 # 10515

Using Carbon Dioxide Measurements to Determine Occupancy for Ventilation Controls

Yu-Pei Ke
Student Member ASHRAE

Stanley A. Mumma, Ph.D., P.E.
Fellow ASHRAE

ABSTRACT

This paper proposes a new method to determine the dynamic zonal occupancy for ventilation control based upon measured carbon dioxide (CO_2) concentrations in the supply and return air. The central thesis of this proposed transient method is that a fixed CO_2 threshold based upon occupancy alone is not possible under the current proposed BSR/ASHRAE Standard 62-1989R. Rather, the actual dynamic occupancy head count must be known since the ventilation requirements consist of two parts—the building component and the occupancy component. The result is that the CO_2 threshold must constantly be changed in time with occupancy. This paper employs simulation results for well-mixed office and conference rooms as the basis for comparison of the proposed transient occupancy-based ventilation with two other accepted methods: the CO_2-based ventilation and the constant airflow ventilation. The simulation results show that calculated occupancy from the transient equation follows the actual occupancy precisely with a time lag equal to the measurement scan interval. With precise occupancy information, the mechanical system can provide the exact ventilation airflow required by standards. From a ventilation perspective, the transient occupancy-based ventilation scheme is better than the conventional CO_2-based ventilation—and without an energy penalty. Furthermore, this scheme is useful for real-time on-line ventilation control and system optimization.

INTRODUCTION

Indoor air quality (IAQ) has attracted much attention in the heating, ventilating, and air-conditioning (HVAC) community for decades. One solution to indoor air pollution is dilution. To dilute indoor air pollutants and maintain IAQ, most engineers choose to design systems that supply the required uncontaminated ventilation air to occupied spaces. The widely accepted ventilation guidelines have been published as *ASHRAE Standard 62*. Since ASHRAE published its first ventilation standard, *ASHRAE Standard 62-1973* (ASHRAE 1973), the ventilation requirement has been exactly proportional to occupancy. In the first standard, 7.5 L/s (15 cfm) of outdoor air (OA) per person was recommended for office buildings. The acute energy supply concerns of the 1970s resulted in a revised *ASHRAE Standard 62-1981*, which recommended a lower minimum ventilation rate of 2.5 L/s (5 cfm) per person for nonsmoking offices (ASHRAE 1981). As a result, IAQ problems surfaced and *ASHRAE Standard 62-1989* responded by requiring an increase in the minimum ventilation rate to 10 L/s (20 cfm) per person for office spaces (ASHRAE 1989). More recently, concern over the fact that the building as well as the occupants contributes to potential IAQ problems has led to a rethinking of how ventilation air requirements should be specified. Using a ventilation strategy based on occupancy only leads to low ventilation rates when the occupancy is low and ignores nonhuman contaminants. To dilute sources from both the building and its occupants, ASHRAE Standard 62-1989R proposed a new equation. The equation contains people and floor area components to calculate the design ventilation rate (*DVR*) as follows (ASHRAE 1996):

$$\begin{aligned} DVR &= V_P + V_B \\ &= R_P \cdot P_D \cdot D + R_B \cdot A_B . \end{aligned} \qquad (1)$$

For office spaces, for instance, R_P is 3 L/s (6 cfm) per person and R_B is 0.35 (L/s)/m^2 (0.07 cfm/ft^2). With a design occupancy density of 6 persons/100 m^2 (1,000 ft^2) and a diversity factor of $D = 1$, the equivalent ventilation rate is 8.8 L/s (17.7 cfm) per person. The revision shows the shift in ventilation philosophy from an occupant-only orientation to a combined occupant-and-building orientation. Nevertheless, the ventilation requirements as well as contaminant concentrations still vary with occupancy for existing buildings because the building component is fixed.

Yu-Pei Ke is a graduate assistant and **Stanley A. Mumma** is a professor in the Department of Architectural Engineering at the Pennsylvania State University, University Park, Pa.

In addition to *DVR*, pre-occupancy (lead) ventilation control is required in Standard 62R for spaces occupied intermittently but regularly. The required lead time, t_L, is

$$t_L = 1.5 V_B / V_L. \tag{2}$$

The pre-occupancy ventilation is mainly to purge contaminants emitted from building materials when the system is off before occupants enter the space.

CO_2-BASED AND OCCUPANCY-BASED DEMAND-CONTROLLED VENTILATION

Heating and humidifying or cooling and dehumidifying OA can consume considerable energy; therefore, overventilation should be avoided. One method to achieve this objective is demand-controlled ventilation (DCV). Conventional DCV is usually CO_2-based, where the OA intake flow rate is adjusted (not necessarily measured) to maintain the return air CO_2 concentration at a threshold setpoint level. This concept was first advanced by Kusuda (1976). Although CO_2 is not really an indoor contaminant, it has been used as the surrogate of human bioeffluents and an index of IAQ. With the ventilation requirements proportional to occupancy and the CO_2 generation rate per occupant assumed constant, CO_2-based DCV (DCV_{CO_2}) changes OA intake dynamically according to occupancy. Theoretically, there will be no unvitiated (unused) OA left in its exhaust air. Literature shows that the DCV_{CO_2} is a workable scheme and beneficial; it saves energy compared with constant OA ventilation (Carpenter 1996; Emmerich et al. 1994; Haghighat and Donnini 1992, 1993; Knoespel et al. 1991; Meckler 1994; Warren and Harper 1991; Woods et al. 1982).

