Original Paper

Indoor+Built Environment

Indoor Built Environ 1999;8:377–391

Accepted: February 2, 2000

Experimental Validation of CO_2-Based Occupancy Detection for Demand-Controlled Ventilation

Shengwei Wang John Burnett Hoishing Chong

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

Key Words

Occupancy detection · Ventilation strategy · CO_2 detection · Energy efficiency · Computer simulation

Abstract

On-line ventilation control based on carbon dioxide (CO_2) measurement and the dynamic CO_2 balance in indoor spaces has been validated using a dynamic algorithm for two existing buildings. Occupancy profiles estimated using the dynamic algorithm were compared with the true occupancy profiles and the occupancy profiles estimated using a steady-state algorithm based on the steady-state CO_2 balance. The dynamic algorithm estimates the changes of occupancy without significant delay. The steady-state algorithm is comparable only at a high air change rate and shows a considerable delay when the number of air changes per hour in a space is small. This phenomenon was investigated using computer simulation.

Introduction

Ventilation with outdoor air is one of the key factors affecting the air quality in air-conditioned indoor spaces. Several strategies exist for air-conditioning which aim to achieve acceptable indoor air quality with minimum energy consumption, among them demand controlled ventilation (DCV). Various studies and applications about DCV have been reported [1–7]. The current ASHRAE standard 62-1989 [8] requires that the minimum design outdoor ventilation airflow rate should be based on the occupancy in the air-conditioned space. The standard also suggests controlling the outdoor ventilation airflow rate by controlling the carbon dioxide (CO_2) concentration in the space within an acceptable limit.

However, recent studies have demonstrated that this DCV strategy cannot adequately consider the ventilation demand in a space in many situations [9]. Firstly, absolute level of CO_2 concentration is not a reliable indicator of ventilation demand. A space may be under-ventilated when the CO_2 in a space is below a certain set limit. The air quality in a space may be acceptable, even when the CO_2 concentration in the space is over the same limit in other situations. Secondly, the DCV strategy cannot efficiently ignore the non-occupant-generated pollutants (from building materials, furnishing), particularly when the pollutants generated by occupants do not dominate.

Therefore, ASHRAE proposed a revised version of the ventilation standard (62-1989R) for public review [9], suggesting that the minimum requirement on the outdoor air ventilation rate should be determined by not only the actual occupancy, but also the occupied area. This ap-

KARGER

Fax + 41 61 306 12 34
E-Mail karger@karger.ch
www.karger.com

1420–326X/99/0086–0377$17.50/0

Accessible online at:
www.karger.com/journals/ibe

Dr. Shengwei Wang
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hom Hung, Kowloon, Hong Kong (China)
Tel. +852 2766 5858, Fax +852 2774 6146, E-Mail Beswwang@PolyU.edu.hk

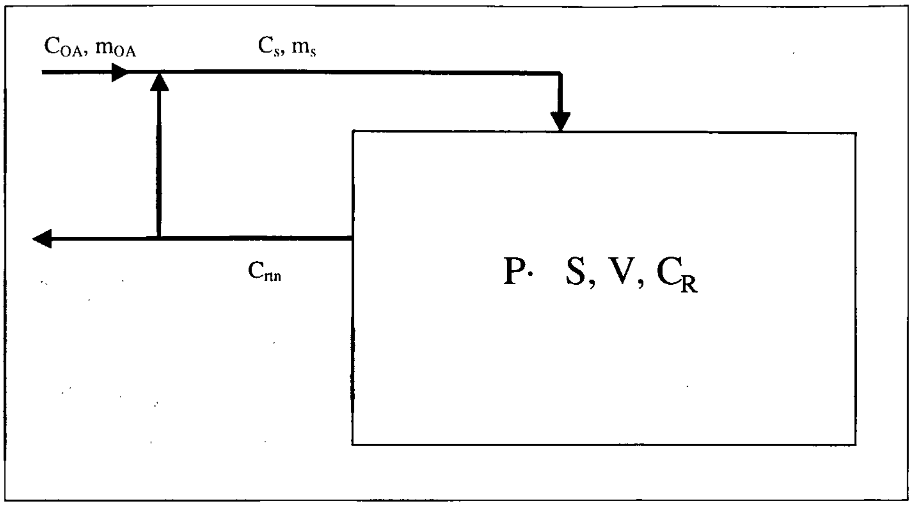

Fig. 1. Model of an air-conditioned space.

proach provides a way to consider the non-occupant-generated pollutants, but it does require the actual occupancy for a space to be identified.

Occupancy sensors are widely used in the control of lighting systems. They are suitable in the cases when only the on/off (occupied or not occupied) status needs to be detected. Some other techniques such as a computer vision technique [10] can be used to detect the number of occupants in a space. However, its application is obviously restricted by the geometrical layout of the indoor space for wide commercial applications in energy management and control systems.

Measurement of CO_2 for ventilation control with outdoor air is a well-developed technology in industry due to the efforts of a number of professionals in the heating, ventilating and air-conditioning and related fields over many years. A steady-state method based on CO_2 measurement is proposed in the *ASHRAE Public Review Draft*. However, simulation studies on the on-line performance of the ventilation control show that there might be significant delay in detecting occupancy changes when using the steady-state method [11]. To accurately detect occupancy and its changes, a dynamic method was developed. This detects the actual occupancy, by measuring the CO_2 concentration and its changes, as well as the outdoor air ventilation rate. The method has previously been validated for a simulated environment [11]. To evaluate the applicability, accuracy and stability of the dynamic detection algorithm in practical applications, experimental studies were conducted in an office building and a lecture theatre.

Methods

For investigations at the two study sites, the outdoor ventilation airflow rate and the CO_2 concentrations of the indoor air and outdoor fresh air were measured by data acquisition systems. At the same time, true occupancy profiles were recorded by counting the number of occupants in the conditioned spaces.

The occupancy profiles in the spaces were predicted using both the dynamic and the steady-state algorithms. The on-line CO_2-based occupancy dynamic detection algorithm was validated by comparing the occupancy profiles estimated using different detection algorithms and filtration methods with recorded true occupancy profiles.

The Occupancy Detection Algorithms

Both the steady state algorithm suggested by the revised ASHRAE standard (62-1989R) and the dynamic algorithm developed by the authors are based on the CO_2 balance of an air-conditioned space (fig. 1) as shown in equation 1.

$$P \cdot S + m_S C_S - m_S C_{rtn} = V \frac{dC_R}{dt} \quad (1)$$

The variable m_S is the supply air volume flow rate, C_S is the CO_2 concentration of the supply air, C_{rtn} is the CO_2 concentration of the return air, V is the air volume in the conditioned indoor space, C_R is the CO_2 concentration in the conditioned indoor space, P is the number of occupants, and S is the average CO_2 generation rate of an occupant.

The air change effectiveness (E_{ac}) can be expressed approximately using equation 2.

$$E_{ac} \approx \frac{C_{rtn} - C_s}{C_R - C_s} \quad (2)$$

The CO_2 balance of the supply air mixing can be expressed by equation 3.

$$m_s (C_{rtn} - C_s) = m_{OA} (C_{rtn} - C_{OA}) \quad (3)$$

The variable m_{OA} is the outside air volume flow rate and C_{OA} is the CO_2 concentration of the outside air.

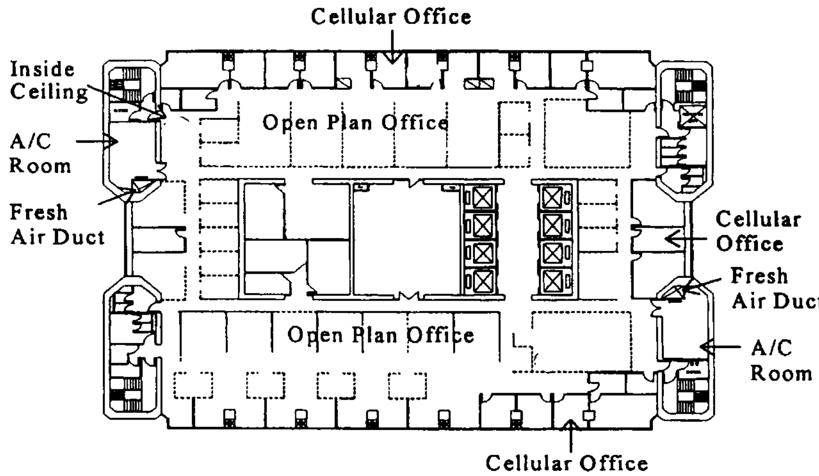

Fig. 2. Floor layout of an open-plan office.

The CO_2 balance of the air-conditioned space can be written as equation 4 after substituting equations 2 and 3 into equation 1.

$$P \cdot S + E_{ac} m_{OA} (C_{OA} - C_R) = V \frac{dC_R}{dt} \tag{4}$$

The main benefit of using the differential CO_2 concentration between the conditioned space and the outdoor air is that it provides greater accuracy in calculating the differences in CO_2 concentration. This is because the difference in CO_2 concentration between the conditioned space and the outdoor air is usually greater than that between the conditioned space and the supply air in systems with recirculation.

Steady-State Detection Algorithm. The steady-state algorithm assumes a steady-state CO_2 balance in a conditioned space (e.g. $dC_r/dt = 0$). The actual occupancy of a space can be estimated using equation 5 when the outdoor airflow rate and CO_2 concentration are available.

$$P = \frac{m_{OA} E_{ac}(C_R - C_{OA})}{S} \tag{5}$$

S is the average CO_2 generation rate of a person.

