AIRCUITY®

OptiNet™ Applications

A Healthier, More Energy Efficient Approach to Demand Control Ventilation

White Paper Series

A Healthier, More Energy Efficient Approach to Demand Control Ventilation

Conventional Demand Control Ventilation

Demand Control Ventilation (DCV) is a design approach that has been applied for the past dozen or more years with varying degrees of success. The concept is simple; vary the amount of outside air delivered within a building based on the occupancy level of a given area. This is normally accomplished by deploying a large number of individual carbon dioxide (CO_2) sensors throughout the building and integrating the feedback with the building control system. When the CO_2 level is detected to be lower than the design value, outside air may be reduced until the building ventilation requirement is met. This ventilation requirement or rate is generally calculated by multiplying the expected number of occupants by a recommended amount of air, expressed as cubic feet per minute (CFM). The recommended amount of outside air is generally 15 to 20 CFM per person for an office environment, but is much higher for other types of spaces such as operating rooms and laboratories. No matter what the design value is for a given type of space, all outside air must be heated, cooled and distributed throughout the building — at a significant energy cost. The quantity of outside air is usually set to a fixed value based on the ANSI/ASHRAE 62.1 standard[1] and an assumed maximum design level of occupancy for a building, irrespective of the actual occupancy of that building. Due to the fact that most designs tend to be conservative and building use fluctuates over time, the result is that the majority of buildings are over ventilated, in some cases significantly so. A July 2003 article in the ASHRAE Journal states:

"Field experience indicates that actual occupancy levels are at least 25% to 30% lower and perhaps as much as 60% to 75% lower in some buildings than design levels." [2]

Contributing further to this unnecessary energy consumption is the common response to nearly all indoor air quality complaints: increase the amount of outside air into a building before analyzing air content and knowing whether additional outside air is truly needed or not. Thus, even if the building was initially designed properly, over time, outside air (OA) levels tend to increase unnecessarily.

Demand Control Ventilation provides a potential energy saving solution to this excess use of outside air by controlling its levels in proportion to the actual number of people in a building. This is accomplished by varying the amount of outside air into the building based on controlling to a set value of the difference in sensed carbon dioxide values indoors vs. outdoors. The resulting total level of CO_2 within the building is then diluted, as outside air is introduced, to a level of CO_2 above ambient outdoor levels based on the volume of outside air. This concept of varying the amount of outside air to maintain a setpoint difference of CO_2 value between indoors and outdoors represents a simple control approach that can produce a healthy, building environment that also conserves energy.

With current energy costs at record levels, potential paybacks of one to two years are realistic for most geographic areas of the U.S. While it would appear that DCV should be a common building ventilation design practice, unfortunately that is not the case even given strong interest in this strategy. This white paper identifies the major obstacles to widespread use of DCV and offers some solutions to address these problems.

Major Issues Inhibiting Widespread Use of DCV

Three major issues with conventional DCV are limiting its widespread application in buildings:

1. Inability to appropriately address non-human pollutants
2. Inaccuracy of control leading to excess use of outside air
3. Carbon dioxide sensor calibration and maintenance considerations.

Concerns over Insufficient Ventilation of Non-Human Pollutants

According to the ASHRAE Journal the single most important issue preventing greater use of DCV is the concern around non-human pollutants:

"Currently, most buildings do not use DCV because of concerns about nonhuman indoor pollutants mentioned previously." [3]

During periods of low occupancy, DCV can reduce ventilation levels low enough that potential building contaminant concentrations can increase to the point of causing occupants to complain. These contaminants can be created by off gassing from new furnishings or construction materials, or increased levels of air contaminants from cleaning materials, high particle or dust levels or other episodic occurrences such as spills of odorous liquids or volatile organic compounds (VOCs). ASHRAE has tried to address the issue of non-human pollutants by recommending a minimum area component of the outdoor air ventilation requirements that is typically 60 cfm per 1000 square feet. However, in many cases this airflow level may be insufficient to eliminate complaints, especially during periods of low occupancy.

For example, in a typical multi-zone office environment with conference rooms or areas with occasional dense occupancies, ventilation levels have typically been set to values equaling 140 cfm to 200 cfm per 1000 square feet. Since DCV is rarely used in these applications, these levels effectively represent a fixed or minimum level of ventilation. ASHRAE's guideline of 60 cfm per 1000 square feet represents a much lower level than has been used in the past.

