# ON-LINE OUTDOOR AIR FLOW CONTROL BY ESTI AIVC 11244 OCCUPANCY

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**Abstract:** This paper presents a dynamic method to estimate the actual occupancy in indoor space by measuring the carbon dioxide concentration of return air and outdoor air flow rate. The accuracy and response speed are tested and compared with the steady-state estimating method under various occupancy profiles. An on-line outdoor air control strategy using dynamic estimating method and the validation of the method are presented. The indoor air quality and energy performance of demanded ventilation using these strategies are evaluated under various indoor occupancy and outdoor weather conditions.

## Introduction

Great effort has been made to remove contaminants in indoor spaces in order to make indoor air healthy with minimum energy consumption. Demanded ventilation is an alternative in VAV systems. Demanded-ventilation attempts to achieve acceptable indoor air quality at reduced energy cost by controlling the outdoor air flow rate based on measured parameters. Recent field and simulation studies have demonstrated potential energy savings of up to 50% using demanded ventilation /1,2/. Carbon dioxide concentration is the most often controlled variable in demanded-ventilation control.

ASHRAE Standard 62-1989 /3/ requires the outdoor air flow rate solely based on occupancy in commercial buildings. When occupant usually is the unique or main source in these buildings, $CO_2$-based demanded-ventilation (i.e. control the $CO_2$ concentration in indoor space with certain limit) is a suitable choice in HVAC system to satisfy the requirement of outdoor air flow rate. Though this method can control carbon dioxide concentration and other pollutants generated by occupants within acceptable level, the $CO_2$-based demanded ventilation cannot effectively control non-occupant generated pollutants concentration when occupancy rate is much less than design rate /4/. Non-occupant generated pollutants, which are produced by building materials and furnishings, may be harmful to occupants or make occupants uncomfortable.

Therefore, ASHRAE has proposed a new standard (ARSHRAE Standard 62-1989R) /5/ suggesting that the minimum requirement of outdoor air ventilation rate shall be determined not only by the actual occupancy but also by the occupied area. This new standard on outdoor air ventilation rate considers both occupant and non-occupant generated pollutants, but it requires to identify the actual occupancy. A steady-state method based on $CO_2$ measurement is proposed in the public review draft. However it is found that significant delay in detecting the occupancy changes using the steady-state method exists.

To accurately detect occupancy and its changes, a dynamic method is developed. It estimates the actual occupancy by measuring carbon dioxide concentration and its changes as well as the outdoor air flow rate. This method is validated in an indoor space under three kinds of occupancy profiles and the response speed is compared with that obtained by steady-state method. In the meantime, an on-line control strategy to satisfy the new standard by estimating the actual occupancy using the dynamic method is developed. An open office building with CAV and VAV system is used to test and evaluate this strategy by examining the indoor air quality and energy consumption.

## Strategies for Estimating Occupancy

For a space of a single or multiple space ventilation system shown in Figure-1, the balance of carbon dioxide is represented by the equation (1). On the basis of carbon dioxide balance, three methods are derived to estimate the occupancy: steady-state estimating method, dynamic estimation method with approximation computation and dynamic estimation method with accurate computation.



$$N + V_S C_S - V_S C_{RA} = v\frac{dC_R}{dt} \tag{1}$$

Where $N$ is total source strength of carbon dioxide. $V_S$ is supply air flow rate. $C_S$, $C_{RA}$ and $C_R$ are carbon dioxide concentration of supply air, return air and space air. $v$ is space volume.

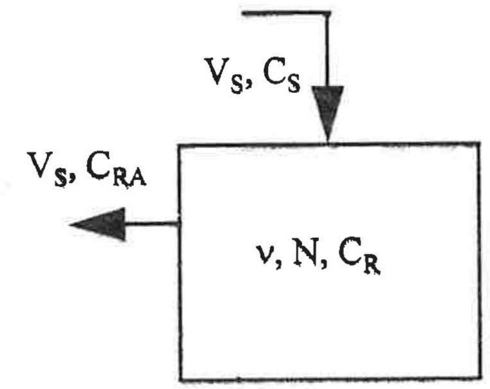



**Figure-1 Diagram of an air-conditioned space**

*Steady-state estimating method*

ASHRAE Standard 62-1989R suggest a steady-state method using the steady-state balance simplified as equation (2). As the ventilation effectiveness ($E_{ac}$) can be expressed approximately equation (3), the carbon dioxide source ($N=P\cdot S$) can be estimated by substituting equation (3) into equation (2). Finally, the occupancy ($P$) can be estimated by equation (4). Where, $S$ is an average generation rate per person.

