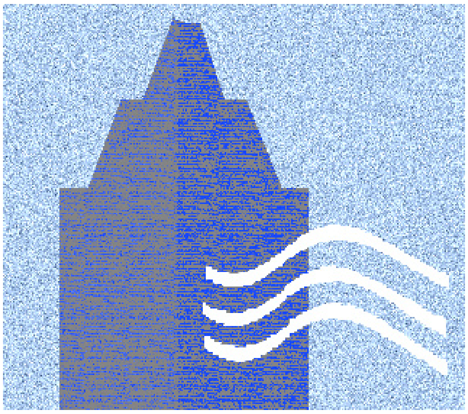

CO_2-Based Demand Control Ventilation

Do Risks Outweigh Potential Rewards?

By **David S. Dougan** and **Len Damiano,** Member ASHRAE

Energy conservation strategies often distract attention from other core design objectives, including occupant health, productivity and avoiding threats to the building structure's long-term integrity. CO_2-based demand control ventilation (DCV) is an energy-conserving strategy that, in some cases, has sacrificed several of these fundamental design objectives. Instead we have embraced short-term energy cost savings and accepted greater risks to occupant health, diminished worker productivity, increased maintenance costs, and life-cycle cost for the structure.

This article examines the sources of risk using DCV, the components typically used and possible ways to minimize risk without sacrificing potential energy savings from dynamically resetting intake rates based on occupancy changes.

Demand Control Ventilation

A typical building has two significant contaminant sources that, without proper ventilation, can lead to unsatisfactory indoor air quality. One source is the building, which in many cases can result in the required removal or dilution of more than 50% of the pollutants.[1,2] The second source is body odor, produced by the occupants as a result of their activities. This latter source has provided many designers with the opportunity to automatically reset outside airflow rates in facilities with variable occupancy, and capture the energy savings available compared to continuous conditioning.

The concept of using CO_2 input for DCV makes sense and can save money on building operating costs under specific circumstances. Building managers can see an energy benefit from reductions of outside air intake rates as the occupant density decreases. However, systems rarely are implemented that account for the code-mandated "actual number" of people in a particular ventilation zone.[3]

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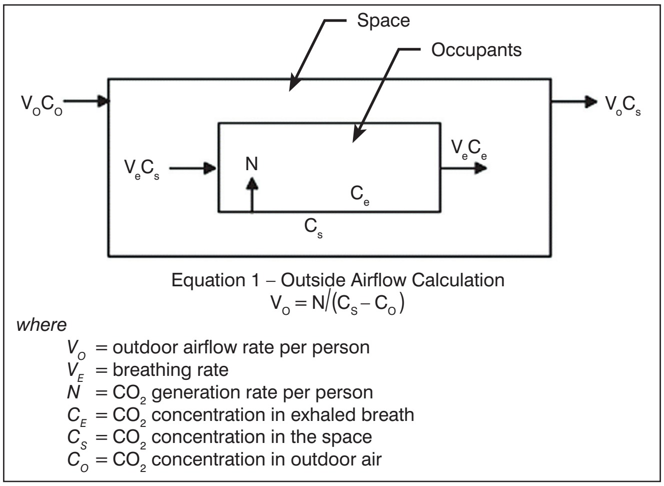

Equation 1 – Outside Airflow Calculation

$$V_O = N/(C_S - C_O)$$

where

V_O = outdoor airflow rate per person
V_E = breathing rate
N = CO_2 generation rate per person
C_E = CO_2 concentration in exhaled breath
C_S = CO_2 concentration in the space
C_O = CO_2 concentration in outdoor air

Figure 1: Two chamber model and outside airflow calculation.

Since people produce CO_2 as a direct result of respiration, it has been an understandable DCV input choice. Unfortunately, a significant number of designers and owners have not fully understood the relationship between CO_2 levels and ventilation. The least of which is that CO_2 is neither a pollutant nor a direct measure of occupancy.[4,5]

CO_2 Levels and Ventilation

CO_2-based DCV often is implemented with little regard to the actual relationship between ventilation rates and CO_2 levels.

