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Literature Review on CO_2-Based Demand-Controlled Ventilation

Steven J. Emmerich
Associate Member ASHRAE

Andrew K. Persily, Ph.D.
Member ASHRAE

ABSTRACT

Many ventilation requirements and recommendations are in the form of outdoor airflow rates per person. Ventilation systems are therefore designed to provide a minimum level of outdoor air based on the designed occupancy level multiplied by the per-person ventilation requirement. Because the indoor generation rate of carbon dioxide is dependent on the number of occupants, it has been proposed to use indoor carbon dioxide concentrations as a means of controlling outdoor air intake based on the actual number of occupants in the space as opposed to the design occupancy. Such demand-controlled ventilation offers the possibility of reducing the energy penalty of overventilation during periods of low occupancy while still ensuring adequate levels of outdoor air ventilation. This paper reviews previous work on carbon-dioxide-based demand-controlled ventilation, including field demonstration projects, computer simulation studies, studies of sensor performance and location, and discussions of the application of the approach. The work is summarized and a number of research needs are identified.

INTRODUCTION

A demand-controlled ventilation (DCV) system attempts to achieve acceptable indoor air quality (IAQ) at reduced energy cost by controlling an HVAC system's outdoor airflow rate based on a measured parameter. These parameters can include measured values of indoor pollutant concentrations or measures of building occupancy based on an occupancy sensor. In a carbon dioxide (CO_2)-based DCV system, CO_2 is used as an indicator of occupancy, and sensors measuring CO_2 concentrations are used to control the ventilation supplied to a space. The potential advantages of CO_2-based DCV are increased ventilation when occupancy is high to ensure acceptable IAQ and decreased ventilation when occupancy is low to save energy. While the energy-saving potential of this approach has been highlighted in several studies, there are still some important questions related to the implementation of CO_2-based DCV. The most critical issue is that low CO_2 levels alone do not guarantee acceptable IAQ (Persily 1993). The concentrations of non-occupant-generated pollutants may not be controlled by such a system, or at least they can become elevated during periods of low occupancy due to decreased ventilation. Also, nonuniformities in air distribution and in building occupancy can present difficulties in locating sensors so that a representative CO_2 concentration is measured.

In the last 10 years, interest in CO_2-based DCV has led to a large body of literature published in journals, conference proceedings, and other forums. An extensive literature review (Raatschen 1990) covering all aspects of demand-controlled ventilation, not just CO_2-based systems, was published at the conclusion of Annex 18, an International Energy Agency effort to develop guidelines for DCV systems. A more limited review was published during Annex 18 by Mansson (1989). The objective of this paper is to summarize the literature on CO_2-based DCV, making the information more accessible to researchers, designers, and other interested engineers and to identify research needs.

Reports on CO_2-based DCV are categorized in this paper as follows: case studies, field tests; case studies, simulations; sensor performance and location; and applications. The first two categories include studies of the performance of CO_2-based DCV systems in real buildings and using computer models. The various case studies that have been conducted focus on a number of different issues, including ventilation rates, energy consumption, economic impacts, and the concentrations of other indoor pollutants, although few studies address all of these issues. The third category includes reports that address the performance of CO_2 sensors and where they should be located in a space. The fourth category discusses the application of CO_2-based DCV, from very general descriptions to detailed discussions of control algorithms.

Steven J. Emmerich is a mechanical engineer and **Andrew K. Persily** is a group leader in the Building and Fire Research Laboratory at the National Institute of Standards and Technology, Gaithersburg, Md.

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CASE STUDIES

Many of the literature reports on CO_2-based DCV are case studies aimed at determining the energy savings and/or IAQ impacts of these systems. This section discusses the case study reports, categorizing them further as field tests and simulations.

Field Tests

There have been a number of demonstration projects in which CO_2-based DCV systems were installed in buildings and certain aspects of performance were monitored. These studies vary in many respects, including the detail with which the DCV systems are described. Some reports contain detailed descriptions of the DCV control algorithms, while others do not even report the setpoint. The studies also vary in the impacts that were monitored, which have included fan operation, damper position, indoor CO_2 concentrations, ventilation rates, energy consumption, the concentrations of other pollutants, and occupant perceptions of the indoor environment. Finally, the studies have taken place in a variety of building types, including offices, schools, auditoriums, and retail stores.

The application of CO_2-based DCV is often discussed with reference to office buildings and in many cases conference rooms within office buildings. One of the earliest studies of CO_2 control in an office building took place in Helsinki (Sodergren 1982). The outdoor air control algorithm is not described, but the CO_2 setpoint was 700 ppm(v). The CO_2 control system was compared to constant outdoor air and timer-based control, and 24-hour plots of CO_2 concentration are presented for each system. Measured concentrations of other pollutants and interviews with occupants did not indicate any IAQ problems.

In addition to describing the principles of DCV, Davidge (1991) presents a demonstration project in a 30,000-m^2 (320,000-ft^2) office building. In this building, the system never controlled the ventilation rate because the outdoor temperatures in the winter were never low enough to go off free-cooling. During the summer, damper leakage was more than enough to control CO_2. Davidge also studied a boardroom, where supplemental ventilation was controlled alternately by a light switch, a motion sensor, and a CO_2 controller. In the case of the CO_2 controller, the fan came on at 800 ppm(v) and shut off at 600 ppm(v). An occupant questionnaire was administered, and it was found that the occupants could not distinguish whether or not the fan was on. However, they rated the CO_2 system highly.

A fairly comprehensive study of CO_2 control took place on two floors of an office building in Montreal (Donnini et al. 1991; Haghighat and Donnini 1992). One floor was equipped with a CO_2 DCV system, while the other floor served as a control. The CO_2 control algorithm was as follows: the damper closed at concentrations below 600 ppm(v); as CO_2 increased above 600 ppm(v) the dampers opened, with the maximum opening at 1,000 ppm(v). The study lasted one year, during which indoor concentrations of CO_2, formaldehyde, volatile organic compounds and particles, ventilation system performance, thermal comfort, and occupant perception were measured once a month. Energy demand was monitored for the whole year. The outdoor air dampers were closed most of the year because there were rarely enough people to raise the indoor CO_2 concentration. The indoor air quality measurements revealed no significant contaminant concentration differences between the CO_2 and the control floor. Thermal comfort was generally adequate on both floors. Annual energy savings of 12% were measured for the floor with DCV. Occupants of the DCV floor complained significantly more about the indoor environment than occupants of the control floor for part of the year.