$$N + V_S C_S - V_S C_{RA} = 0 \tag{2}$$

$$E_{ac} \approx \frac{C_{RA} - C_S}{C_R - C_S} \tag{3}$$

$$N = V_S E_{ac}(C_R - C_S) \tag{4}$$

$$P = \frac{V_S E_{ac}(C_R - C_S)}{S} \tag{5}$$

*Dynamic estimating method (Approximation)*

This method is based on calculation approximately the $CO_2$ derivative ($dCR/dt$) using the measured $CO_2$ concentration and flow rate as equation (6). The occupancy rate ($P'$) at the current sampling step is estimated by equation (7).

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

$$P^i = \frac{E_{ac}(V_S^i + V_S^{i-1})(C_R^i - C_S^i)}{2S} + v\frac{C_R^i - C_R^{i-1}}{S\Delta t} \tag{7}$$

*Where, the superscript i and i-1 represent the current and previous sampling instants. Δt is the sampling interval.*

*Dynamic estimating method (accurate)*

This method is based on the accurate solution of equation (1), which is shown in equation (8), where $B_0$ is a constant. When considering the time of sampling instant $i$-$1$ as $t = 0$ and the initial concentration is known as $C_R|_{t=0} = C_R^{i-1}$, the constant $B_0$ can be obtained as equation (9). The occupancy at current sampling instant can be estimated by equation (10).

$$C_R = B_0 e^{-\frac{V_S E_{ac}}{\nu} t} + C_S + \frac{N}{V_S E_{ac}} \tag{8}$$

$$B_0 = C_R^{i-1} - C_S^{i-1} - \frac{N}{V_S E_{ac}} \tag{9}$$

$$P^i = \frac{E_{ac}(V_S^i + V_S^{i-1})}{2S} \left[ \frac{C_R^i - C_R^{i-1} e^{-\frac{E_{ac}(V_S^i + V_S^{i-1})}{2\nu} \Delta t}}{1 - e^{-\frac{E_{ac}(V_S^i + V_S^{i-1})}{2\nu} \Delta t}} - C_S \right] \tag{10}$$

## Validation of Occupancy Estimating Strategies

*Test conditions*

A single space model is used in simulation, which is a closed indoor space of 150 $m^2$ floor area and 600 $m^3$ air volume. Three occupancy conditions are tested: *conference room,* which has a design occupancy of 80 people; *open office space*, which has a design occupancy of 30 people; *senior office space*, which a design occupancy of 10 people. The carbon dioxide generation rate used is $5.0\times10^{-6}$ $m^3/s$ per person, which is the rate at an activity level of 1.2 met. Three occupant diversity profiles are selected to valid the methods, which are shown in Figure-2.

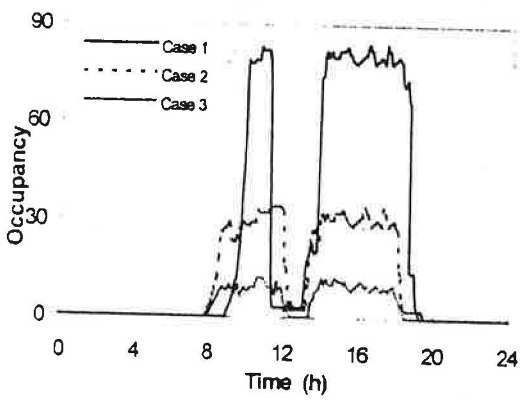



Figure-2 Occupant profile of three case

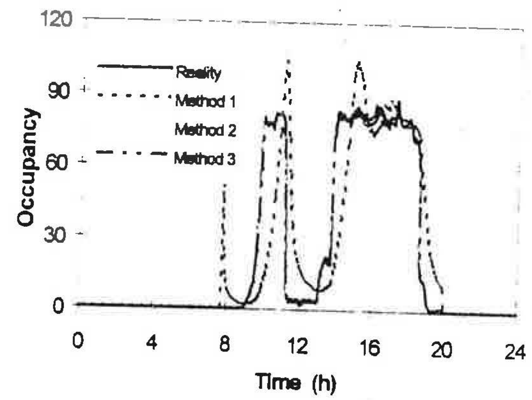



Figure-3 Occupancy estimated in conference room

The building model simulates an indoor space as a node with the even temperature and pollutant distribution. The dynamic response of carbon dioxide sensor is simulated and the deviation of the sensor used in the tests is zero.