Dynamic Detection Algorithm. This method is based on calculating approximately the CO_2 derivative (dC_R/dt) using the measured CO_2 concentration at the current and previous sampling instances as given equation 6. The occupancy (P^i) at the current sampling step is detected by equation 7, where the superscripts i and $i-1$ represent the current and previous sampling instants, and Δt is the sampling interval.

$$\frac{dC_R}{dt} \approx \frac{C_R^i - C_R^{i-1}}{\Delta t} \tag{6}$$

$$P^i = \frac{E_{ac}(m_{OA}^i + m_{OA}^{i-1})(C_R^i - C_{OA}^i)}{2S} + V\frac{C_R^i - C_R^{i-1}}{S\Delta t} \tag{7}$$

The Building Systems and Monitoring Instrumentation

Open-Plan Office Floor. The office floor used in this study was in an office building of the Hong Kong SAR Government. The building is located on Hong Kong Island and consists of 53 floors and a total gross area of 97,000 m^2. The floor selected for this study was an open-plan office floor including a few senior office rooms (fig. 2). The floor has an occupied indoor space of 1,271 m^2 floor area and 3,050 m^3 air volume.

Two identical air handling units (AHU) are used to provide the air-conditioning for the floor (fig. 3). The variable air volume (VAV) system using ceiling supply and return is employed. Outdoor fresh air is supplied from two central primary air-handling units (PAU) located on the mechanical (services) floor. The fresh air for each AHU is supplied from an air duct to the AHU room, which serves as the mixing chamber. The fresh air is not controlled at the AHU, and the total fresh air supplied to the floor is around 850 litres$\cdot$s^{-1}. The normal operation hours of the air-conditioning system are between 7.35 and 18.00.

The monitoring system of an AHU is illustrated in figure 4. A computer-based building energy monitoring system, namely Enerlyst, is installed to monitor the temperature, relative humidity, CO_2 concentration and flow rate of the fresh air, supply air and return air. Averaging airflow sensors (duct type) and infrared environmental CO_2 sensors (duct type) were used. The working range and the accuracy of the CO_2 sensors are 0–2,000 ppm and ±5% (or ±75 ppm). The CO_2 sensors were calibrated and fine tuned in the laboratory, using air samples of known CO_2 concentration before the monitoring tests. The sampling interval of the monitoring system is 1 min.

Lecture Theatre: The second site of study was a lecture theatre on the Polytechnic University campus. This indoor space has a floor area of 198 m^2 and an air volume of 731 m^3. The design peak occupancy is 160 people. The lecture theatre is air-conditioned by an AHU (fig. 5) which is a constant air volume system using ceiling supply and return. Outdoor air is fed directly from the outside of the AHU room. No fresh air control is applied in the system. The AHU room is also used as the mixing chamber from which the supply air duct transfers the air directly to the conditioned space. Two return

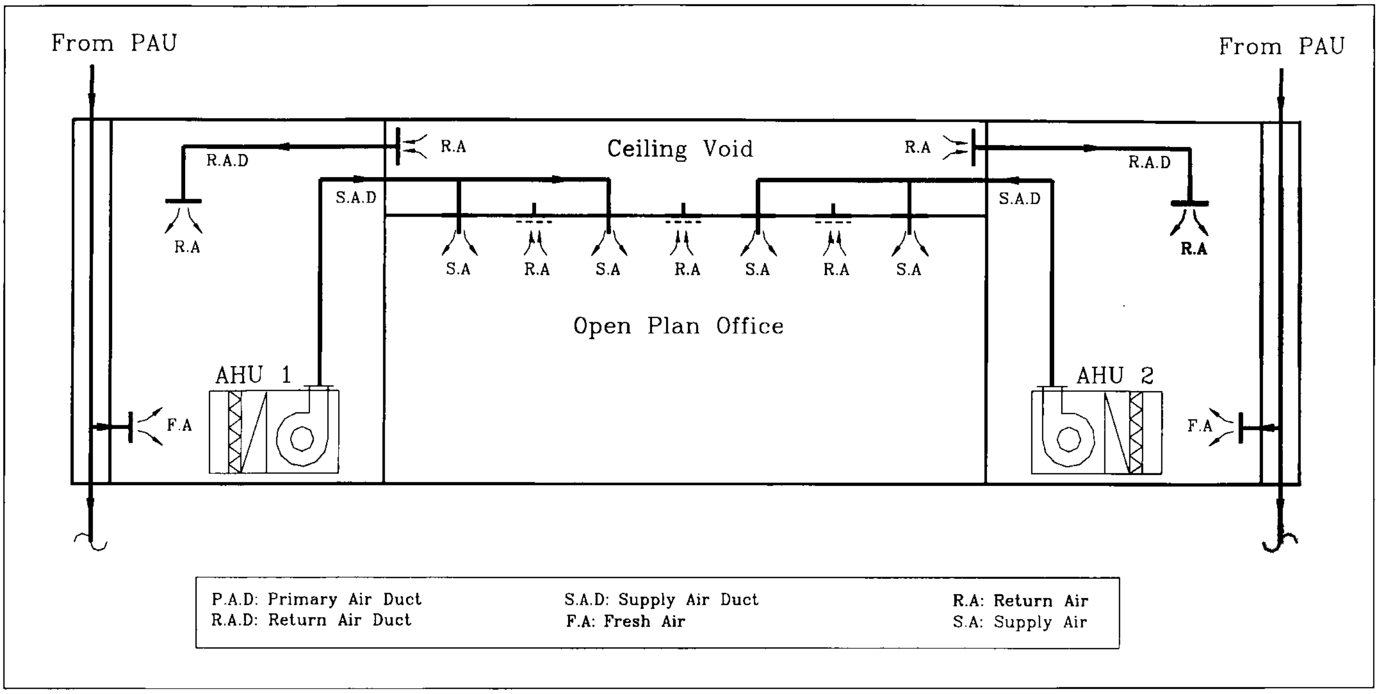

Fig. 3. Air side schematic diagram for the open-plan office.

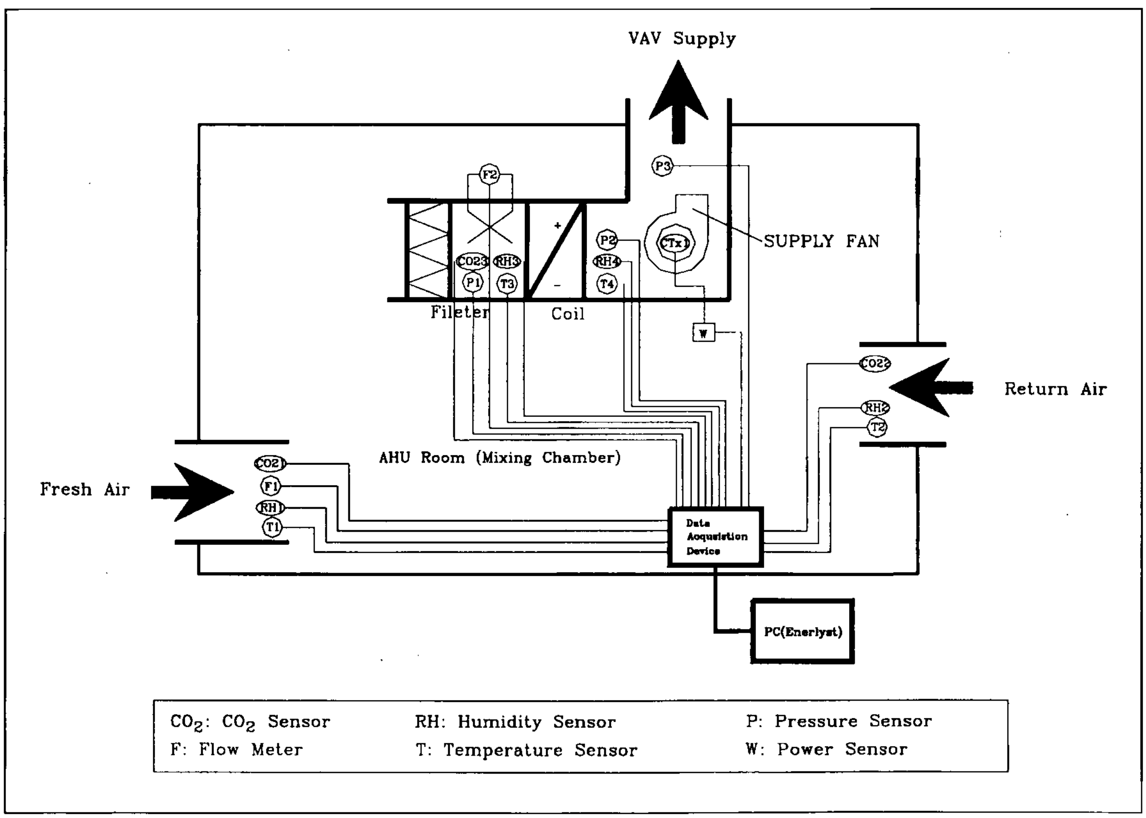

Fig. 4. AHU plant room layout plan and sensor installation locations.

