SIMULATIONS OF INDOOR AIR QUALITY AND VENTILATION IMPACTS OF DEMAND CONTROLLED VENTILATION IN COMMERCIAL AND INSTITUTIONAL BUILDINGS

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ABSTRACT

Carbon-dioxide (CO_2) based demand controlled ventilation (DCV) offers the potential for more energy efficient building ventilation compared with constant ventilation rates based on design occupancy. A number of questions related to CO_2 DCV exist regarding energy benefits, optimal control strategies, and indoor air quality impacts for contaminants with source strengths that are independent of the number of occupants. In order to obtain insight into these issues, a simulation study was performed in six commercial and institutional building spaces. This paper reports on one of the spaces, a lecture hall, in which six different ventilation strategies were compared, three of them using CO_2 DCV. The results depend on occupancy patterns, design ventilation rate and ventilation system operating schedule as well as assumed contaminant source strengths and system-off infiltration rates. In these simulations, CO_2 DCV resulted in significant decreases in ventilation rates and energy loads accompanied by increased indoor CO_2 and volatile organic compound (VOC) concentrations. The increases in CO_2 were generally in the range of 300 mg/m^3. The VOC levels increased by a factor of two or three, but the absolute concentrations were still low. The annual energy load reductions with CO_2 control ranged from about 50 % to 75 % depending on the space type, climate and ventilation strategy.

KEYWORDS: carbon dioxide, control, energy efficiency, indoor air quality, modeling, simulation, ventilation, volatile organic compounds

INTRODUCTION

Ventilation systems heat and cool occupied spaces for thermal comfort and provide outdoor air to dilute contaminants generated by building occupants and their activities and by building materials and furnishings. The outdoor air intake rate is determined from building codes and standards, e.g., ASHRAE Standard 62-2001. Most codes and standards require a certain amount of ventilation per person, and system design intake rates are generally based on the design occupancy, which is generally a maximum. This approach can lead to "overventilation," and increased energy consumption, when the building is occupied below the design level. Demand controlled ventilation (DCV) is a strategy that can be used to address this issue. A number of approaches have been proposed to provide ventilation corresponding to the actual rather than design occupancy, including carbon dioxide (CO_2) sensing. While a number of studies have suggested the extent of such savings, additional work is needed to better define the magnitude of potential energy savings and their dependence on climate, building and system type, and occupancy patterns (Emmerich and Persily 2001). The referenced report and other discussions identify indoor air quality impacts as an important issue in the application of CO_2 DCV, with concerns related to contaminants generated at rates that do not depend on the number of occupants. This paper describes a study employing indoor air quality modeling to investigate how CO_2 DCV impacts ventilation, indoor air quality and energy. In particular, simulations were used to investigate the control of non-occupant contaminants, in this case a generic volatile organic compound (VOC) intended to represent emissions from building materials and furnishings. These simulations were performed in six commercial and institutional building spaces (office, conference room, lecture hall, two classrooms and fast food restaurant play area); this paper reports on the results for the lecture hall. The complete results of the study are available in Persily et al. (2003).

DESCRIPTION OF ANALYSIS

The simulations in this study were performed using the airflow and contaminant dispersal model CONTAMW (Dols and Walton 2002), the latest version of which can simulate the control of ventilation rates based on contaminant concentrations. A lecture hall was modeled as a single zone with a ventilation system that provides outdoor air at a rate determined by the control strategies outlined below and a defined occupancy schedule. The ventilation system is assumed to start operating at 8 a.m. and shut down at 9 p.m. A constant infiltration rate of 0.1 air changes per hour is assumed to exist in each space at all times. This value was chosen as a low infiltration condition to cause a significant buildup of contaminants when the system is off. The simulations accounted for two contaminants, occupant-generated carbon dioxide (CO_2) and a generic volatile organic compound (VOC) intended to represent contaminants from building materials and furnishings. While VOC emissions in buildings are far more complex than the simple approach used here, the objective of these simulations was to capture the impact of DCV systems on non-occupant sources. The emission rate for the generic VOC was assumed to be constant at a rate of 0.25 mg/h per m^2 of floor area during unoccupied periods and 0.50 $mg/h{\bullet}m^2$ during occupancy, which is consistent with the limited field measurements of VOC emission rates (Levin 1995). Sorption and re-emission of VOCs from surfaces were not modeled, and the outdoor concentrations of CO_2 and VOC were assumed to equal 720 mg/m^3 and 0 mg/m^3 respectively.

