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A Review of Demand Control Ventilation

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A Review of Demand Control Ventilation

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Summary: *This paper provides background and update on demand control ventilation (DCV) technology for commercial buildings, its penetration and acceptance in the market, and to identify what evidence there is that such systems are benefiting current building stakeholders in terms of energy savings, improved indoor environmental quality, and reduced complaints. The paper also provides a basis for a study design to assess the effectiveness of existing DCV systems operating under real conditions.*

Keywords: *DCV, indoor air quality, commercial building ventilation, CO_2, energy savings*

Category: *Commercial Building Ventilation -- IAQ and Energy*

1 Introduction

Ventilation of commercial buildings (CBs) is important for removal of airborne contaminants generated by the biological functions of occupants and other living organisms residing indoors, occupant tasks and operations, equipment, supplies and furnishing, building materials, and products of chemical reactions between contaminants from both indoor and outdoor sources. These undesirable contaminants take the form of gaseous or airborne particulate matter, and can be detrimental to the quality of the indoor environment through their odor, reactivity, infectiousness, toxicity, carcinogenicity, or through mechanisms as yet unidentified.

The effects of outdoor air supply rates (i.e., ventilation rates) on human health, comfort, and performance in CBs have been reviewed by a number of researchers [1,2]. The mounting evidence discussed in these works indicates that higher ventilation rates are associated with lower rates of sick leave and the prevalence of common respiratory diseases. Building related illness (BRI), also referred to as sick building syndrome (SBS) has been identified as being linked to lower ventilation rates [1]. Fisk [3] estimates that many tens of billions of dollars could be saved annually in the U.S. through improvement of indoor environmental conditions in commercial buildings. Adequacy of ventilation was one of a few key components needed to achieve these improvements.

Building heating, ventilation, and air conditioning (HVAC) systems in nearly all U.S. climates require a significant amount of energy to condition the outdoor air used for ventilation. Fisk et al. [4] estimate that between 0.75 and 1.5 EJ (0.71 and 1.4 Quad) of energy is consumed to ventilate commercial buildings in the US each year. The 2003 Commercial Buildings Energy Survey is in agreement, with an estimated 1.1 EJ (1.0 Quad), or 5.8% of the CB sector energy, consumed for ventilation [5]. Total HVAC energy consumed in this sector in 2003 is estimated at 5.8 EJ (5.42 Quad), or about 18% of the U.S. total primary energy use [5] That this ventilation component is responsible for about 1% of the US energy budget underscores the need to properly design, fabricate, install, operate and control, and maintain CB outdoor air supply systems.

Ventilation rates for commercial buildings are codified as requirements in numerous state and federal energy standards in the U.S., often based on the recommendations in ASHRAE Standard 62.1 [6]. The rates vary depending upon the specified end-use of the building (i.e., differ for office, classroom, retail store, etc.) and now require both a per-person and per-area component. The rates are typically expressed in units of $Ls^{-1}person^{-1}$ (cfm $person^{-1}$) and m^2 $person^{-1}$ (ft^2 $person^{-1}$) components.

Mechanical provision of outdoor air in CBs is typically supplied by an air handler with a damper system that can divert a percentage of re-circulating air to exhaust and entrain an equal flow of outdoor air into the system. Many air handlers provide only a fixed outdoor air damper position, presumably set to meet the outdoor air demand for the indoor zone it is ventilating, and often improperly set. HVAC economizers have the provision to vary the outdoor air damper position based on a control signal such that fresh air is provided either for cooling or to meet occupant ventilation air demand.