Fleury (1992) reported on the performance of a CO_2-controlled ventilation system in a conference room. In this system, the fan motor speed was adjusted according to the CO_2 concentration, but no information was provided on the specific control algorithm or setpoints. The measured CO_2 concentrations in the space were between 350 ppm(v) and 850 ppm(v), with one peak of 1,100 ppm(v). Based on occupant questionnaires, the air quality was rated from good to excellent. Another study was undertaken in a conference room set up to test DCV sensors, including CO_2, volatile organic compounds, and humidity (Ruud et al. 1991). The CO_2 setpoints were not reported, but the indoor concentration never exceeded 900 ppm(v). Another demonstration in a conference room was reported by Huze et al. (1994). The ventilation rate was varied proportionally to the CO_2 concentration within a 500-ppm(v) band centered around 1,200 ppm(v). Limited results presented include a sample of the CO_2 level and control signal for one day.

One of the most frequently cited demonstration projects took place in a small bank in Pasco, Washington (Gabel et al. 1986). This study involved the measurement of energy consumption, contaminant levels including nitrogen dioxide, formaldehyde, carbon monoxide and particulates, and occupant response based on a questionnaire. The study design included monitoring over the winter, spring, and summer seasons, with one week of normal operation followed by one week of CO_2 control. The system's economizer cycle operated normally throughout the test periods. They found that with the CO_2 control system setpoint at 1,000 ppm(v) to 1,200 ppm(v), air leakage through the closed damper provided sufficient fresh air for typical occupancy, which was only 10% to 15% of design. That is, the indoor CO_2 level never rose to the control setpoints. All measured contaminants were maintained below indoor standards. Based on a curve fit of the measured energy consumption to outdoor temperature for the two modes of outdoor air control, average energy savings of 7.8% for heating and cooling in six climates typical of Oregon and Washington were calculated. Based on the questionnaires, the occupants could not detect differences between background CO_2 levels of 300 ppm(v) and 1,000 ppm(v). The occupants reported feeling warmer during DCV control, although the measured indoor temperatures were no different.

Another frequently cited study took place in a Minnesota high school (Janssen et al. 1982). The ventilation system used CO_2 and temperature to control outdoor air and had separate dampers for temperature and CO_2 control. Indoor contaminants, energy, and subjective response of occupants were monitored.

The measured energy savings were about 20%. The occupant questionnaire showed that the subjects felt warmer with increased CO_2 concentrations. Another study by the same group of researchers took place in a portion of a high school that was retrofitted with a CO_2-controlled system (Woods et al. 1982). During the early months of 1980, the system operated under alternate periods with conventional temperature control and with CO_2 control. System performance was monitored, and the subjective responses of occupants were obtained. The system contained a set of outdoor air dampers that were controlled based on the CO_2 concentration. These dampers modulated between fully closed and fully open damper positions, with the low setpoint at 3,000 ppm(v) and the high setpoint at 5,000 ppm(v). The results indicated the potential for significant energy savings. Occupants felt warmer when CO_2 control operated despite the fact that there was no measurable temperature difference with and without CO_2 control.

A study of two Finnish public buildings, one that had CO_2-controlled ventilation, included measurements of radon, particles, and CO_2 (Kulmala et al. 1984). No description of the CO_2 control algorithm was reported. Daily energy savings were estimated at 13% to 20%.

In several of the studies cited so far, the indoor CO_2 concentration was often not high enough for the CO_2 control system to operate. This may be due in part to the relatively low occupant density in office buildings. The application of CO_2-based DCV is usually viewed as more appropriate in spaces where occupancy is more variable and where the peaks are associated with fairly high occupancy. Auditoriums are good examples of such spaces, and there have been several case studies in these types of spaces. One such study took place in an auditorium with CO_2 and timer control of ventilation at the Swiss Federal Institute of Technology in Zurich (Fehlmann et al. 1993). The measurements included system run time, energy use, climatic parameters, and CO_2 concentrations under winter and summer conditions. In addition, an occupant questionnaire was administered. The ventilation system had two stages of airflow capacity, with the first stage coming on at 750 ppm(v) and the second stage at 1,300 ppm(v). The second stage would turn off at 1,100 ppm(v), and the first stage at 600 ppm(v). With ventilation controlled by CO_2, run time was 67% of the run time with timer control in summer and 75% in winter. Energy consumption with CO_2 control was 80% less in summer and 30% less in winter. Questionnaire results indicated a higher perception of odors with CO_2 control, especially in the summer. It was noted that the occupancy was very low compared to design—only about 10% to 20%.

Zamboni et al. (1991) reported on field measurements in auditoriums in Norway and Switzerland. In the Norwegian building, the CO_2 setpoint was 1,000 ppm(v), and the reported results include indoor temperature, CO_2 concentration, and age of air. In the Swiss building, there was a two-stage controller with the first setpoint at 750 ppm(v) and the second at 1,300 ppm(v). The researchers monitored energy consumption and indoor climate, and administered occupant questionnaires. Heating energy was reduced by 15% during one week of testing in the winter and by 75% in the summer. With CO_2 control, there was less draft but more odor in summer.

Several demonstration projects have been conducted in so-called public spaces, including retail stores and recreational facilities, where occupancy is expected to be more variable and less predictable. Potter and Booth (1994) report on the performance of CO_2-based DCV systems in eight public buildings. The authors note that the results point to some potential problems with CO_2 control, but many of the results are presented simply in the form of plots of indoor CO_2 concentration vs. time. In an office building and a swimming pool facility, the indoor concentration never reached the CO_2 setpoint. Building setpoints were variable and included 1,250 ppm(v), 2,200 ppm(v), and 2,500 ppm(v). Based on the results, the authors identify candidate building types for CO_2 control as cinemas, theaters, bingo and snooker establishments, educational lecture theaters, teaching labs, meeting rooms, and retail premises. They considered the issues of maintenance and reliability, noting that no controllers in the buildings were marked with calibration due date or the date of last service.

Another study of two public spaces took place in a social club and a cinema (Anon. 1986). The control algorithm was not described, but the CO_2 setpoints were usually between 700 ppm(v) and 1,000 ppm(v). The measured fuel savings were 17% in the club and 11% at the cinema. Warren (1982) reports on tests of energy savings with CO_2 control in a theater and a retail store. Energy and cost savings estimates are based on short-term tests in the building, and the dependence of the savings on ventilation system design parameters is discussed. The systems in the two buildings are not described in detail.

Strindehag et al. (1990) reported on a number of examples of how outdoor air intake can be controlled by CO_2 in a conference room, three offices, and a school. The report contains descriptions of the buildings and the CO_2 sensors, and it notes that the CO_2 setpoint was 600 ppm(v). However, the control algorithms are not described, and no specific performance indicators are discussed.