The ventilation rate procedure in ASHRAE Standard 62-2001, *Ventilation for Acceptable Indoor Air Quality,* specifies required minimum ventilation rates for compliance with the standard, not CO_2 levels, for acceptable indoor air quality.[4,5]

Section 6.1.3 of Standard 62-2001 (which was replaced by Addendum 62*n*) states, "Indoor air quality shall be considered acceptable if the required rates of acceptable outdoor air in Table 2 are provided for the occupied space."

Systems must provide adequate dilution airflow rates for compliance. However, even though the standard clearly does not specify acceptable CO_2 levels for compliance, many believe that maintenance of space CO_2 setpoint levels will result in acceptable indoor air quality by indirectly regulating the amount of dilution air provided.

What is the relationship between CO_2 and the outside airflow rate into a space? To answer that question, we must first understand the mathematical model that describes the use of CO_2 and the assumptions required for the model's validity.

The relationship between CO_2 levels and outside air ventilation rates can be described using a simple, two-chamber model, as shown in Figure 1, from Standard 62-2001, Appendix C.

This model relates the differential CO_2 level (inside minus outside) to the airflow rate per person when the following steady-state conditions are true.

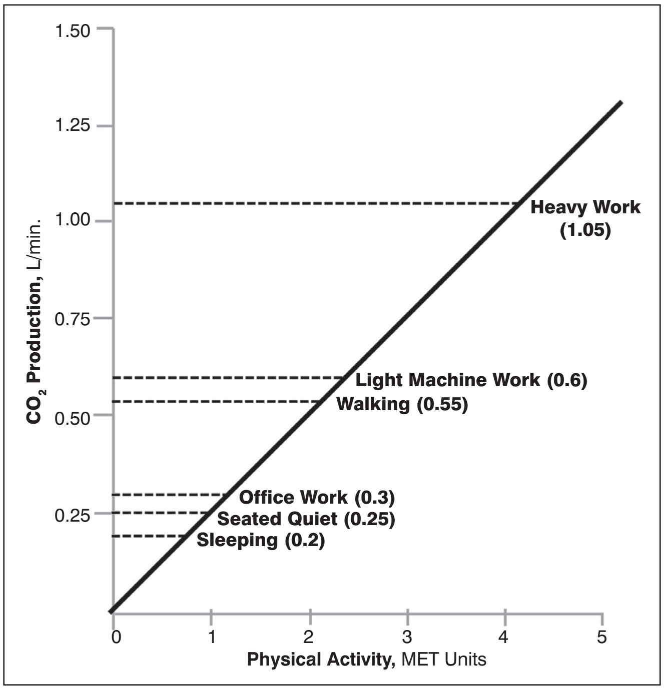

Figure 2: CO_2 production vs. metabolic activity.

1. The occupants are generating CO_2 at an assumed *constant* rate: *N* (cfm* or L/s of CO_2/person), i.e., their metabolic rate, diet, and level of activity are identical.

2. Outside air, of *known CO_2 concentration: C_o,* is introduced into the space at a *constant* rate: V_o (cfm or L/s per person).

3. The indoor CO_2 level: C_s, represents human occupancy within the ventilation zone and there is *no allowance for inaccuracy in measurement.*

Calculating V_o = 7.5 L/s (≈15 cfm per person) with an assumed CO_2 generation rate (*N*) of 0.31 L/min. per person will result in an indoor CO_2 level approximately 700 ppm greater than the level of CO_2 in the outside air. (Solving for the CO_2 differential, $C_s - C_o = N / V_o$ or $0.31 / (7.5 \times 60$ s/min.$) = 0.000689$ $L{\cdot}CO_2 / L{\cdot}$air, or 700 ppm]. This is the underlying mathematical relationship and comfort justification for the ventilation rate tables in the original ASHRAE ventilation standard.[8,10] Studies that were used by ASHRAE have indicated that 15 cfm per person is the rate of outside air required to dilute offensive body odor and the calculated 700 ppm is the CO_2 rise referenced in Standard 62.[6–10] Therefore, the resulting statements appeared in Section 6.1.3 of the 2001 standard:

"Comfort criteria, with respect to human bioeffluents (odor) are likely to be satisfied if the ventilation results in indoor CO_2 concentrations less than 700 ppm above the outdoor air concentration." This may be addressed in a proposed appendix created by Addendum 62*ah* or possibly by reference in the recently contracted User's Manual for Standard 62.