Regardless of the end-use, surveys of provision of ventilation in CBs suggest that few buildings actually maintain outdoor air supply rates consistent with ventilation standards. For example, Persily et al. [7] indicate that in a survey of 100 randomly selected large office buildings in the U.S. studied from 1994-1999, the average of measured outdoor air supply rates was 55 $Ls^{-1}person^{-1}$ (120 cfm $person^{-1}$) using duct traverse measurements[1]. The consensus ventilation standard of the time, ASHRAE 62-1989 [8]required a minimum outdoor air ventilation rate in office buildings of 10 $Ls^{-1}person^{-1}$ (20 cfm $person^{-1}$). On the other hand, a recent survey of California portable classrooms found that carbon dioxide (CO_2) concentrations exceeded 1000 parts per million (ppm) in about 40% of classrooms, and exceeded 2000 ppm in about 10% of classrooms [9]. Current California

[1] Outdoor ventilation rates estimated based on peak carbon dioxide concentrations in the space were lower, with a mean of about 20 L/s $person^{-1}$ (40 cfm $person^{-1}$).

state standards require a ventilation rate of 8 $Ls^{-1}person^{-1}$, approximately equal to steady state CO_2 concentrations below 1000 ppm. Currently about 100,000 portable classrooms are in use in California.

Over ventilated buildings waste energy with little or no benefit to the occupants, while under ventilated buildings may have significant adverse affects on occupants. Demand control ventilation (DCV) is one technical approach to better match building ventilation rates to their occupancy. This paper discusses the current state of the art for DCV in CBs, identifies information gaps regarding the state of DCV in CBs, and suggests research paths to address these gaps.

2 Demand Control Ventilation

Control of mechanically supplied rates of outdoor air intake into buildings based upon occupant demand is referred to as DCV. Largely driven by prescriptive standards for minimum per-occupant outdoor air intake rates, DCV is intended, while faced with variable occupancy rates, to optimize for the competing needs for adequate ventilation of occupied spaces and for minimization of energy use for thermal conditioning of outdoor air.

In its simplest form, DCV could be accomplished by tying ventilation fan and damper operation to a room light switch or occupancy sensor. Such approaches do not meet the intent of varying outside air ventilation by occupancy. For this, some means of providing a control signal that is proportional to the number of occupants is needed to vary the outside airflow rate. The method currently available on the HVAC market is based on sensing the rise in CO_2 in the indoor air relative to that outdoors. CO_2 works because the rate at which it is generated indoors is somewhat proportional to the number of occupants, assuming no significant additional sources of CO_2 are present. In practice this method is not without problems, but from a theoretical standpoint in has the potential meet the needs for DCV. An alternate approach that has thus far had little commercial attention is to use technology that can count people passing into and out of buildings, or individually ventilated zones within buildings. People counters could be used to track the total number of occupants within the ventilated space at any point in time. Current advances in sensing and micro-computing technology suggest that such approaches may now be feasible.

History

Emmerich and Persily [10] reviewed the state of the art of DCV using CO_2 control. Since CO_2-based DCV is the only implementation with significant adoption in the U.S., their review is an excellent starting point for this paper. Although some engineering designs and demonstrations occurred as early as the 1970s, DCV did not receive much attention by HVAC engineers until the 1990s. A number of options for measures of occupancy were considered in this period including CO_2, volatile organic compound (VOC) and humidity concentrations.

In 1997 an interpretation of ASHRAE Standard 62-1989 [8] affirmed that under certain control-related conditions CO_2-based DCV could be used to modulate outdoor air intake rates to meet variable occupancy demands. CO_2-based DCV is now accepted by both ASHRAE 62.1 the International Mechanical Code (IMC) [11], and the California Energy Code [12], and has been required in the California Building Standards Code since 2001 for some-high density applications during low occupancy periods [13]. The CEC code language specifies only CO_2-based sensors for the purpose of meeting the requirement [14].

Since acceptance of requirements of DCV by these standards and regulatory bodies, it has become widely adopted with an estimated 60,000 CO_2 sensors for ventilation control now being sold annually [15]. DCV is commonly implemented by integrating a ventilation demand sensor (i.e., CO_2 sensor) with an economizer damper. All of the major HVAC equipment manufacturers provide the hardware and control software for DCV applications.

Standards

California's minimum code requirements for DCV sensing and control are shown in Table 1. Implicit in this standard is a minimum outside air flow rate of 8 $Ls^{-1}person^{-1}$ (15 cfm $person^{-1}$). These requirements reflect ASHRAE 62.1 and the IMC language.

Table 1. California's 2005 Minimum Code for DCV sensing and control [12].

