Recommendations for Application of CO_2-Based Demand Controlled Ventilation, Including Proposed Guidance for ASHRAE Standard 62 and California's Title 24

Letter Report on Task 3.1.5a and 3.1.6a of CEC-EEB RMT Project

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Abstract

Carbon dioxide (CO_2) based demand controlled ventilation (DCV) has been proposed and implemented for many years as a strategy for increasing energy efficiency by providing outdoor air ventilation rates based on actual occupancy rather than design occupancy. Over the years there have been various simulation studies and demonstration projects, but important questions remain about energy savings potential, indoor air quality impacts, and both when and how to apply the approach. A major element of the CEC-EEB project examined the impact and application of CO_2 DCV via a literature review, field demonstrations, energy analysis, and indoor air quality simulations. Based on the results of these efforts, this report presents a number of recommendations on the application of CO_2 DCV.

1. Introduction

Demand controlled ventilation (DCV) is a ventilation rate control strategy to address the concern that when a space is occupied at less than its design occupancy, unnecessary energy consumption can result if the space is ventilated at the design outdoor air rate rather than the ventilation rate based on the actual occupancy. Furthermore, early during a given day of building occupancy, contaminants generated by people and their activities will not yet have reached their ultimate levels based on the transient nature of contaminant buildup. As a result, it may be possible to delay or lag the onset of the design ventilation rate to take credit for this transient effect. A number of approaches have been proposed to account for actual occupancy levels and to provide for ventilation corresponding to the actual rather than design occupancy. These include time-based scheduling when occupancy patterns are well-known and predictable, occupancy sensors to determine when people have entered a space (though not necessarily how many), and carbon dioxide (CO_2) sensing and control as a means of estimating the number of people in a space or the strength of occupant-related contaminant sources.

Controlling outdoor air intake rates using CO_2 DCV offers the possibility of reducing the energy penalty of over-ventilation during periods of low occupancy, while still ensuring adequate levels of outdoor air ventilation. In addition, CO_2 DCV gives credit for building ventilation due to infiltration through the building envelope, which can be significant even in mechanically ventilated buildings. A number of studies have identified the potential energy savings of CO_2 DCV in commercial and institutional buildings via field studies and computer simulations, and have shed light on the magnitude of energy savings possible and the dependence of these savings on climate, building and system type, control approach, and occupancy patterns. However, important issues remain to be resolved in the application of CO_2 DCV including how best to apply the approach, which in turn includes issues such as which control algorithm to use in a given building, sensor location, sensor maintenance and calibration, and the amount of baseline ventilation required to control contaminant sources that do not depend on the number of occupants. This report presents application guidance based on the CEC-EEB project on CO_2 DCV carried out by the National Institute of Standards and Technology (NIST) and Purdue University.

2. Recommendations Based on Previously Published Literature

An earlier task under this project involved a literature review on the subject of CO_2-based DCV (Emmerich and Persily 2001). Some of this literature contained guidance on the application of this ventilation control approach, which was summarized in an appendix to the literature review report. An updated version of this guidance is presented in this section organized into sections on target buildings where CO_2-based DCV appears to be most applicable, CO_2 sensor technology issues, ventilation control algorithms, control of contaminants not associated with occupants, and other considerations.

Target buildings

The intent of CO_2-based DCV is to reduce energy use compared to ventilation at a constant rate based on design occupancy, while assuring adequate ventilation rates for IAQ control. While CO_2-based DCV systems are likely to save at least some energy in nearly all buildings and climates, the amount of energy saved can vary dramatically depending on the climate, occupancy, operating hours, and other building and HVAC system features. The greatest energy savings are likely to occur in buildings with large heating loads and/or large cooling loads that have dense occupancies that vary unpredictably. Even though a building as a whole might not be a good candidate, CO_2 DCV may be appropriate within specific spaces in such a building that have independent outdoor air supply capability, such as a conference rooms.

CO_2 DCV is less likely to be applicable in buildings or spaces where non-occupant generated pollutants dominate ventilation requirements or where there are significant sources of CO_2 other than occupants. Using CO_2 as the control variable in such applications will not necessarily result in unacceptable IAQ but rather could lead to excessive ventilation rates. Buildings or spaces with CO_2 removal mechanisms other than ventilation would similarly not be good candidates. However, such removal mechanisms and non-occupant CO_2 sources are unlikely to exist in most commercial and institutional buildings.