*Test results*

HVAC system works between 7:45am and 8:00pm. Figure-3 shows that the estimated occupancy using three methods with a sampling interval of 5 seconds when the space is used as a conference room. The occupancy estimated by the steady-state method is about an hour lag behind the real occupancy and the deviation from the real occupancy is about 25%. There is no response when some people come in or out. The occupancy using the dynamic methods have nearly no time lag compared with the real occupancy and the deviation is less than 5%. Both dynamic methods can detect the changes of occupancy. Before the conference room is occupied, the occupancy detected by the steady-state method has a large deviation.

Figure-4 shows the real outdoor air flow rates which are controlled using the occupancy detected by three methods according to the new ASHRAE standard. It can be seen the fresh air supply controlled using the occupancy estimated by the dynamic methods well follow the changes of occupancy. When



a large number of people are in conference room in the morning, outdoor air flow supply controlled by using the occupancy estimated by steady-state method is much less than the required rate, but it reaches its maximum after people has left the room, which is much higher than the required rate. Figure-5 and Figure-6 show that in situations of open office space and senior office. The similar results as conference room can be found.

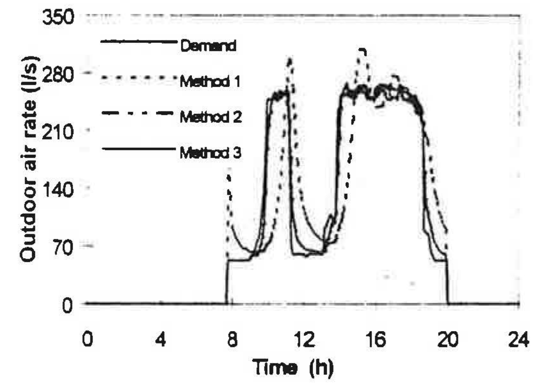



Fig.4 Outdoor air flow rate of conference room

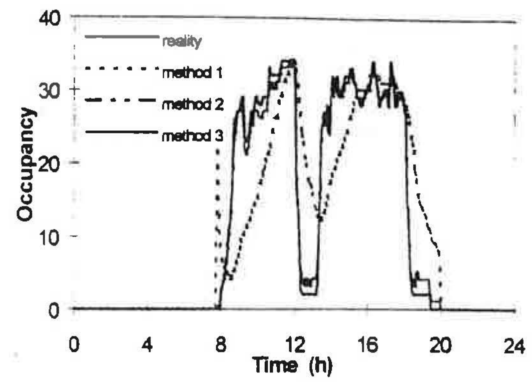



Fig.5 Occupancy estimated in open office space

Results show that both dynamic methods can detect the occupancy with relatively high accuracy and the change of occupancy with fast response. The occupancy detected by using steady state method has large error and has vary slow response, which gives big error in outdoor air flow rate control particularly when occupancy has large changes.

## On-line Outdoor Air Control Strategy and Evaluation

*Building A/C system and test conditions*

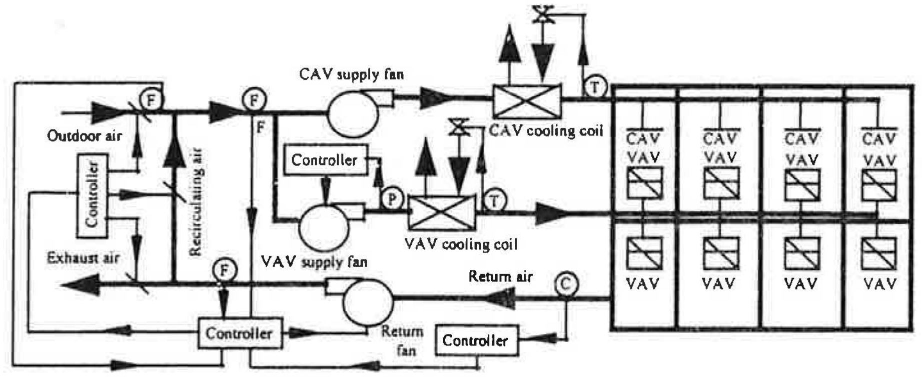
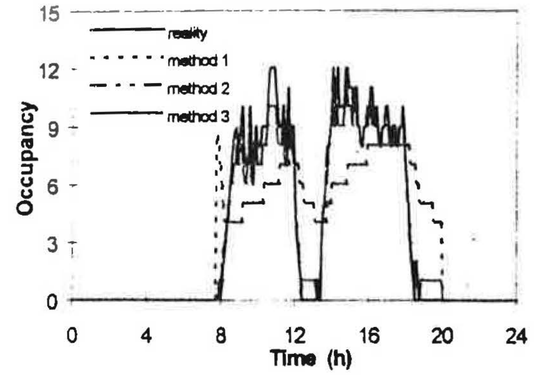