• DCV is required when design occupancy is $\leq 3.7\ m^2\ person^{-1}$ (40 ft^2/person). Classrooms are exempted but allowed
• CO_2 sensors must be located in the breathing zone and not in return air ducts
• Ventilation must be maintained to limit $CO_2 \leq 600$ ppm above the ambient level measured dynamically or assumed to be 400 (approximately equivalent to 8 $Ls^{-1}person^{-1}$; 15 cfm $person^{-1}$)
• Regardless of the CO_2 sensor's reading, the system is not required to provide more than the minimum ventilation rate required for the space occupancy/use type
• The system controls must always provide a minimum ventilation rate setting based on code occupancy/use type.
• CO_2 sensors must have factory certified accuracy of ±75 ppm or less over a five-year period without recalibration in the field
• CO_2 sensors designed to be "self calibrating" must have manufacturer documentation that they meet these calibration requirements

Sensors

Since the 1990s the focus on control for DCV has been almost entirely based on carbon dioxide sensing. Microelectronic technology of the 1980s led to the miniaturization of the stable, sensitive, and accurate non-dispersive infrared (NDIR) sensors that had previously only been available as bulky and energy consuming bench top analyzers. Although the early models of these sensors were reasonably accurate, they were prone to calibration drift and required frequent calibration, causing them to be unreliable.

Improvements in sensor design and addition of integration of microprocessor control led to models with substantially longer-term stability. Two divergent NDIR techniques, single and dual beam optical, and photo-acoustic sensors have been employed in commercial sensors. Variants of these technologies are marketed by at least a dozen manufacturers in the U.S. [15]. Both device types now have specifications that include rated accuracy ranges of ±30 to ±50 ppm, estimated drift rates of 0 to ±10 ppm per year, required calibration intervals of 5 years (one manufacturer claims that their product is self calibrating and never needs to be calibrated), warrantees of 12 months to 5 years, and expected lifespan of up to 15 years. Many of the devices employ an automatic baseline drift correction (ABC Logic) routine, described as self-calibration, which resets the daily lowest measured value to an assumed background CO_2 concentration of 400 ppm.

Unpublished data [16] from the Iowa Energy Center showed long-term output from three "self calibrating" NDIR CO_2 sensors operated side by side. Although these new sensors are guaranteed to hold calibration for five years, one unit was observed to have a positive baseline offset of 105 ppm compared to the other two that registered with 25 ppm at about 400 ppm. Nine months later, the baseline of the same unit had diverged by 265 ppm. The National Building Controls Information Program, Iowa Energy Center is expected to start a wall mount HVAC grade CO_2 sensor testing project later in 2006 to address this issue.

A low cost solid electrolyte electrochemical CO_2 sensor has recently become available and is used in some new DCV control products. Based on published specifications the lifetime and accuracy of this technology is substantially poorer than those of the NDIR sensors and would not be acceptable for use in DCV applications that are specified in state energy codes [12].

Ventilation and Energy Performance

Emmerich and Persily [10] reviewed the ventilation performance information from DCV systems up through 2001. They pointed out that although most studies of DCV performance were conducted on office buildings, the best candidate CBs are public buildings with widely variable occupancies such as theaters, classrooms, meeting rooms, retail stores, and restaurants. They repeat that the key CB use features necessary to take advantage of DCV are 1) the existence of unpredictable variations in occupancy, 2) CBs where heating or cooling is required for most of the year, and 3), assuming and occupant trigger such as CO_2, low pollutant emissions from non-occupant sources. Many of these earlier studies found that the occupancy levels rarely reached the trigger point to increase the outside air damper opening.

