of ventilation is to provide a comfortable indoor environment with a low health risk for the occupants. From the other hand this should be accomplished in such a way, that the energy consumption is low. Adapting the ventilation rate to the actual demand is one of the most promising ideas that may fulfill both of these goals. Combining this type of ventilation with control technology led to the concept of demand controlled ventilation (DCV).

Variable occupancy may be diagnosed directly (e.g. by infrared sensors) or indirectly by measuring the indicator of the occupancy like: relative humidity, specific contaminant concentration or, what is most popular, carbon dioxide (CO₂). At the low concentrations typically occurring indoors CO₂ is odorless and harmless, but is a good indicator of human bioeffluents and when there is no other sources of CO₂ than people it may be used to determine the level of occupancy.

In the last 15 years vital interest in DCV systems, especially based on measurements of CO₂ concentration, resulted in large number of literature published in journals and conference proceedings. All aspect of this type of ventilation from theory, trough simulations and applications, up to case studies may be found in the large set of papers. First state of the art on DCV systems was prepared (Raatschen, 1990) within the scope of International Energy Agency annex 18. Few years later two other extensive literature reviews were published: first covering 65 references devoted only to CO₂ based DCV systems (Emmerich and Persily, 1997), and second covering all methods used to emphasize ventilation demand discussing 43 publications (Fisk and De Almeida, 1998). However, as national standards and codes for minimum ventilation rates may use different type requirements, in author's opinion, it is still some room to discuss the DCV system performance taking into

* Contact author email: Jerzy.Sowa@is.pw.edu.pl

consideration both different detection algorithms and type of expressing requirement in ventilation standard.

Typical ventilation requirements are described using one or mixture of the following concepts: minimum ventilation rate per person, minimum air change rate, minimum ventilation rate per floor area.

ASHRAE Standard 62 -2001 assumes that for non-industrial facilities, in cases when there is no unusual indoor contaminants or sources, indoor air quality shall be considered acceptable if the required rates of acceptable outdoor air are provided for the occupied space. As in most cases, the contamination produced is presumed to be in proportion to the number of persons the ventilation rates per person is used to emphasize the requirements. In some cases, the contamination is presumed to be chiefly due to other factors and the ventilating rates given are based on more appropriate parameters (e.g. ventilation rate per floor area). The standard does not include any remarks concerning DCV systems however it should be noticed that several remarks address spaces with variable occupancy.

European report CEN CR 1752 (CEN, 1998) states that designed ventilation rate is the highest value of the separately calculated ventilation rates based on both comfort and health criteria. In practice recommended values for different classes of indoor environment are evaluated using the theory of perceived air quality or using CO₂ concentration calculations (there is lack of sufficient data for other chemicals). Designing criteria for several types of rooms, valid for specific assumption, are presented in special tables. Required ventilation rate is the sum of minimum ventilation rates for both occupants and building. No specific recommendations for DCV systems are set.

In Poland minimum flow of outdoor air in apartment houses, residential buildings and public buildings is specified in the Polish Standard PN-83/B-03430 (PKN, 2000). This Standard requires at least 30 m³/h of outdoor air for each occupant in air-conditioned room designated for permanent or temporal occupancy. From the other hand there is the requirement that ventilation rate should not be less than 0.5 h⁻¹ even when the room is not occupied.

The paper presents part of the outcomes from the preliminary stage of the project set up by Polish Committee for Scientific Research and devoted to development of the recommended control strategies for DCV systems in Poland. The multiplication of 3 ventilation standards described above by 3 algorithms of occupancy detection gave 9 combinations that were carefully instigated. Results presented in that paper are based on extensive computer simulations. Next steps of the project will be devoted to validation and tuning of the developed algorithms.

METHODS

If people are the only sources of CO₂ in the space, then the mass balance for CO₂ the single room ventilated only with outdoor air can be described by equation (1)

$$M \frac{dC_R}{dt} = e_0 \cdot a \cdot P + (C_{OA} - C_R) \cdot \dot{m}_{OA} \cdot e_{AC} \quad (1)$$

where M is the mass of air in the room, C_R is the CO₂ concentration (mass) in the occupied zone, e_0

is the average CO₂ generation rate (mass) of an occupant in reference activity, a is the activity level of the occupants in the space, P is the number of occupants C_{OA} is the CO₂ concentration (mass) in the supply air, \dot{m}_{OA} is the mass stream of outdoor air used to ventilate the room, e_{AC} is the air change effectiveness and t denotes time.