Interestingly, published research referenced by ASHRAE has indicated that minimum ventilation levels for non-human pollutants required to satisfy at least 80% of the people in a space has varied from a minimum of 30 cfm up to and potentially beyond 400 cfm per 1000 square feet in an office environment.

As another point of comparison the California Energy Commission, in their Title 24 energy efficiency legislation, mandates that 150 cfm per 1000 square feet is the minimum ventilation allowable in an office to meet potential non-human pollutant levels at minimal occupancy. Furthermore, an ASHRAE Journal article by William Fisk, et. al.[3] that analyzed and summarized twenty one ventilation rate studies indicated that a minimum of 20 cfm of outside air per person was recommended for both health and comfort reasons. It was further noted that:

"Existing data do not indicate whether outside air supply per person or per unit floor area is more strongly associated with health and perceived IAQ." [3]

In fact, experience has shown that setting too low of a minimum ventilation level, whether in conjunction with DCV or statically, will cause complaints. In response, the operations and maintenance group often disconnects the DCV system and/or readjusts the minimum outside air level to a much higher fixed level that is frequently higher than appropriate values and wastes significant amounts of energy.

The truth is there is no fixed value of minimum outside air, whether 60, 150 or 400 cfm per 1000 square feet, that is correct for even a single given area over time. Instead the appropriate value of ventilation should be based on the amount of ventilation required to dilute the level of contaminants present in the indoor air at any given point in time. For example, a newly renovated area that has been flushed out may have off gassing materials for a period of time after occupancy that at low ventilation rates can create contaminant levels that exceed recommended guidelines. Specifically, formaldehyde, particle or TVOC (Total Volatile Organic Compounds) levels may be high enough to require a slightly higher ventilation level initially, but can gradually be decreased over time. Another area of complaints and potential health and allergy problems can result from high levels of airborne dust and fine particles due to seasonal or occupant activities. These levels can rise to noticeable complaint levels if proper ventilation doesn't dilute them to normal background levels. Even high levels of moisture in the air due to excessive rainfall, flooding or wet carpet cleaning can create mold growth in a facility with reduced levels of outside air in a short amount of time.

In summary, Demand Control Ventilation's ability to lower the ventilation to minimum levels below that appropriate for occasional high levels of contaminants or humidity levels can create dissatisfaction and potential disabling of an installed system. As a result, what is needed to make DCV healthier and more effective with less occupant complaints is a means to increase ventilation (or at least not reduce ventilation to unoccupied levels) when high levels of non-human pollutants are present.

Excess Use of Outside Air Due to the Normal Tolerances of CO_2 Sensors

Another problem with conventional DCV involves inaccurate control of outside air that can waste significant amounts of energy. To accurately control outside air, CO_2 sensors need to measure both the outside and indoor levels to obtain an accurate measure of the differential CO_2 level. A body of real time measurements across the country as well as many references[4,5,6] state that CO_2 readings often can vary by over 100 PPM, even in a single day, in a typical range of 300 to 500 PPM. Additionally, readings above 500 PPM are also common due to re-entrainment from the air handler's own exhaust outlet, from other nearby air handlers' exhaust outlets, or CO_2 emissions from nearby combustion sources such as flue exhaust, traffic sources, etc.

Additional inaccuracies result from the use of two sensors to measure indoor and outside CO_2, which doubles the error of the differential CO_2 measurement. For example, a typical accuracy specification of a common CO_2 sensor used for DCV is $\pm$ 75 PPM. Since each sensor can have an error range of + or – 75 PPM, the accuracy of the differential measurement is double that of an individual sensor or $\pm$ 150 PPM. To underscore the impact of this type of error on the control of outside air, assume a typical office building operating with at least a 20 cfm per person ventilation level. A large body of evidence shows that occupant health and perceived IAQ will usually be improved by maintaining ventilation rates of at least 20 cfm per person. The results of twenty one CO_2 ventilation studies involving over 30,000 subjects in over 400 buildings concluded that:

"*This review provides persuasive evidence that health and perceived air quality will usually improve with increased outside air ventilation. …The available data indicate that occupant health and perceived IAQ will usually be improved by avoiding ventilation rates below 20 cfm (9 L/s) per occupant…*"[3]