Results from several field studies of DCV performance have been published recently [17,15] and are summarized in Roth et al [18]. Braun et al. reported the application of DCV in semi-matched pairs of fast food restaurants and, and modular classrooms. In the case of the restaurant spaces the DCV lead to increased CO_2 concentrations indoors during occupied periods as ventilation rates modulated with varied occupancy, with maximum concentrations nearly always below 1000 ppm. Baseline indoor CO_2 concentrations in the modular classrooms, consistent with the CARB/DHS study, were typically in excess of 1200 ppm in violation of the state energy standards. With the addition of an economizer damper set to meet the nominal ventilation requirements for the class occupancy, daytime average CO_2 concentrations dropped, but still exceeded 1000-ppm maximum for about 40% of the school day. With the addition of DCV, indoor CO_2 concentrations in both classrooms dropped; one classroom maintained indoor CO_2 levels below 1000 ppm, while the second one exhibited levels between 1000 and 1200 ppm about 16% of the time. An office building in Birmingham Alabama, a hot and humid region of the U.S., had a sophisticated CO_2 DCV system installed after high energy bills pointed to average ventilation rates of 14 to 18 Ls^{-1} $person^{-1}$ (28 – 35 cfm $person^{-1}$). After installation of the DCV system, ventilation rates were reduced to a design level of 10 Ls^{-1} $person^{-1}$ (20 cfm $person^{-1}$). The authors report that humidity levels in the building were reduced by lowering the ventilation rate, and that this improved the comfort of the occupants [15].

DCV can provide energy savings by tailoring the ventilation air conditioning load to actual occupancy. In the example of the restaurant condition discussed above [17] energy savings from DCV use ranged from 50 to 10%, decreasing with increasing outdoor temperature. Payback estimates for the investment in DCV equipment in the restaurant case ranged from about 2.9 to 6.5 years. As would be expected, in the case of the modular classrooms, the relatively stable occupancy patterns minimized energy savings. Broader analyses based on modeling suggest that in the U.S., DCV has the potential to reduce CB heating and cooling loads by about 10% [18]

Control Strategy Issues

Although CO_2-based DCV has been increasingly adopted over the last decade, this method is not without its detractors. An inherent sensor lag time

exists with CO_2 as an indicator of occupancy because it relies on a rise in concentration greater than the natural noise of the sensor signal and concentration fluctuations. More importantly, dependent on the air exchange rate, the rise and decay of CO_2 has time constants from many minutes to many hours. Depending upon the building design and function, and occupant density, a number of different control strategies are available to compensate for these lag times. The three most common control algorithms are set point control (least precise), proportional control, and exponential control (most precise, Schell et al 1998).

Damiano and Dougan (2005) point out that transient inaccuracy in ventilation rate control using CO_2 due to the compound effects of lag time and sensing inaccuracies may lead to substantial transient excesses of ventilation or rates below the minimum standard. They suggest to the risk of non-compliance using this method should be considered. The proposed alternative is accurate outside air flow measurement systems, presumably coupled with people counting devices. Although such systems are desirable, they are not yet widely available. The performance of three different outdoor air flow measurement systems has been recently studied (Fisk et al. 2005). A few people counting device types employing dynamic infrared imaging hardware and software have recently become available at costs approaching the feasible range for building controls. Counting accuracy of these devices can be quite good and may exceed that of the CO_2 sensing approach.

3 Discussion

Although the above overview is by no means comprehensive, it covers the highlights of the current state of DCV technology. The references provided may be consulted for details. The following discussion focuses on research needs for future implementations of DCV and validation of performance in existing installations.

Performance of Existing Systems

Although manufacturers have published considerable anecdotal information regarding the long-term stability of their NDIR CO_2 sensors, very little quantitative information is available on sensor drift, electronic noise, and failures. Presumably major defects are few and far between since users are not reporting chronic problems of sensor failure. Sensor calibration drift a more insidious problem since building managers might not necessarily be aware of it unless they conduct systematic measurements of CO_2 within their building with calibrated instruments. The 5-year recalibration specification leaves considerable time for unanticipated drift problems to occur. For every hundred thousand devices in use, a 1% rate for units with undetected drift would suggest 1,000 buildings may be experiencing either excessive energy use through over ventilation, or non-compliance with minimum ventilation standards and poor IAQ due to low ventilation.

Research Needs

In addition to the long-term laboratory evaluation of sensors planned by the Iowa Energy Center, a longitudinal field evaluation of the energy and IAQ performance of DCV systems in CBs would provide verification of the longevity of the reliability of existing DCV technology. The study should address sensor soiling and calibration drift, reliability of the electronic components, and economizer function. The functionality and extent of wear of the economizer damper mechanical systems and motor drive should be checked. Estimates of rates of uncorrected failure should be derived from this study and the energy and IAQ consequences should be quantified.