There has been limited study of CO_2 control in residential buildings. One study in a single-family residential building examined the use of CO_2 and water vapor for ventilation control (Barthez and Soupault 1983). Little detail is provided on the CO_2-based control approach, but the study concluded that CO_2 was a more suitable control parameter than water vapor. Moffat (1991) reported on the study of five energy-efficient houses, buildings with so-called "low toxicity" construction and a range of mechanical systems consistent with the Canadian residential ventilation standard CSA F326. These houses used DCV systems based on CO_2, volatile organic compounds, absolute humidity, activity sensors, and occupant control. Some of the conclusions of the study were as follows: DCV offers benefits when occupant pollutants dominate building pollutants; CO_2 is an excellent indicator of occupancy and occupant-based ventilation requirements; activity-related pollutants are best controlled by local exhaust; and relative humidity is a poor indicator of occupancy. Kesselring (1996) reported on a field demonstration of a residential ventilation system controller that used a combination of scheduled ventilation and CO_2 maximum limit control. The CO_2 limit is not specified and few sample data are presented.

The studies cited here show that CO_2 control has been demonstrated in a wide variety of building types including offices, schools, public spaces, and some residential buildings. It is apparent in examining these studies that the CO_2 control algorithm is often not described in sufficient detail to understand the system; in fact, some of the studies did not even report CO_2 setpoints. In several of the demonstration projects, the building occupancy was insufficient to raise the indoor CO_2 concentration enough to activate the CO_2 control system. Several of the studies used occupant questionnaires to evaluate performance, with inconsistent results. In some cases, the occupants positively perceived the indoor environment with CO_2 control. In other cases, there were more complaints, specifically with regard to odor during CO_2 control. Several studies noted a feeling of increased warmth with elevated CO_2 concentration despite the fact that the measured indoor temperatures were no higher. When considering these reports of occupant response, it must be kept in mind that the studies employed different questionnaires.

Simulations

As discussed above for field tests, the reported simulation case studies vary widely in both the description of important parameters and discussion of results. Most studies have focused on the potential energy savings of the CO_2-based DCV systems, with CO_2 concentrations reported as a measure of IAQ performance. A few studies have calculated concentrations of other pollutants. As with the field tests, the majority of the studies have involved office buildings, with others examining public spaces, auditoriums, and residential buildings. Another important issue in simulations is the treatment of infiltration and interzonal airflows, with most studies using assumed rates and one study employing a multizone airflow model.

In an early report of a simulation study for an office, Knoespel et al. (1991) investigated the application of a CO_2-based DCV system to a two-zone office space with both constant-air-volume (CAV) and variable-air-volume (VAV) HVAC systems. A multiple-zone pollutant transport model was used and a ventilation airflow controller model was developed as modules for a transient thermal system simulation program (Klein 1994). Other existing modules of the program were used to calculate building energy consumption. Infiltration to the main zone was assumed constant at 0.2 h^{-1}, and an interzonal flow of 12 L/s (24 cfm) from the main office to the conference room was included when the HVAC system was on. Knoespel compared the performance of six ventilation strategies, including constant outdoor airflow at the ASHRAE Standard 62-1989 prescribed flow of 10 L/s (20 cfm) per person, constant outdoor airflow at a "typical" rate of 0.7 h^{-1}, minimum outdoor airflow at the typical rate with a temperature-based economizer, DCV with a step-flow control algorithm, DCV with step-flow control and a temperature-based economizer, and DCV with on-off control. In the step-flow control algorithm, the fraction of outdoor air in the circulation flow was changed in 20% steps depending on whether the measured CO_2 concentration in either zone was above or below the specified limit. On-off control employed an algorithm in which outdoor airflow is set at 100% if the high CO_2 setpoint is exceeded and at 0% if the CO_2 concentration drops below the low setpoint. The setpoints used were 800 ppm(v) and 1,000 ppm(v). Simulations were performed for Miami, Florida, and Madison, Wisconsin. In Madison, the DCV strategies provided acceptable control of CO_2 levels with coil energy savings from 9% to 28% for CAV systems and from 43% to 46% for VAV systems compared to the ASHRAE Standard 62-1989 prescribed rate strategy. The savings for Miami were of similar absolute magnitude but smaller percentages. These results did not include fan energy use. Compared to the economizer and constant outdoor airflow strategies at typical rates, the DCV strategies resulted in similar energy use with better control of CO_2 concentrations for both CAV and VAV systems.

Emmerich et al. (1994) applied the model developed by Knoespel et al. (1991) to examine the performance of DCV systems under less favorable conditions and to study the impact on non-occupant-generated pollutants. Emmerich used the same building, the Madison location, and the HVAC systems described above but varied the conditions simulated to include a pollutant removal effectiveness as low as 0.5 and an occupant density up to 50% greater than design. For all cases examined, the DCV system reduced the annual cooling and heating loads from 4% to 41% while maintaining acceptable CO_2 concentrations. In addition to requiring more energy use, the constant outdoor airflow strategy resulted in CO_2 levels above 1,000 ppm(v) for more than half of occupied hours for cases with poor pollutant removal effectiveness. Emmerich also examined the impact of DCV on non-occupant-generated pollutants by modeling a constant source of a nonreactive pollutant located in the main office zone. Four ventilation strategies were compared, including constant outdoor air at a prescribed rate based on ASHRAE Standard 62-1989, DCV with step control and setpoints of 800 ppm(v) and 1,000 ppm(v), DCV with a constant minimum outdoor airflow rate of 2.5 L/s (5 cfm) per person calculated using the multiple space method of ASHRAE Standard 62-1989, and DCV with scheduled purges of 100% outdoor air from 7:30 a.m. to 8:30 a.m. and 12:30 p.m. to 1:00 p.m. The non-occupant-generated pollutant source strength was specified such that the system with a constant outdoor airflow rate just met a short-term limit of 2 ppm(v) and an eight-hour average limit of 1 ppm(v). Emmerich found that both the straight DCV and the DCV with minimum outdoor airflow rate failed to meet the pollutant concentration limits for both the CAV and the VAV systems, but the DCV with scheduled purge strategy successfully limited the pollutant concentrations. The purge strategy increased building heating and cooling loads over the straight DCV strategy but still reduced the loads by 17% (CAV) and 25% (VAV) compared to the constant outdoor airflow case. The success of the purge strategy was attributed partially to the ability to schedule the purges when most needed.

In another study considering the effects of poor ventilation air mixing, Haghighat et al. (1993) simulated the performance of a CO_2-based DCV system in a large office building in Montreal. The baseline ventilation system had a flow rate of 10 L/s (20 cfm) per person, and a mixing parameter of 0.7 was used in the model. The DCV system used a minimum ventilation rate of 2.5 L/s (5 cfm) per person, and the ventilation rate was adjusted each hour to maintain a CO_2 concentration of 800 ppm(v). Infiltration was 0.4 h^{-1} with the HVAC system off and 0.04 h^{-1} with it on. Four cases of occupant density were examined. The DCV system saved from 7% to 15% in energy use, 2% to 6% in energy cost, and 7% to 17% in peak demand compared to a fixed ventilation rate strategy. In a follow-up study using the same office model with different infiltration, operating hours, and other assumptions, Zmeureanu and Haghighat (1995) found energy consumption for the DCV system ranging from a 5% decrease to a 2% increase. However, because of peak demand reductions, annual energy cost savings ranging from 3% to 26% were found.