The equation (1) describes system behavior in continuous time. However, due to sampling interval and properties of processor calculations, real estimation techniques have to use discrete time. The simplest occupant detection algorithm is based on the assumption that CO₂ concentration reached the state of equilibrium. Steady-state detection algorithm was developed assuming that derivative $dC_R/dt = 0$. Using measurement data of the outdoor air flow rate and both outdoor and indoor CO₂ concentrations, the actual occupancy of a space in moment i can be estimated using equation (2).

$$P^i = \frac{(C_R^i - C_{OA}^i) \cdot \dot{m}_{OA}^i \cdot e_{AC}}{e_0 \cdot a} \quad (2)$$

Some problems may occur when the measured ventilation rate is 0. In that case algorithm is not able to estimate number of the occupants. Is worth to notice that calculated occupancy does not depend on previous estimations. More precise method of the occupancy detection is based on the approximation of the derivative (dC_R/dt) by the difference of CO₂ concentration in occupied zone ($i - 1$ represent previous sampling point) divided by the sampling interval Δt

$$\frac{dC}{dt} = \frac{C_R^i - C_R^{i-1}}{\Delta t} \quad (3)$$

Using this assumption equation (1) can be converted into discrete form.

$$P^i = \frac{(C_R^i - C_{OA}^i)(\dot{m}_{OA}^i + \dot{m}_{OA}^{i-1})}{2 \cdot e_0 \cdot a} + \frac{(C_R^i - C_R^{i-1}) \cdot M}{\Delta t \cdot e_0 \cdot a} \quad (4)$$

Number of occupants can be also estimated using classical proportional formula

$$P^i = \frac{(C_R^i - C_{OA}^i)}{(C_R^\infty - C_{OA}^\infty)} P_D \quad (5)$$

where C_R^∞ , C_{OA}^∞ are the CO₂ concentrations (mass) in designing conditions (steady state) respectively in the occupied space and in outdoor air.

Knowing number of occupants, estimated by one of the described above algorithms, and taking into consideration existing limitations of the system, the mass stream of outdoor air for next step $i + 1$ can be adjusted according to equation (6)

$$\dot{m}_{OA}^{i+1} = \text{MIN}(\text{MAX}(P^i \cdot R_p \cdot r + R_B \cdot A_B; \dot{m}_{MIN}); \dot{m}_{MAX}) \quad (6)$$

where R_p is the outdoor air requirement per person, R_B is the outdoor air requirement per unit area, A_B is the net area of the floor in the occupied zone \dot{m}_{MIN} and \dot{m}_{MAX} are lower and upper limits of the real ventilation system.

The performance of described CO₂-based occupancy detection algorithms was studied using computer simulation. Conference room for 30 persons was selected as a virtual test object. The room has the floor area of 60 m² and volume of 170.5 m³. 100 % outdoor air ventilation system is responsible for maintaining acceptable level of IAQ, while air conditioner is maintaining required thermal environment. Air is supplied by 4 ceiling diffusers and additionally mixed by the air conditioner. This stage of the study was performed for idealized assumption that system itself does not give lower limitations for ventilation rate. \dot{m}_{MIN} was not equal 0 only when ventilation standard additionally required minimum intensity of air change. Required ventilation rates based on different ventilation standards are summarized in Table 1.

Table 1. Ventilation rates in analyzed test room.

| Ventilation standard | Ventilation rate per person l/(s person) | Ventilation rate per area (l/s m ²) | Maximum ventilation rate (l/s) | Additional limitations |
|----------------------|--|---|--------------------------------|----------------------------------|
| ASHRAE 62-2001 | 10 | 0 | 300 | - |
| CR EU1752 (class B) | 7 | 1.4 | 294 | - |
| PN-83/B-03430 | 8.33 | 0 | 250 | Vent. rate ≥ 0,5 h ⁻¹ |

RESULTS

The first test was designed to study the ability to detect rapid jump in occupancy. Simulation covered three scenarios with rapid entrance of 10, 20 and 30 persons. Three scenarios multiplied by three algorithms and by three standards gave 27 combinations. Figure 1 presents part of results for Polish standard PN-83/B-03430. Figure 2 shows results obtained when report CR 1752 was used, while similar graphs at Figure 3 used data when ventilation rate was adjusted according to ASHRAE standard. Two almost identical lines at Figure 2 indicate that there is no significant difference between the dynamic algorithm and the steady state algorithm when report CR 1752 is used. Also it worth to notice that when there is no lower limit of ventilation rate the steady state algorithm is not able to detect occupancy (Figure 3). Second test checked system ability to follow variable occupancy during a simulated workday. Results when Polish standard was used to adjust ventilation rate are presented at Figure 4. Table 2 presents the comparison of percentages of time when the actual ventilation rate was lower than 90% and greater that 110% of actual ventilation rate required by analyzed standards.