Section 6.2 of Standard 62-2001, which was replaced by Addendum 62*n* states, "Using CO_2 as an indicator of bioeffluents does not eliminate the need for consideration of other

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* cfm × 0.4719 = L/s

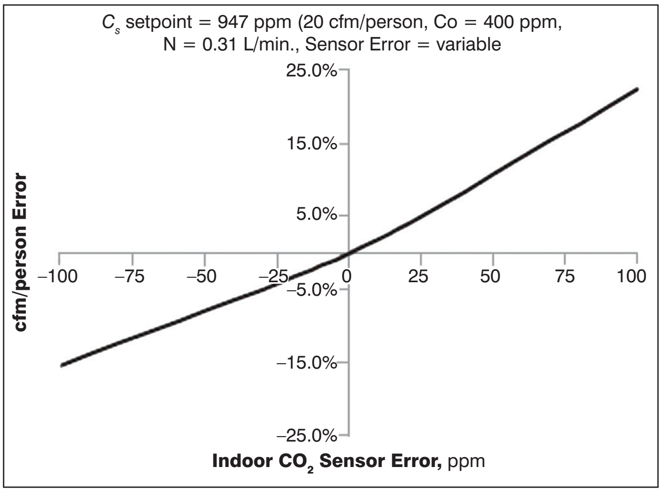

Figure 3: Sensor error.

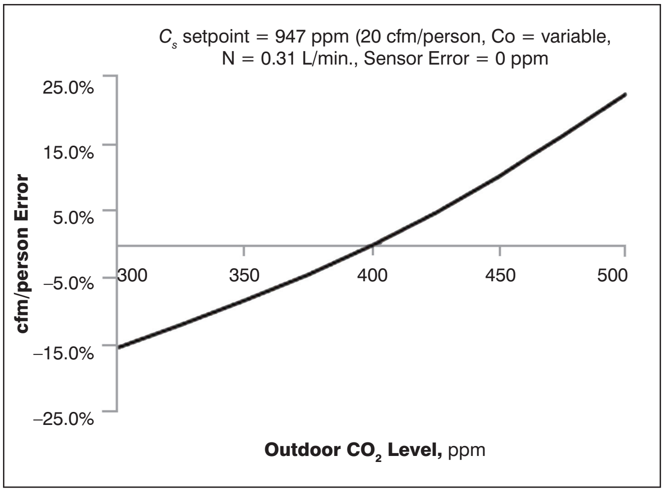

Figure 4: Assumed outdoor CO_2.

contaminants."

Remember, more than 50% of the contaminants in the average office building are non-occupant generated and cannot be addressed by controlling CO_2 levels alone. This appears to be the single strongest motivator for the significant changes included in Addendum 62*n* and its subsequent adoption by ASHRAE and ANSI.

We also should acknowledge that Appendix C covering CO_2 in the current Standard 62 was included primarily to help explain the origin of the rates used in the ventilation tables.[4] It was not intended to support or to justify the use of CO_2 for ventilation control. Yet, the steady-state, two-chamber mathematical model contained in the appendix has been used in applications and referenced to support the use of CO_2 sensors for automatic control purposes.

As an indicator of ventilation adequacy for the dilution of body odor, the 700 ppm rise criteria is perfectly acceptable for a space being evaluated by a diagnostician, in accordance with the requirements of the applicable ASTM standard.[11] The CO_2 generation rate assumed in the model is based on the average generation rate for this minimum activity level (0.31 L/min. per person**). As a result, any increase in the average activity level of the occupants (*N*) would tend to indicate a greater CO_2 differential than that calculated by the steady-state formula and over ventilate the space, negatively impacting the expected potential savings.