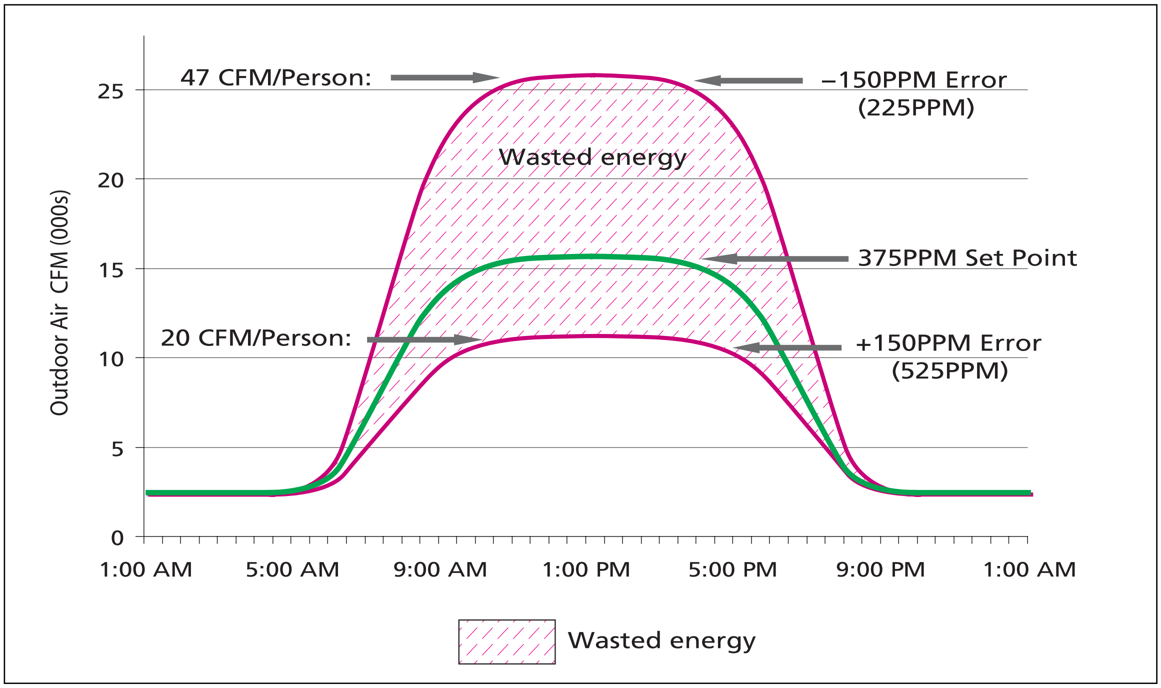

Fig. 1 *A significant amount of energy can be wasted due to the doubling of sensor error.*

A ventilation rate of 20 cfm per person corresponds to an indoor to outdoor CO_2 differential of 525 PPM. To avoid ventilation rates below 20 cfm per person when the differential CO_2 sensor measurement error can be up to $\pm$ 150 PPM, the CO_2 control point must be set to 375 PPM so that given normal sensor tolerances, the ventilation rates will not fall below 20 cfm per person.

As shown in Fig. 1, the DCV system will then control the outside air to maintain a minimum of 20 cfm/person even when the combined sensor error is + 150 PPM. However when the combined error is instead -150 PPM the DCV system will then effectively set the differential CO_2 level to 225 PPM, which corresponds to about 46.7 cfm per person or about 133% additional outside air!

Even if the errors are not at the extremes corresponding to either 20 cfm per person (+150 PPM) or 46.7 cfm per person (-150 PPM), the midpoint of these is still 67% more outside air than is required. As a point of reference, a typical 100,000 square foot office building in Chicago operating at 67% higher outside air during occupied hours will consume approximately an extra $12,750/year or $0.127 square feet/year in energy costs.

In summary, a more accurate means of measuring the differential CO_2 levels is needed to provide a much tighter span of control.

Operating Costs Related To CO_2 Sensor Calibration and Maintenance

The use of conventional Demand Control Ventilation can potentially involve a large number of CO_2 sensors. In addition to the high first cost, the cost of calibrating and maintaining these sensors is significant and can be a deterrent from employing DCV.