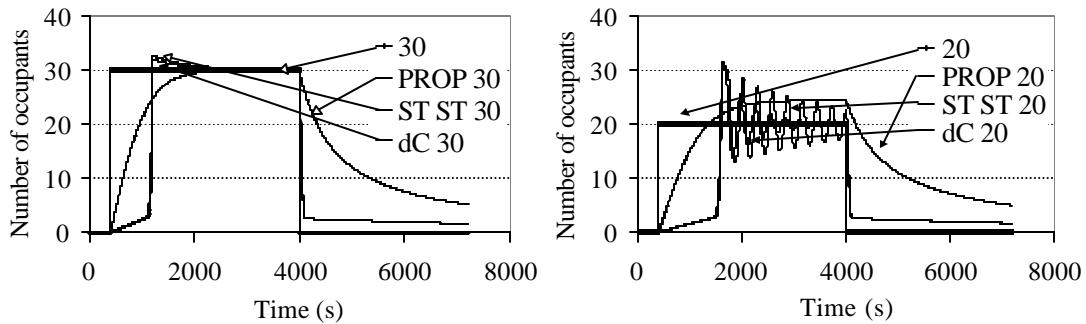


Figure 1. Simulated response of the CO₂ based on-line detection algorithms to occupancy profile 30 person (left) and 20 person (right). Ventilation rate according to PN-83/B-03430.

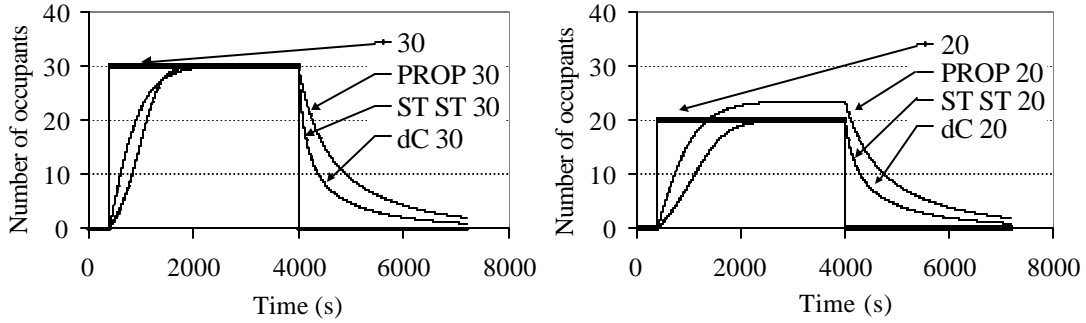


Figure 2. Simulated response of the CO₂ based on-line detection algorithms to occupancy profile 30 person (left) and 20 person (right). Ventilation rate according to CEN CR 1752.

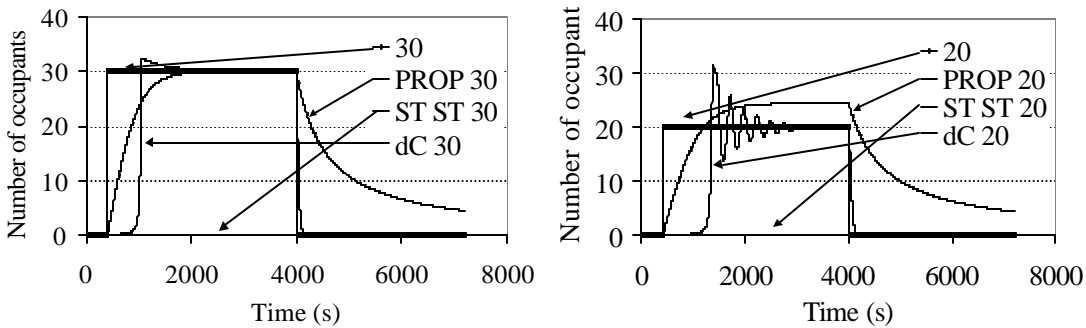


Figure 3. Simulated response of the CO₂ based on-line detection algorithms to occupancy profile 30 person (left) and 20 person (right). Ventilation rate according to ASHRAE 62-2001.