Figure-7 Schematic of the air-conditioning system of an open-plan office floor

One floor open-plan office is selected to test the dynamics, energy performances and controlled indoor air quality in simulation. The office has a floor area of 1166 $m^2$ and is divided into 8 zones in simulation. Six of them are exterior zones and two are interior zones. Four of exterior zones orientating north are equipped with VAV and CAV, others are equipped VAV. One VAV terminal and CAV terminal in each zone are simulated. The total capacities of the VAV and CAV of each zone are simulated by multiplying the simulated flow rates with factors. All components of the air-conditioning system served the space (Figure-7) are simulated. A fan model simulates the energy and hydraulic performances of supply and return fans. The hydraulic resistance of coil, supply duct, return duct and VAV terminals are simulated. The static pressure balance of the system under different fan pitch angles and VAV damper positions is simulated. The dynamics of sensors and actuation devices is simulated.

Realistic controller models simulate the dynamic response of the local PID DDC control loops and supervisory control algorithms. The local control loops include the AHU and VAV temperature control loops, the supply fan and return fan static pressure control loops. The supervisor of return fan static pressure set-point reset controls three dampers' position (mixing damper, exhaust damper and outdoor air damper) to maintain positive pressure in the space and outdoor air intake. One supervisory controller optimizes the outdoor air flow set-point output using minimum outdoor air flow rate required by the new ASHRAE standard according the actual occupancy estimated by the dynamic estimation method using the approximation approach.

A total of 8 tests are performed in two days using four strategies to control the outdoor air flow rate for comparison. The control strategies are: *A. use of estimated occupancy using the dynamic method to reset outdoor air rate set-point; B. use of upper limit of 1000ppm to carbon dioxide concentration; C. use upper and low limits of 1000 and 800ppm respectively to carbon dioxide concentration; D. constant outdoor air flow rate as the minimum rate at design conditions according to the new ASHRAE standard.* The weather data of two days in Hong Kong are selected from Summer and Spring respectively. The outdoor air enthalpy in both days is higher than that of indoor air.



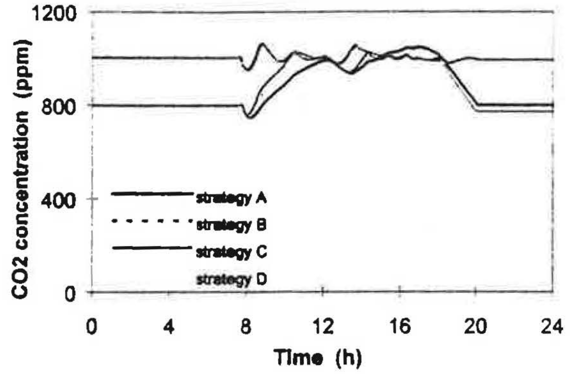
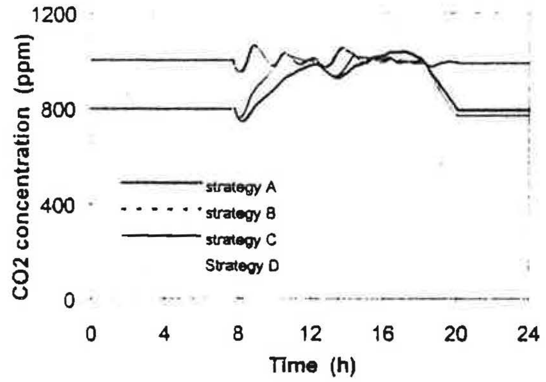




**Fig.6 Occupancy estimated in senior office space** **Fig.8 $CO_2$ of four control strategies in a summer day**

Figure-8 and Figure-9 show the results of the mean carbon dioxide concentration controlled by four strategies in a Summer day and a Spring day respectively. The carbon dioxide concentration controlled by estimating occupancy control strategy is below 1000ppm in most of the office hour. The carbon dioxide concentration both using demand-controlled strategies with upper and low limits and only with upper limit is accepted. The constant outdoor air flow rate control satisfies the comfort criterion when the actual occupancy less than the design, but when the actual occupancy is significantly higher than the design occupancy, it cannot satisfy the requirement to dilute the pollutants generated by occupants as indicated by the higher $CO_2$ concentration in some periods.



