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# Demand-Controlled Ventilation in a Multi-Zone Office Building

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**Abstract**
This study applies indoor air quality modelling to investigate the potential advantages and drawbacks of demand-controlled ventilation as an indoor air quality control strategy. The study uses a multiple zone pollutant transport model to evaluate the performance of several indoor air quality control strategies under a variety of conditions. The pollutant transport model is incorporated into the TRNSYS simulation program to allow simultaneous calculation of both building pollutant concentrations and building energy use. A specific office building situation consisting of a main zone and a conference room was studied. The simulations showed that a carbon dioxide-based demand controlled ventilation system can provide better control of indoor air quality than a constant outdoor airflow at the ASHRAE Standard 62-1989 prescribed level under a wide range of building conditions. The constant outdoor air approach lacks the capability of providing additional outdoor air when required by poor building conditions such as a low pollutant removal effectiveness and a high occupant density. The demand-controlled ventilation system saves energy compared to the constant outdoor air approach under all conditions considered. It was also found that a demand-controlled ventilation strategy consisting of a step controller combined with scheduled 100% outdoor air purges can protect building occupants from exposure to high concentrations of non-occupant-generated pollutants while still providing energy savings.

## Introduction

Contaminants present in a building indoor environment can have an adverse impact on the health and productivity of the occupants. The main sources of indoor air contaminants are outdoor air, building materials, occupants and their activities, and the building HVAC system. The concentration of pollutants can be controlled by eliminating or minimising pollutant sources, using local exhaust, filtering, and ventilating. ASHRAE Standard 62-1989 requires increased outdoor air ventilation rates to achieve acceptable indoor air quality. This indoor air quality control strategy could result in increased building energy consumption without ensuring acceptable indoor air quality. An alternative to this prescriptive approach is a demand-controlled ventilation strategy.

A demand-controlled ventilation system attempts to achieve acceptable indoor air quality at reduced energy cost by controlling the outdoor airflow rate based on a measured parameter. Kusuda [1] proposed a carbon diox-

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ide-based demand-controlled ventilation system. Other possible control variables include relative humidity, specific contaminant concentrations, and occupancy as detected by an activity sensor. General background and specific application information may be found in the International Energy Agency Annex 18 Source Book [2]. Recent simulation and field studies have examined the potential energy and indoor air quality impacts of demand-controlled ventilation in offices, schools, residences, and auditoria [3–11]. These studies have found potential energy savings of up to 50% using demand-controlled ventilation. The objective of the present study is to investigate the potential advantages and drawbacks of carbon dioxide-based demand-controlled ventilation for a multi-zone office.

### TRNSYS Indoor Air Quality Model

This study applies the multiple zone pollutant transport model developed by Knoespel [12] and Knoespel et al. [13] as a new module for the transient thermal system simulation program TRNSYS [14] to investigate the potential advantages and drawbacks of demand-controlled ventilation as an indoor air quality control strategy. Multiple zone modelling takes a macroscopic view of indoor air quality by calculating average pollutant concentrations in the different zones of a building. Other existing modules of the TRNSYS program are used to calculate building energy consumption. Thus, comparisons of both energy use and indoor air quality can be made for alternate indoor air quality control strategies.

The method used by Knoespel [12] and Knoespel et al. [13] to derive the TRNSYS indoor air quality model is a simplified version of a Kirchoff network technique. Each building zone is a node at uniform pressure, temperature, and pollutant concentration. The nodes are connected by flow paths such as HVAC ducts, doors, windows, and infiltration paths, with a resistance element equation relating the mass flow to the pressure drop across it. Mass conservation equations are written for each node and the nodal and element equations are solved simultaneously.

The network model was simplified by assuming that all infiltration and interzone flows would be estimated by the air change method used for the building heating and cooling load module of TRNSYS. This simplifies the calculation by decoupling the nodal balance equations from the element flow equations as all flow terms are known. The main advantage of this simplification is to allow transient calculations of zone pollutant concentrations as contaminant sources and/or ventilation flows vary. Equation 1 is the final form of the pollutant balance equation for zone i and includes all possible airflow paths into or out of zone i.

$$\frac{dC_i}{dt} = \frac{S_i}{V_{AIR,i}} + \frac{\dot{V}_{INF,i}}{V_{AIR,i}} C_{OA} + \frac{\dot{V}_{SUP,i}}{V_{AIR,i}} C_{SUP} - \frac{\dot{V}_{RET,i}}{V_{AIR,i}} \varepsilon_{c,i} C_i + \frac{\Sigma \dot{V}_{IZF,j,i} C_j}{V_{AIR,i}} - \frac{\Sigma \dot{V}_{IZF,i,j} C_i}{V_{AIR,i}} \tag{1}$$