Sorensen (1996) also describes simulations performed for a two-zone office with a conference room. A unique aspect of this study is its focus on examining the short-term dynamics of the system by simulating a 10-hour period with one-second time steps and detailed modeling of the HVAC system. A VAV system with dual-temperature and CO_2 control and a CAV system without CO_2 control are simulated. Because a detailed VAV system model is used, the control algorithm is more complex than in most studies reviewed and involves both dampers and fans. When the CO_2 concentration is above an upper limit of 900 ppm(v), the damper actuator position increases by 1%. If the concentration remains above the upper limit, the position continues to increase until it is fully open or until it drops below the limit. After the damper is fully open, a concentration above the upper limit will increase the fan speed by 5% until the fan reaches maximum speed or the concentration falls below the limit. The algorithm also uses a lower limit of 700 ppm(v) to decrease fan speed and damper position. Detailed results are not presented, but transient CO_2 concentrations and temperatures are presented and it is stated that the VAV system used 31% less energy than the CAV system.

Other recent studies of office applications (Carpenter 1996; EE 1995) examined both the energy and IAQ impacts of CO_2-based DCV in a mid-sized commercial building complying with ASHRAE Standard 90.1 in four climatic zones (Chicago, Nashville, Phoenix, and Miami). Simulations were performed using a combination of an energy analysis program (EE 1990) and the multizone pollutant transport program CONTAM87 (Axley 1988). Three HVAC systems (single-zone, multizone, and VAV) and five ventilation control strategies (fixed ventilation rate, DCV with building return air controlled to 1,000 and 800 ppm(v), DCV with floor return controlled to 1,000 ppm(v), and DCV with each zone controlled to 1,000 ppm(v)) were analyzed. The DCV control algorithm was not described in detail. For single-zone systems, the DCV strategy reduced heating energy by about 30% for a setpoint of 1,000 ppm(v) and by 20% for a setpoint of 800 ppm(v). The DCV system with a setpoint of 800 ppm(v) also reduced average CO_2 concentrations by 50 ppm(v) to 90 ppm(v) compared to the fixed ventilation rate strategy. The DCV strategies had little effect on cooling energy because the DCV system tended to reduce ventilation during the cooler morning and evening hours and increase ventilation during the warmer middle of the day. For VAV systems, the energy savings were similar to those with single-zone systems. For multizone systems, the reduction in heating energy was similar in absolute terms but was smaller in percent (5% to 12%) because of a larger total heating load. DCV with a setpoint of 1,000 ppm(v) resulted in average CO_2 concentrations 70 ppm(v) to 150 ppm(v) higher than the fixed ventilation strategy, while a setpoint of 800 ppm(v) kept concentrations lower than the fixed strategy and the maximum below 1,000 ppm(v) in all zones. Providing additional sensors in return ducts of each floor had little impact on energy use and IAQ. Installing sensors in each zone ensured that the concentration in each zone stayed below 1,000 ppm(v) but at a slightly higher energy use. The performance of DCV with sensors set at 1,000 ppm(v) in each zone was similar to central control with a setpoint of 800 ppm(v). Formaldehyde concentrations were also simulated to evaluate the impact of DCV strategies on pollution from a nonoccupant source. None of the DCV strategies controlled the formaldehyde concentrations as well as the fixed ventilation strategy. It was suggested that a morning purge should be included in a DCV strategy when non-occupant-generated pollutants are a concern, but this option was not simulated. Different DCV control algorithms, including on-off, linear proportional, proportional-integral-derivative (PID), and the Vaculik method (discussed later in this paper), were discussed but not simulated.

Meckler (1994) also simulated the application of CO_2-based DCV in an office building. The energy performance of an idealized DCV system with the ventilation rate varied to maintain 800 ppm(v) and 920 ppm(v) (i.e., no control algorithm modeled) was compared to a baseline system with a constant ventilation rate of 10 L/s (20 cfm) per person. The office building has 10 floors with two air-handling units (AHUs) for outdoor air for each floor, a central hydronic heating and cooling plant, and an economizer. Both energy and economic impacts are presented for five U.S. cities (Miami; Atlanta; Washington, D.C.; New York; and Chicago). Reported energy savings ranged from less than 1% to 3% for electricity and from 16% to 22% for gas. Payback periods of 1.5 to 2.2 years were estimated for all cities.

In a recent study with a focus on humid climates, Shirey and Rengarajan (1996) simulated the impact of a CO_2-based DCV system in a 400-m^2 (4,000-ft^2) office located in Miami, Orlando, and Jacksonville to examine the impacts of ASHRAE Standard 62-1989 ventilation rates on indoor humidity levels. The baseline system, a conventional direct expansion (DX) air-conditioning system with a sensible heat ratio (SHR) of 0.78, was unable to keep the indoor humidity below the target of 60% relative humidity (RH) when the ventilation rate was increased from 2.5

L/s to 10 L/s (5 cfm to 20 cfm) per person. System modifications considered included a low-SHR DX air conditioner, a high-efficiency low-SHR air conditioner, a conventional air conditioner with CO_2-based DCV, a conventional air conditioner with an enthalpy recovery wheel, a heat-pipe-assisted air conditioner, and a conventional air conditioner with a separate 100% outdoor air DX unit. The operation of the DCV system was simulated by matching ventilation rates to occupancy profiles. Four alternative systems (DCV, enthalpy wheel, heat pipe, and 100% outdoor air DX unit) maintained acceptable humidity levels for more than 97% of occupied hours. Of the systems with acceptable humidity performance, only the DCV and enthalpy wheel options did so with less than 5% increases in annual HVAC energy use compared to the conventional system with a ventilation rate of 2.5 L/s (5 cfm) per person. The DCV system also significantly lowered the peak heating demand in Orlando and Jacksonville. An economic analysis showed that the DCV system resulted in annual HVAC operating cost increases of 7% or less, first cost increases of about 14%, and life-cycle cost increases of about 12% compared to the system with 2.5 L/s (5 cfm) per person. A case with high internal loads was also examined, with the DCV and enthalpy wheel systems again resulting in the best performance for the smallest increases in cost.