CO_2 DCV Technology

Most CO_2 sensors used in DCV systems today are based on non-dispersive infrared (NDIR) or photometric detection, both of which can be affected by light source aging. The former approach may also be sensitive to particle buildup on the sensor, while the latter could be affected by vibration or atmospheric pressure changes. In selecting sensors for ventilation control, one needs to consider the appropriate measurement ranges for ventilation control, approximately 540 mg/m^3 (300 ppm(v)) to 2700 mg/m^3 (1500 ppm(v)). The sensors employed also need to be calibrated and maintained according to manufacturer recommendations. Some manufacturers have proposed automated calibration checks using overnight baseline CO_2 readings.

In locating CO_2 sensors for ventilation control, one should avoid locations near doors, windows, air intakes or exhausts, or in close proximity to occupants. Also, a single sensor located in a common return should not generally be used to control ventilation rates for multiple spaces with different occupancies.

Control Algorithms

Control strategies for CO_2-based DCV include two-position (on-off) control, setpoint simple control where the ventilation rate is increased or decreased depending on the indoor CO_2

concentration, proportional control in which the ventilation rate is proportional to the CO_2 concentration, PI (proportional-integral) or PID (proportional-integral-derivative) control which can adjust more quickly and in a more stable manner to changes in the CO_2 concentration. Control strategies should be chosen based on the expected occupancy patterns.

Non-occupant Contaminants

CO_2-based DCV systems should include a strategy to provide for sufficient ventilation, or other means (e.g. reducing contaminant emissions, local ventilation and air cleaning), to control concentrations of non-occupant generated contaminants. Ideally, an analysis of non-occupant sources would indicate the appropriate ventilation rates and other IAQ control technologies needed to maintain the resulting concentrations of contaminants within acceptable limits. However, the information needed to perform such an analysis, primarily contaminant emission rates and air cleaning system efficiencies, are not available in all situations.

Other Considerations

The selection and design of a CO_2-based DCV system cannot be viewed in isolation, as the air quality and energy performance will impact and be impacted by other building and HVAC systems. While the interactions will be building and system specific, interactions can occur with economizers, displacement ventilation, and other technologies. For example, in buildings with an economizer cycle, the economizer should be allowed to override the DCV system at times when the additional ventilation would provide 'free' cooling. For buildings dominated by cooling loads, DCV should not be used in most climates without an economizer. For buildings with displacement ventilation, in which conditions are created such that both air temperatures and contaminant concentrations are stratified, CO_2 sensors should be located within the occupants' breathing zone or the control system should somehow account for concentration gradients due to such stratification.

Also, installation of an outdoor CO_2 sensor should be considered if outdoor levels are expected to vary significantly over time or to deviate significantly (more than about 20 %) from 720 mg/m^3 (400 ppm(v)). The outdoor CO_2 concentrations can be assumed to be 720 mg/m^3 (400 ppm(v)) for most applications, but urban areas may have local effects resulting in higher levels. The higher outdoor level could result in overventilation and it may be economical to install an additional sensor to control the difference between indoor and outdoor concentration directly. Such an installation may also be required by some applicable standards or codes.

3. Recommendations Based on Project Technical Work

Other phases of this project involved technical work by both NIST and Purdue University to examine different aspects of CO_2 based DCV. NIST performed simulations of CO_2 DCV performance in a variety of space types for several different ventilation control approaches (Persily et al. 2003). The results of these simulations were compared in terms of ventilation rates, indoor CO_2 levels, indoor concentrations of a generic VOC (volatile organic compound) contaminant intended to represent non-occupant contaminant sources, and the energy consumption associated with ventilation. Purdue University performed a detailed economic assessment of CO_2 DCV for a range of different building types and climates within California (Braun et al. 2003). In this effort, the economics of CO_2 DCV were compared with competing energy recovery technologies, including enthalpy exchanger heat recovery (HXHR), and heat pump heat recovery (HPHR) using both simulation and field studies. As a result of these efforts, new insights were obtained into the application of CO_2 DCV, which are summarized below.

Recommendations Based on NIST Simulation Effort

The primary finding of the NIST simulation effort is that CO_2 DCV is capable of providing acceptable control of indoor contaminants from both typical occupant and non-occupant sources. However, the results also indicate that the performance depends on the details of the spaces including occupancy patterns, ventilation rate requirements in the relevant standard and ventilation system operating schedule as well as the other values used in the analysis, specifically contaminant source strengths and system-off infiltration rates. Among the findings with implications for the application of CO_2 based DCV are the following:

For some space types, CO_2 DCV has the potential to save a large amount of energy. Characteristics of such spaces are highly variable occupancies with high occupant densities at peak occupancy. Examples of such space types include lecture halls, conferences rooms, and classrooms.

For other space types, the potential energy savings are far more climate specific, and the potential savings in mild climates may be insignificant. Characteristics of such spaces are constant or moderately variable occupancies with low peak occupant densities. An example of this type of space is a typical office, but savings with DCV systems may still be possible in more severe climates.

