CO_2 and Ventilation Reset Precision

How much airflow set point uncertainty can we expect?

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The application of CO_2 sensors for indirect control of minimum ventilation rates continues to create contradictions and controversy due to the lack of specificity in ASHRAE Standards (62.1-2013; 90.1-2013 and previous versions). Numerous studies have highlighted significant deficiencies in the Steady-State-based methodology and in CO_2 sensor performance when used for ventilation control. Assuming a direct linkage between associated elements has fogged the logic and shrouded the key variables: actual ventilation rates and actual space population. Claims of operational adequacy are supported mainly by theoretical analysis, computer modeling, energy simulations and spot measurements.

At what point does V_{ot} or V_{bz} control error (ventilation rate at the air handler or the breathing zone) become unacceptable and effectively prevent compliance? There is an implicit requirement for some level of control precision, otherwise all methods could be deemed acceptable. Currently, the 62.1 standard puts this responsibility of precision in compliance squarely on the design engineer, who is provided with very little science to support the use of CO_2 -based DCV and the evaluation of possible alternatives. Typically, because no complaints are registered or damages recorded, prior design solutions are thought to be successful and reused indefinitely. The image of an ostrich “hiding” in the desert comes to mind.

62.1 and the IMC are concerned only with deficiencies in the ability of a system to maintain the minimum ventilation rates by expressing the requirements in “not-less-than” language. Yet, excessive ventilation is acceptable. In the other corner, 90.1 cannot be optimized when simultaneously requiring compliance with 62.1, which uses vague and incomplete guidance on DCV. “Not-less-than” gives us the bottom of the operational tolerance, but says nothing about the ceiling. How much control error should be considered acceptable? Does -0% / +25% of Reading sound reasonable? How about -0% / +100%? Both are possible with indirect control methods and are technically acceptable under the requirements of the standard.

The focus of many standards on static design requirements for code enforcement comes at the expense of operating performance. Is a compliant building’s poor operational performance important enough to require better results – even if there is no active field enforcement? ASHRAE members and the U.S. DOE are saying ‘yes. Economics motivates some, but may not be a sufficient deterrent to prevent others from violating codes or standards. This puts the public at risk and employers on the wrong side of productivity enhancement. Some designers accept the risk and feel that they can justify (or rationalize) their decisions when seeking cost savings or convenience.

It only makes sense that when required to ‘operate’ in accordance with the ‘minimum’ provisions and ‘under all operating conditions’ that the tolerances are substantially tighter than can be allowed by ignoring control lag-induced deficiencies or persistent over ventilation on population departure, etc. By rationalizing and justifying actions based on conjecture or even educated guesses; we are absorbing a significant amount of risk of non-compliance and less than optimum operational efficiency. It could lead to costly retrofit and field modifications by the owner, excessive maintenance costs, correction of deficiencies and lack of reliability. At worst, occupants’ health will be jeopardized, productivity will drop and the most sensitive may become forever disabled.

Single-input CO_2-DCV

Can it provide sufficient control reliability to satisfy the published intent and language of Standard 62.1 (or any rate-based code)? Or stated another way, Can CO_2 sensors be applied to provide a sustainable and economically justifiable alternative for ventilation control in variable occupancy spaces?

The incentives indirectly supporting this method for some equipment makers, designers and building operators should not be overlooked as a prime stimulant for the growth of CO_2 -based DCV.

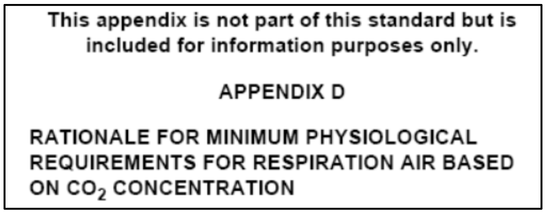
- CO_2 control masks the lack of sufficient ventilation capacity of most packaged equipment to provide the rates required by the Standard under some or most operating conditions.
- Equipment size selections and first cost may be bumped-upward to compensate for the added dehumidification load brought by increases in outdoor air.
- Operationally, owners don't want to know that they are under ventilating. Aside from deniability, under ventilation helps keep their utility costs down. What owners don't understand is that they may save even more on their utilities with control strategies that validate operational variables and maximize system efficiencies.
- Building occupants are the ones at risk. They must contend with a control variable which cannot be sensed directly, unlike temperature. It may not 'feel' under ventilated to the occupant, but when you are sensitive to contaminants, you feel sick.