Confidence in the calculated results can be increased if the ventilation rate into the building and space are held constant during the evaluation, and the occupant density is maintained. The technique is best suited for use with a single, handheld, frequently-calibrated device in the hands of trained professionals, for use in localized areas for time-specific diagnostics.[9,11,12] Unfortunately, misunderstandings regarding the valid application of the technique can be created by those who do not appreciate the differences between monitoring for *evaluation* and monitoring for *control*.[12]

CO_2 generation rates can vary widely as indicated in *Figure 2*, based on activity levels. It may also vary based on diet and health of the occupants. As a result, significant error can exist in the cfm per person calculation (*Table 1*).

The model also is only valid under steady-state conditions. CO_2 DCV, by design, is intended to be used in dynamic situations and implementation of this strategy often negates the validity of the model.[13] In addition, the placement and reliability of the CO_2 sensor is critical and the performance of today's sensors still is reported to be questionable (*Figure 3*).[5,8,14,15]

CO_2 sensors are reported to have noteworthy, technology-specific sensitivities, unresolved issues and application considerations including:

- Drift;
- Overall accuracy;
- Temperature effects;
- Water vapor;
- Dust buildup;
- Aging of the light source;
- Frequency of calibration;
- Mechanical vibration;
- Electrical noise;
- Sensor location in the space;
- Number of sensors required;
- Method of averaging multiple sensors; and
- Compounded error rates from multiple sensors.

Geographically and seasonally, outside CO_2 levels vary widely.[5,13] Outdoor levels are generally not measured, because CO_2 sensors (in varying degrees) have trouble with accuracy above a relatively low velocity threshold, at low ambient air temperatures and may be affected by changes in atmospheric pressure (*Figure 4)*.[5,13]

Sensor manufacturers have developed several methods to improve the reliability of CO_2 measurement. Specific models

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** L/min. × 0.2642 = gallons/min.

Activity	N, L/min.	V_o, cfm
Sleeping	0.20	10
Office Work	0.30	15
Walking	0.55	28
Light Machine Work	0.60	30
Heavy Work	1.05	53

Table 1: Calculation of V_o *at* CO_2 *production levels,* $\Delta C = 700$ *ppm.*

People	Total OA cfm Required	cfm/Person	Required $C_s - C_o$	Comments
7	95	13.5	807 ppm	Overventilated at 700 ppm
6	**90**	**15**	**700 ppm**	
5	85	17	644 ppm	Underventilated at 700 ppm
3	75	26	438 ppm	

Table 2: Required CO_2 *level at various population densities in an office space (area = 1,000* ft^2*). Total OA cfm required = 0.06 cfm/*ft^2 *+ 5 cfm/person (Standard 62***n***, offices).*

that automatically reset to the overnight ambient level have helped reduce the frequency of required calibrations, if the ambient night levels in your area are valid base CO_2 levels, which do not change over time. Others use methods to protect the sensing elements from the environment, while still others apply an internal light-source reference to assist stability.[5]

However, the cumulative uncertainties of the hardware and methodology remain. The total uncertainty's impact on intake rate control can result in significant risk for the designer and building owner who have chosen to implement a CO_2 DCV strategy, unless deliberate care is taken and supplementary actions are used (see *Figures 3, 4*).[5,13] The practitioner must have more than just basic knowledge of the strategy's proposed requirements and limitations.