A nonzero minimum or base ventilation rate should be maintained to handle non-occupant sources. The simulations used a value that was 25 % of the design ventilation rate, and this value maintained indoor contaminant levels close to those seen in an idealized system in which the outdoor air intake tracked occupancy perfectly. Simulations with a minimum ventilation rate of zero resulted in elevated contaminant levels, particularly in the early morning. A minimum below 25 % may be acceptable but was not examined in this study.

In order to deal with the potential for elevated concentrations in the morning, even with a nonzero minimum ventilation rate, DCV systems (and perhaps non-DCV systems as well) should have the capability for increased outdoor air intake before the building is occupied. Sometimes referred to as pre-occupancy "flushout," this capability can help alleviate contaminant overnight buildup while the system is off. The need for such flushing, and the corresponding airflow rate, depends on the contaminant source strengths and the fan-off infiltration rate, both of which are difficult to determine. For odorous sources, early morning odor will provide an indication of the need for a flushing cycle. For non-odorous sources, which can still be a serous concern, the need for a flushing cycle is much more difficult to determine.

When selecting appropriate setpoints for a CO_2 DCV system, they need to be low enough to provide adequate ventilation but high enough to achieve some energy savings. The approach used in this study was to set the upper limit based on the steady-state CO_2 concentration expected at design occupancy and a lower limit about 90 mg/m^3 (50 ppm(v)) above outdoors to avoid the system turning on and off too often. Other approaches to determining these setpoints may also work.

Given the availability of the software tool used in this analysis, and the relative simplicity of the simulations, designers should consider performing similar analyses as part of the design process to examine the impact of various design parameters: setpoints, minimum ventilation rates and operating schedules.

Recommendations Based on Purdue Simulation and Experimental Effort

Compared to competing energy recovery technologies, demand-controlled ventilation coupled with an economizer (DCV+EC) gives the largest cost savings and best economics relative to economizer-only systems for small commercial buildings in California. The greatest cost savings and lowest payback periods occur for buildings that have low average occupancy relative to their peak occupancy, such as auditoriums, gyms and retail stores. From a climate perspective, the greatest savings and lowest payback periods occur in extreme climates (either hot or cold). Mild coastal climates have smaller savings and longer payback periods. In most cases, the payback periods associated with DCV+EC are less than two years.

The savings and trends determined through simulation for DCV were verified through field testing in a number of sites. Field sites were established for three different building types in two different climate zones within California. The building types included: 1) a play area for a fast food restaurant, 2) modular school rooms, and 3) a drug store. In each case, nearly duplicate test buildings were identified in both coastal and inland climate areas. For cooling, greater energy and cost savings were achieved for the restaurant play area and drug store than for the modular schoolrooms. Primarily, this is because these buildings have more variability in their occupancy than the schoolrooms. The largest energy and cost savings were achieved in the hotter, inland climates. The payback period for the inland drug store is less than a year and about 3 years for the inland fast food restaurant play area.

There were no substantial cooling season savings for the modular school rooms. The occupancy for the schools is relatively high with relatively small variability. The school sites are also on timers or controllable thermostats that mean the HVAC units only operate during the normal school day. The schools are also generally unoccupied during the heaviest load portion of the cooling season. Furthermore, the results imply that the average metabolic rate of the students may be higher than the value used in ASHRAE Standard 62-2001 to establish a fixed ventilation rate. The DCV control resulted in lower CO_2 concentrations than for fixed ventilation rate at the modular schoolroom sites in Sacramento.

From an economic perspective, CO_2 DCV with an economizer is the recommended ventilation strategy for most small commercial buildings in California.

4. Potential Revisions to ASHRAE Standard 62 and California Title 24

The latest versions of ASHRAE Standard 62 and Title 24 allow the use of CO_2 DCV. However, based on the results of this project and other recent efforts, some modifications of both documents merit consideration. This section contains initial proposals for such revisions.

ASHRAE Standard 62

Given the structure of ASHRAE Standard 62, including current proposals for revising the standard, the following modifications of the standard should be considered:

- Add a definition of demand controlled ventilation to Section 3 Definitions.
- Add requirements to Section 5 Systems and Equipment that must be met when using CO_2 DCV that address the control capabilities and the CO_2 sensors themselves
- Add requirements to Section 6 Procedures on ventilation rate design procedures when using CO_2 DCV.
- Add requirements to Section 8 Operations and Maintenance for components of CO_2 DCV systems.

A proposed definition of demand controlled ventilation is as follows:

> a ventilation control strategy in which the outdoor air intake rate provided by a system is varied based on actual occupancy of the spaces served by that system rather than on fixed occupancy levels for those spaces. Actual occupancy may be determined directly using occupancy sensors or some other means or indirectly based on established schedules or a surrogate for occupancy such as indoor carbon dioxide concentrations.

