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Occupancy-Based Control of Indoor Air Ventilation: A Theoretical and Experimental Study

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ABSTRACT In this paper, the theoretical and experimental studies of the occupancy-based control of the ventilation are presented to demonstrate the practical usefulness of the occupancy-based scheme for real-time air ventilation control and energy saving. The CO_2 concentration is widely used as an indicator of the pollutant contaminant in indoor air and it often changes with time on account of the number of occupants. With the proposed methodology, the number of occupants can be estimated from the real-time measurement of the CO_2 concentration of the outdoor air and the indoor air. As known, not only occupants but also buildings themselves contribute to potential indoor-air-quality problems. ASHRAE Standard 62-1989R guideline gives the design ventilation rate based on both occupancy and building space. According to ASHRAE Standard 62-1989R, the estimated number of the occupants and the area of ventilation-controlled space are used to determine the design ventilation rate required for acceptable indoor air quality. This design ventilation rate allows the Heating, Ventilating and Air-conditioning system to produce the acceptable indoor air quality at efficient energy usage. The experimental results show the viability of the proposed method- controlling ventilation based on estimated occupants.

KEYWORDS: occupancy-based ventilation, occupant estimation, CO_2 control, indoor air quality and energy saving.

INTRODUCTION

Nowadays, it cannot be denied that a great number of people are exposed to an indoor air environment longer than to an outdoor one because they spend most of their time for daily activities indoors. One reason is that the outdoor air environment may be uncomfortable to the delicate body of human being. Normally, the Heating, Ventilating and Air-Conditioning (HVAC) system is implemented to control the comfort variables such as temperature, humidity, etc of not only the indoor air but also the supply air from outdoor. The main purpose of bringing outdoor air into the air-conditioned space is to dilute the indoor air pollution so that the Indoor Air Quality (IAQ) is maintained at acceptable level. Therefore, the air ventilation has significant roles on the air quality and energy consumption of the HVAC system. The make-up outdoor air requirements lead to considerable energy consumption. Hence, over-ventilation should be avoided. One method to achieve acceptable IAQ at minimized energy cost is Demand-Controlled Ventilation (DCV). Up to now, there has been much research on CO_2-based DCV system although CO_2 is not the only indoor air pollutant.[1] It can be used as an index of IAQ. This may be because CO_2 is a human-waste fluid and if the CO_2 concentration is controlled at the desired level, then other pollutants will be controlled at acceptably low level as well. Carpenter (1996)[2] reported that CO_2-based DCV system was applicable and it saved energy compared with constant ventilation. In a study by Vaculik and Plett (1993)[3], the control strategies of the CO_2-based DCV were investigated by simulations for a typical occupancy profile during a working day. It was found that the adjustment with CO_2-based DCV for the rate of air ventilation meets the requirements of ASHRAE Standard 62-1989.[4] However, Ke and Mumma (1997)[5] introduced the occupancy-based DCV in order to determine the changeable occupancy for the ventilation control based on the CO_2 concentration in the outdoor air and the return air. Simulation studies showed better performance on the basis for comparison of the occupancy-based method with two other conventional methods: the CO_2-based method and the constant airflow method. Additionally, this occupancy-based DCV method better fulfills the requirements of the current revised ASHRAE Standard 62-1989R.[6] The revised Standard 62-1989R guideline considers not only the people-related factors but also the building-related factors in the determination of the minimum outdoor air intake. It does not stress the assumption of a constant CO_2 concentration at 300 ppm for the outdoor air, which is quite realistic. For example, the CO_2 concentration near the main road in a big city may be significantly higher.

Attention of this work is now focused on a further extension of the occupancy-based DCV method to real-time implementation of air ventilation control. The theoretical derivation of the occupancy-based DCV method is first developed and its application is preliminarily investigated by the real-time control of the rate of the air ventilation in the classroom building.

Experiments

The experiments took place at air-conditioned classrooms within main building of Sirindhorn International Institute of Technology. There are two classrooms used in this study. First, the 10x20x4 m^3 classroom with 55-student capacity was used to verify the applicability of the mathematical models in Section 3. Secondly, the 7.5x6x3 m^3 classroom with 30-student capacity was used to investigate the viability of the proposed methodology in a real-time ventilation control. A diagram of controlling the rate of the air ventilation with the occupancy-based DCV method is illustrated in Fig 1. Two CO_2 sensors of Telaire 7001 were used for the on-line measurement of the CO_2 concentration of indoor (return) air and outdoor (supply) air. With the measurements of the CO_2 concentration, the air ventilation demand is computed by the occupancy-based DCV method. The rate of air ventilation for the air-conditioned room is accordingly adjusted by regulating the ventilating fan. The data acquisition system for analog/digital conversion was performed by ADAC-PCM5508.