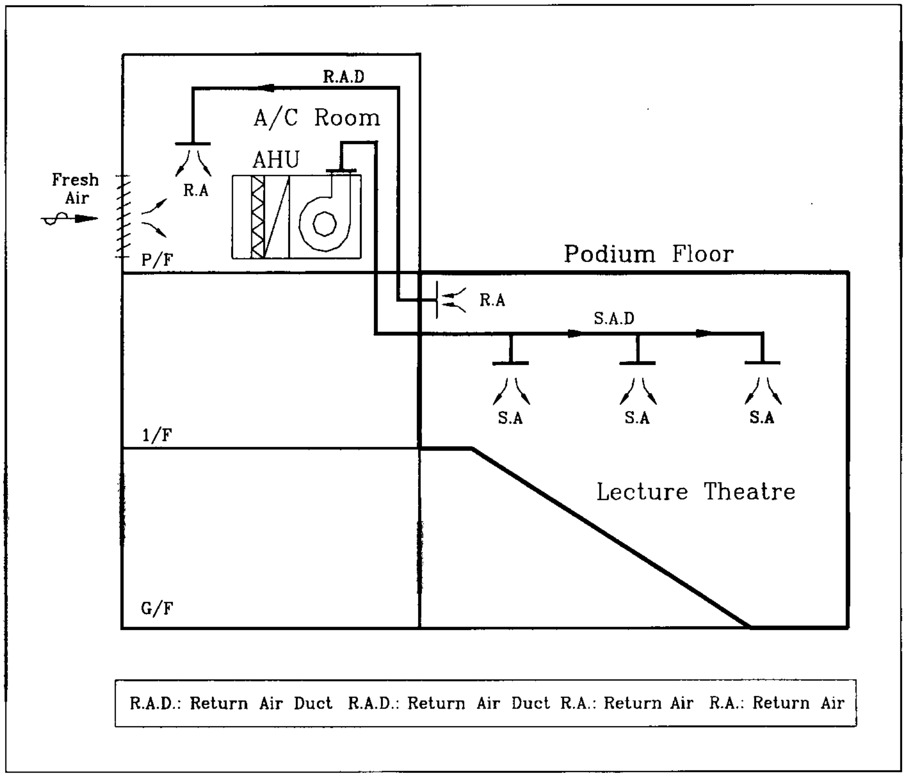

Fig. 5. Air side schematic diagram for the lecture theatre.

air diffusers are installed for air recirculation only. Two exhaust air ducts connected directly to the outside are installed for air balance purpose. The air-conditioning system normally works between 8.00 and 22.30 during weekdays.

The fresh airflow rate was measured manually over a period before the CO_2 monitoring tests and found to be 1,780 litres$\cdot$s^{-1}. It was assumed to be constant over the entire test period. Portable CO_2 transducers were used to monitor the fresh air and return air CO_2 concentrations at the locations illustrated in figure 5. The CO_2 transducers were calibrated using reference air standards with known CO_2 concentrations before the monitoring tests. The transducers recorded CO_2 concentration at 1-min intervals.

The CO_2 generation rate used by both algorithms was 5.0×10^{-6} m$^3\cdot$person$^{-1}\cdot$s^{-1}, which is the average generation rate for a person at an activity level of 1.2 met. The air change effectiveness in both test systems was selected to be 0.8 according to recommendations in the ASHRAE handbook and considering the air distribution and return system configurations. The value of the air exchange effectiveness has a large effect on the results of the estimation. In practical applications, this value can be checked and fine tuned using the measurements for certain case conditions when the occupancy profile is known.

Computer Simulation Model

To investigate the effect of air change rate on the algorithms, two simulation exercises were conducted. Both the steady-state and dynamic algorithms were used in a model to estimate the number of occupants in a space of 1,000 m^3 (300 m^2 floor area). The assumption was made that the air in the space was well mixed.

In the first exercise, the same occupancy profile was used throughout. The number of occupants in the space was suddenly increased from 0 to 60 at 1 h and then reduced from 60 to 30 at 6 h. The fresh air flow rate in each test was constant. The air changes per hour were 0.5, 1.0, 2.0, 4.0, 8.0 and 12.0 ach in the 6 tests, and the corresponding fresh airflow rates were 0.167, 0.333, 0.667, 1.33, 2.67 and 5.33 m$^3\cdot$s^{-1}, respectively.

In the second exercise, different occupancy densities of 5, 10, 20, 30 and 50 persons in a 100-m^2 floor area were used in different tests. The space was not occupied until 1 h into the test and was empty after 6 h. The level of the fresh airflow rate was set to be 0.667 m$^3\cdot$s^{-1} with air changing at 2.0 ach in all the tests.

Results and Analysis

Open-Plan Office Floor

Two days of test results for the office floor are presented here. The true occupancy in the office was monitored by counting the number of occupants entering and leaving the office. The occupancy profiles in these 2 test days are shown in figure 6. It can be seen that most office staff went to the office around 08.30, and left the office around 17.00. Occupancy during the period 12.00 to 14.00 decreased since most of the office staff were out for lunch during this period. The occupancy on the first test day was

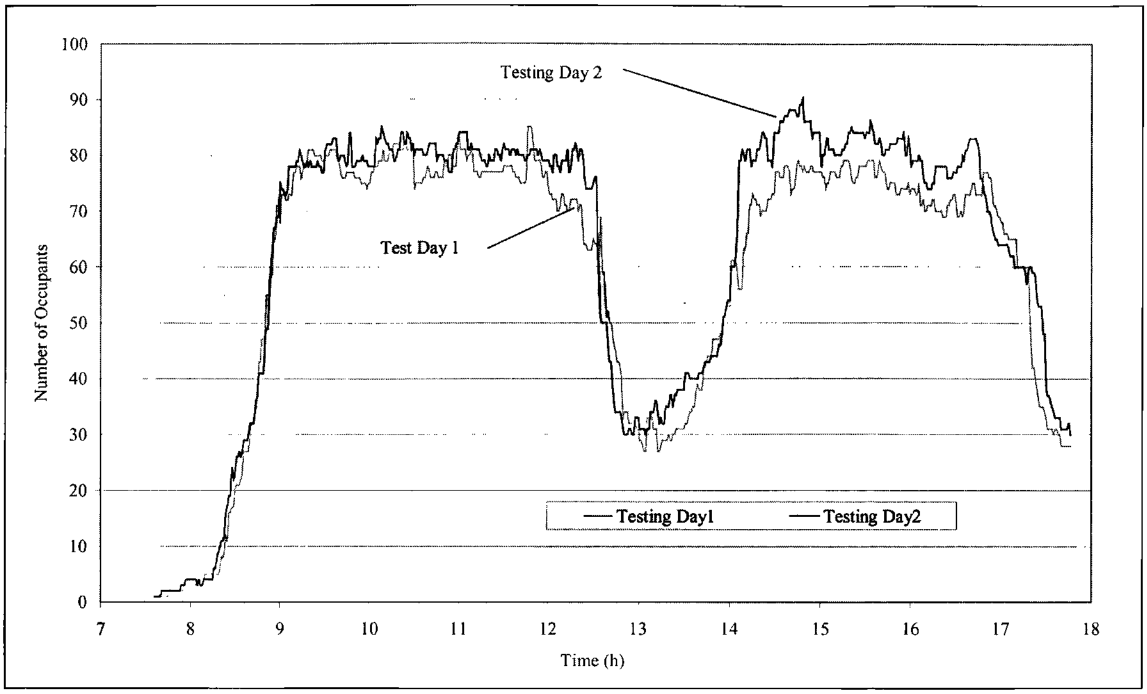

Fig. 6. True occupancy profile in the open-plan office (test day 1).

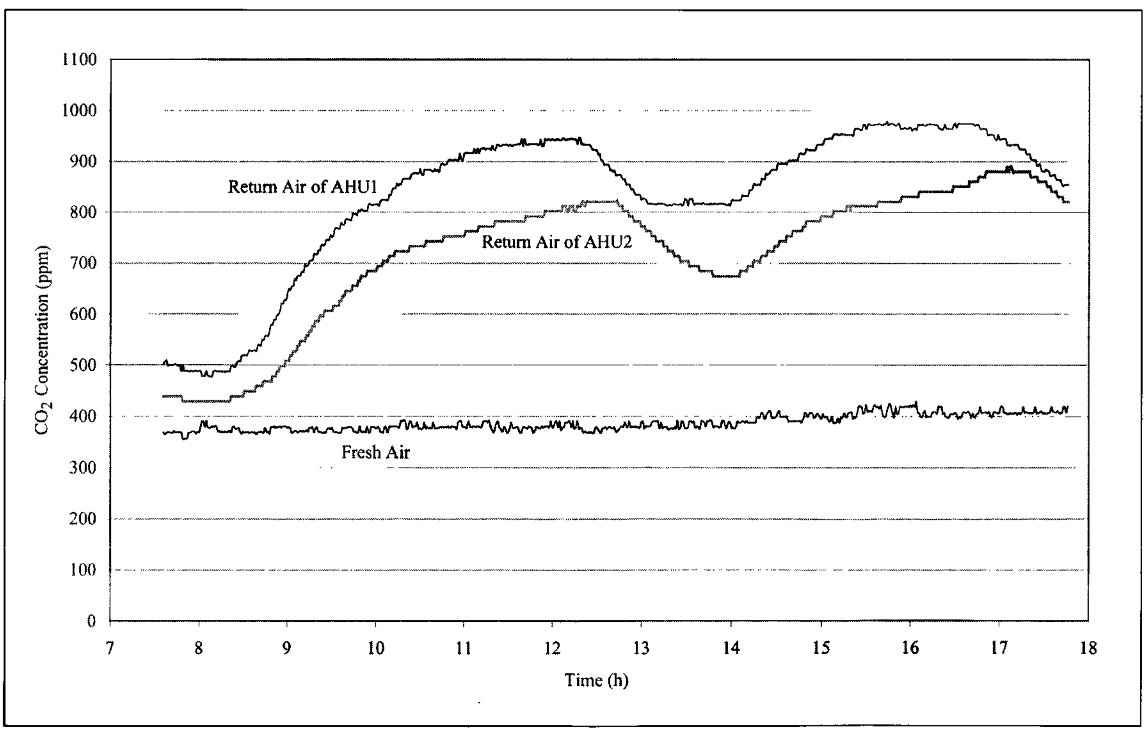

Fig. 7. CO_2 concentration profile of fresh air and return air in the open-plan office (test day 1).