The first term on the right-hand side of equation 1 is the pollutant volume source located in zone i. The second term accounts for the air infiltration volume flow rate into the zone with pollutant at the outdoor air concentration. The third term represents the air circulation flow to the zone with pollutant at the supply air concentration. The fourth term represents the pollutant leaving with the return airflow. The average zone concentration is modified by the zone pollutant removal effectiveness, $\varepsilon_{c,i}$. The pollutant removal effectiveness, as described by Seppanen [15], is the zone return duct concentration divided by the zone average concentration and it accounts for a non-uniform pollutant distribution in the zone. The pollutant removal effectiveness is not an efficiency and its value can be larger than unity. Values less than unity only mean the ventilation flow is removing pollutant at a concentration lower than the room average concentration, while values greater than unity mean the ventilation flow is removing pollutant at a concentration higher than the room average concentration. The pollutant removal effectiveness is treated as constant during a simulation, although it might vary due to airflow rate, temperature, occupancy, etc. The last two terms in equation 1 represent the pollutant transported by interzonal airflow between zone i and zone j; these interzonal airflows are assumed to be at the room average concentration.

The supply airflow rate is provided by the circulation/outdoor airflow controller module written for the TRNSYS indoor air quality model [12]. Interzone flows are specified as input data. The flow control module can be used to model either a constant air volume (CAV) or a variable air volume (VAV) HVAC system. Either constant outdoor air supply or four options for carbon dioxide-based demand-controlled ventilation (step flow control, on/off control, scheduled purge control, and temperature-based economiser control) may be modelled. This study only used the step control and scheduled purge control options.

The step controller increases and decreases the fraction of outdoor air in the circulation flow in 20% steps. For example, if the controlling pollutant concentration at one time step is above the high limit setpoint, the outdoor air will be increased from 0 to 20%. If the concentration remains above the limit at the next time step, the outdoor air will be increased to 40%. If the concentration is between the high and low limits, the outdoor air will remain at 20%. If the concentration falls below the low limit, the outdoor air will be decreased to 0%. Scheduled purge control adds the capability of switching to 100% outdoor airflow according to a user-defined schedule.

For all control options, the high and low concentration limits are compared to the zone pollutant concentrations for the chosen carbon dioxide sensor location. The available sensor location options are the zone average, the breathing zone average, the return duct, the wall, and the air handling unit. The breathing zone is defined as the space from 3 feet to 6 feet from the floor and 1 foot from all walls. This study only used the zone average concentration. The zone with the highest concentration is the controlling variable for that time step.

*Building Model*

All simulations used a model of a two zone office space. The first zone is the main office which was modelled after a typical modern office building [16]. This zone is approximately 1,300 $m^2$ (14,000 $ft^2$) in floor area with an air volume of 3,370 $m^3$ (119,000 $ft^3$). The pollutant modelled for demand-controlled ventilation studies is carbon dioxide generated by the building occupants. The maximum occupancy of the zone is 100 people, which corresponds approximately to an occupancy density of 7 people per 100 $m^2$ (1,000 $ft^2$) of floor area. Table 2 of ASHRAE Standard 62-1989 gives this as the estimated occupant density for a commercial office space [17]. The carbon dioxide generation rate used was $5.0 \times 10^{-6}$ $m^3/s$ ($1.77 \times 10^{-4}$ $ft^3/s$) per person, which is the rate for an activity level of 1.2 met [17].

A conference room was added as a second zone of the office model [12]. The conference room has a floor area of approximately 31 $m^2$ (340 $ft^2$), an air volume of 81 $m^3$ (2,850 $ft^3$), and a maximum occupancy of 10 people. The conference room is a completely interior space. The CAV system circulation flow (and maximum VAV circulation flow) used in the simulations was 6.0 air changes per hour (ach) and the infiltration to the main office zone was 0.2 ach. An interzone flow of 48.6 kg/h (107 lb/h) from the main office to the conference room was included when the HVAC system was on (5 a.m. to 9 p.m.). None of the systems used an economiser cycle. Reheat was employed in the systems to meet the desired supply air temperature. Thermostat and humidity settings were maintained the same for all simulations.

**Table 1.** Annual coil for ventilation strategies

| Ventilation strategy and simulation condition | CAV | | VAV | |
|---|---|---|---|---|
| | annual coil energy, GJ | relative coil energy | annual coil energy, GJ | relative coil energy |
| Constant oudoor air all conditions | 2,260 | 1 | 1,780 | 1 |
| Demand control | | | | |
| Condition A | 1,670 | 0.74 | 1,050 | 0.59 |
| Condition B | 1,730 | 0.77 | 1,070 | 0.6 |
| Condition C | 1,950 | 0.86 | 1,340 | 0.75 |
| Condition D | 2,170 | 0.96 | 1,600 | 0.9 |

**Table 2.** Annual coil energy for indoor air quality control strategies

| Indoor air quality control strategy | CAV | | VAV | |
|---|---|---|---|---|
| | annual coil energy, GJ | relative coil energy | annual coil energy, GJ | relative coil energy |
| Demand control | 1,670 | 0.74 | 1,050 | 0.59 |
| Demand control with minimum outdoor air | 1,720 | 0.76 | 1,190 | 0.69 |
| Demand control with scheduled purges | 1,870 | 0.83 | 1,340 | 0.75 |