Problems began to arise using CO_2 for IAQ when the tracer gas method for ventilation measurement migrated from diagnostics to continuous control; when the number of sensing devices multiplied; and when sensor recalibration and maintenance are overlooked. ASTM Standard D6245 estimates the intake airflow rate per person based on the metabolic activity of the occupants. It includes the use of a single hand-held CO_2 instrument and limits the differential measurement uncertainty to the bias error of the one device. This is far different than the multiple sensing instruments and methods normally used by HVAC systems in CO_2 -based DCV.

62.1, CO_2 and Steady-State Limitations

There are several sources for the interpretations that have historically caused opposing views on this subject.

The origin of the problems with CO_2 -based DCV can be traced to the Standard's original Informative Appendix D (relabeled C in the 2010 version) that was first published by ASHRAE in 1989. Its purpose was to explain the scientific basis for the derivation of the rates in the ventilation tables. It was never intended as a justification for the use of interior CO_2 in ventilation control. The mathematical relationships developed in the original controlled "chamber" studies did not consider variability in any of its assumptions to establish the mathematical relationships.



This appendix is not part of this standard but is included for information purposes only.

APPENDIX D

RATIONALE FOR MINIMUM PHYSIOLOGICAL REQUIREMENTS FOR RESPIRATION AIR BASED ON CO_2 CONCENTRATION

These original studies established a relationship between differential CO_2 and ventilation rates per person, through a "steady-state" model. The relationships and variables are stated as follows:

$$V_o = N / (C_s - C_o)$$

where

V_O = outdoor airflow rate per person
N = CO_2 generation rate per person
C_S = CO_2 concentration in the space
C_O = CO_2 concentration in outdoor air

Steady-state conditions must exist for the model to be valid. If any one of them is found to be untrue or deficient, the entire model is jeopardized and cannot be upheld as valid. Therefore:

1. The outdoor airflow rate into the space must be constant.
2. The CO_2 level in the space must reach a constant level.
3. Each person must generate the same and constant level of CO_2 (usually assumed to be a low 0.31 L/min, regardless of their activity level, metabolism or diet).
4. The outdoor CO_2 level must be known and either constant or be accurately determined.
5. The indoor CO_2 level must be accurately determined and maintained at a constant level above the outdoor CO_2 level.

It startles most people to realize that these conditions cannot exist in a dynamically operated building, least of all in a space with a highly variable population. Steady-state cannot be reached by the very nature of a variably and intermittently occupied space, thereby invalidating the relationship between the values sensed and those calculated.

The Steady-State Equation under the best of circumstances, can provide us with an air intake rate "per person" which is difficult and almost impossible to use energy efficiently to control ventilation rates, if compliance with 62.1 or the IMC§4 are prerequisites.

Rationalization vs. scientific confirmation

An exemption from the Steady-State conditions is offered by one author, attempting to cling to the relationships of the 'steady-state' equation without subscribing to the assumptions that were required for its justification, in the first place. In trying to justify the use of CO_2 inputs for DCV, this 5-year old article stated:

> *"It is bioeffluent (odor) concentration we are trying to control, and if the source strengths of CO_2 and bioeffluents are proportional, CO_2 concentration may be used as an indicator of bioeffluent concentration. Thus the steady-state assumption in Equation 11 is made not because the actual system is at steady-state but because the ventilation rate equation, Equation 1, is based on steady-state conditions.*
>
> *This steady-state relationship is simply being used to establish the relationship between CO_2 (odor) concentration and airflow setpoint in Equation 11. Therefore, while the rate of air supplied using Equation 11 will not exactly track the source strength of bioeffluents due to transient effects; it **should** maintain an acceptable bioeffluent concentration."*
>
> Taylor, S., 2006. *CO_2-Based DCV Using 62.1-2004*, ASHRAE Journal (Vol. 48, May 2006).