"Other issues discouraging widespread DCV adoption include the need for savvy system installation and operational personnel, which cost more and are hard to find; CO_2 sensor maintenance issues; and the limited number of control systems that support CO_2 sensor input for ventilation control." [2]

Focusing on the issue of CO_2 maintenance, real world experience has shown that twice a year verification and potential calibration of the CO_2 sensors is needed to maintain the desired levels of energy savings. Further support for this level of sensor maintenance is provided in section 8.4.1.7 of the ASHRAE 62.1-2004 ventilation standard that states:

Sensors: *Sensors whose primary function is dynamic minimum outdoor air control, such as flow stations at an air handler and those used for demand control ventilation, shall have their accuracy verified as specified in the Operations and Maintenance Manual. This activity shall occur at* ***a minimum of once every six months*** *or periodically in accordance with the Operations and Maintenance Manual. A sensor failing to meet the accuracy specified in the Operations and Maintenance Manual shall be recalibrated or replaced.*

The cost of checking sensors every six months and recalibrating them as needed is significant, but critical due to concerns about sensor accuracy. As a potential way to reduce the cost of calibration many CO_2 vendors offer an auto-calibration feature stating that their sensors do not need to be calibrated for 5 years. Although this is a tantalizing concept, it is important to understand the underlying assumptions that make it less than ideal for use with DCV applications. Auto-calibration assumes that in the middle of the night or early morning hours, the building will have been flushed to outdoor background levels which should be constant at about 400 PPM. Based on this, the sensor averages the nighttime values and periodically recalibrates its offset using a one point calibration to this averaged nighttime value.

This auto-calibration function often causes more accuracy problems than it solves, particularly when used with DCV, due to three major flaws and problems. First, in many buildings, particularly during the week, nighttime CO_2 building levels do not reach background or outdoor levels, particularly if fans are turned off at night, or the flow levels are reduced during unoccupied times. This latter case is often true since at night the DCV controls should be significantly reducing outdoor airflow rates to some minimum level. As a result, outdoor background levels may not be reached inside the building. Consequently, the CO_2 sensor will read a level higher than the background level, such as 600 PPM, and operate as if it is the assumed outdoor background level of 400 PPM. Over time this will cause a sensor error of 200 PPM or 33% error.

A second problem is that outdoor background levels can vary significantly by more than 100 PPM. As a result, if in the middle of the night the building did reach outdoor background levels, this level is likely not to be the assumed 400 PPM and will probably vary over time. If instead the nighttime level is 500 PPM, and the assumed background level is 400 PPM this alone will create an error of 100 PPM or 25% error.

The third error source is use of a one point or an offset only calibration method by the auto-calibration system. As a minimum, any recalibration process should use a two-point recalibration, enabling a gain and offset adjustment for acceptable accuracy. For example, if the sensor's gain has drifted by 10%, an offset only recalibration at 400 PPM will still generate an error in the differential indoor to outdoor value of 10%, representing a change in outdoor airflow of 10%. In total, all three error sources can result in combined errors of several hundred PPM.

In summary, since commercial quality CO_2 sensors can have significant drift characteristics, for many applications the auto-calibration routine is a good concept because it limits the sensor error to only a few hundred PPM or less depending on the application. Unfortunately, auto-calibration is not appropriate for DCV applications where more accurate differential readings are required to save energy. The potential level of outside flow error generated can be extremely costly. As a result, twice a year CO_2 sensor checking and potential sensor recalibration as required by ASHRAE 62.1 is necessary and appropriate for ensuring the desired energy savings. To make certain that sensor calibration and maintenance does not consume a large percentage of the expected operating savings, what is needed is a simpler, less expensive approach.

The Solution: Multi-parameter DCV

Requirements for Healthier, More Energy Efficient DCV

To remedy the stated concerns that have limited widespread use and effectiveness of DCV, an improved approach needs to meet the following unique requirements:

1. *Economic sensing and control of non-human pollutants and humidity*
2. *Accurate differential sensing of CO_2 and other parameters*
3. *Cost effective, simple sensor calibration and maintenance.*

An excellent solution to the first requirement is to implement DCV to vary ventilation based not only on the level of occupancy in a space using CO_2, but also react to the real-time levels of multiple contaminants in an area or space. Expanding the number and type of sensed parameters to include other key air quality indicators, including non-human pollutants is known as multi-parameter DCV or MpDCV. With this concept, if the air in a space is clean and the occupancy level is low, there is no reason to dilute clean indoor air with clean outdoor air. Instead, the minimum ventilation levels can be decreased to those stated in the ASHRAE 62.1-2004 standard. Potentially, levels can be even lower during unoccupied times as long as the building's positive pressurization level is maintained. Conversely, when CO_2, contaminant, or humidity levels are higher than recommended; ventilation levels can be increased to dilute the room air to restore a healthy environment. Additionally, the level of outdoor contaminants can be checked and if the source of the contaminant is from outdoors, then airflow into the building can be reduced to minimum levels to limit the entry of these contaminants.

