# THE USE OF $CO_2$ READINGS WITH FIXED VENTILATION TO PREDICT ENERGY SAVINGS WITH DEMAND-CONTROLLED VENTILATION

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## ABSTRACT

In a university building in Boston, IAQ complaints prompted an increase in outdoor air ventilation, causing a large increase in energy use. $CO_2$ readings were then taken in an auditorium, cafeteria, offices, and classrooms. The readings were used to calculate occupancy estimates and to simulate operation of a demand-controlled ventilation (DCV) system. The differential equations were solved in a spreadsheet program using a Runge-Kutta macro. A PID control system was also simulated. Ventilation adjustments were input to DOE-2 to estimate energy savings. A two year payback was estimated. DCV was also shown to provide a small savings when compared to lower design ventilation rates, while improving IAQ.

## INTRODUCTION

ASHRAE Ventilation Standard 62-1989 specifies *fixed* rates of outdoor air ventilation for building areas based on *maximum* expected occupancy (1). In densely occupied areas, bioeffluents (e.g., body odor) are the primary pollutants. During periods when occupancy is lower or higher than the assumed maximum, the potential exists to reduce or increase outdoor air intake, thus either saving energy used to condition the outdoor air or improving IAQ.

The carbon dioxide concentration in indoor air has been found to be a reliable indicator of human occupancy (2). Based on human respiration rates for specified activity levels, ASHRAE 62-1989 provides an equation which can be used to convert a recommended per person ventilation rate to a steady state $CO_2$ concentration. For example, the 10 L/sec/person rate recommended for offices is equivalent to 800 ppm $CO_2$ (assuming outdoor air at 300 ppm $CO_2$). 1000 ppm $CO_2$ is generally considered the upper limit for indoor spaces. $CO_2$ itself is not harmful at this level; it is used as a surrogate indicator of body odor.

Specifying a $CO_2$ limit for indoor air allows for the use of feedback control to adjust the outdoor air damper. This is known as "demand-controlled ventilation" (DCV). Figure 1 illustrates the process; the different levels of shading represent the relative $CO_2$ concentrations in the air (though exaggerated). Using DCV to maintain the room $CO_2$ concentration at a steady level below the limit, the flow of outdoor air is adjusted to the point at which the lower $CO_2$ concentration in the supply air balances the additional $CO_2$ added by the occupants.

### Study building

A sudden rash of unsubstantiated IAQ complaints occurred in a university building in Boston, Massachusetts. Building operating personnel responded by increasing the outdoor air

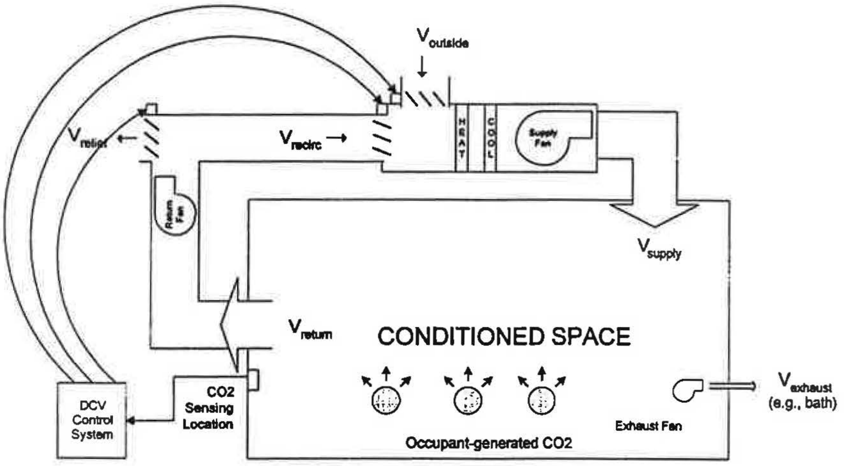

Figure 1 Simplified illustration of demand-controlled ventilation

ventilation rate to 50% of total supply air, from the design level of 33%, for all HVAC systems in the building. Energy use rose substantially, with no assurance that IAQ was improved. A $CO_2$ monitoring system was then installed for a two month period in Dec. 1995 and Jan. 1996. Outdoor air ventilation remained fixed at 50% during the monitoring period.