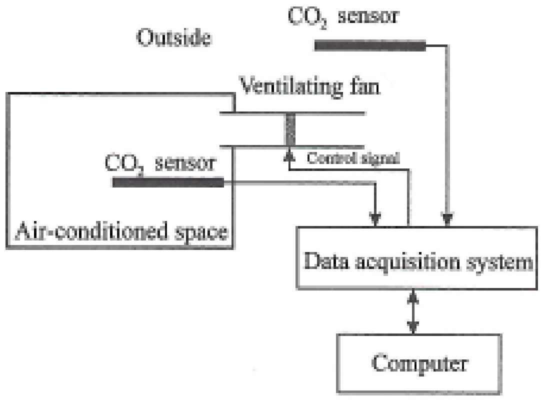

Fig 1. Implementation of occupancy-based control of indoor air ventilation.

Development of Occupancy-Based DCV Method

According to Standard 62-1989R, air ventilation is an attempt to dilute the indoor air pollution caused from both building and its occupants. The Design Ventilation Rate DVR can be determined by:

$$DVR = c_p n_p D + c_b a_b \quad (1)$$

where c_p is the coefficient factor of the air ventilation rate per person, c_b is the coefficient factor of the air ventilation rate per area, n_p is the number of the occupancy, a_b is the area of the air-conditioned space and D is the diversity factor.

Typically, the area of the air-conditioned space can be measured and all the coefficient factors are known by the purpose of the space utilization. For instance, the values of c_p and c_b for the office space are 3 L/s per person and 0.35 L/s per m^2 respectively.

From Eq (1), the DVR value of for a given air-conditioned space can be determined if the number of the occupants is available. However, the occupancy is normally different from specified schedules in many cases. To satisfy the dynamic ventilation, the occupancy-based DCV method is used. The simple scheme of this method is that the CO_2 concentrations of both outdoor air and indoor air are used to estimate the number of the occupants. In the estimation of the number of occupants, let's consider the control volume of a single-zone air delivery system as shown in Fig 2. It should be noted that the derivations below can be implemented with respect to any individual space in a multi-zone system.

Based on the well-mixed condition, a mass balance on the contaminant can be written as:

$$v\frac{dC}{dt} = Q_s C_s + Q_i C_i - (Q_o C + Q_e C) + N \quad (2)$$

where C is the CO_2 concentration in the room, v is the volume of the room, N is the CO_2 generation

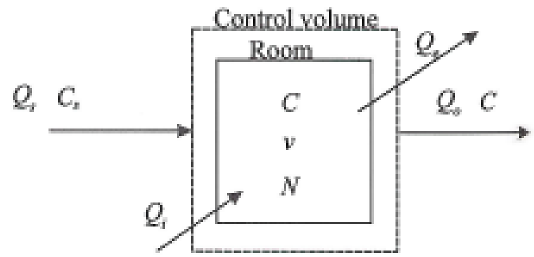

Fig 2. Control volume of single-zone system.

rate, C_s is the CO_2 concentration of the outdoor air, C_i is the CO_2 concentration of the infiltration air, Q_s, Q_i, Q_o and Q_e are the air-flow rate of supply air, infiltration, leaving air and exfiltration respectively.

To simplify Eq (2), assume that the infiltration and exfiltration of air are negligible. This hypothesis agrees with the fact that the fully air-tightened envelope of the air-conditioned space is usually designed for energy saving. However, any large infiltration or exfiltration may cause an overestimated or underestimated number of occupants. In such a case, these effects are to be taken into account.

The rate of the change in the CO_2 concentration can be determined by:

$$v\frac{dC}{dt} = -Q_s(C - C_s) + N \tag{3}$$

To derive the CO_2-based estimator of the number of occupants, the finite difference approximation is applied to Eq (3) and the resulting equation is rearranged. This yields

$$N(t) = v\frac{C(t) - C(t-\Delta t)}{\Delta t} + Q_s(t)\left(C(t) - C_s(t)\right) \tag{4}$$

where Δt is the sampling time period.

