ASHRAE Journal

Assessing CO_2 Control In Retrofits

By **Mike Schell,** Member ASHRAE, and **Doug Smith**

CO_2 control benefited an Energy Star-rated building.

Although CO_2-based ventilation control often is used in new construction, retrofits of existing buildings involving CO_2 control are less common. This is probably because retrofit projects typically need a high degree of documentation of possible savings and benefits. In addition, control retrofits are perceived as complex. Ironically, the most significant opportunity for energy savings is in existing buildings where a clear track record of energy usage patterns is available for analysis.

This article presents a methodology for assessing the potential for a CO_2 retrofit on an existing building. Discussion includes an actual assessment and retrofit of a Class-A office building that uses this methodology and the resulting performance enhancements. The subject building is a U.S. Environmental Protection Agency (EPA) Energy Star®-rated building that has a state-of-the-art direct digital control (DDC) system.

Background

Ventilation control of outside air (OA) in most buildings is passive and unresponsive to changes in occupancy. The traditional approach to ventilation has been to provide a fixed rate of OA ventilation based on a total calculated building occupancy at design. In the majority of buildings without airflow stations, an air balancer probably set the fixed rate during building commissioning. Once the building was occupied, ventilation settings likely were adjusted, and the original occupancy assumptions may no longer be valid. Ventilation control with CO_2 is an operational strategy for a building that ensures that OA ventilation rates are maintained throughout the operating life of a building.

If you don't measure it, you can't control it. In the case of ventilation, affordable and stable sensor technology uses CO_2 concentrations to estimate fresh air ventilation rates at the zone level.[1] By properly using CO_2 measurements in a space, we can control ventilation to ensure that the cfm/person ventilation rates are provided at all times.[2]

The most obvious applications for CO_2 ventilation control have been considered spaces where occupancy is highly variable, or intermittent. This includes theaters, meeting rooms,

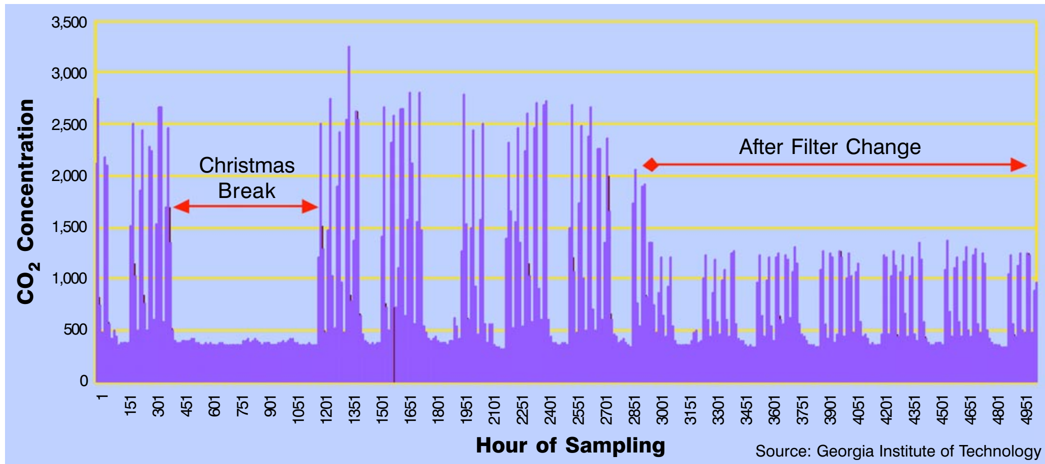


Figure 1:** CO_2 **levels and air filter cleaning in a school from December 1998 to March 1999.

school gymnasiums, classrooms, retail spaces and hospitality.

However, ventilation control using CO_2 sensors also can be effectively applied in buildings that experience more static occupancies and lower densities. Zone control CO_2 integrated with an automated building control system provides an ongoing method to confirm that the original design ventilation rates of the building are met throughout its operational life. Inevitable changes in occupant densities and occupancy schedules can be measured and compensated for with CO_2 ventilation control.