## Demand-Controlled Ventilation Performance

The performance of CAV and VAV systems using carbon dioxide-based demand-controlled ventilation systems was compared by Knoespel [12] to similar systems using constant outdoor airflow at the ASHRAE Standard 62-1989 prescribed flow of 10 litres/s per person (20 cfm/person). All of the systems provided nearly equivalent indoor air quality control with the demand controlled ventilation strategy saving from 10% (for a CAV system) to 50% (for a VAV system) in heating and cooling loads compared to the constant outdoor airflow rate strategy. Buildings located in Miami and Madison were simulated, with comparable percent savings for both locations.

The results obtained by Knoespel [12] were for conditions which are favourable to achieving acceptable indoor air quality. In this paper, comparisons are also made for building conditions which are not favourable to achieving acceptable indoor air quality. Two of the main factors which impact the indoor air quality in a zone are the pollutant removal effectiveness and the pollutant generation rate. The 'favourable' conditions simulated by Knoespel [12] employed a pollutant removal effectiveness of 1.0 and a carbon dioxide generation rate based on occupancy at the Standard 62-1989 design level. A pollutant removal effectiveness of 0.5 and a 50% increase in occupancy were chosen to represent 'unfavourable' conditions. The lower pollutant removal effectiveness might represent a building with a ventilation system design which is less capable of removing pollutants from the zone. A low value is chosen to represent a limit and establish maximum expected effects. It is lower than what has been measured. For example, in laboratory tests, Seppanen [15] measured pollutant removal effectiveness ranging from 0.64 to 1.9 for a source in a 50-$m^3$ room. The increase in occupant density would represent the common problem in ventilation system design of underestimating actual occupancy loads [18].

A total of 16 simulations were performed with four sets of conditions for each of four ventilation strategies. The four sets of conditions were: A. pollutant removal effectiveness = 1.0, standard number of people; B. pollutant removal effectiveness = 1.0, 50% more people; C. pollutant removal effectiveness = 0.5, standard number of people; D. pollutant removal effectiveness = 0.5, 50% more people. The four ventilation strategies considered were: 1. CAV system with constant outdoor airflow rate; 2. CAV system with demand control of outdoor airflow rate; 3. VAV system with constant outdoor airflow rate; 4. VAV system with demand control of outdoor airflow rate.

The amount of the constant outdoor airflow rate used was the minimum required by Standard 62-1989 as corrected for a multiple zone system by equation 6-1 of the Standard [17]. Due to its higher occupant density, the conference room is the critical zone for the two-zone office model. The resulting required minimum outdoor airflow for the office model is 2.3 ach [12].

For these simulations, acceptable indoor air quality is defined as less than 1,000 ppm of carbon dioxide. This limit is a criterion recommended for comfort in table 2, ASHRAE Standard 62-1989 [17]. The high and low setpoints used for the demand controller were 1,000 and 800 ppm, respectively, and the outdoor air concentration was 310 ppm.

Figures 1–4 show the results of the 16 annual simulations for the main office zone (zone 1) during the occupied hours between 8.00 a.m. and 5.00 p.m. on weekdays. Each figure is a histogram showing the number of hours during the year that the carbon dioxide concentration is within a 100 ppm interval. For example, figure 1 shows the carbon dioxide concentration is between 400 and 500 ppm approximately 500 h during the year.

Figure 1 shows that the CAV system with constant outdoor air at the Standard 62-1989 prescribed level provides acceptable indoor air quality for the standard conditions of pollutant removal effectiveness and occupancy as the carbon dioxide concentration is well below 1,000 ppm at all times. However, with unfavourable conditions, the zone 1 carbon dioxide concentration increases. At the worst conditions modelled (pollutant removal effectiveness value of 0.5 and 50% more people), the zone 1 carbon dioxide concentration is above the desired limit of 1,000 ppm for all but a few hours. Figure 3 shows a similar deterioration in the zone 1 indoor air quality as the conditions degrade for the VAV system with constant outdoor air. At the worst conditions for the VAV system, the carbon dioxide concentration is above the 1,000 ppm limit most of the time.

In contrast, figures 2 and 4 show that the demand-controlled ventilation systems maintain the carbon dioxide concentration below 1,000 ppm nearly all of the time under all of the conditions applied. Under unfavourable conditions, the demand-controlled ventilation system performs better than the constant outdoor air approach for both CAV and VAV systems. The demand-controlled systems are able to react to unplanned increases in occupancy or poor ventilation air distribution by increasing the ventilation supplied.