For the steady state condition, the derivative term can be dropped out. The generation rate of the source can be given as:

$$N(t) = Q_s(t)\left(C(t) - C_s(t)\right) \tag{5}$$

Referring to Eqs (4) and (5), the CO_2 generation rate can be determined if the CO_2 concentrations of the indoor and outdoor air are measured in real time. Further, if the generation rate of the CO_2 source is proportional to the CO_2 generation rate of the occupants per person G, then the number of the occupants can be obtained as:

$$n_p = \frac{N}{G} \tag{6}$$

Some of the values of G[7] are listed in Table 1.

Once the number of the occupants is estimated from Eq (6), the value of the *DVR* can be calculated by Eq (1) for the ventilation requirement according to ASHRAE Standard 62-1989R. This scheme simply requires the CO_2 concentration measurements of the air entering and leaving the controlled space in order to estimate the number of occupants. The good estimation of the number of the occupants can be obtained as long as the value of G can closely represent the actual activities of the occupants. In some cases, the activities may change with respect to time. The value of G is to be adjusted accordingly. Typically, the value of G is known *a priori* since the activities of occupants in air-conditioned space are known ahead of time. For example, the value of G used in this work was set to be constant during real-time computation in the experiment since the students are virtually seated and worked lightly during the class period.

Results and Discussion

The mathematical models of Eqs (4)-(6) are used to estimate the number of the occupants. The applicability of those models is investigated as follows. The CO_2 concentration in the air-conditioned classroom with 10x20x4 m^3 was measured as shown in Fig 3. The sampling period was chosen to be 5

Table 1. Values of CO_2 generation rate of the occupancy per person *G*.

	Type of activity	*G* (L/min per person)
Very light work:		
	Seated, writing	0.27
	Seated, typing	0.29
	Seated, talking	0.29
	Seated, filing	0.31
	Standing, talking	0.31
	Standing, filing	0.35
Light work:		
	Walking	0.44
	Lifting, packing	0.53

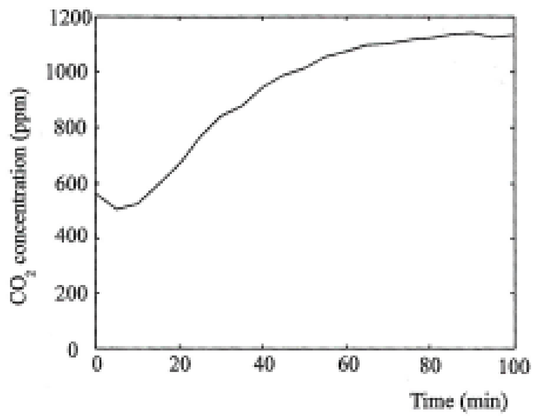

Fig 3. Plot of measured CO_2 concentration against time.

minutes. The fresh air from outside was taken into the room with a constant rate of 288 L/s. A CO_2 sensor placed in the classroom measured the CO_2 concentration of the classroom while the mean CO_2 concentration of the outdoors was measured at 230 ppm. From Fig 3, it should be mentioned that the initial CO_2 concentration (~500 ppm) at starting time is higher than that of the outdoor air. This is because there is no air ventilation before the class begins. As the students start entering to the class, the CO_2 concentration increases until it reaches the steady state. Fifty-five students attended this class. In Fig 4, the circle symbol shows the actual students in the class against time. The mathematical models of Eq (4) and Eq (5) were used to estimate the number of the students. In calculation, the numerical value of the CO_2-concentration generation rate was used to be 0.3 L/min per person for very light working condition according to Table 1. In Fig 4, the solid line presents the estimated number of students, determined from the model in Eq (4), while the dashed line indicates the estimated number of the students, computed from the model in Eq (5). It can be seen that the model in Eq (4) can closely approximate the dynamic behavior of the student number at initial time. This can be interpreted intuitively that the derivative term can provide anticipative number of students based on the linear extrapolation. On the other hand, the profile of the number of the students estimated by the model in Eq (5) is similar to the profile of the CO_2 concentration. Similarly, there is no difference of the estimated number of occupants from the models in Eq (4) and Eq (5) at the steady state of the CO_2 concentration. With these satisfactory facts, the model in Eq (4) is used to determine the estimated number of the occupants in the real-time control of air ventilation.