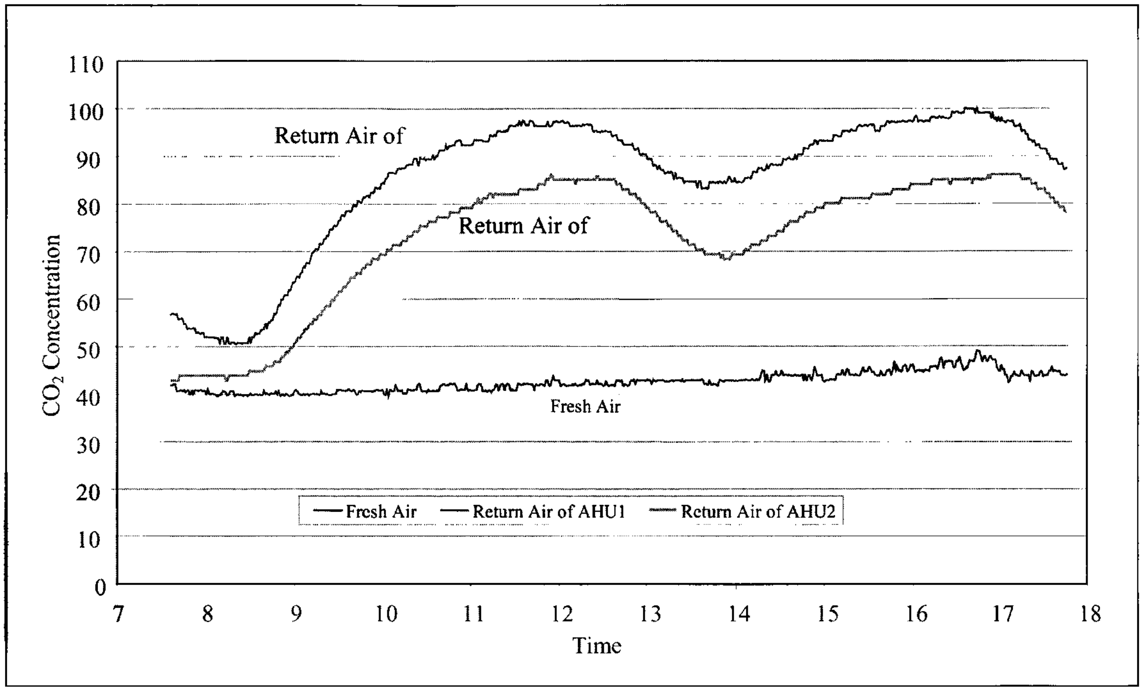

Fig. 8. CO_2 concentration profiles of fresh air and return air in the open-plan office (test day 2).

noticeably lower than that on the second test day, although the occupancy patterns over the 2 days were similar.

The CO_2 concentrations of the fresh air and the return air in 2 AHUs are shown in figures 7 and 8. The CO_2 concentration in the conditioned space increased gradually after the office staff arrived at the office in the morning. It decreased during the lunch period, but increased again during the afternoon. The CO_2 concentrations in the return air to the 2 AHUs followed the same pattern, but differed due to uneven distribution of occupancy and poor air mixing due to the large volume and the presence of partitions. The outdoor air CO_2 concentration increased gradually and slowly over both test days. This is probably the result of CO_2 generated by traffic and the increased occupancy during the daytime in the crowded commercial region of Hong Kong Island.

In the analysis, the CO_2 level in the return air was used to represent approximately the CO_2 in the conditioned space. Although the measured CO_2 concentrations in the 2 AHUs used for the office floor were different, this can be accommodated by the mathematics. The total occupancy is then the sum of two occupancies estimated using the algorithms described in equations 5 and 7. The actual steady-state occupancy detection algorithm can be illustrated by equation 8.

$$P = \frac{m_{OA1} E_{ac}(C_{rtn1} - C_{OA1})}{S} + \frac{m_{OA2} E_{ac}(C_{rtn2} - C_{OA2})}{2} \quad (8)$$

The actual dynamic occupancy detection algorithm can be illustrated by equation 9.

$$P^i = \left[\frac{E_{ac}(m^i_{OA1} + m^{i-1}_{OA1})(C^i_{rtn1} - C^i_{OA1})}{2S} + \frac{V}{2}\frac{C^i_{rtn1} - C^{i-1}_{rtn1}}{S\Delta t}\right] + \left[\frac{E_{ac}(m^i_{OA2} + m^{i-1}_{OA2})(C^i_{rtn2} - C^i_{OA2})}{2S} + \frac{V}{2}\frac{C^i_{rtn2} - C^{i-1}_{rtn2}}{S\Delta t}\right] \quad (9)$$

Figures 9 and 10 show the occupancy profiles estimated by the dynamic and steady-state detection algorithms, and the comparison with the true occupancy profiles over the 2 test days. It can be seen that the occupancy estimated by the steady-state detection algorithm is stable, but has significant delay compared with the true occupancy profiles. The occupancy estimated by the dynamic detection algorithm was strongly oscillating. This is because the dynamic detection algorithm employs the difference between two consecutive CO_2 measurements at the current and previous sampling instant. Due to interference effects, the CO_2 measurements contain appreciable noise. This noise is enhanced by the use of two consecutive measurements at current and previous sampling instants for estimating the occupancy.

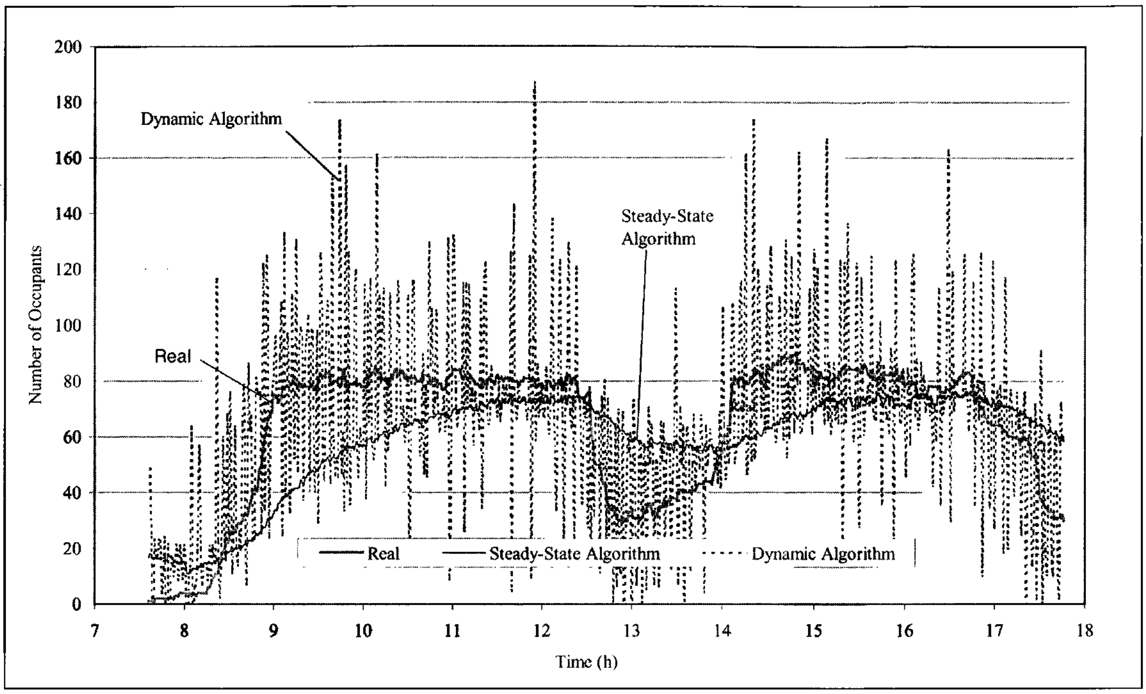

Fig. 9. Occupancy estimated using different algorithms in the open-plan office (test day 1).