Creating a Single Multi-parameter DCV Control Signal

Implementing MpDCV is relatively straightforward and very similar to using DCV except that rather than employing a feedback signal equal to the difference in carbon dioxide levels between indoor and outdoors, MpDCV uses a single composite feedback signal. This composite combines differential air signals from a number of air quality based sensors with the differential CO_2 signal used for conventional DCV. This is done by scaling each differential signal around the same action or trigger level above which increased ventilation is warranted. The individual air parameter signals are then high selected together to create a single demand control ventilation signal. To determine which air parameters are important to sense, current EPA[7] and State of Washington IAQ standards and guidelines for evaluating building indoor environmental quality are used. These same guidelines for determining good Indoor Environmental Quality (IEQ) conditions within buildings are also referenced by the U.S. Green Building Council LEED® NC version 2.2 rating system (EQ Credit 3.2 for flush out of new or renovated buildings). It recommends measurement of TVOC, particles, carbon monoxide, and formaldehyde due to their occurrence as common building contaminants strongly influenced by outside air ventilation levels. Appropriate levels of these materials are clearly stated by these guidelines and may be used to establish control levels for DCV similar to those commonly used for CO_2. Many Asian and European countries have already adopted similar guidelines for measuring indoor air pollutants.

An additional parameter that influences IEQ is relative humidity or dewpoint temperature. If the dewpoint temperature or similarly the absolute humidity of a space is significantly higher than the supply air feeding the space, and is in excess of 65%, then increased ventilation is highly

MpDCV Air Parameters	Typical Sources
TVOC	Cleaning compounds, new building materials and furnishings, carpets, paints, consumable products
Fine particles	Construction activity, smoke, dust, combustion products, aerosols, deteriorating materials, cooking
Carbon monoxide	Leaking vented furnace, combustion, or flue gas exhaust, unvented combustion appliances, parking garages
Formaldehyde	Pressed wood products, furniture and furnishings
Relative humidity	Water spills, rain leaks minor flooding, leaking and condensing pipes

Fig. 2 The table summarizes the recommended air parameters for MpDCV in addition to CO_2.

recommended. Increased ventilation will prevent potential mold growth resulting from excess humidity levels. For example, humidity levels can increase due to a water spill, wet carpets or other sources of condensation or moisture that originate in the space versus from outside or from the supply air.

Implementing Multiple-parameter DCV

One approach to implementing MpDCV is to use an individual sensor for each of the contaminants listed in the guidelines, in addition to a CO_2 sensor, for a total of 6 sensors per each room or air duct. Sampling data from the sensors can be combined by a BMS system to provide the required combined MpDCV control signals. A major drawback of this approach is the cost impact of having numerous individual sensor packages that must be separately mounted and wired into the BMS system.

A more cost effective approach is to use sensor equipment that combines at least two or more sensors into one enclosure or onto one circuit board. For example, several manufacturers combine temperature, humidity and carbon dioxide sensors into one package. As a result perhaps only 2 or 3 sensor units need to be mounted and wired to accomplish sensing the 6 required parameters. The total cost of the sensors themselves should also be reduced due to some sharing of signal processing overhead, power and packaging. One disadvantage of this combined approach versus individual sensors is that it offers less control in selecting the quality level of the sensors used. Some of the sensors in these combination units may be of a lower commercial grade with higher drift and lower accuracies which are not appropriate for this application.

Beyond the potential first cost and installation implications of sensing 6 parameters in each space or duct, it is important to remember, that many sensors (i.e. metal oxide TVOC or formaldehyde) potentially have significant drift. The amount of drift will vary from sensor to sensor creating inaccurate differential sensing as well as significant calibration expenses. Additionally, sensing outdoor humidity is also difficult to accomplish using commercial humidity sensors. To accurately measure humidity, more expensive, industrial grade devices are needed to operate properly due to the extremes of temperature, humidity levels and atmospheric dust that can significantly degrade and affect outdoor sensors.

An improved concept over these conventional approaches is needed to overcome the aforementioned issues and meet the requirements for healthier, more energy efficient DCV.

New Technology Provides Better, Very Cost Effective MpDCV

A new sensing architecture known as a Multiplexed Sensing System or MSS solves the issues identified in preceding sections and changes the age-old paradigm of sensing while decreasing calibration and maintenance expenses.