In the Ventilation Rate Procedure of ASHRAE Standard 62-1989 (or older versions), all ventilation rates are proportional to occupancy only. This makes the CO_2 threshold concentration setpoint a constant when a fixed generation rate per person and constant OA CO_2 concentrations are assumed. Therefore, maintaining the CO_2 concentration at the threshold setpoint limit is equivalent to controlling the ventilation rate in conventional DCV_{CO_2}. In such a case, the controlled ventilation rates will follow the varying occupancy. That is, DCV_{CO_2} is an alternative of occupancy-based DCV (DCV_{occ}). Nevertheless, it is not valid for Standard 62R since the ventilation requirement is no longer proportional to occupancy. Therefore, DCV_{CO_2} may over- or underventilate spaces. As Standard 62R states in Appendix F.2.2, Standard 62R differs from Standard 62 in two important ways:

> First, Standard 62-1989 ventilation rates are based primarily on a rate per person basis (Table 2). . . . In other words, outdoor air intake could be controlled directly by CO_2 concentration without having to also measure the actual rate of air being supplied. This is no longer possible with the philosophy of this revised standard since the minimum outdoor air quantity now has both a people related and building related term. CO_2 cannot be used alone to control the ventilation system because the CO_2 setpoint would be a function of the number of people in the space, which is unknown at any given time. (If it were known, it would not be necessary to use CO_2 as a surrogate for the number of people.)
>
> Second, Standard 62-1989 assumed that outdoor air concentration of CO_2 stayed relatively constant at 300 ppm (which gave rise to the 1000 ppm room CO_2 concentration guideline based on 15 cfm/person outdoor air rate). In practice, however, CO_2 concentrations can be significantly higher particularly in urban areas and near roads and freeways because CO_2 is a product of combustion. Measuring differential CO_2 concentration ensures that acceptable dilution of bioeffluents will take place at the minimum outdoor air intake rate regardless of the fluctuations of outdoor CO_2 concentrations.

To minimize the energy operating costs associated with conditioning the OA, the ventilation requirements should change with occupancy. The first paragraph above justifies the point that dynamic zonal occupancy must be known to meet the new standard and keep OA at the minimum acceptable level. This point is also important for real-time on-line system optimization (Mumma and Bolin 1994; Ke and Mumma 1997). Instead of counting people directly, the ventilation airflow rate and CO_2 concentration difference between OA and exhaust air could be used to compute the actual number of people. To achieve this operation with existing CO_2 sensors and to comply with the second point, this paper develops a new applicable scheme.

In addition to the nonproportionality problem, the conventional DCV_{CO_2}, as applied under Standard 62, is actually a steady-state application. This is not a problem if the room air CO_2 concentration has reached the setpoint. The setpoint for DCV_{CO_2} is usually the saturation CO_2 concentration at steady state of design occupancy. For example, if the OA CO_2 concentration is 300 ppm and the ventilation airflow rate is 10 L/s (20 cfm) per person for office workers at 1.2 met (0.005 L/s [0.01 cfm] per person of CO_2 generation rate), the saturation CO_2 concentration is 800 ppm. When the CO_2 concentration is at the setpoint, the DCV_{CO_2} controller will adjust the OA intake with varying occupancy correctly if the ventilation requirement is proportional to the occupancy, as in the past. When the CO_2 concentration is far below the setpoint, such as the starting period of a day, the transient state plays a significant role in proper ventilation. During this period, the DCV_{CO_2} is usually at its minimum (or zero) flow rate and room CO_2 concentration is building up. The significance of the transient effect on the starting period depends on the ventilation time constant, or the length of time before the controller is activated by the CO_2 concentration. The ventilation time constant is the inverse of the air change rate. The smaller the time constant, the sooner steady state is reached. Since the DCV_{CO_2} is at minimum airflow rate before its setpoint is reached, the space is seriously underventilated. For the recommended occupancy density of Standard 62R with a 3-m (9-ft) ceiling height, the ventilation time constant for the building component alone is more than two hours. This means there will be a long period before the DCV_{CO_2} controller takes action, and the space will be underventilated during that period. Some researchers have recognized the starting period problem and