For each of the simulations discussed above, the annual coil energy load was calculated. This includes the energy required at the coil to meet the zone heating and cooling loads (including latent loads) and to condition the outside air supplied by the ventilation system, but not the reheat energy. Since the HVAC system was not modelled, the energy use does not include the electricity delivered to the compressor or to the circulating fans. Fan energy use will vary between the various systems with and without demand-controlled ventilation depending on the airflow rates. Table 1 shows the coil energy use results.

The comparison of energy use yields two important results. First, for both CAV and VAV systems, the demand-controlled ventilation strategy requires less energy than the constant outdoor air strategy for a building with favourable conditions. Less energy is required because less outdoor air is needed to maintain the carbon dioxide concentration below 1,000 ppm. The annual energy saving is about 26% for the CAV system and about 41% for the VAV system. These results are consistent with the results of Knoespel [12].

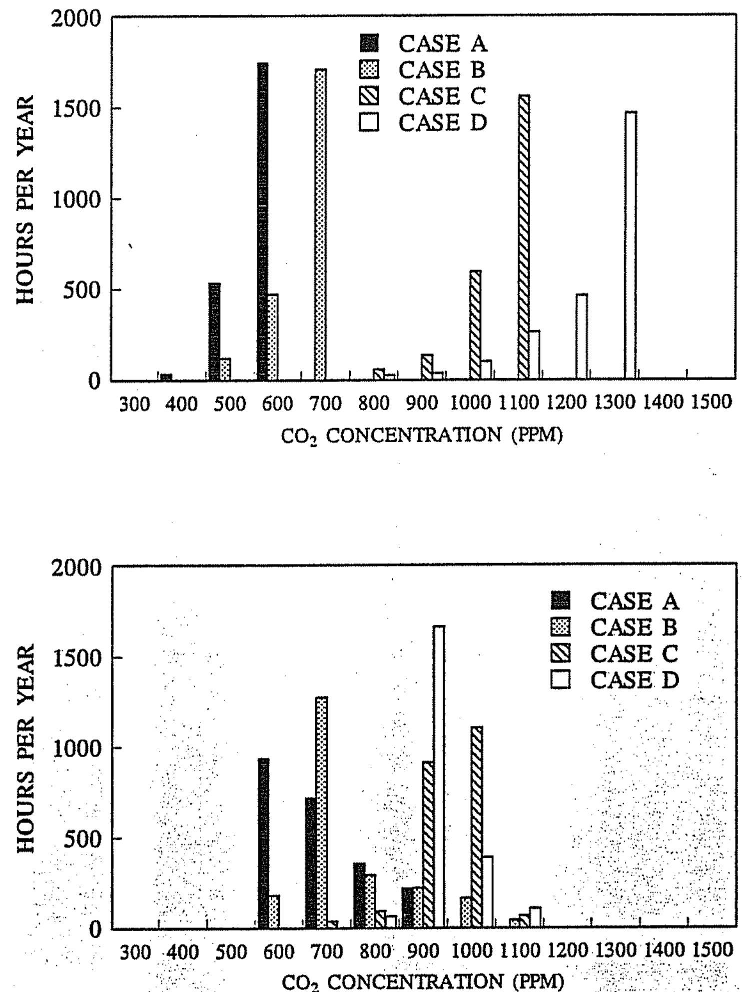


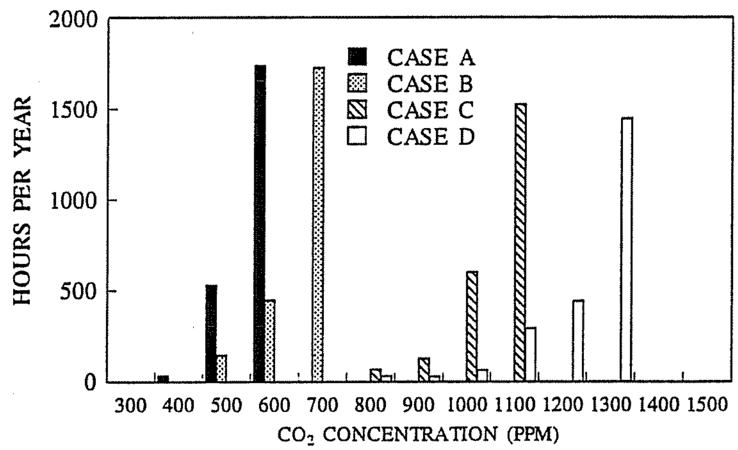

**Fig. 1, 2.** Zone 1 $CO_2$ concentration histogram for CAV system with constant outdoor air (**1**) and demand control (**2**).

For buildings with very unfavourable conditions (condition D), demand-controlled ventilation still saves energy compared to the prescribed constant outdoor air approach. The annual energy saving is about 4% for the CAV system and 10% for the VAV system. These savings are significantly less than for the building with favourable conditions because of the additional ventilation required to maintain the carbon dioxide concentration below 1,000 ppm.

These energy results are for a Madison, Wisc., location. A previous simulation study found comparable energy savings for a Miami location [12]. This previous study also considered operation of an economiser with a low minimum outdoor airflow rate. The economiser system required approximately the same energy use as the demand-controlled system, but failed to maintain the desired carbon dioxide concentration limit.