This ability to measure and control OA ventilation is an important tool for building operators. Initial air intake settings often are adjusted from originally commissioned settings in response to complaints. In some cases, maintenance staff use a 20% rule of thumb for outdoor air/return air ratio to set outside air intake dampers. Given that the relationship between damper position and airflow is exponential, a 20% damper position often results in an outside airflow rate much greater than 20%. This post-commissioning adjustment means that many buildings are significantly over-ventilated—even above original design airflows. A CO_2 control strategy eliminates the need for manual adjustment of air intake dampers and maintains the appropriate outside airflow based on current building occupancy.

A CO_2-based control strategy can enhance building operation regardless of occupant density, or whether occupancy is static or highly variable as follows.

• CO_2 levels provide a good indication of occupancies and can be used to tighten building operating/setback cycles. CO_2 levels can be used to directly activate setback and operational cycles. Some thermostats use CO_2 levels to determine occupied and setback periods now.

• Ventilation air can come from a variety of sources aside from the primary mechanical air delivery system. This includes transfer air within the building, infiltration, and also open doors and windows. If all, or part, of the ventilation requirements are satisfied by these means, a CO_2 ventilation control system will not require that additional conditioned outside air be needlessly delivered by the mechanical system.

• CO_2 levels can provide an indicator of building operating status particularly if a deviation from baseline levels occur. For example, if CO_2 levels are exceptionally high or low in a space that is to be controlled, some breakdown in the air delivery system can be identified. Elevated CO_2 levels in supply air also have been used to identify the presence of combustion air entering air intakes (combustion air typically contains 8% to 12% CO_2 by volume).[3] As shown in *Figure 1,* CO_2 levels have also been used in classrooms to indicate when clogged air-handling filters are reducing effective air delivery to a classroom.[4]

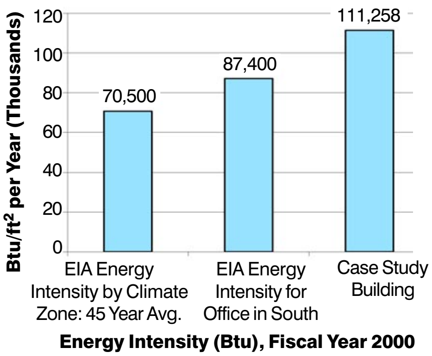
For a CO_2 ventilation control system to work properly, the entire building control system must be operating properly. Often, existing building problems are identified that must be fixed before implementing CO_2 ventilation control.[5] In addition, the process of upgrading to CO_2 ventilation control may reveal building problems that previously were unknown or ignored.

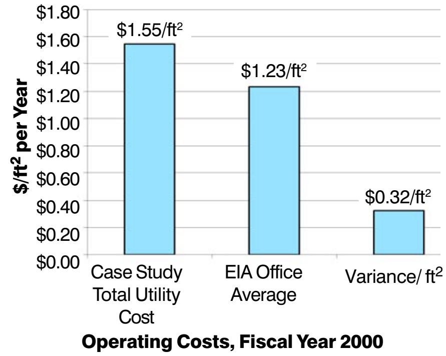
Candidates for CO_2 Upgrades

The complexity of a CO_2 ventilation control retrofit is related to the type of building control system currently in place.

About the Authors

Mike Schell is director of sales and marketing for ATI AirTest Technologies Inc., Santa Barbara, Calif. **Doug Smith** is vice president of engineering and technical marketing for Energy Savers Inc., Solvang, Calif.