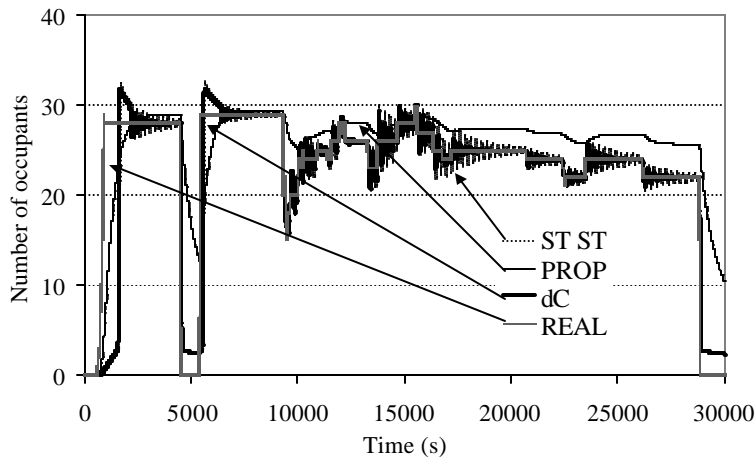


Figure 4. Simulated performance of three occupancy detection algorithms. Ventilation rate adjusted according to Polish standard PN-83/B-03430.

DISCUSSION

Performed tests showed that all algorithms of occupancy detection have problems with automatic start up the ventilation systems. The analysis indicated that problem is connected with the minimum air change rate (air change rate when there is no occupancy at all). There is very strong influence of ventilation rate on time necessary to reach assumed levels of steady

Table 2. Percentages of time when the actual ventilation rate was lower than 90% and greater than 110% of actual ventilation rate required by analyzed standards.

| Ventilation standard used for adjusting ventilation rate | Steady state algorithm (ST ST) | | Dynamic algorithm (dC) | | Prop. algorithm (PROP) | |
|--|--------------------------------|--------|------------------------|--------|------------------------|---------|
| | < 90% | > 110% | < 90% | > 110% | < 90% | > 110% |
| ASHRAE 62-2001 | 5.07 % | 3.32 % | 4.89 % | 2.13 % | 5.74 % | 38.27 % |
| CR EU1752 (class B) | 6.58 % | 1.39 % | 6.47 % | 1.39 % | 6.47 % | 18.91 % |
| PN-83/B-03430 | 6.38 % | 3.94 % | 5.23 % | 2.07% | 5.23 % | 38.43 % |

state concentration after appearance of constant emission. Time of response dramatically increases for low air change rates. Proportional algorithm is less sensitive for this phenomenon. In analyzed cases these values were 0 h⁻¹ according to ASHRAE Standard, 0.5 h⁻¹ according to Polish Standard and 1.77 h⁻¹ according to report CR 1752.

In spite of the problems with start up, the dynamic algorithm of occupancy detection gives the best results. In comparison with the steady state algorithm dynamic algorithm has lower oscillation and faster reaches the real occupancy. It is worth to point out that when the part of the ventilation rate not associated with occupancy is big enough (e.g. report CR 1752) oscillation disappear and estimated occupancy asymptotically follow the real value. Although the performance of 3 algorithms and 3 types of ventilation requirements has been checked carefully in idealized virtual world, the results may not be the same in reality. Several factors may affect the performance in the real test room: variable background level, placement of sensors, airflow patterns in the room, infiltration etc.

CONCLUSION

The study showed that not only different detection algorithms but also type of expressing requirement in ventilation standard influence DCV system performance. The importance of minimum ventilation rate for start up the system and part of ventilation rate not associated with occupancy for its stability has been showed. Further tests and tuning of the strategies using real systems would be appropriate prior to practical application of the results of this modeling. Real data of CO₂ concentrations will probably require additional study on signal filtration.

ACKNOWLEDGMENTS

The study is part of a project funded by the Polish State Committee for Scientific Research.

REFERENCES

- ASHRAE, 2001, ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
- CEN, 1998, CEN CR 1752, Ventilation for Buildings - Design Criteria for the Indoor Environment. European Committee for Standardization.
- Emmerich S J, Persily A K, 1997, Literature review on CO₂-Based Demand-Controlled Ventilation, *ASHRAE Transactions*, V 103 part 2.
- Fisk W J, De Almeida A T, 1998, Sensor-based demand-controlled ventilation;: A review. *Energy and Buildings* no 29 pp. 35-45
- PKN, 2000, Polish Standard PN-83/B-03430 with correction Az3:2000 Ventilation in dwellings and public utility buildings. Specifications. (in Polish).
- Raatschen W ed. 1990, Demand controlled venting system State of the Art. Review D9 Stockholm Swedish Council for Building Research.