The results of the $CO_2$ monitoring, a set of building plans, and information on building operating schedules and equipment were the only data available to the authors. The objective of the study was to produce a computer simulation of the operation of a DCV system, based on $CO_2$ readings obtained with fixed outdoor air ventilation, in order to evaluate the potential for DCV to provide energy savings and/or improved IAQ in the study building.

## METHODS

Four zones in the building were chosen for analysis: two single-room zones: an auditorium and a cafeteria; and two multiple-room zones: an office zone and a classroom zone. The office zone consists mainly of two large open office areas. All zones are heated to 21°C and cooled to 23.3°C. Each of the four zones has a separate HVAC system with constant-volume ventilation. All HVAC systems are shut off overnight, at about 9 p.m., except at 5 p.m. in the cafeteria. Summer and January schedules are similar to Fall and Spring, though with lower occupancy, and the auditorium is unused and minimally heated in January. Heating is electric resistance and cooling is by chilled water from centrifugal chillers. Most rooms have electric reheat. Each room is equipped with supply and return ducts located in the ceiling, except for the auditorium return ducts which are at floor level. Each zone has a single outdoor air damper, theoretically providing the same percentage of outdoor air to each room in the zone.

The $CO_2$ monitoring system consists of a central $CO_2$ sensor, datalogger, PC, and a vacuum pump with flexible tubing for collecting air samples from up to 24 rooms. The $CO_2$ sensor requires 75 seconds to evaluate an air sample, resulting in a 30 minute sampling interval for each monitored room. $CO_2$ sampling tubes were located in the ceilings of all monitored rooms, except in the auditorium where the sampling tube was placed in a return duct.

**Computer modeling**

DCV modeling was accomplished in two parts. First the outdoor air ventilation adjustments were determined in a spreadsheet program, as described below. The results were then input to the DOE-2 building energy analysis program (3) to determine energy use. The two months of data were extrapolated to a full year based on seasonal HVAC operating schedules and reported building usage patterns.

A mass balance on the $CO_2$ in a multi-room space produces a set of differential equations:

$$\mathrm{Vol}_j \cdot \frac{dC_j}{dt} = G_j \cdot N_j \times 10^6 + f\dot{V}_j C_0 - \dot{V}_j C_j + (1-f)\cdot \dot{V}_j \cdot \left[ \left( \sum_{k=1}^{n} \dot{V}_k \cdot C_k \right) \Big/ \left( \sum_{k=1}^{n} \dot{V}_k \right) \right] \quad \ldots(1)$$

where the subscript j refers to the room under consideration, n is the number of rooms in the space, Vol = room volume in $m^3$, C = room $CO_2$ concentration in ppm (assuming constant density, mass concentrations have been converted to volume concentrations), t = time in hr, G = generation rate of $CO_2$ per person in $m^3$/hr, N = number of people in the room, f = fraction of outdoor air in the supply air, $\dot{V}$ = ventilation rate of supply air into room in $m^3$/hr, $C_0$ = outdoor air $CO_2$ concentration in ppm. Well-mixed air has been assumed. For a single-room zone, assuming a constant number of people and a constant outdoor air $CO_2$ during each sampling interval, Equation 1 can be reduced and solved, producing (4):

$$C_f - C_0 = \left( G \cdot N \times 10^6 / f\dot{V} \right) \left[ 1 - \exp\left( -f\dot{V} \cdot t/\mathrm{Vol} \right) \right] + \left( C_i - C_0 \right) \cdot \exp\left( -f\dot{V} \cdot t/\mathrm{Vol} \right) \quad \ldots(2)$$

where $C_i$ and $C_f$ = $CO_2$ concentration in the space at the beginning and end of the interval.

The equations were used in the spreadsheet in two steps. First, using the $CO_2$ readings obtained with a fixed outdoor air setting, the equations were solved for N, the number of occupants during each sampling interval. For the multi-room case, the boundary-value problem for the set of differential equations was solved using a shooting method with a fourth order Runge-Kutta method in a macro. Then, using the number of people determined, the equations were re-written for each sampling interval. An adjusted outdoor air fraction for DCV, calculated using PID modeling described below, was also substituted into the equations. The equations were then solved for $C_f$, the $CO_2$ level at the end of the interval. For the multi-room case, the initial-value problem for the set of differential equations was solved with a Runge-Kutta macro similar to that used in the boundary-value problem, with an 18 second solution time step. To determine overnight $CO_2$ levels after HVAC system shutoff, a form of Equation 2 was used to determine natural infiltration rates based on $CO_2$ decay rates.