The results in table 1 compare favourably with a field study of a similar situation. Donnini et al. [6] reported annual energy savings of 12% for a demand-controlled ventilation system in which two floors of a high-rise office building were compared. One floor had a CAV system controlled by sensors and the other a CAV system with an economiser and an outdoor air flow rate as specified by code. The energy savings of 12% actually measured are within the range of potential savings given in table 1.

Other reported studies for the effect of demand-controlled ventilation on energy use are for quite different situations. In simulation studies energy savings up to 50% were found for auditoria [4–7]. The ECD Partnership [10]

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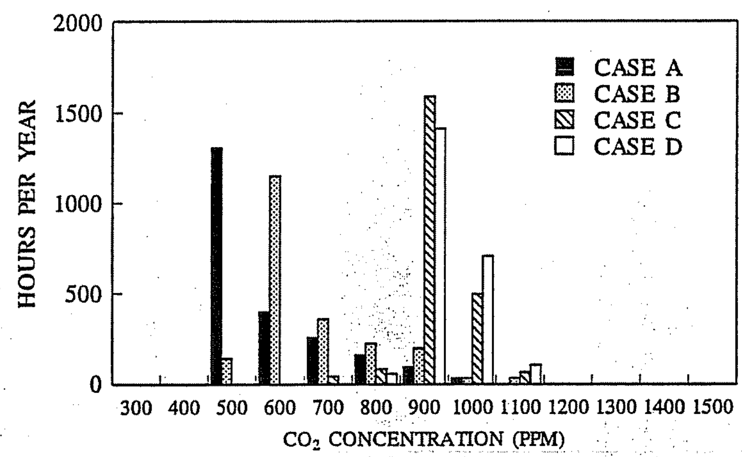


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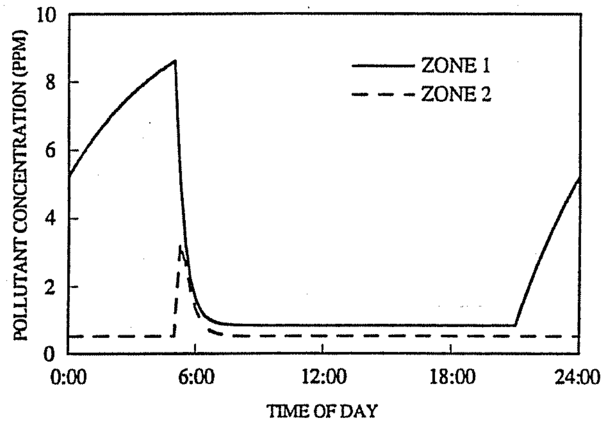
**Fig. 3, 4.** Zone 1 $CO_2$ concentration histogram for VAV system with constant outdoor air (**3**) and demand control (**4**).

measured 17% savings for a club and 11% for a cinema in London. Norell [9] reported 50% savings for a school in Sweden. The general conclusion is that occupancy, comfort level, climate, and the balance between heating and cooling all play a significant role in potential savings due to demand-controlled ventilation.

## Demand-Controlled Ventilation and Non-Occupant Generated Pollutants

One of the major concerns regarding the use of carbon dioxide-based demand-controlled ventilation is the potential impact on non-occupant-generated pollutants. Occupants are only one of the possible sources of indoor air pollutants, and other major sources such as building materials and furnishings are often present. Although, the most effective means of controlling exposure to a pollutant is source control, it is not possible to completely eliminate all non-occupant sources. The effectiveness of different indoor air quality control strategies at controlling non-occupant-generated pollutants was evaluated. The reduced ventilation flow during periods of low or zero occupancy could result in pollutant concentrations rising to unacceptably high levels. Simulations were performed to evaluate and compare the impact of several indoor air quality control strategies on occupant exposure to non-occupant-generated pollutants.

The non-occupant-generated pollutant was modelled as a constant source located in the main office zone only.

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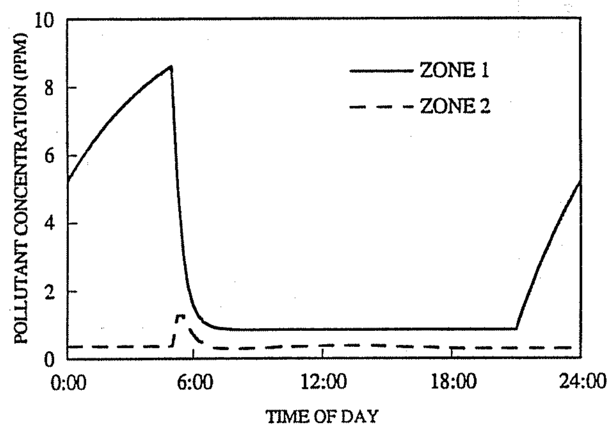


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**Fig. 5, 6.** Pollutant concentration for CAV (**5**) and VAV (**6**) systems with ASHRAE Standard 62-1989 constant outdoor air.