Multiplexed Sensing System Architecture and Benefits

This new architecture, rather than locating multiple sensors in each area or room, routes packets or samples of air from multiple locations sequentially, in a multiplexed fashion, to a shared set of sensors (Fig. 3). Every 30 to 45 seconds a sample of air from a different area or duct is routed on a common air sampling backbone to the same set of multi-parameter sensors, including CO_2. Groups of sensors are housed in a unit known as a sensor suite which can be customized to measure any number of non-human pollutants, dewpoint temperature, as well as specialty gases (i.e. ammonia). These sequential measurements are then "de-multiplexed" for each sampled area or air stream to create distinct sensor signals that can be used for multi-parameter DCV as well as other applications.

This sensing concept can also make "true" differential measurements without the accuracy concerns mentioned previously for commercial grade CO_2 sensors. Since the same sensor is used for both indoor/outdoor CO_2 and other parameter levels nearly simultaneously, any sensor errors will be the same from both measurements and will thus cancel out, enabling a very accurate measurement. Additionally, since only one sensor is required for every 20 or so locations, more accurate industrial grade sensors can be used for even more precise measurements.

Due to the limited number of sensors deployed, and the central location of such sensors, calibration expense is minimized. The calibration process is streamlined through an exchange program whereby a factory set of calibrated sensors periodically replaces the on site sensors,

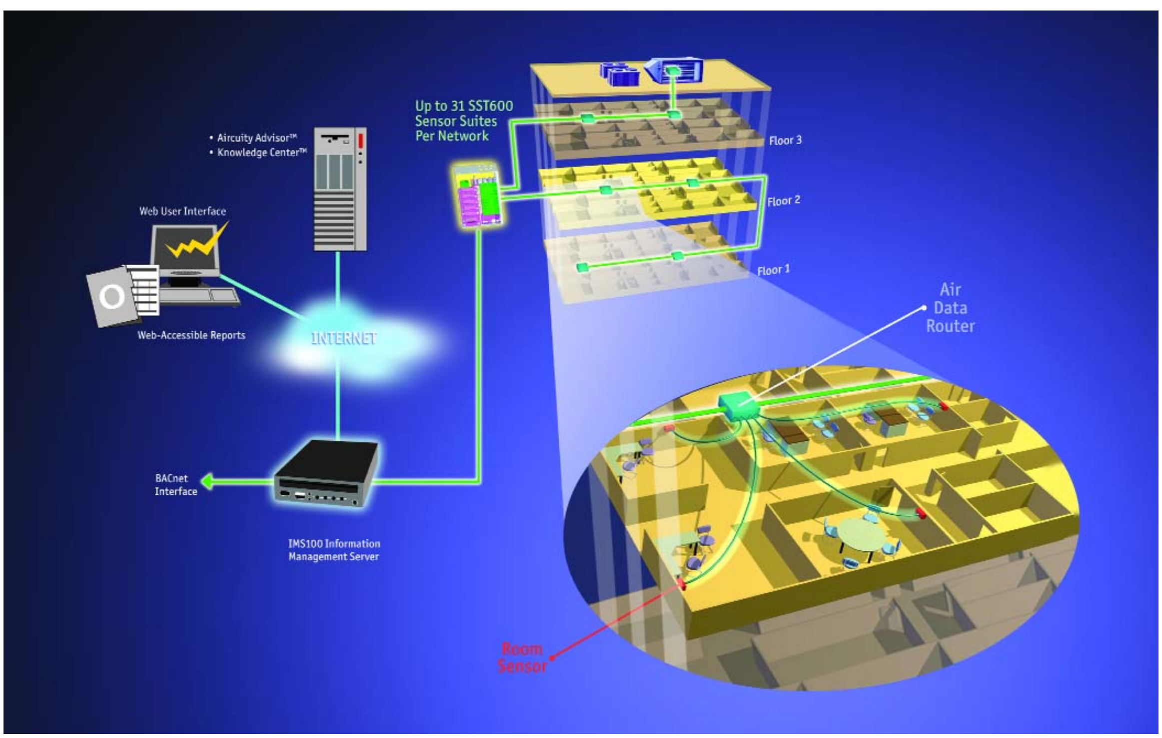

Fig. 3 Facility-wide sensing architecture.

such as every 6 months. The system is therefore assured to operate at peak performance with minimal, or no disruption to facility operation.