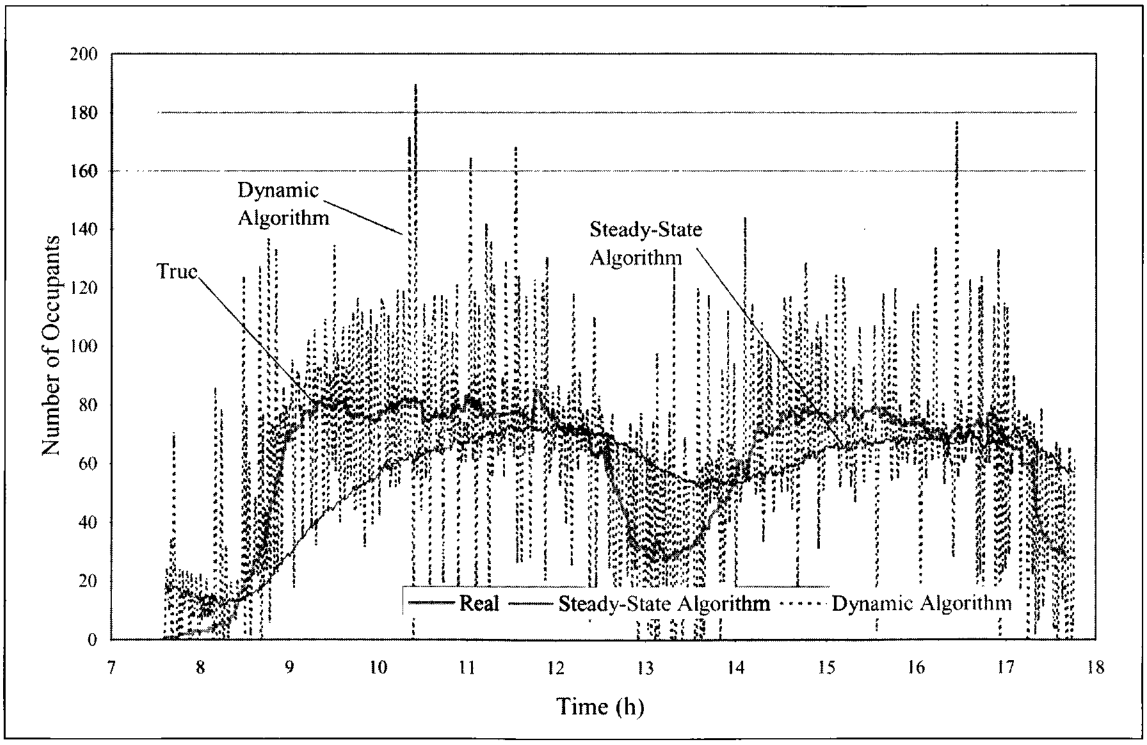

Fig. 10. Occupancy profiles estimates using different algorithms in the open-plan office (test day 2).

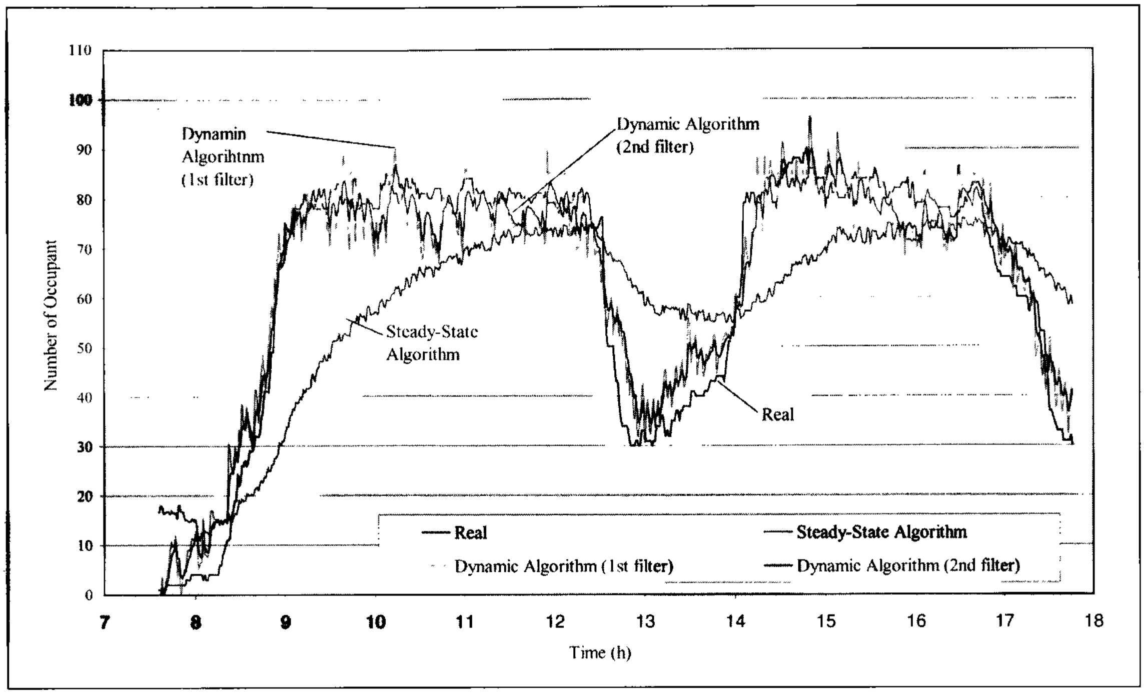

Fig. 11. Occupancy profiles estimated using different algorithms in the open-plan office (test day 2).

To solve the problem of noise, a filter (equation 10) was used to smooth the estimated occupancy directly.

$$Y^i_{out} = \lambda Y^{i-1}_{out} + (1 - \lambda) Y^i_{in} \quad (10)$$

where Y_{out} is the output signal of the filter, Y_{in} is the input signal to the filter, λ is a forgetting factor, i and $i - 1$ represent the current and previous sampling instants.

The 2-day occupancy profiles after using the first-order filter and second-order filter (i.e. use same filter twice in serial calculations) are presented in figures 11 and 12, respectively. It can be seen that most of the noise was filtered out by the first-order filter. The occupancy profiles after using the second-order filter were even smoother and should be stable enough for the purpose of on-line outdoor air control.

Although the occupancy estimated using the dynamic detection algorithm with noise filtration noticeably deviates from the true occupancy, it actually follows quite well the change of the true occupancy when compared with the occupancy estimated using the steady-state detection algorithm. Thus, the difference should be acceptable for the technique to be used for outdoor airflow control.

Lecture Theatre

The results of 2 days of tests in the lecture theatre are presented. The true occupancy in the lecture theatre was monitored by counting the number of occupants and changes in the theatre. Occupancy profiles over the 2 test days are presented in figure 13. It can be seen that the occupancy varied appreciably both in the morning and in the afternoon. The theatre was empty during the lunch hour on both test days. Recorded CO_2 concentrations of the return air and fresh air for these days are presented in figures 14 and 15. It can be seen that there was noticeable variation in fresh air CO_2 concentration on both days. Following changes in occupancy, the CO_2 concentration in the theatre changed very considerably. During the lunch hour, the CO_2 concentration of the return air was very close to that of the fresh air.

For the purposes of estimating the occupancy the CO_2 concentration of the return air was used to represent approximately the indoor space CO_2. The occupancy estimated using the dynamic detection algorithm for the first test day is shown in figure 16. The results are similar to those observed in the office test with very strong instability in the estimated occupancy. To smooth the results, the same filter was used to filter measurement noise, applying

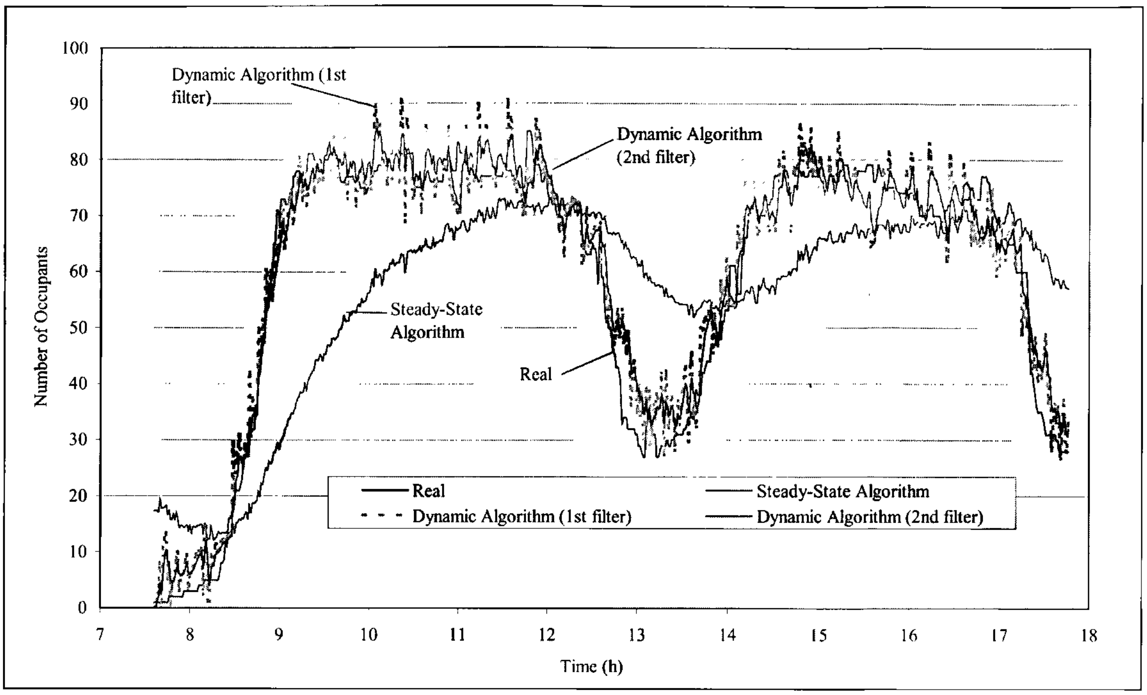

Fig. 12. Occupancy profiles estimated using different algorithms in the open-plan office (test day 2).