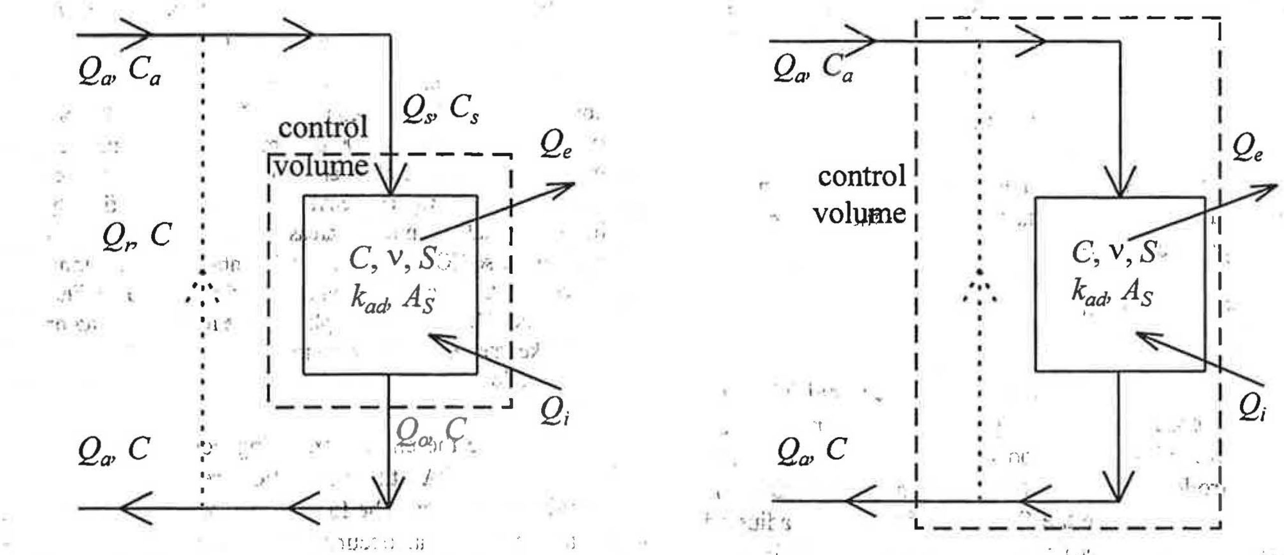


***Figure 1** Single-zone system: (a) control volume on the space only; (b) control volume includes recirculation.*

presented solutions employing the well-mixed model. Vaculik and Plett (1993) and Vaculik (1987) defined the occupancy profile as a combination of ramp functions and proposed an algorithm for CO_2 controllers. When the occupancy is very random or far from specified schedules, such algorithms lead to large errors and are not very useful.

Because of the nonproportionality of OA to occupancy and transient effects, it is not practical to use DCV_{CO_2} to meet Standard 62R. To satisfy the dynamic ventilation, $DCVocc$ should be used. Many schemes can achieve $DCVocc$; the simplest one is to use CO_2 measurements. The following sections explain its principles and applications.

WELL-MIXED MODEL

To use the room CO_2 concentration as the control variable, one must know the relationship between the CO_2 concentration and the room and system's characteristics. The most popular and the simplest model for describing this relation is the well-mixed model. The model can be applied to any contaminant and is stated as follows.

Consider the control volume of a single-space air delivery system as shown in Figure 1a. Based on the well-mixed condition and applying a mass balance on the contaminant, the differential equation relating contaminant concentration and time is

$$v\frac{dC}{dt} = Q_s C_s - Q_o C + Q_f C_a - Q_e C - k_{ad} A_S + N. \quad (3)$$

If there is no infiltration ($Q_f = 0$), exfiltration ($Q_e = 0$), or adsorption ($k_{ad} = 0$), then the airflow rate out equals the supply airflow rate ($Q_o = Q_s$), and Equation 3 is simplified to

$$v\frac{dC}{dt} = -Q_s(C - C_s) + N \quad (4)$$

or

$$\frac{dC}{dt} + \frac{Q_s}{v}C = \frac{Q_s \cdot C_s + N}{v}. \quad (5)$$

Equation 5 is a linear ordinary differential equation; all variables in it except v are usually functions of time. Its general solution is

$$C(t) = \exp\left(-\int\frac{Q_s}{v}dt\right)\left[\int\exp\left(\int\frac{Q_s}{v}dt\right)\frac{Q_s \cdot C_s + N}{v}dt + c\right] \quad (6)$$

where c is an integration constant determined by the initial contaminant concentration. Unless C_s, Q_s, and N are some special functions, Equation 6 is difficult to integrate. If C_s, Q_s, and N are also constant and $Q_s \neq 0$, Equation 6 can be reduced to

$$C(t) = C_s + N/Q_s + (C_i - C_{ss})\exp(-St) \quad (7)$$

where

$$S = Q_s/v \quad (8)$$

is the air change rate, which is also the inverse of the space ventilation time constant. C_{ss} is the steady-state concentration when time approaches infinity, or $dC/dt = 0$ in Equation 5.

$$C_{ss} = C(t \to \infty) = C_s + N/Q_s \quad (9)$$

If $Q_s = 0$, Equation 6 becomes

$$C(t) = C_i + (N/v)t \quad (10)$$

Equation 10 has no steady state. This means that, for an unventilated space, the contaminant concentration is always increasing linearly with the contaminant generation rate.

Equations 3 through 6 can be applied to any zone; Equations 7 through 9 are only valid theoretically to zones with constant C_s, Q_s, and N. Although Figure 1a is a single-zone system, the above derivations are valid for individual spaces in a multizone system,

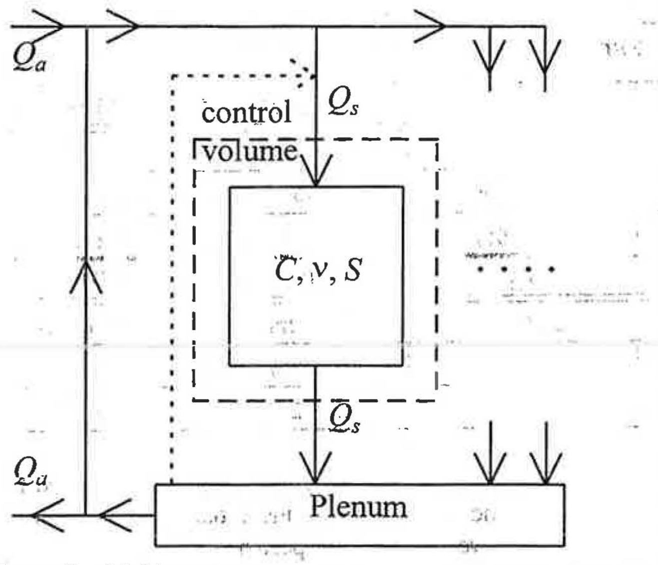


***Figure 2** Multi-zone system.*

as shown in Figure 2. Note that the above equations assume no contaminant-removal devices, e.g., filters, in the system. Equations for systems with contaminant-removal devices can be found in the literature (Heinsohn 1991).