How the MSS Creates Multi-parameter DCV Control Signals

One other powerful advantage of the multiplexed sensing system is that it significantly reduces the cost of implementing DCV by eliminating much of the signal processing and programming needed to implement multi-parameter or MpDCV. This is because the MSS is a facility-wide integrated sensing system that can possess significant pre-programmed signal processing power specifically designed for DCV applications. As such it removes much of the computational processing, programming and project commissioning costs that MpDCV or even normal DCV can add to a building controls system's first cost.

For example, rather than having to high select, combine, and difference what could be dozens of different sensor signals, the MSS does all of this instantly. It then sends a single demand control ventilation signal to the BMS that can be used in a simple airflow control loop to command the outside air flow of an air handling unit. Furthermore, when multiple control loops are used, a BACnet interface can provide a single digital connection for all the control and potentially monitoring signals while further lowering the cost of integration and installation.

The specific signal processing algorithms and control approach required for a given MpDCV application depends on the amount of energy savings that is desired versus the first cost required to achieve them. There are three major levels of multi-parameter DCV applications that can be implemented that provide a good, better, best approach in terms of increasing building energy savings for multiple zone HVAC systems:

Good: Use sensing supply air properties to control outdoor air intake.

Better: Sense multiple room spaces and control outdoor air intake based on the room with the highest levels.

Best: Sense multiple room spaces and sequence individual control of room supply air based on high air parameters with control of outdoor air intake based on the room with the highest levels.

Summary

Demand Control Ventilation has always offered the opportunity for significant energy savings but has never realized its full potential due to concerns about the presence of non-human pollutants, inaccurate control of outside air due to differential sensing errors, and the cost and complexity of system sensor calibration and maintenance. A new approach called multi-parameter DCV provides a solution to maximize energy savings while still maintaining excellent indoor environmental quality. It does so by maintaining building ventilation at lower levels of outdoor air *unless* increased levels of non-human pollutants are sensed. Implementing MpDCV with a Multiplexed Sensing System provides a simple, very cost effective solution that has both high differential sensing accuracy and low sensor calibration and maintenance expenses to preserve high operating savings. The result is a healthier indoor environment operating with maximum energy efficiency.

References

1. ANSI/ASHRAE Standard 62.1-2004, Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

2. Kurt W. Roth, Ph.D., John Dieckmann, P.E., and James Brodrick, Ph.D., Demand Control Ventilation, ASHRAE Journal, July, 2003: 91-92.

3. Olli Seppänen, William J. Fisk, P.E., and Mark J. Mendell, Ph.D. Ventilation Rates and Health, ASHRAE Journal, August 2002: 56-58.

4. Persily, A. Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide, ASHRAE Transactions 1997, V. 103(2): 193-204.

5. Lawrence Berkeley National Laboratory, 2003. "Ventilation rates and technologies: How are CO_2 concentrations related to ventilation rates?" http://eetd.lbl.gov/IEP/viaq/v_rates_3.html.

6. David H. Mudarri, Ph.D. "Potential correction factors for interpreting CO_2 measurements in buildings." ASHRAE Transactions, 1997, 103(2): 244-255.

7. EPA Protocol for Environmental Requirements, Testing for Indoor Air Quality, Baseline IAQ and Materials for Research Triangle Park Campus, Specification Section 01445.

About Aircuity

Founded in 2000, Aircuity is the leading manufacturer of facility monitoring systems that cost-effectively reduce building energy and operating expenses while simultaneously improving indoor environmental quality. Aircuity's goal is to optimize building ventilation for energy efficient performance without sacrificing occupant comfort, health or productivity.

Following the introduction of the portable Optima™ system, the company developed a permanently installed version for continuous measurement and analysis of building indoor environmental conditions. Known as OptiNet™, this multi-point air-sampling network can deliver significant energy savings while ensuring healthy indoor environmental quality. OptiNet was named an R&D100 Technology winner for 2006 by R&D magazine, which annually recognizes the 100 most technologically significant new products and processes.

The company's systems are suitable for a broad range of commercial building applications where energy efficiency and enhanced indoor environmental quality are important, including offices, laboratories, hospitals, educational institutions, museums, convention centers and sports arenas.

Aircuity, Inc.
39 Chapel Street ▪ Newton, MA 02458 ▪ 617.641.8800 ▪ 617.969.3233 fax ▪ www.aircuity.com

DCVWP F072606