The volumetric generation rate used was $2.0 \times 10^{-6}$ $m^3/s$ ($0.70 \times 10^{-4}$ $ft^3/s$). The desired pollutant concentration limits used were 2 ppm for short-term and 1 ppm for an 8-hour time-weighted average. The parts per million concentration limit and source strength were chosen together so that a constant outdoor airflow rate equal to the ASHRAE Standard 62 prescribed rate would just meet the desired average limit.

Four different indoor air quality control strategies were compared for control of the zone pollutant concentration. The first strategy is constant outdoor air at the ASHRAE Standard 62-1989 prescribed ventilation rate. The next strategy is demand-controlled ventilation using the step controller with carbon dioxide setpoints of 800 and 1,000 ppm and the zone average carbon dioxide as the control variable. The third strategy is demand-controlled ventilation using demand control combined with constant minimum outdoor air of 2.5 litres/s per person (5 cfm/person) calculated for both zones per ASHRAE Standard 62-1989. The resulting minimum outdoor air used was 0.7 ach. The final strategy is demand-controlled ventilation using proportional control combined with scheduled purges. This strategy involved turning on fans to flush the building with 100% outdoor air from 7.30 a.m. to 8.30 a.m. and from 12.30 p.m. to 1.00 p.m. Annual simulations were performed to calculate both typical daily pollutant concentrations and annual building energy use for CAV and VAV systems with each strategy.

The resulting pollutant concentrations for a typical day are given by figures 5, 7, 9, and 11 for the CAV system and figures 6, 8, 10, and 12 for the VAV system. Figures 5 and 6 show that the ASHRAE Standard 62-1989 prescribed ventilation strategy provides acceptable indoor air quality by maintaining both the zone 1 and zone 2 pollutant concentrations below 1 ppm during all occupied building hours for both the CAV and VAV systems.

Figure 7 shows that the simple demand control strategy for the CAV system results in zone 1 and zone 2 concentrations above 1 ppm throughout most of the day. The concentration is far above 1 ppm until about 10.00 a.m. because the build-up of concentration levels of pollutant overnight remains high until the ventilation rate responds to the gradually increasing carbon dioxide concentrations. The pollutant concentration also exceeds the 2 ppm short-term limit during the early afternoon when the carbon dioxide concentration is low due to a significant number of occupants leaving the office for lunch. Figure 8 shows that the VAV system performs somewhat better than the CAV system but still does not meet the desired limits.

Figure 9 shows that adding a low minimum outdoor airflow to the demand control strategy does not result in a significant improvement in indoor air quality. The average pollutant concentration is still above 1 ppm with peaks above 2 ppm in the morning and early afternoon. Again, the VAV system (fig. 10) performs slightly better than the CAV system but does not achieve the desired results.

The demand control strategy combined with scheduled 100% purges results in significantly improved indoor air quality. For the CAV system, figure 11 shows that the