The ventilation rates in the spaces were based on ASHRAE Standard 62-2001 (ASHRAE 2001) and the proposed revision to those rates contained in Addendum 62n (Persily 2001). Six ventilation control scenarios were simulated, with the first three serving as reference cases:

62/2001: Constant outdoor air intake based on ASHRAE Standard 62 and the design occupancy.
62n: Constant outdoor air intake rates based on draft addendum 62n and the design occupancy.
62tracking: Outdoor air intake that tracks occupancy perfectly using the Standard 62 rates, i.e., outdoor air intake is always the number of occupants times the per person requirement.
C-ZeroMin: CO_2 DCV control with maximum based on Standard 62; minimum equals zero.
C-25%Min: CO_2 DCV with maximum based on Standard 62; minimum is 25% of maximum.

C-62nAreaMin: CO_2 DCV with maximum based on design occupancy and the requirements in addendum 62n; minimum equal to 62n "area" requirement times the floor area.

Each of the cases was simulated for a period of 7 days, yielding a CO_2 and VOC concentration at each 5 min time step. The heating and cooling energy associated with the different cases was estimated using a simplified approach based on the sensible and latent heat capacity of the outdoor air relative to the indoor air. The energy analysis accounts for only the load due to ventilation air, and not the energy required to meet that load. The details of these calculations are presented in Persily et al. (2003). These loads were determined for each case over an entire year of weather data for four California climates (Bakersfield, Los Angeles, Sacramento, and San Francisco) selected to cover a range of coastal and inland climates. As points of reference, Miami (hot and humid) and Minneapolis (cold) were also analyzed.

RESULTS

This section presents the simulations results for ventilation, CO_2 and VOC concentrations and energy consumption. Figure 1 is a plot of the ventilation rates, including infiltration, for the lecture hall for a Friday. In this figure, the 62-2001 and 62n cases are straight horizontal lines indicating constant ventilation rates when the system operates. The 62tracking case is a solid black line, with the ventilation rate corresponding to the occupancy schedule. The control approaches based on the Standard 62 rates (C-ZeroMin and C-25%Min) both exhibit a pattern similar to the idealized 62tracking case, though the rates are consistently higher. This "overshooting" occurs during the short periods of elevated occupancy because these occupancy peaks are below the design value but the maximum ventilation rates in the control algorithm are based on the design occupancy. C-62nAreaMin has the lowest ventilation rates as expected based on the lower ventilation requirements in 62n. While the CO_2 DCV cases have lower ventilation rates during periods of the day than the constant ventilation approaches, overall they provide more ventilation air than a "perfect" control system, presumably a desirable and conservative outcome from an indoor air quality perspective.

TABLE 1
Summary of Indoor Carbon Dioxide and VOC Concentrations During Occupancy

	CO_2 concentration (mg/m^3)		**VOC concentrations (mg/m^3)**	
	Average	**Maximum**	**Average**	**Maximum**
62/2001	1436	1980	0.02	0.28
62tracking	1926	1980	0.04	0.32
C-ZeroMin	1606	1980	0.03	0.42
C-25%Min	1568	1980	0.03	0.37
62n	1962	2952	0.03	0.33
C-62nAreaMin	2299	3024	0.06	0.42

Table 1 presents the average and maximum CO_2 concentrations during occupancy, which are lowest for 62/2001. While the CO_2 control cases using the Standard 62 rates have higher average CO_2 concentrations, they are within 200 mg/m^3 of the 62/2001 values, and at least 300 mg/m^3 below the idealized 62tracking case. 62n and C-62nAreaMin have higher concentrations as expected due to the lower ventilation rates in addendum 62n, but the average concentration for the 62n DCV case is again within 300 mg/m^3 of the baseline 62n case. Figure 2 presents the CO_2 concentrations over one day in the lecture hall. The concentrations are fairly similar for the three cases using Standard 62 rates, while the two 62 cases exhibit higher concentrations. 62tracking has higher levels during occupied periods because there is no mechanical ventilation at these times, only infiltration, leading to significant CO_2 buildup over night.