APPLICATIONS OF THE WELL-MIXED MODEL

One way to determine the current occupancy in a zone is to install pedestrian counters (sensors) at each of the zone's passageways. However, this kind of sensor is not well tested or widely used today. On the other hand, CO_2 sensors are becoming more accurate, less expensive, and widely used. Combined with direct digital control (DDC) systems, CO_2 sensors can be used to determine the current occupancy. The application of CO_2 concentration measurements to calculate occupancy follows.

First, writing Equation 4 in finite-difference form and rearranging yields:

$$N(t) = v\frac{C(t) - C(t - \Delta t)}{\Delta t} + Q_s(t)[C(t) - C_s(t)] \quad (11)$$

where Δt is the scan time interval between measurements. Another invalid, but popular, use of Equation 4 is to omit the transient term dC/dt. With this omission, Equation 11 becomes

$$N(t) = Q_s(t)[C(t) - C_s(t)]. \quad (12)$$

Next, the contaminant generation rate can be calculated if the variables on the right-hand side of Equations 11 and 12 are measured. Furthermore, if the contaminant source strength (CO_2) is proportional to the occupancy with a constant G, then the occupancy is

$$P(t) = N(t)/G. \quad (13)$$

As long as the occupancy is determined, the DDC system can calculate the ventilation requirement by a built-in formula according to Standard 62R, e.g., Equation 1, and command the OA damper to induce the proper OA. In case the room air mixing is not perfect, the resulting ventilation rate should be divided by the room's ventilation effectiveness to obtain the actual needed flow rate.

This scheme needs the CO_2 concentration measurements entering and leaving the space as well as the supply airflow rate and an assumed per-occupant CO_2 generation rate to compute occupancy. Both Equations 11 and 12 use the CO_2 concentration differential between room and supply air, independent of the OA CO_2 concentration. This means the variations in the OA CO_2 concentration do not affect the determination of occupancy or the required OA flow rate. Therefore, this scheme matches the two different points of Standard 62 and 62R stated above.

In addition, for single-room systems, if Q_s and/or C_s (supply air variables) are not measurable but Q_a and C_a (OA variables) are available, Equations 4 through 15 still work when the subscript s is replaced with a. This point can be justified by extending the control volume in Figure 1a to include the recirculation path as shown in Figure 1b. That is, the above scheme applies to single-zone systems and entire multizone systems with or without recirculation.

COMPUTER SIMULATIONS

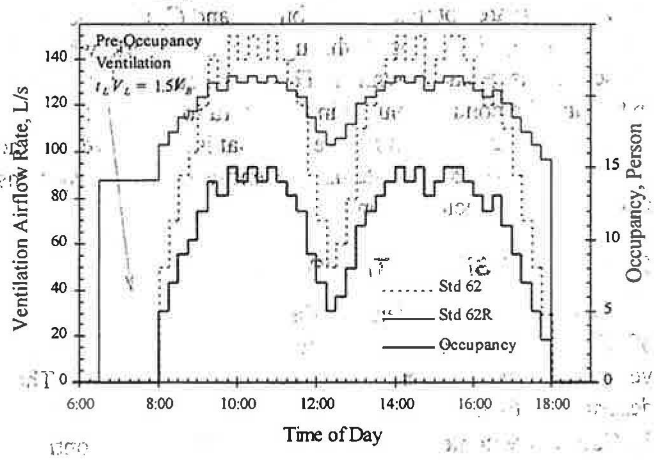
To compare and understand the difference and consequence of CO_2-based and occupancy-based controlled ventilation, four ventilation controls were investigated in this research. Their descriptions follow.

1. Constant-volume ventilation (*CVV*)—The controller induces a fixed *DVR* regardless of the occupant variation during occupied periods.
2. CO_2-based DCV (DCV_{CO_2})—An on-off controller modulates the ventilation rates within the limitation band. When the concentration hits the upper limit, the *DVR* is induced; when the concentration decreases to the low limit, only the building component V_B is induced.
3. Quasi-steady-state *DCVocc* (*DCVocc,ss*)—Equations 12 and 13 are used to calculate current occupancy. Then the controller induces the ventilation rate accordingly. Basically, this algorithm is identical to that of Appendix F.2.2 of Standard 62R. In Standard 62R, this scheme is in the name of CO_2-based DCV, but the OA flow rate is measured and adjusted, not the CO_2 concentration.
4. Transient *DCVocc* (*DCVocc,tran*)—Equations 11 and 13 are used to calculate current occupancy. Then, the controller induces the ventilation rate accordingly.