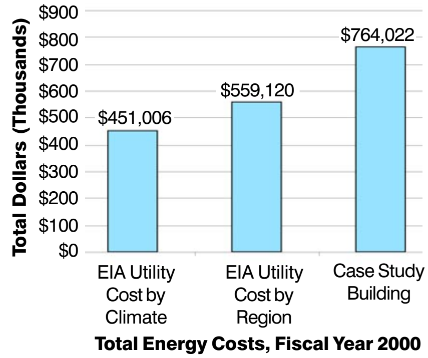


Figure 2 (left): Comparing Btu energy consumption to DOE benchmark data. Figure 3 (center): Comparing annual $/ft² energy cost to DOE benchmark data. Figure 4 (right): Comparing annual energy cost to DOE benchmark data.

Ideally, sensing and control must occur at the floor-plate or zone level and at the central air handler.

The ideal candidate is a building with a DDC system that has available input and output (I/O) points for zone-based sensors, and has the capability or potential to be programmed to provide CO_2-based ventilation control.

Sensor selection should not be made on the basis of cost alone, but rather on documented accuracy, stability and signal repeatability. Additionally, many automation engineers simply are not experienced in the complexity of developing and writing a DCV design sequence. Therefore, the services of an experienced consultant should be considered to avoid potential pitfalls. Although new systems often are plug-and-play, a retrofit configuration requires an additional level of expertise.

Some new developments in sensors will make retrofit easier for some applications, such as:

• Several systems integrate CO_2 and temperature control as part of the overall VAV system with one combined CO_2 and temperature sensor installed in each zone.

• Sensors are available that can take over local control of the VAV box to modulate the box based on both temperature and CO_2.

• Inexpensive single zone CO_2 sensors are available that integrate the capability for setback temperature control, CO_2 ventilation control and economizer control.

Often, to save money, designers install a single CO_2 sensor in a return air duct to reduce system cost. While this is acceptable for single-zone systems, this approach is not recommended in multizone systems for the same reason that temperature sensors are never placed into return air ducts. An in-duct measurement represents the average of all zones served and cannot indicate if particular zones are over- or under-ventilated.

Methodology

The methodology described in this article has been developed during the past several years while working with companies that collectively own and/or manage buildings throughout the United States. The methodology was developed in response to the requirements of these building owners who must be able to assess the possible economic impact of a CO_2 retrofit vs. other building upgrade initiatives.

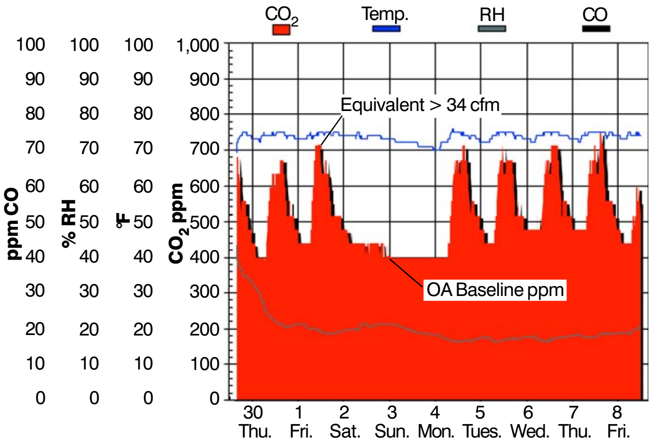
The CO_2 retrofit assessment methodology and its steps are briefly outlined here. Further details are provided in the case study that follows.

1. Pre-Project Energy Consumption Analysis. Energy consumption data for the previous 12 months is collected and compared with statistical energy and operational building data available from the U.S. Department of Energy (DOE).[6] This DOE data includes local climatic weather data (heating and cooling degree days) that can be used to normalize energy data for year-to-year fluctuations in energy use based solely on weather effects. Analysis of this data can indicate how energy consumption of the target building generally compares to other buildings in the area.

2. Site Data and Profiling Analysis. The second phase involves collecting a representative sampling of indoor conditions using data logging monitors that record temperature, relative humidity, and carbon dioxide. Other gases such as carbon monoxide also can be measured. Measurements should be made during at least one full workweek. At least one monitor should be placed in each area where outside air from an air handler regulates ventilation. If an area contains zones that have different densities or occupancy patterns, monitors should be placed in each of these zones. This data allows for assessment of occupancy patterns, and provides for an estimation of ventilation rates based on CO_2 concentrations. Ideally, measurements should be made when the building is not using a economizer strategy for cooling as CO_2 concentrations in economizer mode will be very low and not representative of CO_2 and OA ventilation levels when the building is in a normal heating or cooling mode.