In a recent follow-up study, Davanagere et al. (1997) applied the same methodology with many of the same assumptions as Shirey and Rengarajan (1996) to study HVAC system options including CO_2-based DCV in a Florida school. As in the previous study, the baseline for comparisons was a conventional system with ventilation as required by ASHRAE Standard 62-1981. In addition to DCV, the options simulated included the conventional system with ASHRAE Standard 62-1989 ventilation rates and various combinations of pretreating outdoor air, thermal energy storage, enthalpy recovery wheels, gas-fired desiccant systems, and cold air distribution systems. Results reported included energy use, humidity levels, first costs, and life-cycle costs. In general, the DCV system resulted in the smallest or close to the smallest increases in energy costs and installed first costs compared to the baseline system. The thermal energy storage system options generally resulted in the smallest increases (or even decreases) in peak cooling demands and life-cycle costs. DCV was the only option that reduced peak heating demands. Although the DCV system reduced humidity levels compared to the baseline system, many of the other simulated options controlled humidity even better. Nakahara (1996) also discusses a simulation of DCV in a school building with an emphasis on multiple zones and the potential benefit of zoning the ventilation system based on the level of CO_2 demand instead of based on room position. However, little detail is provided on the model, and the baseline for the resulting potential thermal load reduction of 46% is not clearly defined.

Residential applications have also been simulated by several researchers. Hamlin and Cooper (1991) used an energy analysis program combined with CONTAM87 to examine the energy impacts of a CO_2-based DCV system in a single-family house located in Toronto, Winnipeg, and Vancouver. Most simulations were performed for January to March weather data, and the results were extrapolated to annual savings. Ventilation strategies simulated included continuous exhaust only, continuous balanced flow with heat recovery (HRV), DCV with the setpoint equal to the heating-season average CO_2 concentration with continuous ventilation (matched-average strategy), and DCV with the setpoint equal to peak CO_2 concentration with continuous ventilation (matched-peak strategy). Simulations were performed with both three and six occupants, natural infiltration constant at 0.1 h^{-1}, and baseline system ventilation plus infiltration rates of about 0.3 air changes per hour (ACH). The results considered impacts on both space heating energy (assuming gas heat) and fan energy. The DCV systems resulted in total energy savings from 4% to 7% for the matched-average strategy and from 14% to 15% for the matched-peak strategy compared to the continuous exhaust strategy. Cost savings per year ranged from about \$20 to \$70. The HRV resulted in larger space-heating energy savings than the DCV systems but required more fan energy. The net cost savings of the HRV and DCV systems were similar. The peak CO_2 concentrations for the DCV cases ranged from 655 ppm(v) to 823 ppm(v) for the cases with three occupants. The use of a 1,000-ppm(v) setpoint was not examined but could have resulted in substantially larger energy savings.

Another simulation study of DCV in a single-family residence was described by Yuill and Jeanson (1990) and Yuill et al. (1991). The simulations were performed using a combination of CONTAM87 (Axley 1988) and a multizone airflow program (Walton 1989). The house modeled—based on a house in Winnipeg—is a single-story, three-bedroom house with a basement and four occupants. All interior doors were modeled as open, and all exterior doors and windows were modeled as closed. Simulations were performed for weather data for a typical day. Yuill and Jeanson (1990) compared the IAQ performance of four ventilation strategies including a heat recovery ventilator (HRV) with continuous ventilation of 31 L/s (62 cfm), HRV with CO_2 DCV, a laminar airflow super window (LAFSW) with continuous ventilation of 31 L/s (62 cfm), and a LAFSW with DCV. The LAFSW draws air into the house at the bottom of a window. The air flows between the panes of glass and is discharged into the house at the top of the window. Concentrations of radon, formaldehyde, and an arbitrary pollutant generated from six point sources were also calculated. The DCV systems were modulated such that the CO_2 concentration in the exhaust flow was maintained at a constant 800 ppm(v). It was concluded that the continuous HRV system provided the best control of radon, the continuous control outperformed the DCV in controlling formaldehyde, the DCV strategies performed significantly better at controlling human-generated pollutants, and the continuous LAFSW system performed best at minimizing occupant exposure to point source pollutants. One potential shortcoming of the simulation method is indicated by a figure showing that the CO_2 concentration at the end of the day for the continuous ventilation strategies was at or above 1,000 ppm(v) while it started at around 700 ppm(v). This indicates that the concentration for the next day will be higher than for the day presented. However, transient concentrations are not presented for the other pollutants. Yuill et al. (1991) compared the performance of four ventilation strategies including central continuous, distributed continuous, central DCV (setpoint of 632 ppm), and distributed DCV (setpoint of 658 ppm(v)) for the same houses, weather data, and pollutant sources described above. The DCV strategies showed no clear advantage over continuous ventilation, with reduced exposure to some pollutants and increased exposure to others. In some cases, the relative performance of DCV depended on whether the supply was central or distributed. As discussed above, the concentrations at the end of the day did not match the concentrations at the beginning.

In a much earlier simulation study, Thellier and Grossin (1981) examined the application of DCV to a 100-m^2 (1,000-ft^2) apartment. They estimated an average reduction in ventilation flow of 60% compared to the French ventilation standard, with annual energy savings of 1,500 kWh.

In addition to offices and residences, public spaces have also been the subject of DCV simulation studies. Warren and Harper (1991) evaluated the potential heating energy savings for a CO_2-based DCV system applied to an auditorium in London. Energy simulations were performed using a building energy analysis program (Clarke and McLean 1986), with ventilation rates calculated separately based on occupancy profiles. Assumptions included CO_2 generation of 4.7×10^{-6} m^3/s (1.7×10^{-4} ft^3/s) per person, auditorium volume of 11,150 m^3 (406,000 ft^3), high CO_2 setpoint of 1,000 ppm(v), peak daily occupancy of 629, and an infiltration rate of 0.4 h^{-1}. Three ventilation scenarios were compared, including 100% outdoor airflow at a rate of 5,020 L/s (10,000 cfm), DCV with a minimum outdoor airflow rate of 3,770 L/s (7,500 cfm), and DCV with no minimum. The DCV with a minimum outdoor airflow rate rarely exceeded the minimum rate to maintain CO_2 concentrations below 1,000 ppm(v) and saved 26.4% in heating energy use compared to the 100% outdoor airflow case. The DCV with no minimum saved 53.3%.

Ogasawara et al. (1979) evaluated the potential energy savings for a DCV system in a 30,000-m^2 (320,000-ft^2) department store in Tokyo, Japan. Three ventilation strategies were compared, including fixed outdoor air at design rate, manual control with maximum ventilation on Sundays (the busiest day) and half of that on weekdays, and DCV. The DCV algorithm used was proportional control with a closed damper at 800 ppm(v) and a fully open damper at 1,000 ppm(v). Infiltration assumptions were not specified. Energy use was calculated for four cooling months and four heating months. The DCV system reduced energy use by 40% for the cooling season and by 30% for the heating season. An economic analysis showed an advantage for the DCV system.