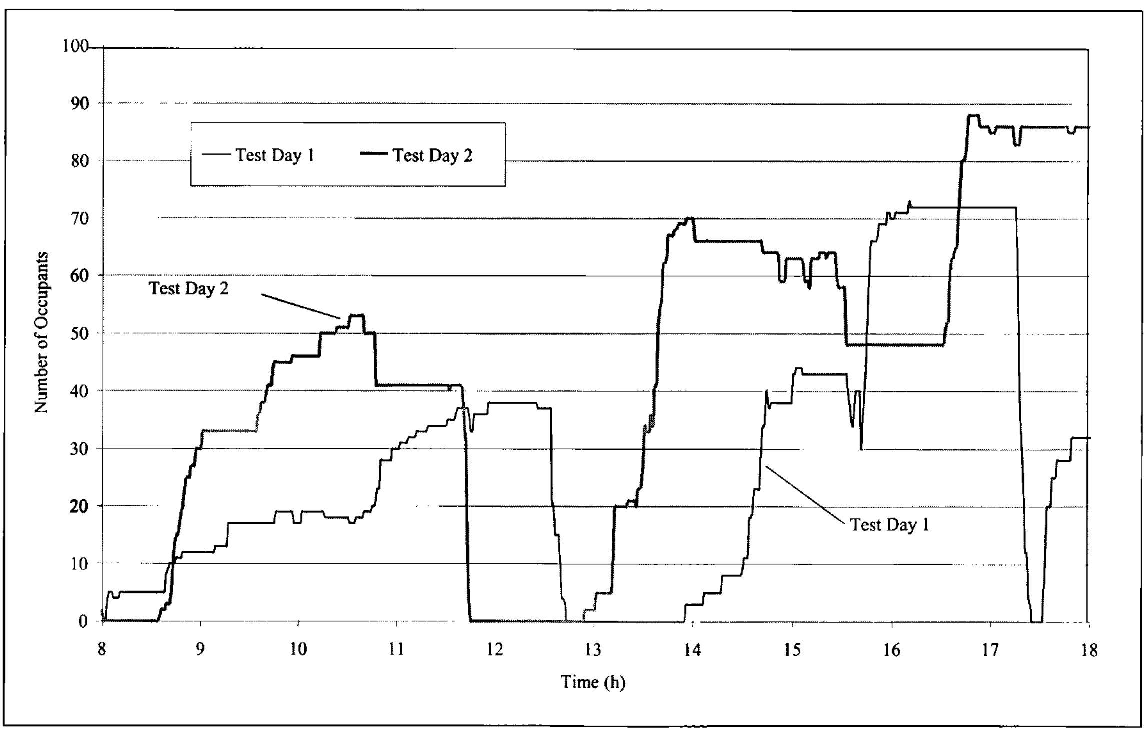

Fig. 13. True occupancy profiles in the lecture theatre on 2 test days.

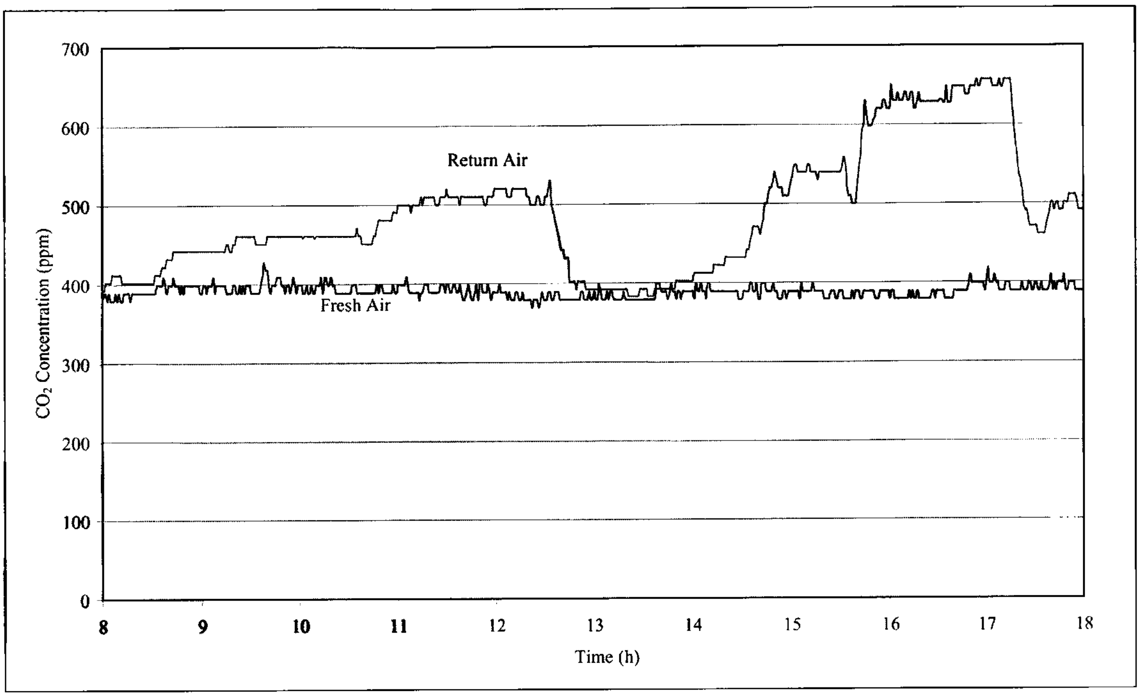

Fig. 14. CO_2 concentration of fresh air and return air in the lecture theatre (test day 1).

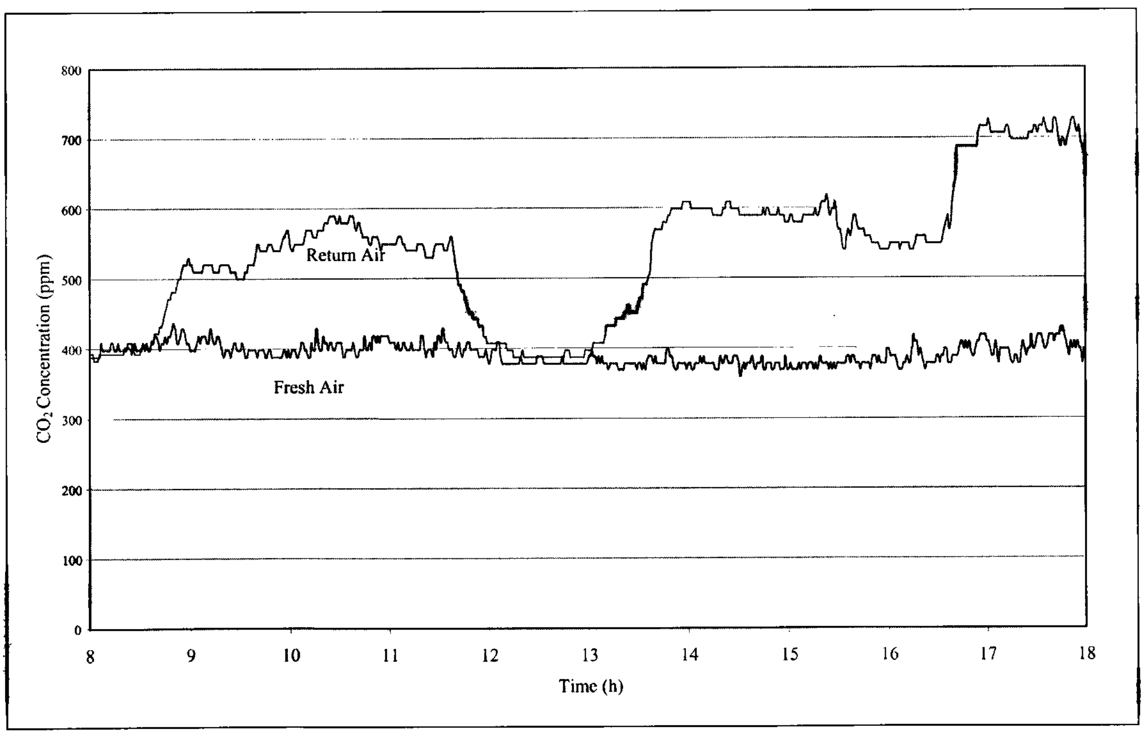

Fig. 15. CO_2 concentration of fresh air and return air in the lecture theatre (test day 2).