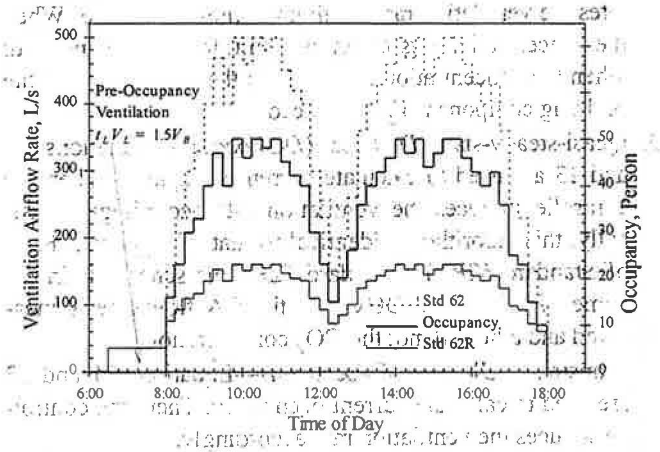
Two single-room systems using the above algorithm are illustrated. Their data are listed in Table 1. Further assumptions are: unity air change effectiveness; no in/exfiltration; OA CO_2 concentration constant at 300 ppm; an occupant activity level of 1.2 met, i.e., CO_2 generation rate of 0.3 L/min (0.01 cfm) per person; and varied, but constant within 15-minute intervals, occupancy schedules (Figure 3). According to the occupancy schedule, applying Standards 62 and 62R results in different ventilation requirements, as shown in Figure 3. In Figure 3, the

TABLE 1
Physical Data of Simulated Rooms

Item	area, A_B	volume	Occup. density	People, P_D	[CO_2] setpoint
units	m^2 (ft^2)	m^3 (ft^3)	per./m^2 (/ft^2)	-	ppm
office	250 (2500)	750 (26500)	0.06 (0.006)	15	866.0
conference	100 (1000)	300 (10600)	0.5 (0.05)	50	1862.5
Item	R_B	R_P	V_B	V_P	DVR
units	L/s/m^2	L/s/person	L/s (cfm)	L/s (cfm)	L/s (cfm)
office	0.35 (0.07)	3.0 (6)	87.5 (175)	45 (90)	132.5 (265)
conference	0.35 (0.07)	2.5 (5)	35.0 (70)	125 (250)	160.0 (320)



(a) office



(b) conference room

Figure 3 *Occupancy and ventilation requirements.*

lead ventilation rate (V_L) was specified to be equal to V_B, i.e., t_L = 1.5 hours from Equation 2. The steady-state CO_2 concentrations of the last column in Table 1 are the setpoints of DCV_{CO_2} with a bandwidth of 100 ppm (±50 ppm). In addition, the sampling time step used in the one-day simulations was three minutes. Within a time step, the CO_2 concentration varies according to Equation 7. All controllers were assumed to respond "perfectly," i.e., no control equipment induced lag or over/undershoot. To eliminate the initial condition effects, the simulations were executed repeatedly until all four strategies were periodically steady, i.e., their daily CO_2 concentration profiles remained unchanged. The results are plotted in Figures 4 through 6 and summarized in Table 2. The nighttime data from 19:00 to 6:00 hours are not shown in these figures since the values remain unchanged over the time period.

RESULTS AND DISCUSSION

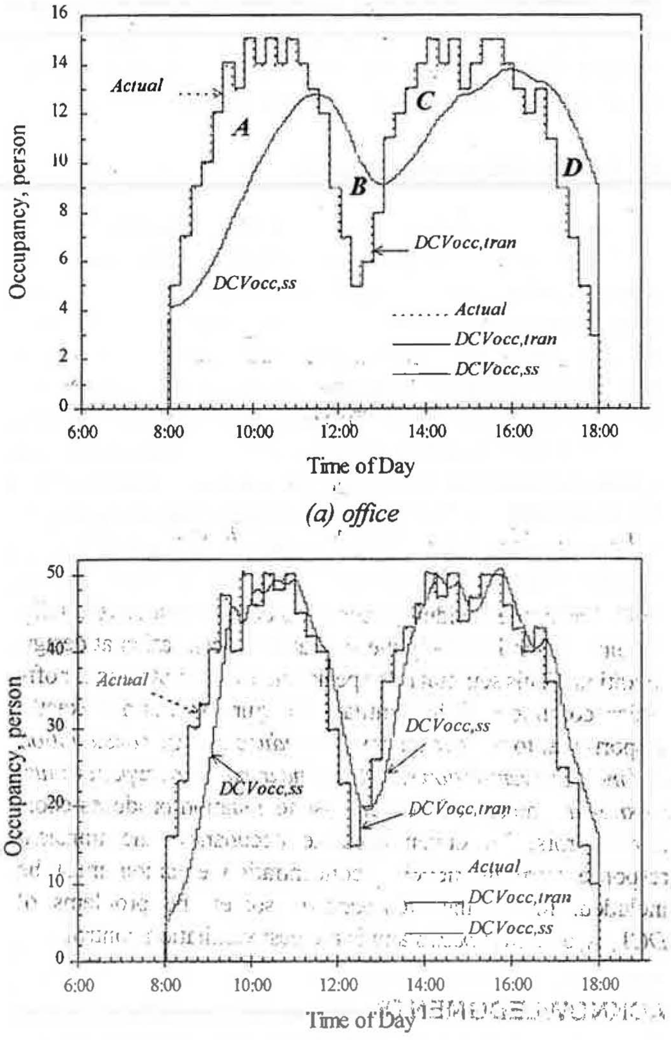
Figure 4 shows the calculated occupancy. The *DCVocc,tran* occupancy traces the actual occupancy well. It has a time lag of one time step and a tiny deviation when the occupancy is changing. The *DCVocc,ss* curve, on the other hand, has a big lag in time; it has large underestimation and overestimation when the occupancy is increasing and decreasing, respectively, in Figure 4a. Notice that in this figure from 8:00 to 11:30 (area A), the *DCVocc,ss* underestimated occupancy in the office (with a peak occupancy of 15) by 12.9 person-hours. From 12:00 to 13:00 (area B), the *DCVocc,ss* overestimated the occupancy by 4.8 person-hours. From 13:00 to 16:00 (area C), the *DCVocc,ss* underestimated the occupancy by 6.0 person-hours. Finally, after 16:00 (area D), the *DCVocc,ss* overestimated the occupancy by 6.3 person-hours. In Figure 4b for the conference room, *DCVocc,ss* has a similar trend as in Figure 4a but with a smaller lag. This is accounted for by the smaller ventilation time constant. Both the office and conference room have the same R_B, but the conference room has a much higher occupant density that results in a higher ventilation airflow rate and a smaller time constant. The time constants for the office at DVR and V_B are 1.57 and 2.38 hours, respectively, and 0.52 and 2.38 hours for the conference room.