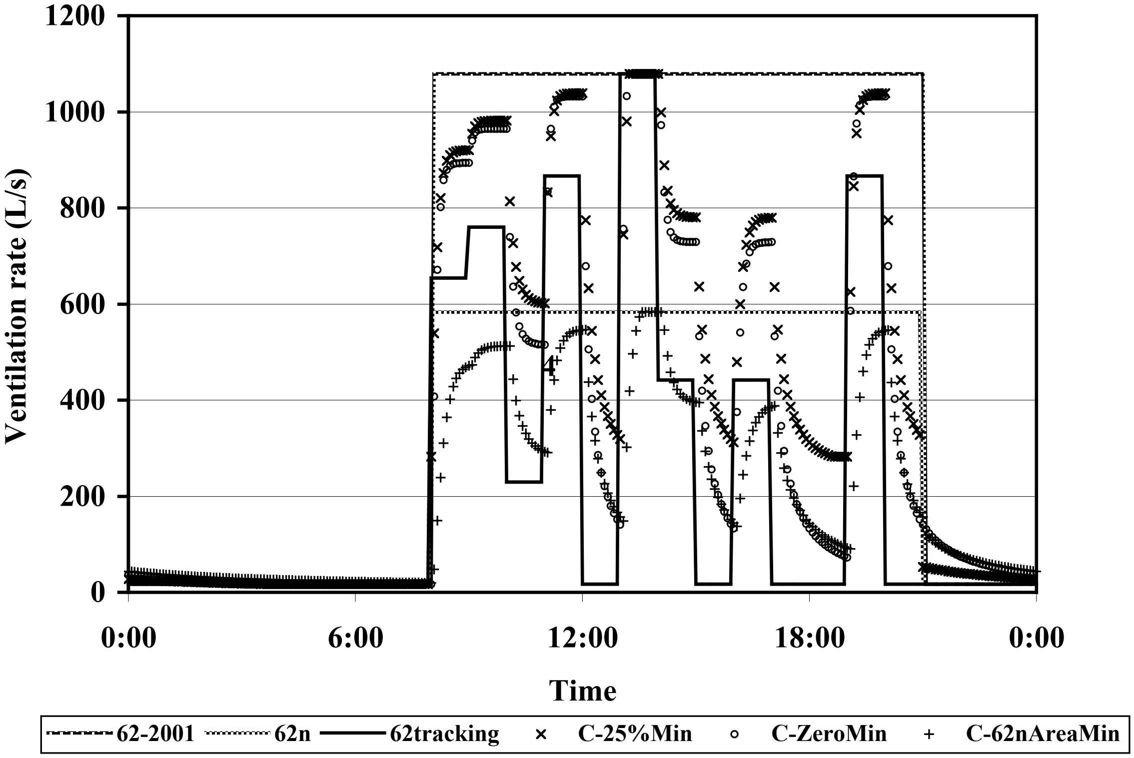


Figure 1 Lecture Hall Ventilation Rates during Weekday

Table 1 also summarizes the indoor VOC concentrations. Note that the averages are 0.06 mg/m^3 or less in all cases. While these concentrations are on the low end of those measured in the field, they depend on the assumed source strengths and infiltration rate during unoccupied periods. The maximum concentrations are between about 0.3 mg/m^3 and 0.4 mg/m^3 due to the increases over unoccupied periods. The average and maximum VOC concentrations are lowest for 62/2001, and while the 62tracking and 62-based CO_2 control cases have higher averages, they are at most 0.02 mg/m^3 higher. The average for 62n is similar to the other cases. C-62nAreaMin has the highest average concentration, but it is still fairly low in absolute terms. Figure 3 presents the VOC concentrations in the lecture hall. The patterns and levels are similar for the different ventilation cases with the exception of the elevated concentrations during periods of low occupancy, particularly at night when the system is off and the building is ventilated only by infiltration. Under these conditions, the VOC concentration increases steadily, reaching its maximum value just before the system comes back on. The average and maximum VOC concentrations in Table 1 are both heavily influenced by the elevated concentrations at the start of occupancy.