Appendix B of NISTIR Report 6729 for the California Energy Commission of March 2001 concluded, in part, that good practice usage of CO_2-based DCV also would incorporate "other IAQ control technologies."[5] The report recognized most of the limitations of DCV and felt that supplementing this technology would provide more overall reliability. Because CO_2-based demand control ventilation has a tendency to overstate changes in occupancy, direct measurement and control inputs for the actual intake rates may be useful in preventing overventilation and intake shutdowns.[9,16]

Mounting airflow measurement devices in the outside air intake to limit the lowest reset point of outside airflow rates during periods of lowered density (or diminished occupancy), can reduce IAQ risk from underventilation. This modification also may reduce the risk of wasting energy by allowing the establishment of an upper limit, never to be exceeded.[16]

DCV and Building Pressure

When the outside dew point exceeds 65°F,† humidity levels in negatively pressurized building envelopes can exceed 70% RH, the minimum humidity level in which many molds can grow. High humidity conditions in and near the building envelope will result in mold growth.[17]

Some molds may be toxic to humans while most molds produce allergens. Many can damage the building's structure and can be extremely expensive to remove from spaces that are difficult or impossible to access, e.g., inside exterior walls. Recent publications have recognized the relationship between building pressure and mold growth.[17–23] The widespread use of CO_2–based DCV has limited the amount of outside air introduced into a building. Without a positive pressurization flow (the difference between the outside air intake and the total exhaust flow rates), a building cannot be pressurized.

Designers must carefully consider space pressurization control when using demand control ventilation strategies (CO_2 or others). The amount of control error allowable at the intake for pressurization diminishes when the total amount of intake air is reduced, making the accuracy of intake control more important. DCV systems may satisfy their differential CO_2 setpoints while ignoring differential flow (pressurization) and the amount of dilution air needed to mitigate the effect of non-occupant sources of contamination.[16]

Complications From Changes by Addendum 62*n*

Changes to the ventilation rate procedure of ASHRAE Standard 62 resulted in outside airflow rates that vary significantly on a "per person" basis (*Table 2*). Addendum 62*n* recognizes this and has modified the table's structure to address the magnitude of building-generated pollutants. Under ideal conditions, CO_2 levels can only relate to the rate that outside air enters the building on a per person basis (i.e., cfm/person). Therefore, it is difficult to envision how CO_2–based DCV can be implemented under the new requirements of Standard 62 and simultaneously "maintain" the required minimum intake rates "under all load conditions,"[4] without significant energy cost impacts (in contrast to the savings expected from its use).

SSPC 62.1 publicly announced the intention to develop a CO_2 appendix to Standard 62 this year. Addendum 62*ah* might be considered by some to be the magic bullet for intake rate control. Some rationale and application criteria is expected to be offered in this appendix, allowing the use of CO_2 inputs for indirect ventilation control and compliance with the requirements of the ventilation rate procedure.

Also the possibility exists that CO_2-based DCV methodology may be introduced in a user's manual to Standard 62, whose contract award was announced last January. The difficulty we have with a user's manual being used to endorse or validate systems and equipment not addressed in the standard is that the content requires review and approval only by Standing Standards Project Committee (SSPC) 62.1 and Society board. The public will not be aware of the contents until it is ready for publication. Until then, we are left with many questions and little in the way of scientifically verifiable data to support the

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† (°F – 32) × 1.8 = °C

validity of CO_2 measurement input's as suitable and otherwise comparable in reliability to other available methods of ventilation rate control.

This lack of supporting test data and the absence of applications guidance were deficiencies identified as a few of the many problems in the blanket use of CO_2–based ventilation control schemes by the recent California Air Resources Board report to the writers of the state ventilation code, the California Energy Commission (CEC).[24]

However, we should expect that the SSPC 62.1 committee and the contractor for the user's manual will be thorough when identifying the limitations and requirements for the use of CO_2-based DCV, the realistic performance expectations and published limitations for specific applications, hopefully substantiated by both laboratory and full-scale testing *before* including it as a Society-endorsed method of control.

Other Defficiencies of Indirect Ventilation Control

In literature reviews on CO_2-based DCV, it was apparent that many opinions exist regarding the validity of the control strategy in relation to the specifics of an application. The "voice of reason" originates from a qualified source—specifically, Andrew Persily, Ph.D., Fellow ASHRAE, who is a former chair of SSPC 62.1 and an employee of the National Institute for Standards and Technology (NIST).