Figure 5 illustrates the OA flow rate for each of the four ventilation control approaches. The *DCVocc,ss* and *DCVocc,tran* have OA intake profiles that follow the occupancy calculated from the steady-state and transient equations, respectively (Figure 4). In Figure 5a for the office space, the DCV_{CO_2} controller keeps the OA flow rate at V_B = 87.5 L/s (175 cfm) until 11:18, when the CO_2 concentration is high enough (Figure 6a) to require more OA. This means the zone is underventilated during

TABLE 2
Outdoor Air Intake for Different Ventilation Controls

	Controls	Std-62R	*CVV*	*DCV*$_{co_2}$	*DCVocc,ss*	*DCVocc,tran*
total OA m³/day (10³ ft³/day)	office	4851(171.3)	5243(185.2)	4165(147.1)	4768(168.4)	4851(171.3)
	conference	4820(170.2)	5949(210.1)	4374(154.5)	4742(167.5)	4819(170.2)
OA ratio to Std-62R	office	1.000	1.081	0.859	0.983	1.000
	conference	1.000	1.234	0.908	0.984	1.000
peak [CO₂] ppm	office	821.8	806.2	918.5	835.4	821.7
	conference	1851.3	1818.2	2008.5	1874.6	1854.0

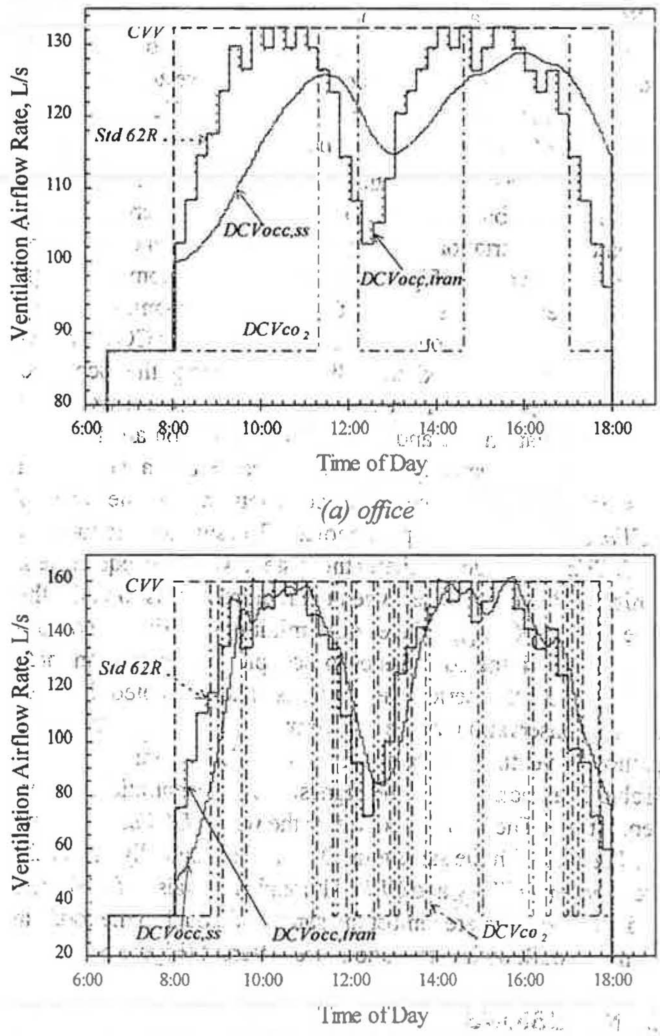
the three-hour CO_2 build-up period. From then, the DCV_{CO_2} switches the ventilation rate between design low and high limits, 87.5 and 132.5 L/s, respectively, to maintain exhaust CO_2 concentration at 866 ± 50 ppm. In Figure 5b, the faster response of CO_2 concentration activates the controller earlier at 8:51, a one-hour underventilation. Under DCV_{CO_2} the conference room switches the ventilation flow rate more frequently than the office. This can be explained by the V_B/V_P ratio. The ratios for the office and conference rooms are 1.94 and 0.28, respectively. The higher the ratio, the slower the response for changes in CO_2 concentrations.