During placement of measurement devices, a walk-through with the building manager is needed to understand the operation of the building control system. Tenant complaints or known building operating issues also are reviewed. Occupancy patterns and density are noted for each zone.

Using the site data, it is possible to assess if the building is generally over-ventilated and represents an energy savings



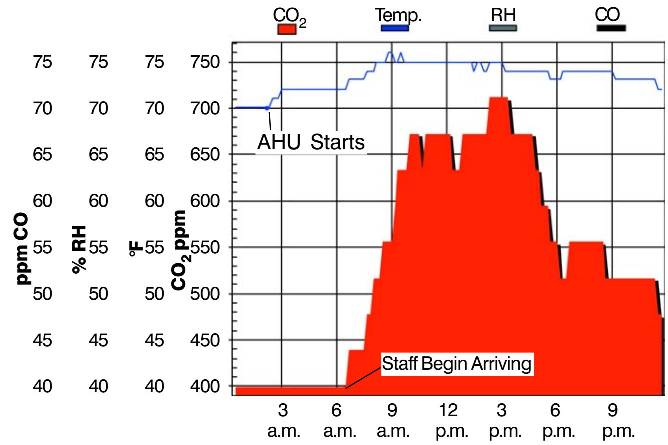


Figure 5 (left): Seven-day environmental profile for one floor of case study building. Figure 6 (right): One-day environmental profile of a sample floor of the case study building.

opportunity, or under-ventilated, representing an additional operating cost to configure the building to meet target ventilation rates. In either case, ventilation control with CO_2 may offer the most economical approach to meeting ventilation requirements and minimizing energy use.

One issue some building owners may face is: should ventilation rates be maintained at the levels that were required by code at the time of construction, or should the system reflect current ventilation standards if rates are now higher or lower? Often, regardless of the owner's desire to increase the OA amount, mechanical/building design constraints prevent such an increase. The air-handling unit (AHU) may lack the capacity to condition an increased volume of OA, or more OA cannot be delivered to the AHU without extensive capital investments in all of the associated equipment.

3. HVAC System Evaluation. This phase involves reviewing the original building design documentation to find building operating sequences and schedules, assumed design occupancies, design ventilation rate requirements and the version of the code or standard used as the basis of design. Current operation should be compared to the original design.

4. Building Automation System Evaluation. Next, the potential for the building control system to integrated CO_2 ventilation control is assessed. Factors to consider include:

• Is the system capable of integrating the appropriate CO_2 control algorithms into its programming?

• Are there points in the system to modulate outside air at the central air intake and at the zone or floor level? Additional equipment may be needed if this control capability does not exist.

• Are there sufficient input points into the building control system for the CO_2 sensors?

• What other equipment, control strategies or programming changes should be recommended to ensure optimum operation of the building?

5. CO_2 Control Simulation and Energy Savings Analysis. Based on the CO_2 measurements recorded throughout the course of a week, an estimate of the ventilation rate delivered to each zone is made using the peak CO_2 concentrations. This approach requires that CO_2 concentrations have peaked and leveled indicating equilibrium of CO_2 production and OA ventilation rates has occurred.

Then, an energy analysis is performed to compare the cost of preconditioning outside air at the estimated ventilation rate to the use of CO_2 control based on observed occupancy density and patterns. Several sensor and equipment manufacturers offer simulation programs that use local energy and climatic data to perform this type of analysis. The program used for the case study that follows was one that was developed by the authors. The CO_2 analysis portion of this program has been published in *ASHRAE Transactions*.[7] The program uses hourly dew point and temperature data and discounts for economizer operation when conditions for free cooling occur. Other programs, such as DOE-2, can be used for this type of analysis.