The simulation case studies reviewed indicated energy savings for DCV systems of 4% to 53% compared to ASHRAE Standard 62-1989 or other design ventilation rates. The energy savings varied widely depending on the type of building, control algorithm, building location, occupancy, and other assumptions. No parametric or sensitivity analysis has been performed to determine which variables have the most influence on potential energy savings. Also, energy savings are reported with respect to different baseline cases for different studies. A small number of the studies examined peak demand, economic impacts, humidity, and concentrations of other pollutants. These studies verified the concern for increased concentrations of non-occupant-generated pollutants, and one study examined potential solutions including scheduled purges. Shortcomings of most of the studies included inadequate treatment of infiltration and interzonal airflows and control algorithms.

SENSORS

The performance of a CO_2-based DCV system will clearly depend on the measured CO_2 concentration as reported by the system sensors. The two key issues related to these sensors are their performance, that is, their accuracy and reliability, and their location in the building. This section discusses the research that has been done on sensor performance and location.

Performance

In the most extensive report on sensor performance, Fahlen et al. (1991, 1992) describe an evaluation of the performance characteristics of two CO_2, nine humidity, and five mixed-gas sensors in both lab tests and long-term field tests. The lab tests consisted of both performance and environmental tests, while the field tests consisted of a repeat of the performance tests after the sensors had been installed in the field for 11 months. The CO_2 sensors displayed acceptable performance for control purposes, with a deviation of less than 30 ppm(v) at a level of 1,000 ppm(v). However, several problems were identified, including a time-consuming calibration process, sensitivity to humidity below a threshold value, and cross-sensitivity to voltage, temperature, and tobacco smoke. Characteristic curves comparing the sensor performance before and after the field trial are presented. At 1,000 ppm(v), the deviation from the original result was between 0 ppm(v) and 100 ppm(v).

Meier (1993) reports on the performance of two CO_2 and 17 mixed-gas sensors in five different facilities at a Swiss university. Measurements of CO_2, air quality units (AQU), and occupancy are presented for one day in a restaurant. It is concluded that both mixed-gas and CO_2 sensors are suitable for registering the occupancy level in the restaurant and can provide the reference variable for DCV. The results of the mixed-gas sensors and CO_2 sensors are compared, but no conclusion is reached as to which sensor type is more suitable.

Recently, Okamoto et al. (1996) described the development and field testing of a CO_2 sensor employing solid-state electrolyte technology. The sensor is stated as having an accuracy of ±20% and acceptable sensitivity to temperature, humidity, and miscellaneous gases. However, the basis of the statements (i.e., laboratory test results) is not presented. Limited field tests of the sensors in a school and two conference rooms are described. In these tests, the sensors were used as monitors with low, medium, and high setpoints of 700 ppm(v), 1,400 ppm(v), and 2,500 ppm(v) but were not used to control the ventilation system directly.

Several other reports contain more limited discussion of CO_2 sensor performance. The literature review by Raatschen (1990) describes the various types of sensors available. The CO_2 sensors discussed use infrared absorption and are available as two types—photoacoustic and photometric. No actual performance tests were conducted, but a summary of manufacturers' data is provided. Houghton (1995) also describes available sensor types; manufacturers' specifications are presented for five sensors available in the U.S. Issues of accuracy, drift, and temperature and pressure sensitivity are also addressed, although no independent performance tests are reported. Helenelund (1993) also discusses the various sensor options available for DCV systems but does not report on their performance. Based on other published reports, interviews, and obtained test results, the suitability of various sensors for different types of facilities is presented from the point of view of both technological and economical performance. In a field test, Sodergren (1982) reported that the sensor calibration drifted from 100 ppm(v) to 150 ppm(v) during the study. In another field test, Ruud et al. (1991) found that one CO_2 sensor had to be connected to the supply voltage for several days before the output signal became stable.

Location

In an experimental study aimed at determining the proper location for DCV sensors within a room, Stymne et al. (1990) investigated the dispersion of CO_2 from simulated people in a four-room test house. Factors were discussed that should be considered when designing a DCV system in a multiroom environment, including the transfer of CO_2 from the sources to different locations (referred to as *transfer probability*), the expected equilibrium concentration at a location (purging flow rate), the rate constant of approaching equilibrium from a nonequilibrium state, and concentration fluctuations. The total ventilation flow rate to the test house was varied between two levels, with the fraction to each room remaining constant. People were simulated by metallic bodies heated by a 100-W lamp and emitting 0.0069 L/s (0.015 cfm) of CO_2 mixed with prewarmed air. Measurements were taken at 19 locations. Tracer gas measurements were also performed. The measurements showed that good mixing was achieved in rooms with closed doors, and, therefore, the sensor location is not critical. However, if a room is connected to other spaces by open doors, large differences and instabilities in the CO_2 concentration may occur. The distribution pattern of the tracer gas was similarly nonuniform, indicating that the cause of the distribution pattern is air movement through open doorways and its interaction with air movement from the heated bodies, radiators, cold external walls, and the jet from the inlet duct. It is recommended that the DCV sensor be placed at mid-height in a room and away from doorways, radiators, windows, people, and air inlet devices if possible. It is also recommended that the DCV system have a large time constant so that it will not react to the fluctuations in concentration due to nonuniform distribution patterns.

In a follow-up study, Stymne et al. (1991) investigated the CO_2 distribution pattern in an office room with a displacement ventilation system. People were simulated by heated dummies emitting tracer gas. Graphs of isoconcentration contours are presented for several cases. The lack of normal disturbances such as body movements, breathing, other heat sources, lighting, and solar heat gain is mentioned as a limitation of the study. It is shown that pollutants emitted from the "people" are transported to the upper mixed zone in the room and that pollutants emitted at a small heat source or near the wall accumulate below the interface between the upper and lower zones. The interface is displaced about 0.2 m (0.66 ft) upward around the heated bodies, ensuring the occupants better air quality than the surrounding air, even if they are above the interface. A test with a mixing ventilation system showed a similar plume above the heated dummies but no stratification outside the plume. It is concluded that DCV in a displacement ventilated room is a suitable means of controlling the level of the interface between the uncontaminated air in the upper zone and the polluted air in the lower zone. The sensors should be located at the height of the occupants' heads. Also, the setpoint should be lower than usual, for example below 800 ppm(v), so that the DCV system will be activated.