Building-related pollutants (e.g., formaldehyde) are generated continuously regardless of human occupancy. To dissipate these pollutants, a continuous minimum level of outdoor air ventilation is usually recommended. Recommendations vary from about 0.5 air changes per hour (ach) to 1.1 ach (5,6). 1 ach was used as a minimum in the current study. The corresponding outdoor air fractions ranged from 12% to 20% for the four zones. Building-related pollutants can also build up overnight during HVAC shutoff. A morning purge cycle at maximum outdoor air ventilation has been recommended to alleviate the buildup (7). In the current study, a 1-hour morning purge cycle was calculated to be sufficient and was included.

**PID simulation**

A Proportional-Integral-Derivative (PID) control system is represented by the following equation:

$$CO(t) = K_p \cdot e(t) + K_i \cdot \left( \int_0^t e(\tau)d\tau \right) + K_d \cdot \left( \frac{d}{dt} e(t) \right) + B \qquad ...(3)$$

where CO = controller output (in this case, fraction of outdoor air for the current time step, or "f "), t = time, e = error, i.e., difference between $CO_2$ level and $CO_2$ setpoint ($C - C_{setpt}$), $K_p$ = proportional tuning constant, $K_i$ = integral tuning constant, $K_d$ = derivative tuning constant, B = bias, i.e., controller output required for stability when e = 0, in this case "f " from the previous time step. A trapezoidal approximation was used for the integral term, and a backward difference approximation for the derivative term. The resulting equation was used in the spreadsheet to determine the required outdoor air fraction during each sampling interval. Integral windup was prevented by limiting the integral term to the previous hour. Tuning, the process of choosing the optimum $K_p$, $K_i$, and $K_d$, was accomplished iteratively, seeking the least sum of the squares of errors from the desired limit. Since errors above the limit are far less desirable than errors below the limit, the former were weighted by a factor of seven, a figure arrived at empirically by comparisons.

## RESULTS

Table 1 presents the calculated annual percentage HVAC energy cost savings for DCV. Comparisons to both the existing ventilation rate of 50% outdoor air (OA) and the original design rate of 33% OA are included. Both continuous damper modulation and damper adjustments limited to steps of 20% of maximum were included as control options. Results for the classroom zone are not included in Table 1 due to insufficient data. Based on partial data, the energy savings percentage for the classrooms could be near 13% compared to 50% OA, and 3% compared to 33% OA. The payback period for an installed DCV system in this building was estimated to be 2 years compared to 50% OA, and 6 years compared to 33% OA.

Table 1 Annual percentage HVAC energy cost savings with DCV

| Zone: | **Auditorium** | | **Cafeteria** | | **Offices** | |
|---|---|---|---|---|---|---|
| Savings relative to: | 50% OA | 33% OA | 50% OA | 33% OA | 50% OA | 33% OA |
| DCV continuous | 31.5% | 17.1% | 13.7% | 6.4% | 15.5% | 4.5% |
| DCV 20% damper | 28.4% | 13.3% | 11.5% | 4.0% | 15.4% | 4.5% |

As an example of the $CO_2$ levels achieved with DCV compared to fixed ventilation, Figure 2 presents results for a typical day in the office zone. Note that the $CO_2$ limits were adjusted upward by 100 ppm, since the outdoor air $CO_2$ at this location rarely dropped below 400 ppm. For the full month of December in the main office area, both DCV and 50% OA are able to maintain $CO_2$ levels below 1000 ppm, although DCV allows levels above the desired 900 ppm limit 5.5% of the time as opposed to only 2% of the time for 50% OA. 33% OA allows $CO_2$ levels above 900 ppm 30% of the time, however. So compared to the original design specification of 33% OA (circa 1971), DCV can improve IAQ (at least with respect to occupant-generated pollutants) while still providing some overall energy savings, as shown in Table 1. The peak occupant density was double the norm for offices, which increases DCV potential.