The material relevant to CO_2 DCV in the Systems and Equipment section should cover the "hardware" requirements that must be met when employing this ventilation approach. This could be accomplished through a new subsection, which could be based on the following proposed language.

> 5.x CO_2-Based Demand Controlled Ventilation: Outdoor air ventilation may be controlled based on indoor CO_2 concentration when building occupants are the only significant indoor source of CO_2. When outdoor air ventilation is to be controlled based on indoor CO_2 concentration, the system shall meet the following requirements:
>
> > 5.x.1   Controls and system components shall be provided to automatically modulate the amount of outdoor air intake based on the output of one or more CO_2 sensors.
> >
> > 5.x.2 CO_2 sensors shall be located in each space served by the system being controlled using CO_2-based demand controlled ventilation. **Exception**: Multiple spaces of the same type per Table 2 (Table 6.1 in Addendum 62n) and with similar load, occupancy patterns and outdoor air fraction may share a sensor.
> >
> > 5.x.3   An outdoor CO_2 sensor shall be included in the control system unless it can be shown that the outdoor CO_2 concentrations are relatively stable, in which case the outdoor value may be assumed to be constant at the lower end of the expected range at the building site.
> >
> > 5.x.4   The CO_2 sensors employed shall have an accuracy of at +/- 90 mg/m^3 (50 ppm(v)) or less.

Section 6 on design procedures is a more complex issue with respect to CO_2 DCV. One perspective is that the section already contains ventilation requirements on a per person basis that still need to be met, even if the number of people by which these requirements are multiplied is varied during operation. The 2001 version of the standard does not speak to a minimum ventilation rate when there are no occupants, but the recently approved addendum 62n actually contains requirements on a per person basis and on a per unit floor area basis (Persily 2001). Under normal conditions, one multiplies the number of people by the per person requirement and the floor area by the per floor area requirement and then adds the two products to determine the total ventilation requirement for the space. When applying CO_2 DCV, one would simply use the floor area requirement for the minimum ventilation requirement. Another potential approach to CO_2 DCV in Section 6 is to describe exactly how one would implement the control approach for different system types, but this would require a fairly lengthy description to cover all system types and circumstances and might best be left to application manuals.

Section 8 of Standard 62 deals with Operations and Maintenance issues. It covers sensors in section 8.4.1.7 and in Table 8-1, nothing that their accuracy needs to be verified every 6 months or as required by an O&M manual identified elsewhere in the standard. Section 8.4.1.7 specifically refers to sensors used in demand controlled ventilation, and therefore CO_2 DCV sensors would be covered. However, it may be worth considering the identification of CO_2 sensors specifically in these sections of the standard.

California Title 24

The California Building Energy Standards AB970 (CEC 2001), also referred to as Title 24, already contains requirements for DCV systems in section 121(c). The most relevant requirements in the 2001 version include the following:

- Outdoor air intake rates may be reduced to 0.75 L/s•m^2 (0.15 cfm/ft^2) of conditioned floor area if DCV is used.
- When DCV is based on CO_2 levels, the indoor CO_2 must be no more than 1280 mg/m^3 (800 ppm(v)) when the space is occupied, unless the ventilation rate to the space is 7.5 L/s (15 cfm) per person or meets L/s•m^2 (cfm/ft^2) requirements for selected space types.
- Locate sensors in the space or the return airstream from the space with no less than one sensor every 2500 m^2 (25,000 ft^2), unless the manufacturer recommends more dense sensor placement.

Based on the results of the simulations performed by NIST, the minimum ventilation rate of 0.75 L/s•m^2 (0.15 cfm/ft^2) is probably higher than necessary, as it precludes the use of DCV in offices. A revision of Title24 should consider the floor area requirements in Addendum 62n to ASHRAE Standard 62 as replacement values for these minimum requirements.

5. Remaining Issues

Previous research efforts, as well as those conducted under the NIST and Purdue projects, have provided much useful information and guidance on the application of CO_2 DCV. However, some important questions remain. In particular, the reliability of CO_2 sensors and other control hardware has not been proven through long-term field testing. For example economizer controls used with packaged air conditioning equipment can sometimes be unreliable, and the use of DCV with such systems adds hardware and new reliability issues. Automated diagnostics for DCV applications may be worth considering in future investigation. Additional questions include: sensor performance versus cost, control algorithm requirements as a function of system and occupancy, baseline minimum ventilation rates for different applications, and appropriate methods for pre-occupancy flushing of building.

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7. Disclaimer

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