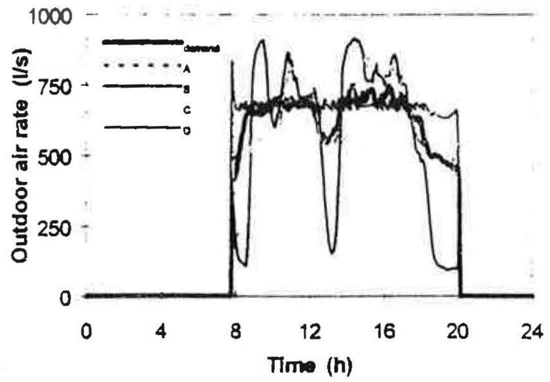




**Figure-9 $CO_2$ of four ventilation strategies in a summer day**

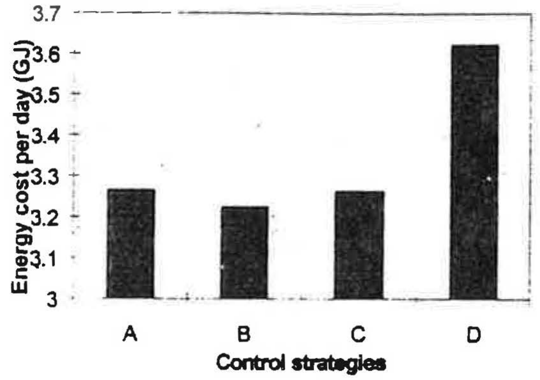
**Figure-10 Outdoor air rate of four ventilation strategies in a summer day**

<u>*Test results*</u>

Figure-10 shows the actual outdoor air flow rates controlled by four control strategies. Though the carbon dioxide concentration is accepted, i.e. the pollutants generated by occupants are diluted to satisfy occupant demand, the outdoor air flow rates controlled by the two demanded-control strategies



using carbon dioxide limits can not satisfy the new standard when the occupancy is significantly lower the design occupancy. It can be seen that the outdoor air flow rate is below the minimum requirement of new ASHRAE standard in nearly half of the office hour. It results in that the pollutants generated by non-occupant, such as sensory contaminants emitting from building materials and furnishing, from non-occupant activities and processes taking place and from the HVAC system itself, will affect occupants' health and comfort. The strategy using dynamic estimating strategy can satisfy the requirement on outdoor air flow rate all the time.



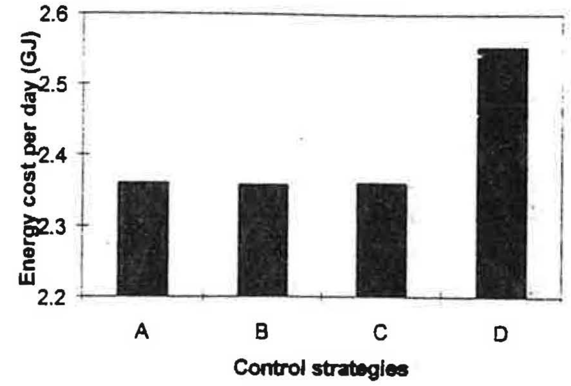




**Fig.11 Energy consumption of four ventilation strategies in a summer day**

**Fig.12 Energy consumption of four ventilation strategies in a spring day**

Using constant overall chilling system COP of 2.2, the total energy consumption using four control strategies in two test days are obtained using the cooling coil loads and fan energy consumptions in the tests. The total energy consumption in two days using different strategies are shown in Figure-11 and Figure-12. The energy consumption controlled by the strategies using estimated occupancy and two carbon dioxide limit based demand-controlled strategies are very close and about 10% less than that when using constant outdoor air flow rate.

## Conclusions

The dynamics, i.e. the change of carbon dioxide concentration, needs to be considered to accurately estimate the occupancy and the changes of occupancy. The control strategy using the dynamic occupancy estimation method can control the outdoor air flow rate well following the changes of occupancy, while the energy saving potential is similar to the $CO_2$ limit based demanded control strategies in the test cases. The ten percent energy saving is obtained in the test cases compared with cases using constant outdoor air flow rate and the indoor air quality could be even better when the occupancy is significantly higher than the design occupancy.

### References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