Based on the results of the analysis and an estimate of costs for completing the retrofit, a return on investment is calculated for the project.

6. Post-Installation Evaluation. The overall performance of the building is checked against projected savings and actual climatic data. Status reports are prepared and delivered to the customer six months and 12 months after completion of the project using the same metrics used to assess the project initially.

Case Study of a CO_2 Retrofit

The case-study building is a 28-story corporate-owned and managed property. The building is located in a southern tier state with a high degree of cooling-dominated HVAC loads, and has winter heating loads. The client's portfolio is comprised of many other buildings, so its energy rates are quite low. This makes the process of extracting energy cost savings more difficult. The building has a full DDC automation system.

The building is an Energy Star certified and recognized facility, therefore the client was skeptical at first that further improvements could be realized, even with CO_2-based ventilation control.

In this installation, wall-mount CO_2 sensors were placed in areas representative of typical occupancy or "critical" ventilation spaces on each floor. Outside air ventilation delivery to each floor was controlled in a proportional manner based on the highest CO_2 concentration measured on the floor. A minimum ventilation rate was maintained within the building during occupied hours to control non-occupant-related sources and to maintain building pressurization.

Within the first six months of operation, electrical and steam loads dropped sharply, with corresponding decreases in energy exceeding 57% of predicted annual savings (only 50% of the year was under active ventilation control with CO_2). The original simple Return On Investment (ROI) projections were for a 2.2-year ROI, and now are expected to be better than a 1.5 year ROI.

The following discussions provide details on how the CO_2 retrofit methodology was applied to the case study building.

1. Pre-Project Building Consumption Analysis. Using the previous full-year energy consumption for both electricity and steam. When graphed, and compared to the EIA indices for a similar building type in both the Climatic Zone and Region, the overall performance of the building can be compared to a larger database of similar buildings.

Figure 2 shows the building is consuming more energy in terms of Btu/ft^2/yr than a building in the EIA Climatic Zone or the "average" building in the south region. So, while the building is designated and rated as an Energy Star building, it was not operating at its optimum ability to minimize energy costs. Reasons for this could include over ventilation, excessive reheat and or excessive operating schedules. This initial data shows further performance improvement is possible. The operating costs also were compared on a cost-per-square-foot basis.

In *Figure 3* the operating cost is higher than the EIA average for an office building. From both indices, it can be concluded that the project building has strong potential for energy reduction that may include ventilation control with CO_2. The actual potential for CO_2 will be assessed as part of the monitoring phase of the building assessment.

The final part of Step 1 is to assess the potential annual savings of the performance improvements. Actual energy consumption data is compared in terms of total energy costs by reversing the data analysis and multiplying the purchased utility costs by the EIA indices to establish operating costs for a building of the actual size (*Figure 4*).

Overall, the building assessment indicates an opportunity to

Advertisement in the print edition formerly in this space.

reduce operating energy costs by nearly \$205,000 annually.

2. Site Data Profiling and Analysis. Indoor environmental data were collected for the major building zones. Most floors were configured as an open floor plate. *Figure 5* shows results for a typical floor having a density of 7.5 people/1,000 ft^2. Other floors displayed similar results, varying only slightly depending on staffing levels.

When using CO_2 measurements to estimate ventilation rates, two important rules to remember are:

• The calculation must be based on inside/outside CO_2 differential concentrations and must consider the activity level of people in the space.

• The concentrations must be at or close to equilibrium concentrations, meaning that concentrations must have stabilized in the space. Generally, this point occurs when CO_2 levels have peaked and no significant change in concentrations occurs for one to two hours.