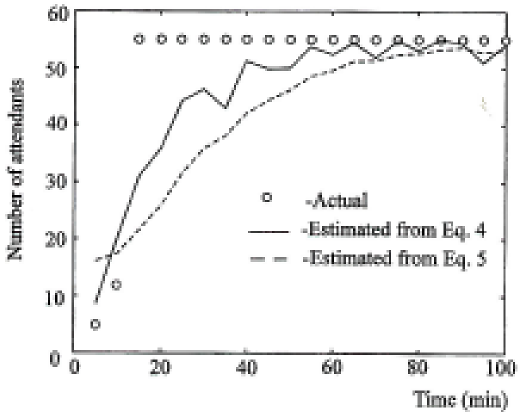

Fig 4. Implementation of models from Eqs (4) and (5) in estimating number of attendants.

As mentioned in Section 2, the air-conditioned classroom with 7.5x6x3 m^3 was used for the experiment of DCV. The class takes about three hours and has two 15-minute breaks. With the real-time measurement of CO_2 concentration, the model in Eq (4) is used to estimate the number of students. Regardless of the area factor, the DVR was computed from Eq (1) on-line with the coefficient factor[4] c_p of 8 L/s per person and the diversity factor of 1 for this experiment. The plot of the DVR and the CO_2 concentration are shown as Fig 5. Originally, the rate of the ventilation air in the classroom was fixed at the full capacity of 300 L/s. The simulation of the CO_2 concentration with constant full ventilation rate as illustrated in Fig 6 can be determined by using Eq (3) and the CO_2 generation rate from the estimated number of students. Compared with the measured CO_2 concentration with DCV, it can be seen that the proposed DCV method does provide efficient ventilation rate to the classroom in order to reduce the CO_2 concentration close to the case with full ventilation rate. From the energy aspect, the

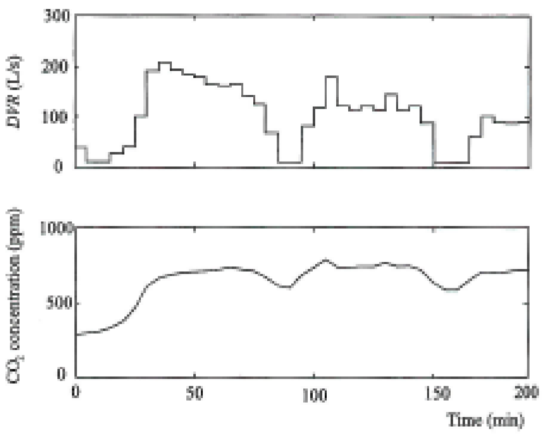

Fig 5. Plot of DVR and corresponding measured CO_2 concentration against time.

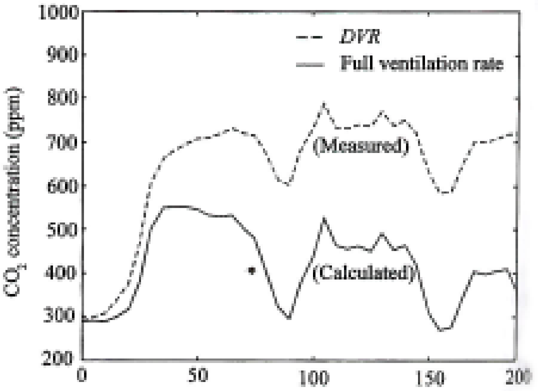

Fig 6. CO_2 concentration in classroom with full ventilation rate.

properties of indoor air and outdoor air such as temperature, humidity and enthalpy were first measured and determined during the DVR implementation as illustrated in Fig 7 and Fig 8 respectively. In the case of full ventilation rate, the values of the temperature and humidity of the indoor air in the time domain were approximated to be the ones in the case of DVR. In fact, the experiment with full ventilation rate cannot be performed in order to measure temperature and humidity at the same time when the DVR experiment was going on. However, the difference between the approximate values and actual values (if possible to measure) of the temperature and humidity is expected to be small since the condition of the indoor air is to be controlled tightly at the same conditions. This can be noticed from the small variation of temperature (~25°C) and humidity (~52 %RH) in Fig 7. The