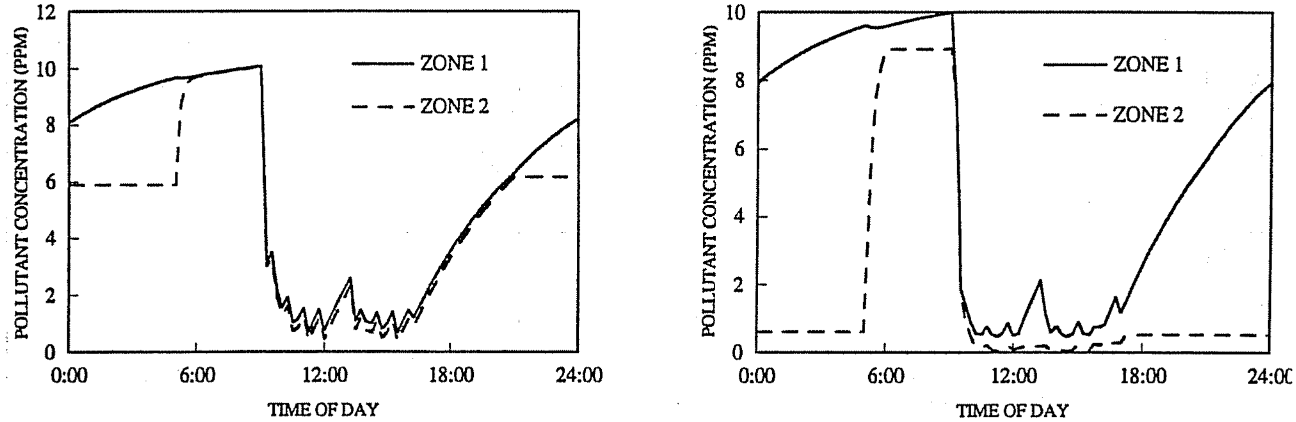


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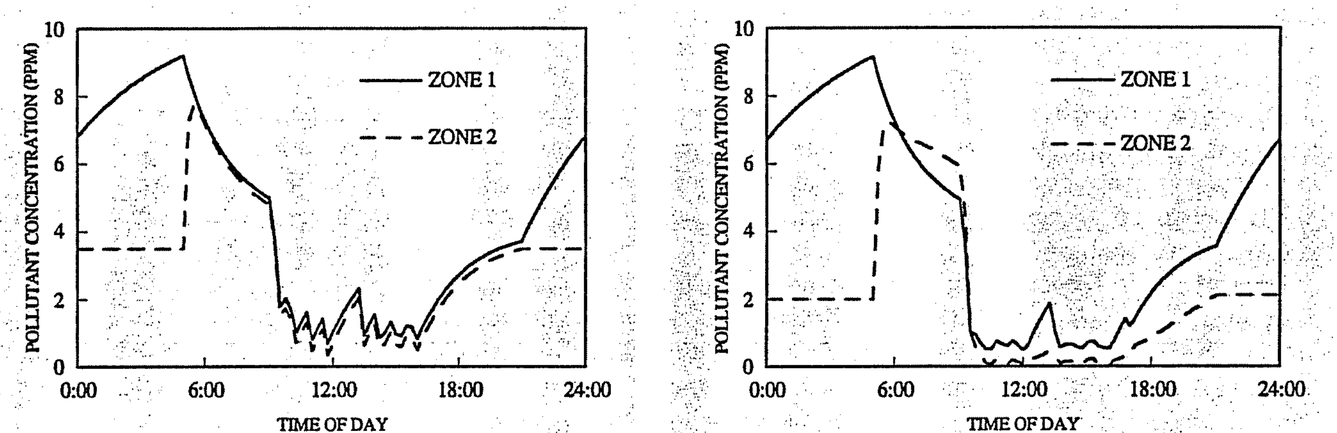
**Fig. 7, 8.** Pollutant concentration for CAV (**7**) and VAV (**8**) systems with demand control.

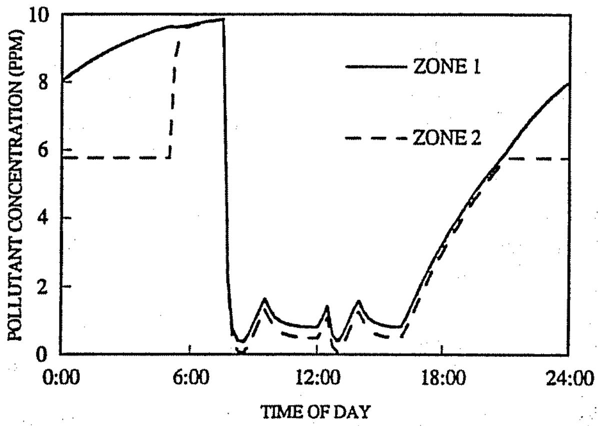



9 10

**Fig. 9, 10.** Pollutant concentration for CAV (**9**) and VAV (**10**) systems with demand control and minimum constant outdoor air.

average zone 1 and zone 2 pollutant concentrations are both below the 1 ppm limit during occupied building hours. This strategy also meets the desired short-term limit of 2 ppm. Both the CAV system and the VAV system (fig. 12) perform significantly better with this indoor air quality control strategy.

The strategy of demand-controlled ventilation combined with scheduled purges is effective at meeting the target limit. However, part of the reason for the effectiveness of this strategy is that the building operating characteristics (i.e. the occupancy schedule and its impact on carbon dioxide concentrations and the resulting ventilation flow) are known. This enables the purges to be scheduled when most needed. It may be difficult to apply this strategy to buildings for which such information is not available. However, it is likely that an effective operating ventilation strategy of this type could be developed for many buildings.

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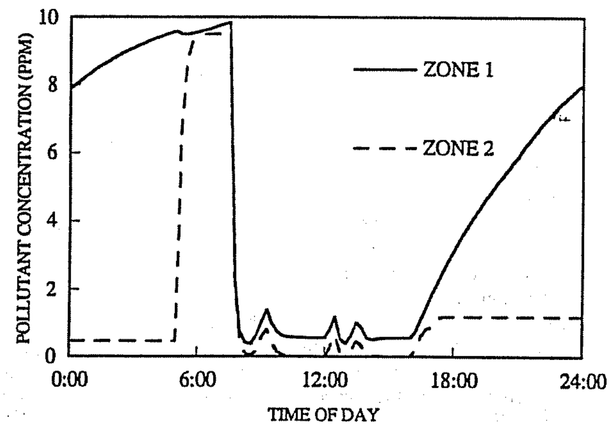


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**Fig. 11, 12.** Pollutant concentration for CAV (**11**) and VAV (**12**) systems with demand control and scheduled purges building energy use.