A common alternative to locating DCV sensors in individual rooms is to locate them in the ventilation system return ductwork. Reardon and Shaw (1993) and Reardon et al. (1994) compared CO_2 concentrations in the central return air shafts, individual floor return intakes, and occupied space in a 22-story office building. Measurements showed that the individual floor return intakes represented the spatial average concentrations in the occupied space, and that the measurements at the top of the central return shafts represented the concentrations at the floor return intakes. Therefore, it was concluded that the top of the return shafts is an appropriate location for the sensors of a DCV system. However, the setpoint should be adjusted (lowered) to account for variability in the occupied zones to avoid high local exposures.

Bearg (1994) also compares the merits of single- and multiple-point DCV systems. A system is described with multiple sampling points and a single detector installed in a five-story building. In addition to operating the DCV system, advantages credited to the multipoint system include identifying both leakages in the system and episodes of increased outdoor contamination such as vehicle exhaust at a loading dock. Also, the use of a single detector ensures that differences in measured concentrations for different sampling points are not due to calibration differences. Such a system could also be automatically recalibrated with a known CO_2 concentration. Houghton (1995) discusses this multipoint system, including its accuracy and automatic calibration advantages. However, the system is claimed to be more costly than a system with multiple detectors and a central computer. Some data collected by the multipoint system are presented.

Several other reports briefly discuss sensor location issues. In a field test in a house, Barthez and Soupault (1983) found that during the night the concentration in the bedroom is 100 ppm(v) to 300 ppm(v) higher than that detected in the ventilation shaft. In another field test, Sodergren (1982) presented graphs of the CO_2 concentration at multiple locations in an office but did not make specific recommendations on sensor location. In a test in a conference room, Ruud et al. (1991) found that concentrations measured at the wall and in the exhaust air were nearly identical with the wall-mounted sensor having a two-minute delay compared to the exhaust air. In a simulation study of a DCV system applied to an office building with floors having different occupant densities, investigators (EE 1995) found that a system with sensors in the return duct of each floor had little impact on IAQ and energy use compared to a system with a sensor in the central return. Installing sensors in each zone ensured CO_2 concentrations below 1,000 ppm(v) (the setpoint) in all zones and increased energy use slightly but at a higher installation cost due to the additional sensors. Central control with a setpoint of 800 ppm(v) offered similar performance to individual zone control with a setpoint of 1,000 ppm(v) but at a much lower installation cost.

Although many DCV studies have touched on the subjects of sensor performance and location, only a few have examined these issues in detail. In general, sensor performance characteristics have been found to be adequate for controlling a DCV system, although concerns about calibration and sensitivity to humidity and temperature have been expressed. Conflicting opinions on sensor location have been expressed, with some studies advocating a system with a single central measurement in the HVAC return system and others preferring a system with multiple measurement points.

APPLICATION

In addition to the studies of the performance of CO_2-based DCV systems, there have also been a number of reports that describe the application of these systems. These reports range from general descriptions of CO_2-based DCV to detailed descriptions of control algorithms. This section reviews a number of these reports.

One of the earliest discussions of the possibilities of using CO_2 to control outdoor air intake as a means of saving energy was presented by Kusuda (1976). This paper presented some of the theoretical background of how indoor CO_2 concentrations vary as a ventilation system is modulated between on and off. Sample calculations of potential energy savings of 40% for an office space were presented. Another early discussion of the energy-saving potential of CO_2 control was presented by Turiel et al. (1979). This paper discussed a number of DCV control options including water vapor and concluded that CO_2 appeared to be the most satisfactory control approach.

A general discussion of the principles of DCV in office buildings is presented by Davidge (1991) and Houghton (1995). These papers discuss the circumstances under which DCV might be expected to be most effective, including the existence of unpredictable variations in occupancy, a building and climate where heating or cooling is required for most of the year, and low pollutant emissions from nonoccupant sources. Davidge points out that when such a system is considered, one must address the base ventilation rate that is not controlled by DCV in order to control these nonoccupant pollutant sources. The impact of free cooling on DCV systems is also discussed, with reference made to the fact that long periods of free cooling will reduce the potential energy savings. The potential for purge ventilation, both before and after occupancy, to control nonoccupant sources is also discussed.

Detailed discussions of the application of CO_2-based DCV are presented by Houghton (1995) and by Telaire (n.d.). These contain background information on why CO_2 can be used to control ventilation and describe the potential energy savings benefits. Strategies for the use of CO_2-based DCV are also described, including simple setpoint control where the outdoor air intake damper is either open or closed depending on the indoor CO_2 concentration, proportional control in which the intake damper or outdoor air fan flow is proportional to the CO_2 concentration, and PID (proportional-integral-derivative) control, which considers the rate of change in the CO_2 concentration. Recommendations are made on the application of these techniques based on the occupancy level.

Descriptions of specific control algorithms are presented by Vaculik and Plett (1993), Federspiel (1996), and Bjorsell (1996). Telaire (n.d.) also describes the Vaculik control algorithm. In their paper, Vaculik and Plett discuss the principles of CO_2-based DCV including setpoint and proportional control. They then describe the Vaculik method, which accounts for differences between CO_2 concentration at the measurement location and the critical location in the building and in which the control setpoint is adjusted to account for differences between the measured concentration and the setpoint.

Federspiel (1996) reports on a control algorithm, referred to as *on-demand ventilation control* (ODVC), and presents a simple simulation to demonstrate it. The ODVC strategy attempts to set the ventilation rate proportional to the occupant density (even under transient conditions) by using a well-mixed single-zone model to estimate the current CO_2 generation rate from measured concentrations and airflows. A simple example is presented to show how the ODVC strategy controls the CO_2 concentration below 1,000 ppm(v) by reacting quickly to a step change in occupancy, while a strategy of PI control of measured CO_2 concentration allows CO_2 to overshoot the setpoint value. Issues regarding the impact on energy use and the potential effect of well-mixed single-zone model inadequacies are not addressed.

Like Federspiel, Bjorsell (1996) also focuses on the description and simulation of a DCV control algorithm with the presentation of a simple simulation example. The control algorithm described, called *linear quadratic*, attempts to calculate the optimal system flow to minimize a cost function that depends on concentration and ventilation flow. However, the cost function is not specified, and, although the control method may be optimal with respect to a given cost function, it also depends on all physical data being known and may not be practical to implement.

The use of CO_2 control of outdoor air is discussed relative to other approaches of outdoor air control in papers by Elovitz (1995) and Janu et al. (1995). Elovitz discusses various options for controlling minimum outdoor air intake rates in VAV systems, including sequencing supply and return fans, controlling return or relief fans based on building pressure, measuring outdoor air intake rates directly, fan tracking, controlling the pressure in the intake plenum, using an outdoor air injection fan, and using CO_2 control. Advantages and disadvantages of each approach are discussed. Elovitz points out that CO_2 control does not necessarily ensure satisfactory indoor air quality, depending on the existence and strength of contaminant sources that are not proportional to the number of occupants. Janu et al. (1995) discuss some of the same methods of outdoor airflow control and raise the same cautions regarding CO_2 control concerning nonoccupant contaminant sources.