As leader of the Indoor Air Quality and Ventilation Group, Building Environment Division at the Building and Fire Research Laboratory in Gaithersburg, Md., Persily is in the middle of almost everything IAQ. He has been prolific and his work in the field has been exemplary.

In particular, the NIST report for the CEC mentioned earlier included a number of conclusions based on the reference materials available prior to publication. An examination of them highlights many of the limitations of current CO_2 sensor technology and those inherent in the use of indirect measurements for control (controlled values tend to grow larger or smaller very quickly, due to the magnification of combined errors and uncertainties). Climate, occupancy, operating hours and other building and HVAC system features make the savings expectations extremely variable and not guaranteed.[5]

Some conclusions about CO_2 sensor technology and applications were made from a NIST review of current literature on the subject.[5] Some of the relevant ones include the following:

1. The greatest savings likely are to occur in buildings with large heating or cooling loads and with dense and unpredictable occupancies;
2. DCV may not be appropriate in mild climates;
3. Avoid DCV in spaces with significant sources other than people;
4. Avoid buildings with CO_2 removal mechanisms;
5. Both non-dispersive infrared detection (NDIR) and photometric detection can be affected by light source aging—NDIR by particle buildup and photometric by vibration or atmospheric pressure changes;
6. Consideration must be given to selecting only for the appropriate range of operation;
7. Drift is still an issue and calibration recommendations must be followed;
8. The preferred locations for sensors are multiple ones placed in the occupied zones;
9. Do not use sensors that are not intended for control purposes;
10. Do not use sensors near doors, windows, intakes or exhausts, or in close proximity to occupants;
11. Single sensors in the return air should not be used for multiple spaces with very different occupancies;
12. Economizers should be allowed to override DCV; and
13. Higher outdoor levels of CO_2 will result in overventilation when levels are assumed (not measured) and an outdoor sensor may be required by applicable standards or codes.

Persily included a list of questions that remain, suggesting that the current use of the CO_2 -based DCV control strategy is more risky and less predictable than other, more direct methods, and that reliable applications research is still lacking. Some of the questions also indicate limitations that designers and users should seriously consider before implementing this control strategy:

1. Is it acceptable to use a single sensor in a common return for multiple zones with similar expected occupancies?
2. Can a lower setpoint compensate for differences in concentrations between zones?
3. How much could this approach reduce energy savings?
4. Are there significant advantages to using a single sensor with multiple measurement locations (eliminating the compounding of multiple-sensor error rates)?
5. Should CO_2 setpoints be varied for buildings with occupants whose CO_2 generation is expected to vary?
6. Is a control algorithm that maintains a constant ventilation rate per person necessary for acceptable IAQ?
7. What level of minimum ventilation is needed?
8. Can scheduled purges replace the minimum ventilation rate?
9. Is displacement ventilation an appropriate and compatible distribution design with DCV? If so, where should the sensors be located and can the setpoint be lowered?

Analysis of Risk and Benefits

Compared to the potential benefit, implementing a strategy with significant assumption-flaws is extremely risky. Literature suggests that such a gain could be realized if outdoor airflow rates were maintained at acceptable levels.[8,10,25–29] *Table 3* illustrates the potential benefit of a 5% productivity gain. When compared to potential energy savings, improved ventilation and Indoor Environmental Quality (IEQ) significantly outweighs "minimized" ventilation.[30]

Based on Addendum 62*n* changes, the reduction in outside airflow rates with decreasing occupancy in low density zones (i.e., offices) is small. A 57% reduction in the occupancy (seven to three people per 1,000 ft^2)[††] only results in a 21% decrease in the required outside air. When we consider that the entire energy bill for a typical owner-occupied structure amounts to about 1% of the annual cost to the building owner,[30] is this limited savings really worth the risk of potential liability and the loss of productivity benefits from an improved working or learning environment?