Non-occupant Sources and IEQ under DCV

As reflected in ASHRAE 62.1-2004, ventilation is required in buildings for removal of contaminants emitted from fixed indoor sources such as buildings materials, furniture, cleaning products, office equipment, retail products, etc., as well as for occupant-generated bioeffluents. The current standards attempt to account for this by 1) providing a minimum ventilation rate based on floor area, and 2) restricting DCV implementation to spaces that do not have significant material or process emissions. Nonetheless, verification of the overall effectiveness of DCV systems to broadly provide adequate IAQ in buildings having large swings in occupancy should be considered. The concern about non-occupant emissions in classrooms was the impetus behind their exemption from the Title 24 DCV requirement (Jenkins 2002).

Research Needs

Field verification that CO_2 based DCV systems operating in buildings with large temporal swings in occupancy are able to effectively remove common contaminants not generated by the occupants. These contaminants might include VOCs and aldehydes emitted from furniture and office equipment, pesticides from pest control activities, legionella dispersed from water systems, particles and allergens entrained from vacuuming, combustion products (carbon monoxide, nitrogen dioxide, water vapor) from poorly vented heating or cooking processes, etc. Minimum ventilation rate settings for should be checked to ensure that air contaminants are being removed. These rates should be scrutinized from the standpoint of the health of the occupants.

Health and Performance Basis for Per-person Ventilation Rates

The per-person rates in the current ventilation standards such as Table 6-1 in ASHRAE 62.1 have their origins in occupant satisfaction with body odor removal (ASHRAE 2004, Yaglou 1938). To date, no health-relevant basis for ventilation rates have been established. As discussed in the introduction, some

evidence exists that building related occupant symptoms and performance degradation are associated with ventilation rates higher than the minimum in the standards. Although this is a broad issue related to ventilation of buildings, DCV could potentially exacerbate problems related with inadequate ventilation. Since many CBs are over ventilated, tightening down on outside air supply rates using DCV leads to lower average rates during occupied periods. If the current minimum rates are not sufficient for some or all occupants, health problems such as sick building syndrome may become more prevalent in CBs.

Research Needs

The need exists to develop a scientifically justifiable understanding of the relationship between CB ventilation rates and occupant health and symptom prevalence, respiratory disease transmission, absenteeism, productivity, and learning performance. Studies employing epidemiological design to elicit the prevalence of symptoms or other building related outcomes as a function of measured ventilation rates, across a wide range of outside air rates would be needed. Such studies would need to be replicated in a number of building types with different uses. Results from such studies would provide a substantial improvement in justification for any particular ventilation rate.

Alternatives to CO_2 based DCV

For the reasons presented above, there are arguments for controlling ventilation based upon actual measured outside air flow rates and occupancy counts rather than with CO_2 or other ventilation rate surrogates. Both occupancy counting and outside air flow rate measurement components are needed to accomplish this. Progress has been made in technology development in both these areas.

Research Needs

Electronic integration of occupancy counting and outside air flow measurement systems with economizer damper for control and use of appropriate software is required to realize DCV using this approach. Laboratory testing and validation, and then field installation and testing will be necessary before such systems are ready for commercialization. The potential benefit is more accurate matching of outside air to occupant demand.

4 Conclusions

DCV technology has matured in the last decade and is now employed in hundreds of thousands of buildings in the U.S. Occupancy sensing using CO_2 is now considered inexpensive to operate and reliable over periods of years. The technology is now prescribed in state, national, and international standards as a means of ensuring adequate ventilation and conserving energy. When applied properly it appears able to provide these benefits. Excessive ventilation rates have been brought under control and energy has been saved. Likewise, under ventilated buildings have been improved by provision of a minimum outside air supply rate.

With these technical advances comes the responsibility to maintain and verify the performance of the equipment. Although one building at a time, maintenance is surely being provided, very little quantitative information on the long term reliability and performance has been collected. Roughly a decade into the era of DCV it is time to take stock and see what is working well and what might need improvement.

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