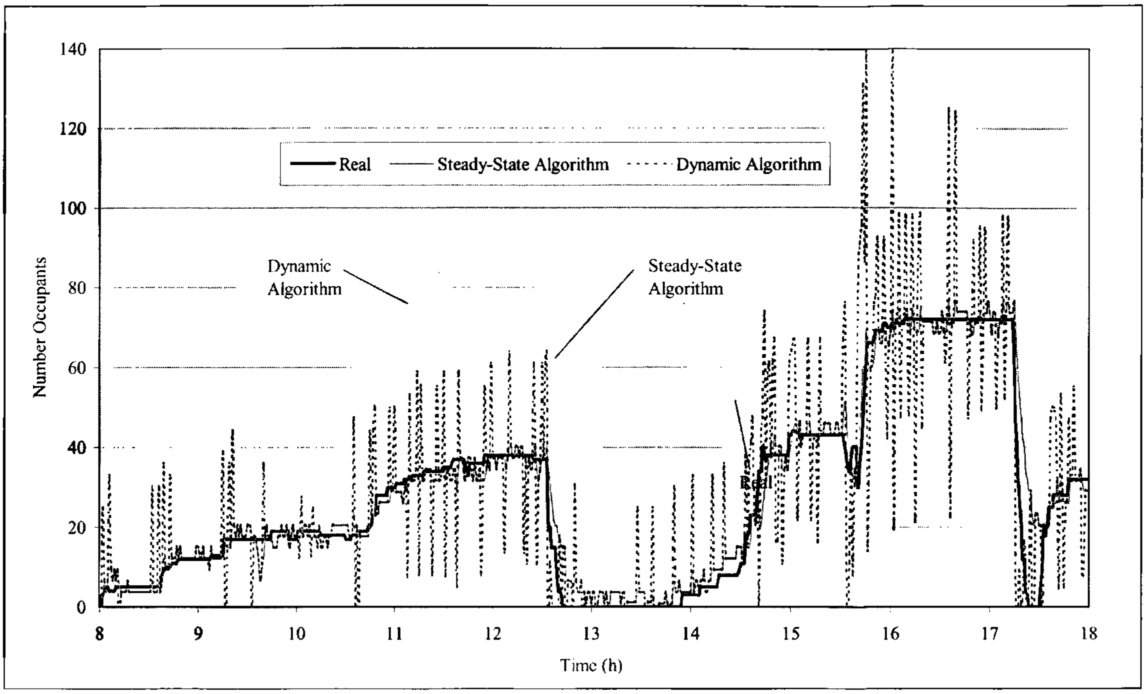

Fig. 16. Occupancy estimated using different algorithms in the lecture theatre (test day 1).

it directly to the estimated occupancy. The estimated occupancy profiles after smoothing for the 2 test days are presented in figures 17 and 18. It can be seen that the instability in the estimated occupancy disappeared after the first filter and was even more stable after the second-order filter than the occupancy estimated by the steady-state algorithm. It can be seen that the occupancy profiles estimated by the steady-state and dynamic algorithms followed well the true occupancy profile. The delay by which the true occupancy lagged that estimated using the steady state detection algorithm was slightly larger than that estimated by the dynamic detection algorithm.

Computer Simulation

In a computer simulation designed to show the effect of changes in the airflow rate, occupancy profiles were estimated using the steady state and dynamic detection algorithms (fig. 19). Another simulation estimated occupancy profiles using the steady-state algorithm and compared these with the true occupancy profiles, as shown in figure 20.

Discussion

Comparing the results of the tests at the two sites, it can be seen that the dynamic detection algorithm in both the office floor and lecture theatre cases provided a fast and accurate estimation of occupancy. However, the estimation of the occupancy by the steady-state algorithm was very considerably in error in the office tests, whilst the response speed and accuracy of occupancy estimation in the lecture theatre were acceptable. This, it seemed to us, could be due to very different air change rates at the two test sites. The air change rate (ach) on the office floor was 1.0. The ach in the lecture theatre was 8.5.

To investigate this difference, two computer simulation exercises were conducted, and both the steady-state and dynamic algorithms were used to estimate the number of occupants in a simulated space.

In the first exercise, the same occupancy profile was used throughout. The number of occupants in the space was suddenly increased from 0 to 60 at 1 h and then reduced from 60 to 30 at 6 h. The air changes per hour from 0.5 to 12.0 ach in the 6 tests cover what in practise would be a very wide operation range. Occupancy profiles were estimated using the steady-state and dynamic detection algorithms (fig. 19). It can be seen that those esti-

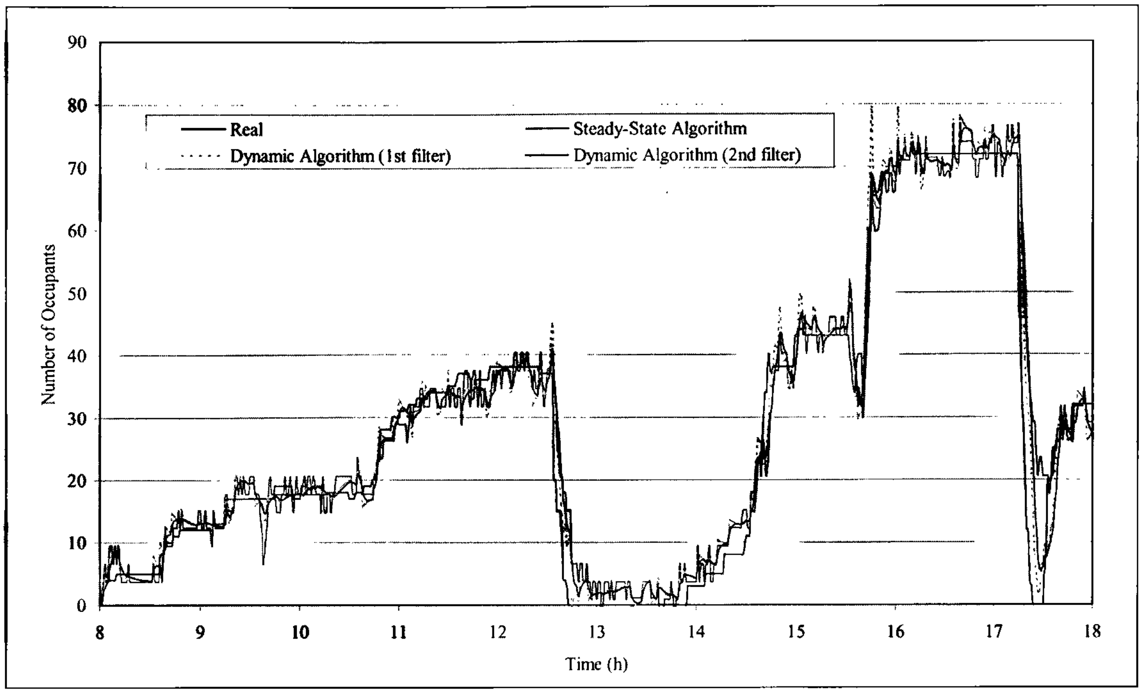

Fig. 17. Occupancy profiles estimated using different algorithms in the lecture theatre (test day 1).

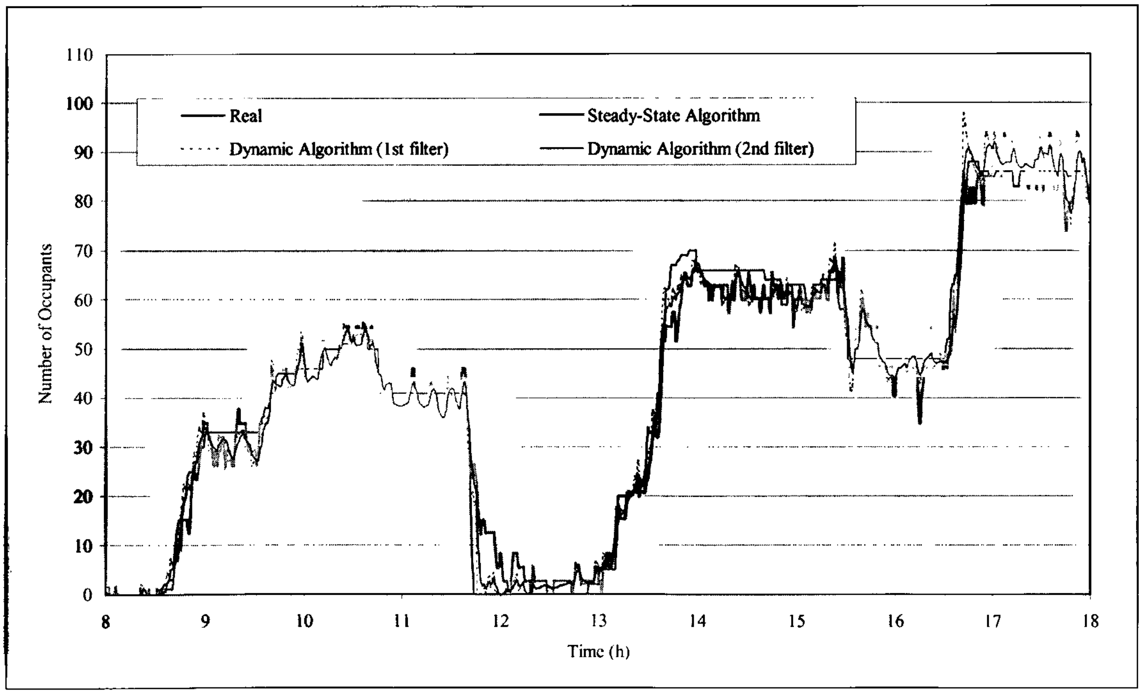

Fig. 18. Occupancy profiles estimated using different algorithms in the lecture theatre (test day 2).