The equation used to derive the cfm/person ventilation rate from inside/outside CO_2 differential is:

$$Voa = N/(Cs - Coa) \quad (1)$$

where

Voa = Outdoor air delivery rate to the space in cfm or L/s per person

N = CO_2 generation rate per person based on activity level in the space (see *1997 ASHRAE Handbook—Fundamentals,* Chapter 8, Table 4 for guidance)

Cs = Equilibrium CO_2 concentration in the space

Coa= CO_2 concentration in outside air

For this building, outside concentrations were found to be stable at close to 400 ppm based on measurements made during a 10-day period. The activity level for the space was observed to be typical for an office environment. Therefore, an activity level of 1.2 met (70 W/m^2) was assumed. *Figure 6* provides a close-up view of the trend data for one day, and shows that concentrations stabilized for a number of hours near a concentration level of 675 ppm with some periodic CO_2 variation occurring due to normal occupancy variation. Assuming a CO_2 equilibrium level in the range of 675 to 720 ppm, and using *Equation 1*, the space appears to be ventilated at a rate in excess of 34 cfm/person (17 L/s).

As can be seen from *Figure 5,* the ramp up and peak CO_2 concentrations were fairly consistent on all of the workdays during the monitored period. If this space was ventilated at 20 cfm (10 L/s), the resulting CO_2 equilibrium concentration would be expected to be 930 ppm. Concentrations observed on Saturday are low and indicate a high level of ventilation, which is consistent with the lower weekend occupancy that typically occurred. Even with this lower occupancy, the building is operated as if fully occupied.

The interior space temperature changes daily in response to the occupancy pattern. This is a function of the night setback temperature to reduce energy costs, and the result of OA being drawn into the building by negative pressure created during unoccupied periods.

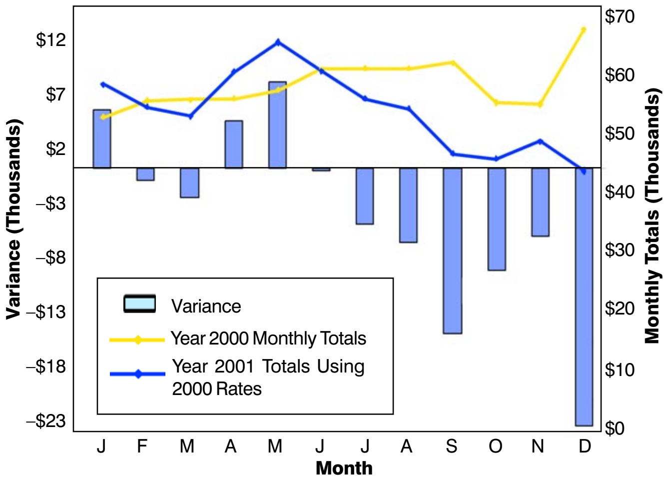
The negative pressure is a result of the building exhaust fans running continuously even though the AHUs for the individual floors are off. The evidence of this is provided by the extremely rapid decay rate of observed CO_2 levels on the individual floor (*Figures 5* and *6*), as well as a recorded drop in space temperature. Within a few hours of full occupant departure, the CO_2 levels plummet approaching OA baseline conditions. Were the exhaust to be significantly reduced or eliminated, the decay of CO_2 levels overnight would be slower and result in less OA infiltration, thus reducing the need to condition this OA later during occupied hours.

Given this building is in a humid climate, the indoor air quality impact of moisture drawn into the building during unoccupied hours is a concern. Correcting this exhaust problem would improve space conditions year-round and result in the ability to significantly delay the start time of the HVAC systems on each floor to further reduce energy use. A closer look at one day in this cycle provides more insight into day-to-day system dynamics (*Figure 6*).

As observed by the change in space temperature recorded slightly before 2:45 a.m., the floor AHU starts to precondition the space after the building has been shut down for only one day during the weekend, Sunday, anticipating that it would take several hours to bring the comfort back into line. However, it can also be seen that within less than 20 to 30 minutes, the space is at the desired winter heating setting of 72°F (22°C). However, staff do not begin to occupy the space until several hours later, beginning after 6:30 a.m. This data will be used, as with the other floors, to effectively recommission the start/stop times of all AHUs.