Annual energy use calculations were also made for these indoor air quality control strategies with the results shown in table 2. The reference value is the constant outdoor airflow rate of table 1. As also shown previously in table 1, the simple demand control strategy requires significantly less energy than the ASHRAE Standard 62-1989 prescribed constant outdoor air strategy. Table 2 also shows that adding either minimum outdoor air or scheduled purges to the simple demand control system results in reduced energy savings. The annual building energy savings for the demand control with scheduled purges strategy, which maintained the desired concentration limit, are approximately 17% for the CAV system and 25% for the VAV system.

## Conclusions

In this paper, the results of simulations performed with the TRNSYS multiple zone pollutant transport model are presented for a specific building in Madison, Wisc. The performance of demand-controlled ventilation systems was compared to that under the prescribed constant outdoor air approach of ASHRAE Standard 62-1989 for a range of indoor air quality conditions. Under favourable building conditions, both constant outdoor air and demand-controlled ventilation strategies were found to maintain the zones under the desired limits. The demand-controlled ventilation systems required significantly less energy use than the constant outdoor air approach.

Under unfavourable building conditions, the constant outdoor air approach did not maintain the desired carbon dioxide concentration limit. However, the demand-controlled ventilation systems still maintained the desired limits while using less energy than the constant outdoor air approach.

The impact of a carbon dioxide-based demand-controlled ventilation system on occupant exposure to non-occupant-generated pollutants was also investigated for a generic pollutant source. The results showed that a simple proportional control demand-controlled ventilation system did not maintain the desired pollutant concentration limits during times of reduced ventilation flow. However, an indoor air quality control strategy of demand control combined with scheduled purges maintained desired concentration limits and required less coil energy than the prescribed constant outdoor air approach. This strategy has potential for controlling indoor air in zones where source control cannot effectively eliminate all non-occupant-generated pollution problems. Although the results are specific to the building and climate studied, they provide insight into the performance of demand controlled ventilation strategies.

## References


1 Kusuda T: Control of ventilation to conserve energy while maintaining acceptable indoor air quality. ASHRAE Trans, vol 82, part 1, Atlanta, ASHRAE, 1976.

2 IEA: Annex 18: Demand Controlled Ventilation Source Book. International Energy Agency, 1992.

3 Gabel S, Janssen J, Christoffel J, Scarbrough SE: Carbon Dioxide-Based Ventilation Control System Demonstration. Bonneville Power Administration, 1986.

4 Zamboni M, Berchtold O, Filleux C, Fehlmann J, Drangsholt F: Demand controlled ventilation: An application to auditoria. Proc 12th AIVC Conf, Air Infiltration and Ventilation Centre, 1991.

5 Hamlin T, Cooper K: The potential for residential demand controlled ventilation. Proc 12th AIVC Conf, Air Infiltration and Ventilation Centre, 1991.

6 Donnini G, Haghighat F, Nguyen VH: Ventilation control of indoor air quality, thermal comfort and energy conservation by carbon dioxide measurement. Proc 12th AIVC Conf, Air Infiltration and Ventilation Centre, 1991.

7 Warren BF, Harper NC: Demand controlled ventilation by room carbon dioxide concentration: A comparison of simulated energy savings in an auditorium space. Energy Buildings 1991; 17:87–96.

8 Fleury B: Demand controlled ventilation: A case study. Proc 13th AIVC Conf, Air Infiltration and Ventilation Centre, 1992.

9 Norell L: Demand controlled ventilation in a school. Proc 12th AIVC Conf, Air Infiltration and Ventilation Center, 1991.

10 ECD Partnership: Ventilation Control by Measurement of Carbon Dioxide Levels in Public Entertainment Buildings. Final Rep ED/85/172, ETSU, 1986.

11 Haghighat F, Donnini G: IAQ and energy-management by demand controlled ventilation. Environ Technol 1992;13:351–359.

12 Knoespel P: Indoor Air Quality Modelling; MS thesis, Mechanical Engineering, University of Wisconsin-Madison, 1990.

13 Knoespel P, Mitchell J, Beckman W: Macroscopic Model of Indoor Air Quality and Automatic Control of Ventilation Airflow. ASHRAE Trans, vol 97, part 2. Atlanta, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1991.

14 Klein S: TRNSYS, a Transient Simulation Program. Version 13.1 Users Manual. Solar Energy Laboratory, University of Wisconsin-Madison, 1992.

15 Seppanen O: Ventilation efficiency in practice, in Managing Indoor Air for Health and Energy Conservation. Atlanta, American Society of Heating, Refrigerating, and Air- Conditioning Engineers, 1986.

16 Ruud M: Building Thermal Storage; MS thesis, Mechanical Engineering, University of Wisconsin-Madison, 1990.

17 ASHRAE: ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality. Atlanta, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1989.

18 Sterling E, Sterling T: Interrelations among Different Ventilation Parameters and Indoor Pollutants. ASHRAE Trans, vol 91, part 2A. Atlanta, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1985.