As mentioned earlier in the sections on field and simulation case studies, a variety of control setpoints have been used, and many descriptions of the application of CO_2 control contain only limited discussion of how to determine the appropriate setpoint. Schultz and Krafthefer (1993) present a method for determining a CO_2 setpoint based on the indoor air quality procedure in ASHRAE Standard 62-1989. This method employs a two-zone model of the ventilated space and considers the ventilation efficiency of the space. Nomographs are presented for use in determining the CO_2 setpoints.

SUMMARY AND CONCLUSIONS

This literature review has attempted to describe the research into the application of CO_2-based demand-controlled ventilation. It has covered case studies conducted in the field and through computer simulation, research on sensors, and discussions of the application of CO_2 control. This section summarizes a number of findings of the literature review and identifies research needs. A table summarizing the literature reviewed in terms of the type of report and topics addressed is included for reference.

There is fairly wide consensus on when to use CO_2 control. Most discussions of CO_2-based DCV mention the following building types as good candidates for such systems: public buildings such as cinemas, theaters, and auditoriums; educational facilities such as classrooms and lecture halls; meeting rooms; and retail establishments. However, it is interesting to note that many of the case studies have investigated office buildings. As presented by Davidge (1991), the following building features correspond to situations where CO_2-based DCV are most likely to be effective:

- the existence of unpredictable variations in occupancy,
- a building and climate where heating or cooling is required for most of the year, and
- low pollutant emissions from nonoccupant sources.

There have been a number of valuable demonstration projects in real buildings, and many of these have shown significant energy savings through the use of CO_2 control. However, several cases exist where the indoor CO_2 concentration was rarely high enough for the outdoor air intake dampers to open, suggesting a mismatch between building occupancy, ventilation rates, and control setpoints. A significant shortcoming of several of the field tests, as well as of the computer simulation studies, was the inclusion of little or no description of the CO_2 control algorithm investigated in the study. These omissions make it hard to evaluate which approaches work and which do not.

While CO_2 control can control occupant-generated contaminants effectively, it may not control contaminants with nonoccupant sources, such as some building materials and outdoor sources. The control of such nonoccupant sources is a difficult issue because one cannot engineer for these sources unless the source strengths and indoor concentration limits are known. However, both types of information are not readily available for most contaminants and most sources. A practical solution is to maintain a base ventilation rate at all times, which can be proportional to floor area, that is adequate to control nonoccupant sources. A morning purge of the building with outdoor air may also be a good idea, but it is probably equally applicable to non-DCV systems. An outdoor air purge cycle during the day is another possibility for DCV systems for controlling nonoccupant sources.

The research on sensors appears to indicate that currently available technology is adequate for use in these systems, though some questions have been raised regarding calibration frequency, drift, and temperature effects (Fahlen et al. 1992; Houghton 1995). A key issue that has been identified is sensor location, in particular whether to use a single sensor centrally located in the system return or multiple sensors located in the returns for whole floors or in particularly critical spaces, such as conference rooms. Whenever a central location is suggested, the issue of variability among spaces is almost always mentioned. Using a lower setpoint with a central sensor is often suggested as a means of dealing with the variability issue.

A number of needs for more research and information were identified in this literature review. For example, more system-specific guidance on application of CO_2-based DCV is needed. This guidance should be based on system type, zoning, and expected variations in occupancy patterns among the zones. Prior to the development of this guidance, sensitivity analysis using simulation programs would be desirable to determine the factors that impact energy savings and other performance issues. In addition, there have been many applications of CO_2 control in buildings that have not been documented. It would be extremely useful to investigate these installations and document them in terms of design and performance. Another issue meriting attention is the use of CO_2-based DCV to increase ventilation rates and provide sufficient ventilation to occupants, as opposed to its use to reduce ventilation rates.

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Summary of Reviewed Literature

	Field Test	Simulation	Sensor performance	Sensor Location	Application	Energy	IAQ	Economic	Control Algorithm	Office	Residential	School	Conference Room	Other Building
Anon. 1986	X					X								X
Barthez and Soupault 1983	X		X			X					X			
Bearg 1994				X	X									
Bjorsell 1996		X							X		X			
Carpenter 1996/Enermodal 1995		X		X		X	X		X	X				
Davanagere et al. 1997		X				X	X	X				X		
Davidge 1991	X					X	X			X			X	
Donnini et al. 1991/Haghighat and Donnini 1992	X					X	X	X		X				
Elovitz 1995					X									
Emmerich et al. 1994		X				X	X			X			X	
Fahlen et al. 1991 and 1992			X	X										
Federspiel 1996		X							X				X	
Fehlmann et al. 1993	X					X	X							X
Fleury 1992	X						X						X	
Gabel et al. 1986	X					X	X			X				
Haghighat et al. 1993/Zmeureanu and Haghighat 1995		X				X		X		X				
Hamlin and Cooper 1991		X				X	X				X			
Helenelund 1993					X									
Houghton 1995			X		X									
Huze et al. 1994	X												X	
Janssen et al. 1982/Woods et al. 1982	X					X	X					X		
Janu et al. 1995					X									

Summary of Reviewed Literature (Continued)

	Field Test	Simulation	Sensor performance	Sensor Location	Application	Energy	IAQ	Economic	Control Algorithm	Office	Residential	School	Conference Room	Other Building
Kesselring 1996	X										X			
Knoespel et al. 1991		X				X	X			X			X	
Kulmala et al. 1984	X					X								X
Kusuda 1976		X			X	X				X				
Meckler 1994		X				X		X		X				
Meier 1993			X											
Moffat 1991	X						X				X			
Nakahara 1996		X				X						X		
Ogasawara 1979		X				X		X						X
Okamoto et al. 1996			X											
Potter and Booth 1994	X				X									X
Raatschen 1990			X		X									
Reardon and Shaw 1993/Reardon et al. 1994				X										
Ruud et al. 1991	X			X									X	
Schultz and Krafthefer 1993					X									
Shirey and Rengarajan 1996		X				X	X	X		X				
Sodergren 1982	X		X	X			X			X				
Sorensen 1996		X				X			X	X			X	
Strindehag et al. 1990	X									X		X	X	
Stymne et al. 1990/Stymne et al. 1991				X	X									
Telaire Systems, Inc					X				X					
Thellier and Grossin 1981		X				X					X			
Turiel et al. 1979					X	X								
Vaculik and Plett 1993				X	X				X					
Warren 1982	X					X								X
Warren and Harper 1991		X				X								X
Yuill and Jeanson 1990/Yuill et al. 1991		X					X				X			
Zamboni et al. 1991	X					X	X							X