(a) office

(b) conference room

Figure 4 Calculated and actual occupancy.



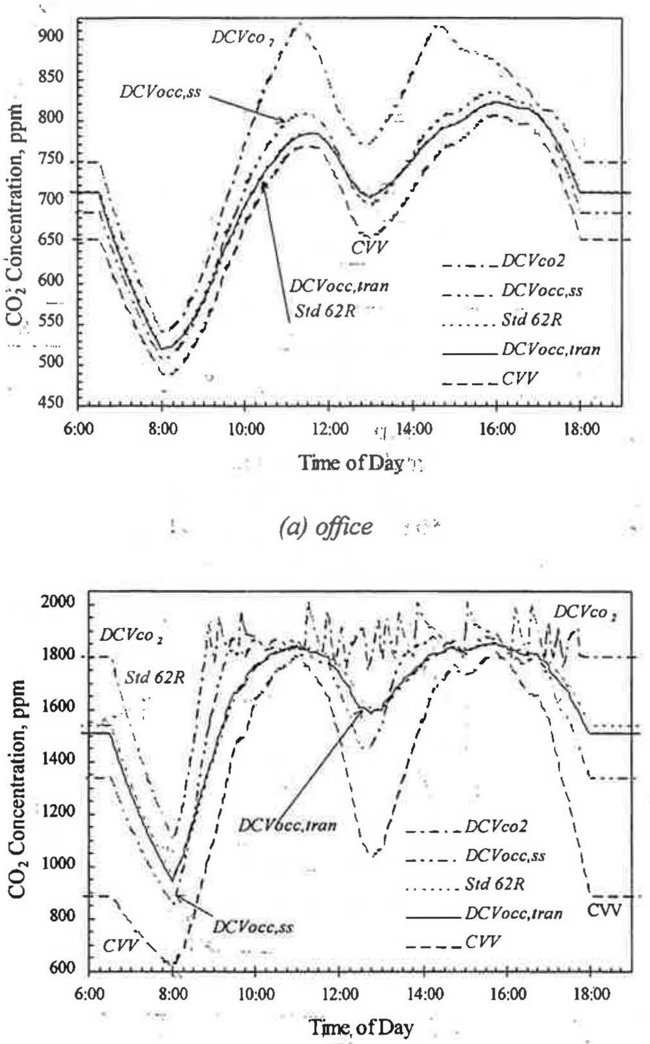
(a) office

(b) conference room

Figure 5 Required and actually induced ventilation airflow rates.

Figure 6 displays the CO_2 concentration variation as a function of time for each of the different ventilation controls. The CO_2 concentration curve, based on exactly meeting Standard 62R is also presented for reference. The reference Standard 62R, CO_2 curve is based on assuming that the OA flow rate matches the occupancy exactly and instantaneously. The *DCVocc,tran* curve follows the ideal curve closely; they are difficult to distinguish. The DCV_{CO_2} curves are always above the Standard 62R curves; the *CVV* curves are always below the Standard 62R curves. The *DCVocc,ss* curves cross the Standard 62R curves several times for both the office and the conference room. Only the DCV_{CO_2} and *DCVocc,ss* curves reach the saturation values (CO_2 setpoints in Table 2). Furthermore, Table 2 shows the DCV_{CO_2} peak CO_2 concentrations overshoot the upper limits of both spaces due to the intermittent measurements and control actions. If other better controllers (e.g., PID or fuzzy controllers) were used, the DCV_{CO_2} curves might be flat after reaching the saturation concentrations. Better controllers, however, will not change the CO_2 concentration during the buildup periods. The *DCVocc,ss* curve has the second highest concentrations for most of the occupied hours. That is, during the hours of increasing occupancy, *DCVocc,ss* overshoots the ideal curve and then drops below it when the occupants are leaving. The *CVV* curves are the lowest since *CVV* overventilates the spaces most of the time.

In the office example, the V_B/V_P ratio is 1.94. This large ratio means the building component dominates; therefore, CO_2 concentration variations among the four ventilation controls are small, as illustrated in Figure 6a (maximum 162 ppm). For high occupant density areas, such as the conference room, the V_B/V_P ratio is lower (0.28). Consequently, the variation in CO_2 concentrations is larger (maximum 892 ppm during the occupied period). As mentioned previously, the time constants at the lowest ventilation rate and at the design condition are 1.57 and 2.38 hours, respectively, for this office. From a ventilation perspective, these large time constants make the use of *DCVocc,ss* and DCV_{CO_2} poor choices. The sluggish response of the *DCVocc,ss* underventilates the system when the requirement is high and overventilates when the requirement is low. On the other hand, DCV_{CO_2} induces only minimum (building component) OA until the zone has been occupied for more than three hours. During this period, the system is underventilated. From an energy conservation viewpoint, however, DCV_{CO_2} is the most economic ventilation control. It has the least total OA intake (Table 2) associated with the highest CO_2 concentration (underventilation). The *CVV*, of course, is the worst. *DCVocc,tran* and *DCVocc,ss*, with the same total OA intake eventually (Table 2), are between DCV_{CO_2} and *CVV*. Although the totals of *DCVocc,ss* and *DCVocc,tran* are almost the same and equal to the totals in Standard 62R, their distributions are different (Figure 5).