Table 2 summarizes the energy consumptions associated with ventilation for the lecture hall. For each city, this table presents the annual energy load associated with ventilation for each strategy in units of MJ/m^2 to account for differences in the sizes of the spaces. In general, the CO_2 control cases use less energy than the constant ventilation rate cases, and the 62n case uses less than 62/2001. The magnitude of these reductions in a particular city and space combination is a function of climate and ventilation rate per unit floor area. The two 62-based CO_2 control cases have loads that are 40 % to 60 % lower than 62-2001. Compared to 62/2001, the 62n rates decrease the ventilation-induced load by 50 % to 70 % depending on the city. Implementing CO_2 control under 62n leads to further variable reductions, ranging from around 40 % to 75 %.

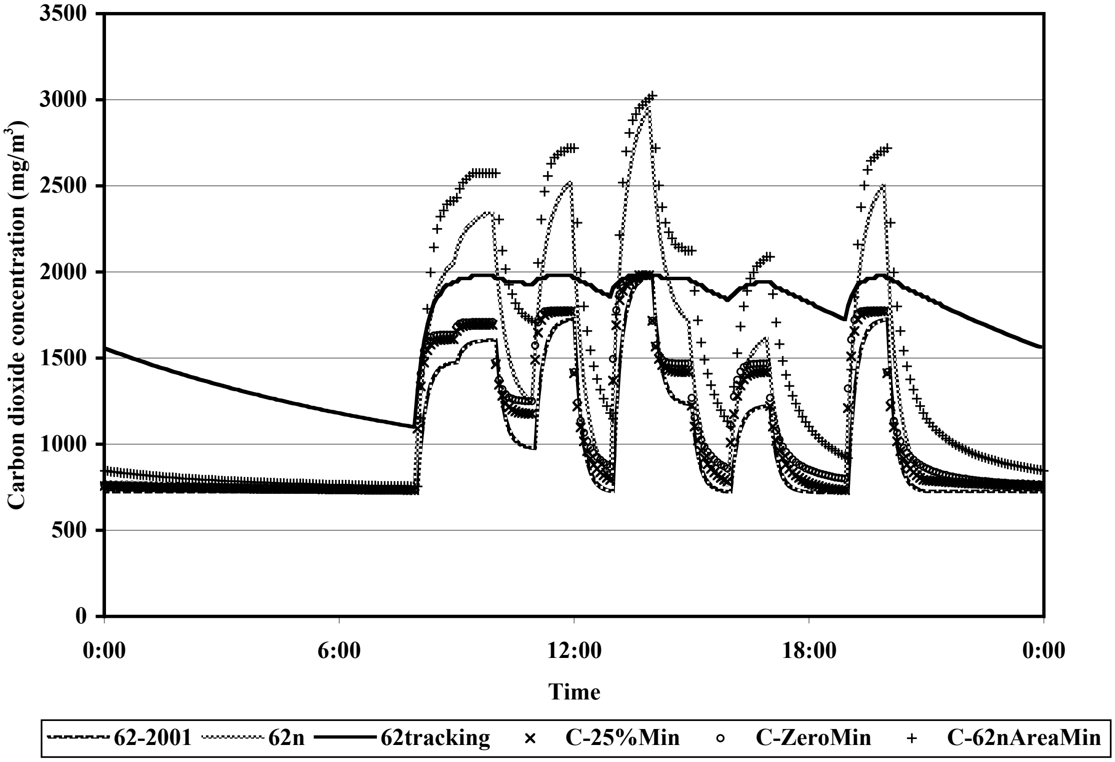


Figure 2 CO_2 Concentrations during Weekday

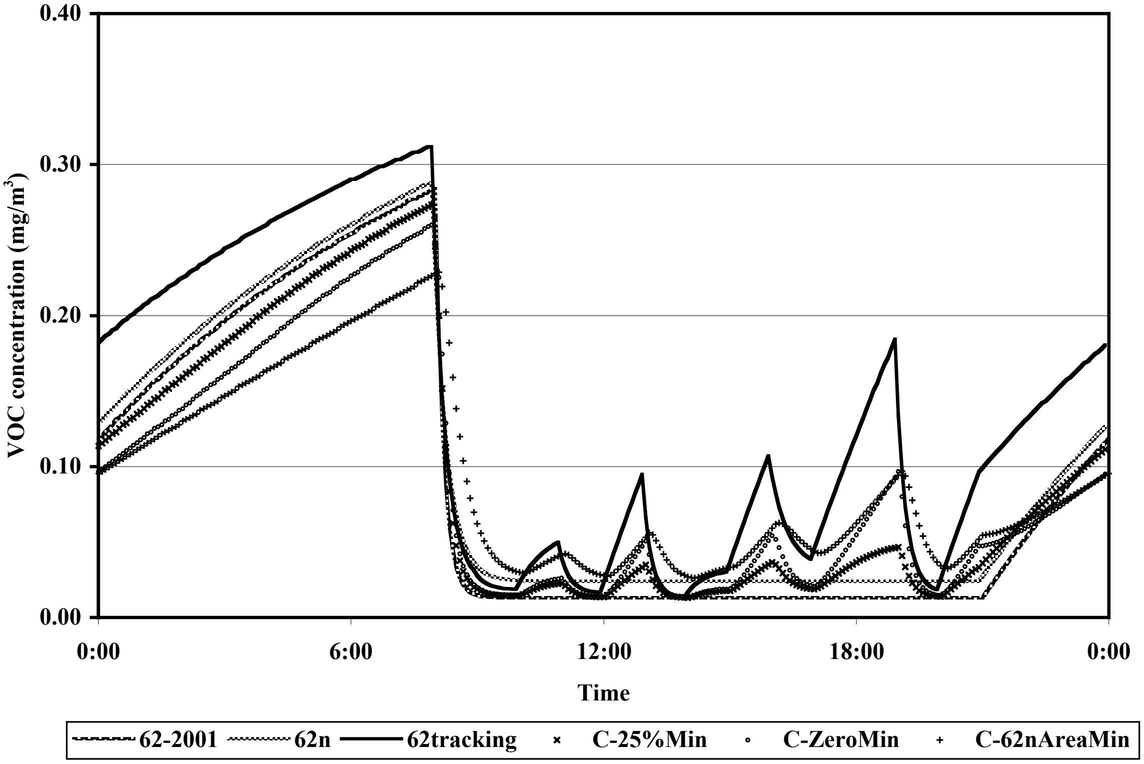
TABLE 2
Summary of Energy Load Due to Ventilation

	Annual Energy Load (MJ/m^2)					
	Bakersfield	Los Angeles	Sacramento	San Francisco	Miami	Minneapolis
Office						
62/2001	1049	528	1010	931	1943	2168
62tracking	383	142	362	292	790	841
C-ZeroMin	568	219	537	428	1143	1231
C-25%Min	645	248	614	502	1278	1395
62n	508	157	479	372	1025	1117
C-62nAreaMin	242	40	215	95	620	618

DISCUSSION

The objective of this study was to examine ventilation, indoor air quality and energy impacts of CO_2 demand controlled ventilation in different space types and climates. The results indicate that these impacts depend on the details of the spaces including occupancy patterns, ventilation rate requirements and ventilation system operating schedule, as well as contaminant source strengths and system-off infiltration rates. The results and conclusions presented in this paper, and the longer report on which it is based, are therefore specific to the cases studied. In terms of the ventilation, basing ventilation rates on design occupancy levels results in “overventilation” for many hours depending on the occupancy schedule as expected. CO_2 control helps avoid such overventilation, but contaminants associated with the building (as opposed to those associated with occupancy) can be elevated early in the day when occupancy is low. The extent of such contaminant buildup is dependent on the source strengths in the unoccupied building and fan off infiltration rates, which are building specific and weather dependent. Pre-occupancy "flush out" strategies may be helpful in lessening such early morning concentration increases.

Figure 2 VOC Concentrations during Weekday



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