In addition, recent changes to commercial general liability insurance policies exclude compensation for mold damage. Lowering outside air ventilation rates decreases the margin of error in pressure control. Effective and stable pressurization strategies, such as those that directly control the pressurization flow, or the intake/exhaust and supply/return air volumetric differentials, will have to be implemented to minimize designer and owner risk, bolstering the benefits to the occupants.

Annual Income	Annual Benefit/Person	Annual Benefit/ft^2 *
$20,000	$1,000	$6.94
$40,000	$2,000	$13.89
$60,000	$3,000	$20.83
$80,000	$4,000	$27.78
$100,000	$5,000	$34.72

* Based on 144 ft^2 per person.

Table 3: Potential benefit of 5% productivity gain.

Conclusions and Commentary

Clearly, energy benefits can be realized by implementing a demand controlled ventilation strategy, if the number of occupants and the actual ventilation rate (cfm/person) can be determined with a reasonable degree of accuracy; and if building pressure can be maintained simultaneously. Unfortunately, assumptions needed to justify the CO_2-DCV approach leave designers and owners vulnerable to unnecessary risk. Changes to the ventilation rate procedure of ASHRAE Standard 62 in Addendum 62*n*[12] may result in diminished benefits from this technique, hence, higher risk.

We have attempted to demonstrate that the use of the steady-state formula previously discussed, combined with suitable PID controls and one of the currently available types of CO_2 sensors is not supported by sufficient scientific authority to avoid the risks associated with its use. Designers and owners should weigh the risks and benefits prior to implementing a CO_2 -DCV strategy. If and when selected, CO_2 -DCV applications should be limited to only those spaces with high densities and unpredictably variable or intermittent occupancy, and only after having provided a reliable method to maintain a continuous base ventilation rate, while preserving a minimum pressurization flow.

One way to limit the risk without sacrificing the potential energy benefits of DCV is to add a suitable and reliable, duct or plenum mounted airflow measuring station in the outside air intake. This additional control input would allow you to verify and maintain the design minimum levels of outside air "under any load condition,"[4] as required by Section 5.3 of ASHRAE Standard 62-2001. The user could guarantee an operational ceiling, a maximum intake rate based on design calculations or preference, never to be exceeded and which should not be overridden by other control inputs. Any reliable method of occupancy determination may then be used to reset the intake flow rates between the predetermined minimum base rate (including differential CO_2) and the design maximum, for energy optimization and verifiable compliance with Standard 62 or any code-mandated ventilation rate requirement.[16]

Direct measurement of outside air intake rates has been demonstrated to eliminate the uncertainty of indirect measurement, even though the application may be considered "too difficult" by those unfamiliar with the latest research findings for the application of the most recognizable velocity measurement technologies.

The tradeoff between direct vs. indirect measurements usually tends to be between *accuracy and effort,* respectively. The cost differences can sometimes be exchanged for accuracy gained or lost. When both are similar in total cost, the decision should always go to direct measurement, which delivers less uncertainty and less risk of error, and therefore less risk of the resultant impacts from under- or overventilation.

Improvement in indirect measurement accuracy can be made in some situations by extending the time intervals involved and/or recalibrating sensors more frequently to account for drift. When the risk of errors or the cumulative error rate becomes too large, the method itself must be questioned. Without direct measurement for comparison in the same system, only theory can be argued.

Some velocity measurement devices or combinations of velocity pressure components are just as unworthy of consideration for outside air application. Some technologies can claim to be more exact than others and possess documentation to support the claim. Others may be easier or more difficult to apply, less or more repeatable, susceptible or resistant to fouling, requiring regular and repetitive recalibration or never needing periodic adjustments.

The key to the successful implementation of any automatic control strategy is the *repeatability* of the sensing system or method. Until CO_2-based DCV can be realistically demonstrated to challenge the performance of direct intake measurement, with scientific validity, it will always convey a larger risk of noncompliance with any rate-based standard than with direct methods of ventilation control.

[††] ft^2 × 0.0929 = m^2

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