(a) office

(b) conference room

***Figure 6** CO_2 responses under different ventilation controls.*

CONCLUSIONS

This paper presents a simple but applicable method to determine dynamic occupancy. It also investigates four ventilation controls. The *CVV* overventilates the system most of the time. The conventional DCV_{CO_2} will underventilate the system, especially during the buildup period. Besides, it must have a CO_2 setpoint, which is usually the saturated concentration at design conditions. This setpoint is the peak value and is not valid for off-design conditions if the ventilation requirement is not exactly proportional to the occupancy. *To reduce energy consumption and meet the ventilation standard, the dynamic occupancy must be known.* The use of the steady-state equation produces enormous errors. To obtain accurate occupancy, the transient response term in the CO_2 concentration equation must be included. In all, the *DCVocc,tran* solves the problems of DCV_{CO_2} and *DCVocc,ss* and is the best ventilation control.

ACKNOWLEDGMENTS

The authors wish to thank Thomas Leonardis, Robert Alpers, Robert Kelly, and the Staefa Corporation for their support of the research that provided the information for this paper.

NOMENCLATURE

A	=	area
C	=	concentration of contaminant; room contaminant concentration if no subscript
c	=	integration constant
CVV	=	constant volume ventilation
D	=	diversity factor
DCV	=	demand-controlled ventilation
DCV_{CO_2}	=	conventional CO_2-based DCV
DCVocc	=	occupancy-based DCV
DCVocc,ss	=	steady-state *DCVocc*
DCVocc,tran	=	transient *DCVocc*
DDC	=	direct digital control
DVR	=	design OA ventilation rate
G	=	CO_2 generation rate per person
IAQ	=	indoor air quality
k_{ad}	=	contaminant adsorption constant of indoor surface
N	=	contaminant generation rate
OA	=	outdoor air
P	=	number of people
Q	=	airflow rate
R_B	=	minimum OA flow rate per unit floor area
R_P	=	minimum OA flow rate per person
S	=	air change rate per unit time
t	=	time
V	=	volumetric ventilation rate
Δt	=	time step
v	=	room volume

Subscripts

a	=	outdoor air
B	=	building (floor)
D	=	design value
e	=	exfiltration
f	=	infiltration
i	=	initial condition
L	=	lead period
o	=	leaving air
P	=	people
S	=	room surface
s	=	supply air
ss	=	steady state

REFERENCES

ASHRAE. 1973. *ASHRAE Standard 62-1973, Standards for natural and mechanical ventilation.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1981. *ASHRAE Standard 62-1981, Ventilation for acceptable indoor air quality.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE 1989. *ANSI/ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1996. BSR/ASHRAE Standard 62-1989R, *Ventilation for acceptable indoor air quality.* Public Review Draft. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Carpenter, S.C. 1996. Energy and IAQ impacts of CO_2-based demand-controlled ventilation. *ASHRAE Transactions* 102(2): 80-88.

Emmerich, S.J., J.W. Mitchell, and W.A. Beckman. 1994. Demand-controlled ventilation in a multi-zone office building. *Indoor Environment* 3: 331-340.

Haghighat, F., and G. Donnini. 1992. IAQ and energy-management by demand controlled ventilation. *Environmental Technology* 13: 351-359.

Haghighat, F., and G. Donnini. 1993. Conventional vs. CO_2 demand-controlled ventilation systems. *Journal of Thermal Biology* 18(5/6): 519-522.

Heinsohn, R.J. 1991. *Industrial ventilation: Engineering principles*, chap. 5. New York: John Wiley & Sons, Inc.

Ke, Y.-P., and S.A. Mumma. 1997. Derivation of equations necessary for primary airflow redistribution in VAV systems to reduce outdoor air intake while meeting ventilation requirements. *International Journal of HVAC&R Research* 3(1): 3-18.

Knoespel, P.D., J.W. Mitchell, and W.A. Beckman. 1991. Macroscopic model of indoor air quality and automatic control of ventilation airflow. *ASHRAE Transactions* 97(2): 1020-1030.

Kusuda, T. 1976. Control of ventilation to conserve energy while maintaining acceptable indoor air quality. *ASHRAE Transactions* 82(1): 1169-1181.

Meckler, M. 1994. Demand-control ventilation strategies for acceptable IAQ. *Heating/Piping/Air Conditioning* 66(5): 71-74.

Mumma, S.A., and R.J. Bolin. 1994. Real-time, on-line optimization of VAV system control to minimize the energy consumption rate and to satisfy ASHRAE Standard 62-1989 for all occupied zones. *ASHRAE Transactions* 100(1): 168-179.

Vaculik, F. 1987. Air quality control in office buildings by a CO_2 method. *Practical Control of Indoor Air Problems, IAQ '87*, pp. 244-251. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Vaculik, F., and E.G. Plett. 1993. Carbon dioxide concentration-based ventilation control. *ASHRAE Transactions* 99(1): 1536-1547.

Warren, B.F., and N.C. Harper. 1991. Demand controlled ventilation by room CO_2 concentration: A comparison of simulated energy savings in an auditorium space. *Energy and Buildings* 17: 87-96.

Woods, J.E., G. Winakor, E.A.B. Maldonado, and S. Kipp. 1982. Subjective and objective evaluation of a CO_2-controlled variable ventilation system. *ASHRAE Transactions* 88(1): 1385-1408.