3. HVAC System Evaluation. The core HVAC design of the case-study building includes twin AHUs on each floor serving an equal geographic quadrant, with the OA supplied to these units and controlled by relay (open/closed) dampers in the original design. The general building exhaust is served by twin vertical riser ducts, though of slightly differing airflow. The primary HVAC systems are, with some minor modifications, ideally suited for DCV application.

4. Building Automation System Evaluation. The case-study building had a DDC BAS that was deemed capable of executing a DCV strategy, and had sufficient capacity to add the required components (CO_2 sensors, peripheral I/O modules, etc). Each floor AHU required that the relay-operated OA damper actuator be replaced with a fully modulating electrical motorized actuator to allow modulation of air delivery to each floor. To alleviate the constant negative pressure relationship in the building, a new building static pressure sensor was located off of the lobby level, on the lee side of the building away from prevailing winds to minimize false positive or negative readings. For the twin exhaust fans, variable frequency drives (VFDs) were added to



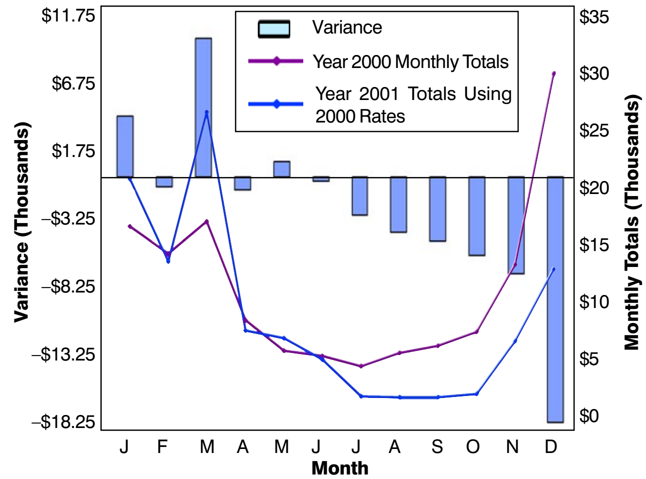


Figure 7 (left): Before and after energy usage for case study. Figure 8 (right): Before and after steam usage for case study.

balance the OA intake with the required exhaust, while maintaining a positive pressure relationship to the outside.

5. CO_2 Control Simulation and Energy Savings Analysis. The case-study building was modeled, floor-by-floor, to accurately assess the annual energy savings. The software compares the cost of conditioning outside air delivered at a fixed ventilation rate to control of ventilation rates based on CO_2. The control algorithm assumed the CO_2 concentrations would be proportionately modulated based on the indoor CO_2 concentration. Occupancies were assumed to be similar to that observed during the 10 days of monitoring.

For the case-study building, the CO_2 modeling projected that annual savings in excess of $81,000 would be achieved. These savings are equivalent to a 10% reduction in total energy costs, an average of >$3,000 per floor/year, and $0.22/ft^2/year ($2.37/m^2/year) of gross area. These savings were calculated to yield a 2.2-year simple return on investment.

6. Post-Installation Evaluation. As a result of the building investigation, which was primarily conducted to determine the potential for CO_2-based ventilation control, other building operational issues were discovered that could further reduce energy use. Modification to the system for CO_2 control included installing sensors, installing modulating OA damper actuators on each AHU and programming the DDC system to modulate OA delivery based on space CO_2 concentrations. Other changes to the building, not directly related to the CO_2 control system, included:

- Slightly modifying the time-of-day (TOD) occupancy schedules for the air-handling units to reflect occupancy patterns observed during the monitored period and to accommodate a shorter pre-occupancy conditioning period than was used previously.
- Relocating the pressure sensor in the building and installing VFDs on the building intake and exhaust to reduce infiltration and improve building pressurization control.