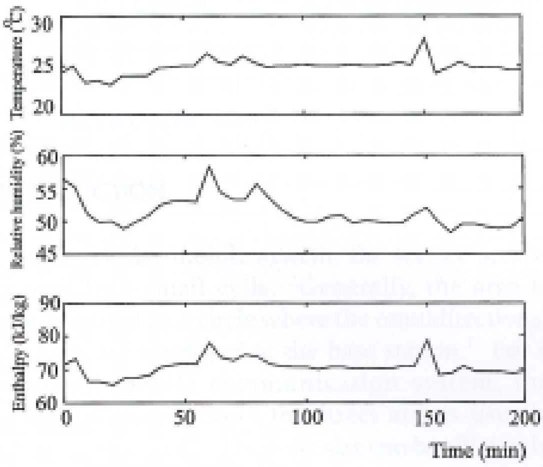

Fig 7. Measured properties of indoor air during DCV implementation.

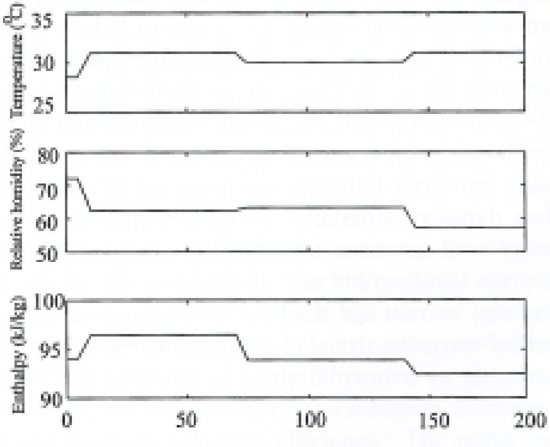

Fig 8. Measured properties of outdoor air during DCV implementation.

energy consumption of making up air from the ambient condition of the outdoor air to the room condition can be determined by Eq (A1). Fig 9 shows the ventilation loads due to DVR and the full ventilation rate. The DCV system consumed 9.11 kWh while the original system with full ventilation rate consumed 28.10 kWh. By implementing the occupancy-based DCV method, the energy consumption can be reduced to 32 % of the original ventilation load while acceptable air quality can also be obtained.

Conclusions

Increased make-up air requirements with the acceptable IAQ and the low energy cost are making the task of air ventilation controls more and more challenging. ASHRAE Standard 62-1989R provides a realistic guideline for the design ventilation rate based on both occupancy and building. To achieve the acceptable IAQ, both the number of the occupants and the area of air-conditioned spaces need to be known for the design ventilation rate according to ASHRAE Standard 62-1989R. The area of air-conditioned space can be simply measured. On the other hand, it is not easy to assess the number of occupants, which is strongly dependent on time. With the proposed method, the number of the occupants can be systematically estimated from the real-time measurement of the CO_2 concentration of the indoor air and outdoor air, provided the type of human activity (the value of G) is known *a priori*. The experimental results of the occupant estimation show that the mathematical models can closely capture the dynamics of the number of the occupants. From the experimental results of real-time air ventilation control, the proposed occupancy-based DCV method can be used as an effectively practical approach for both acceptable IAQ and energy saving.

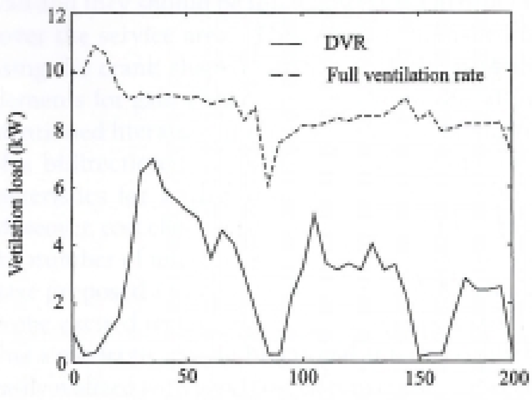

Fig 9. Comparison of ventilation loads between DVR and original full-ventilation rate.

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Appendix

The ventilation load can be determined by:

$$E = \dot{m}(h_0 - h_i) \tag{A1}$$

where E is the ventilation load, $\dot{m}$ is the rate of ventilation air, h_0 is the enthalpy of outdoor air and h_i is the enthalpy of the indoor air.

The conversion factor of CO_2 concentration from ppm to L/ m^3 is 0.001013439.