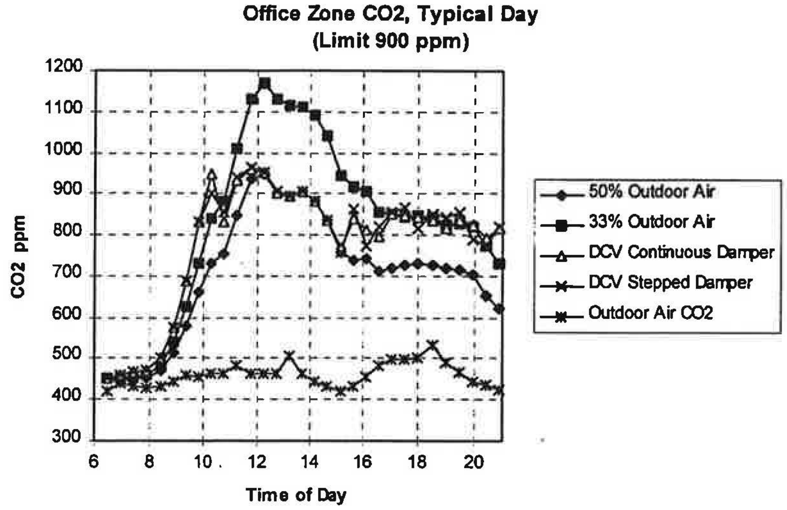

Figure 2 $CO_2$ levels in the main office area on a typical day in December

Fig. 2 shows little difference between continuous and stepped damper control. But in the other three zones there are greater variations in occupancy, and continuous damper control maintains the $CO_2$ closer to the desired limit. This is indicated in the greater energy savings in Table 1 for continuous control. The "choppiness" of the $CO_2$ levels with DCV in Fig. 2 is an indication of the limitations of the lengthy 30 min. sampling interval. An extreme example of this problem occurred on one day in the auditorium. There was apparently a rapid influx of people shortly after a $CO_2$ reading was taken, causing a peak $CO_2$ near 1400 ppm before the DCV system could react. This was only a single instance in the two month monitoring period, however, and such brief spikes are unlikely to be considered a serious problem.

On the other hand, a long sampling interval can reduce energy savings. Rapid variations in occupancy necessitated a lower $CO_2$ setpoint. The optimum setpoint was found to be 200 ppm below the desired limit for the classroom zone, but only 60 ppm below for the more uniformly occupied office zone. The cafeteria required a setpoint 100 ppm below the limit to prevent overshooting at noontime, reducing potential savings later in the day. A shorter sampling interval would allow for higher setpoints, improved $CO_2$ control, and greater energy savings.

The integral and derivative terms in the PID simulation did not provide a substantial improvement in $CO_2$ control. In one case, the cafeteria with stepped damper control, the addition of I & D terms provided no improvement over simple proportional control.

## DISCUSSION

Drangsholt also found that integral and derivative terms were not of much benefit with DCV (8). Knoespel's study concluded that simple proportional control is sufficient (5). The results of the current study may have been different, however, with a shorter sampling interval. PID theory is corrupted by long sampling intervals, which also introduce error into the ventilation calculations in the simulations. Knoespel used a 15 minute sampling interval in a DCV simulation and concluded that a shorter interval is preferable for satisfactory control. For HVAC controls in general, a sampling interval of about one-half the time constant is usually acceptable. In the study building, this translates to a sampling interval of about 7 minutes.

Air change effectiveness, natural infiltration during HVAC operation, and interzonal flows were ignored. Emmerich provides an equation including these factors (7). Air flow rates were assumed to be equal to design rates. Air flows and outdoor air fractions should be measured.

In multi-room zones, the $CO_2$ data indicate that $CO_2$ levels can vary widely among rooms. This seems to rule out $CO_2$ control using a central $CO_2$ sensor in the main return duct for a multi-room zone, as others have suggested. Smith's study supports this conclusion (9).

The method presented here may be useful for determining DCV potential for constant-volume systems. See (10) for more details. The proposed ASHRAE 62R may require a different approach, however, in particular treating building- and occupant-related pollutants as additive.

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