Within the first six months, all of the improvements resulted in the following gross savings:

- Unadjusted (for annual variance in climatic effects) savings since installation equaled $46,879;
- Total energy index decreased by13,724 Btu/ft^2;
- Electricity energy intensity decreased by 2 kWh/ft^2;
- Total utility costs decreased by $0.05/ft^2/year;
- Total kWh consumption decreased by 1,141,500 units;
- Steam consumption decreased by 132 MLbs.

At the same time, increases were seen in the cost of purchased energy units as follows:

- Cost of purchased electricity (cost/Btu) rose by 9%.
- Cost of purchased steam (cost/Btu) rose by 9.7%.

Figures 7 and *8* depict the major vector changes in utility usage and consumption within the case-study building, and affirm the projected energy savings predicted for CO_2-based ventilation control. In fact, the resulting savings appear to be greater that predicted at the project's onset. Additional savings likely were realized from the changes in operating schedules and improvements made to the building pressurization control system. According to the building manager, staff comfort complaints dropped during the summer months because the building is less humid as a result of conditioning less OA daily. These secondary benefits lead directly to another benefit, the minimization or possible elimination of mold-related indoor air quality problems as the drier surfaces of all building components inhibit the opportunity for the growth of mold and bacteria.

Figure 7 shows that once the CO_2-based ventilation control and other improvements were brought on-line in late July, electrical consumption declined sharply. In most previous months, the amount of kWh units purchased was equal to, or greater than similar months in the prior year.

Similarly, *Figure 8* shows that steam consumption made a major vector change beginning in July.

Conclusion

Through application of a reasonable and simple assessment methodology it is possible to assess the energy-saving potential of retrofitting CO_2 demand control into a building. Without a systematic assessment of the building's operation, equipment and current ventilation rates, it is difficult to accurately predict the effect CO_2 control can have on the energy consumption of a building. The outlined measurement methodology can be applied to most existing buildings that have an established history of energy usage.

As shown in this case study, and in a similar case study documented by EPRI (Electric Power Research Institute),[8] the authors have confirmed that by investigating a building for the potential for CO_2 ventilation control retrofit, other opportunities may be found for improving the energy, comfort and general operational performance of a building. In some cases, this methodology will identify previously unknown problems (such as the building pressurization control issue).

Significant energy savings are possible through the application of a well-conceived, designed, planned and executed ventilation control strategy. These savings can be achieved while meeting current standards for ventilation for acceptable indoor air quality. Through application of CO_2-based ventilation control, the subject building was able to achieve a new level of energy efficiency in excess of that presently required by the Energy Star compliance rating. Similar opportunities in other buildings can be identified through the use of the methodology described in this article.

References

1. Schell, M., D. Int-Hout. 2001. "Demand control ventilation using CO_2." *ASHRAE Journal* 43(2).
2. Emmerich, S.J., A.K. Persily. 2002. "State of the art review of CO_2 demand controlled ventilation technology and application." A report prepared for the California Energy Commission by the National Institute of Standards and Technology (NISTIR 6729).
3. Stickford, G.H., et al. 2002. "Reentrainment of flue gases and building air exhaust by packaged HVAC equipment." *ASHRAE Transactions* 108(2).
4. Bayer, C. 2002. Personal communications based on extensive investigation of air quality in schools in the southeastern U.S.
5. Schell, M. 2002. "Real-time ventilation control." *Heating/Piping/Air Conditioning Engineering*.
6. U.S. Department of Energy, Energy Information Administration. 2002. "Commercial Buildings Energy Consumption Survey." www.eia.doe.gov/emeu/cbecs/.
7. Schell, M.B., S.C. Turner, and R.O. Shim. 1998. "Application of CO_2 based demand controlled ventilation using ASHRAE Standard 62: optimizing energy use and ventilation." *ASHRAE Transactions* 104(2):1213-1225.
8. Electric Power Research Institute. 1997. "Environmental and energy code compliance, 3.2, demand controlled ventilation." *Office Complexes Guidebook: Innovative Electric Solutions* pp. 79–86.

Advertisement in the print edition formerly in this space.