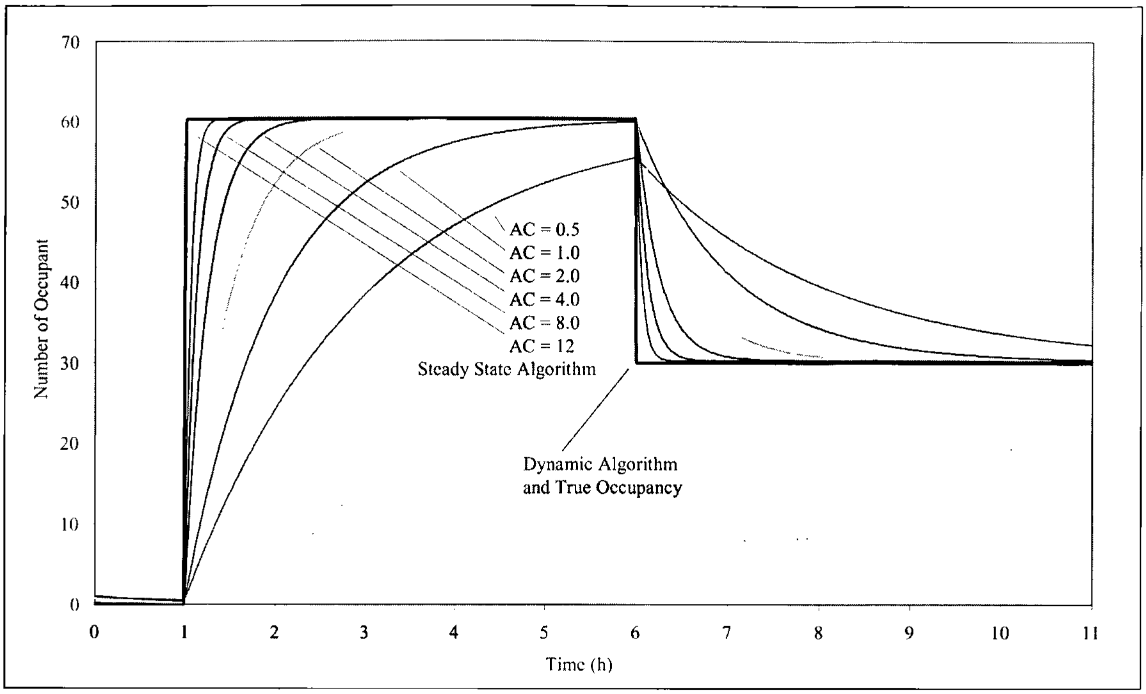

Fig. 19. Occupancy profiles estimated using steady state and dynamic algorithms with different ach.

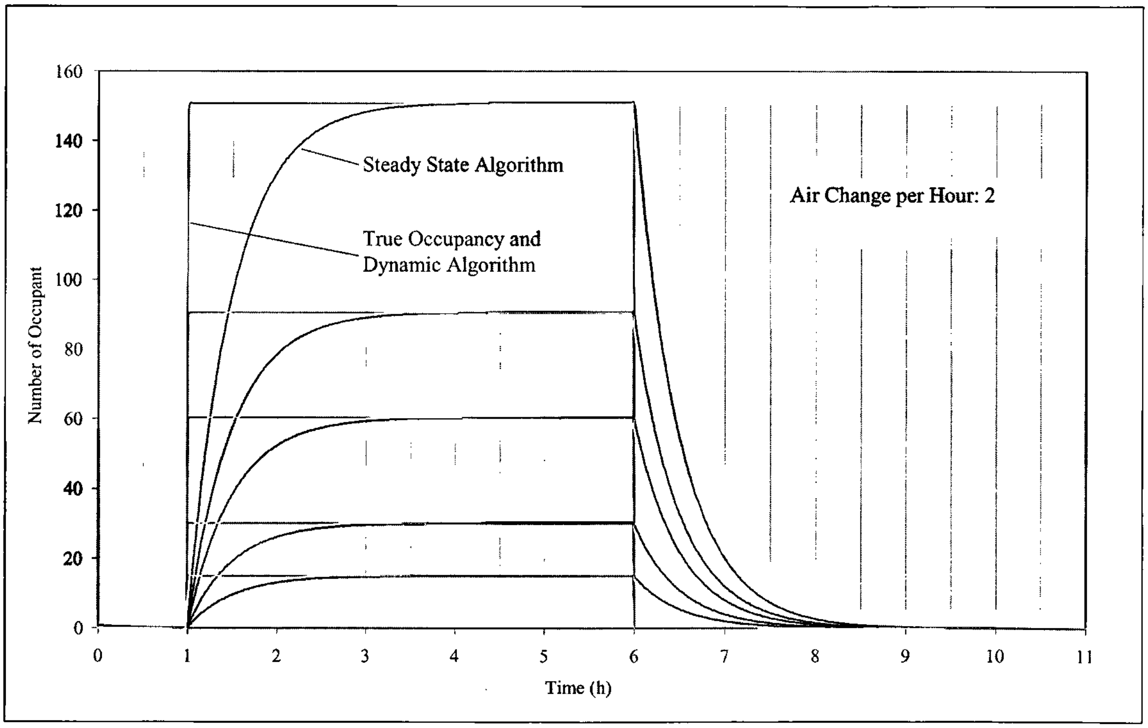

Fig. 20. Occupancy profiles estimated using steady state and dynamic algorithms with different occupancy levels.

mated using the dynamic detection algorithm were almost the same as the true occupancy profile in all the tests. This shows the dynamic algorithm can very accurately estimate the occupancy and the change without delay under ideal test conditions. When the number of air changes exceeded 8.0 ach, there was little delay in the estimated occupancy profile. The estimation delay increased as the ach was reduced.

In the second exercise, different occupancy densities of 5–50 persons in a smaller 100-m^2 floor area were used in different tests. This covers a wide range of occupancy density. The space was not occupied until 1 h into the test and was empty after 6 h. The occupancy profiles estimated using the steady-state algorithm were compared with relevant true occupancy profiles (fig. 20). It can be seen that the steady state detection algorithm has an appreciable response delay at different occupancy densities, although the response delay following large occupancy changes looks small. Since the same proportion of the difference between the estimated occupancy in large-step occupancy changes might not be visible in small-step occupancy changes, the actual effects of occupancy density and scale of change would be unimportant in practise.

We conclude that the number of occupants in an indoor conditioned space and changes in occupancy can be estimated by measuring the CO_2 levels in the space and the fresh outside air flow rate into the space with acceptable accuracy and response speed using a dynamic detection algorithm. This has been demonstrated in real building systems. Since the dynamic detection algorithm is particularly affected by measurement noise, the use of signal filters is necessary to provide an acceptable estimation of the occupancy which has stability, accuracy and response speed adequate for applications which require outdoor air control. However, in spite of the detection accuracy, this algorithm cannot be used for detecting the occupancy 'on/off' status (occupied or empty) of a space for the on/off controls of an air-conditioning, lighting or other system.

The response speed of the dynamic detection algorithm is not affected by the fresh air flow rate and the scale of occupancy change. Conversely, the fresh air flow rate has a very considerable effect on the response speed of the steady-state detection algorithm. This algorithm shows a long delay in responding to changes of occupancy when the air change per hour in a space is small. However, when the air change per hour in a space is very large, the response delay of the steady-state algorithm is much less and not important for practical applications.

In the actual tests at the office site, the ach was 1.0, at which level the simulation test shows that the response delay of the steady-state algorithm is considerable. In the lecture theatre test case, the ach was 8.5, at which level the simulation tests show that the response delay of the steady-state algorithm was small. However, in such real building systems, the estimation is also affected by measurement accuracy and noise as well as system dynamics. The effect of this might be that results using either the dynamic or the steady-state detection algorithms would provide similar estimations for the changes of actual occupancy when the air change rate is very large, as in the lecture theatre test case. However, at a low air change rate, only the dynamic detection algorithm gives an answer comparable with the true value of occupancy.

Acknowledgment

The authors would like to acknowledge the assistance of the Electrical and Mechanical Services Department, Hong Kong SAR Government for site measurements. The study is part of a project funded by the US-Asia Environmental Partnership.

References

1 Kusuda T: Control of ventilation to conserve energy while maintaining acceptable indoor air quality. ASHRAE Trans 1976;82:1169–1175.
2 Haghighat F, Donnini G: IAQ and energy management by demand controlled ventilation. Environ Technol 1992;13:351–359.
3 Norell L: Demand controlled ventilation in a school. Proceedings of 12th AIVC Conference, Ottawa, 1991, vol 2, pp 257–274.
4 Warren BF, Harper NC: Demand controlled ventilation by room carbon dioxide concentration: A comparison of simulated energy savings in an auditorium space. Energy building 1991; 17:87–96.
5 Ruud SH, Fahlen P, Andersson H: Demand controlled ventilation – Full scale tests in a conference room. Proceedings of 12th AIVC Conference, Ottawa, 1991, vol 2, pp 187–200.
6 Bearg DW: Second Generation Demand-Controlled Ventilation System, IAQ '94. Atlanta, 1994.
7 Davidge B: Demand Controlled Ventilation in Office Buildings. Proceeding of 12th AIVC Conference, Ottawa, 1991, vol 2, pp 157–162.
8 ASHRAE: ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality. Atlanta, 1989.
9 ASHRAE: ASHRAE Standard 62-1989R, Ventilation for Acceptable Indoor Quality (Public Review Draft). Atlanta, 1996.
10 So ATP, Chan WL, Chow TT: A computer vision based HVAC control system. ASHRAE Trans 1996;102:661–678.
11 Wang SW, Jin XQ: CO_2-based occupancy detection for on-line outdoor air flow control. Indoor Built Environ 1998;7:165–181.