Doesn't this statement: "*…Equation 1, is based on steady-state conditions"* invalidate the equation? If the basis of the equation (steady-state conditions) is not true, can the results of the adapted equation be assumed valid for a different purpose? More troubling are the direct linkage between CO_2 and Odors. It is also assumed, without substantiation, that the new formula can maintain the same relationship between CO_2 and ventilation rates outside of steady-state conditions. It seems to me that the evidence overwhelmingly concludes that CO_2 concentration alone cannot determine intake rates or space population, both of which are needed to satisfy the standard. Also, troubling are the multiple conditional statements made leading to conclusions stated as fact. The use of "if", "may", and "should" weaken the argument to the point of conjecture.

Contrary to what this article wants you to believe, the relationship between *CO_2 ~Bioeffluents ~ Odors ~ Dilution Rates* are not directly linked. It is not a linear relationship and they are not proportional to each other. One variable cannot be used interchangeably with another and substituted. But, this is how some have tried to use them in bolstering their arguments. Even if these linkages are possible, many assumptions could be required to make the associations valid. We also need to question the assumption that the maintenance of "acceptable bioeffluent concentrations" gets us 'close' to intake rate compliance. Can bioeffluents or odors be measured directly and compared to CO_2 levels? No. Odors cannot be measured. Then, to what level of certainty are the results? We must establish a range of acceptability otherwise we need to ask, what level of uncertainty in control is considered unacceptable?

Unfortunately this type of reasoning fails to recognize that regardless of the justification and source for the rates used in the ASHRAE 62.1's tables, the standard **requires specific minimum dilution ventilation rates for compliance** in all three sanctioned procedures**.** NOT bioeffluents, NOT odors and NOT interior or differential CO_2 concentrations. That is the flaw of this alternative argument.

Andrew Persily explained the usage and relationships of CO_2 very plainly in his paper for the *Indoor Air '96* conference. A long-time researcher and scientist at NIST, an ASHRAE Board member, Chair of 189.1 and the former Chairman of SSPC 62.1; Dr. Persily presented his conclusions in: *The Relationship between Indoor Air Quality and Carbon Dioxide,* that are quoted in part below.

> *The relationship between CO_2 and outdoor air ventilation rates is well understood and is based on the consideration of CO_2 as a tracer gas. ….However, to make quantitative estimates of ventilation parameters based on measured CO_2 concentrations one must employ a specific tracer gas technique* [e.g. ASTM D6245] *that is appropriate to the conditions that exist in the building……….**The Ventilation Rate Procedure in the standard is based on outdoor air ventilation rates requirements, not on the maintenance of indoor CO_2 levels**………*

The Forward in Standard 62-99 very specifically discounted CO_2 as a contaminant and contemporary interpretations have warned against using it as a surrogate for other contaminants (that includes bioeffluents), as doing so ignores more serious contaminants from non-human sources (ASHRAE).

> *Addendum 62 f addresses a lack of clarity in ANSI/ ASHRAE Standard 62-1989 that has contributed to several misunderstandings regarding the significance of indoor carbon dioxide (CO_2) levels. The standard previously led many users to conclude that CO_2 was itself a comprehensive indicator of indoor air quality and a contaminant with its own health impacts, rather than simply a useful indicator of the concentration of human bioeffluents.*

Standard 62-2001, §6.2.1 on the IAQ Procedure warned: *"Using CO_2 as an indicator of bioeffluents does not eliminate the need for consideration of other contaminants."* This eventually led to addendum 'n' that split the rate tables between that part required for people-generated contaminants and a separate fixed dilution rate for building-generated contaminants. These 'other' contaminants are addressed broadly by dilution, thereby reinforcing the necessity of compliance the minimums outlined in the tables, especially after many of the rates were decreased in 2010, and emphasizing the importance in avoiding violations of the requirements.

Odors that result from bioeffluents can be used as part of the IAQ Procedure in a subjective survey, as they cannot be measured directly, but they are not the sole requirement for compliance or even the primary one. The IAQP is still a method of determining minimum ventilation rates, however reduced by this procedure.

Propagation of Errors from Multiple Sources and the Tendency to Over Ventilate

Many have attempted to adjust the differential concentrations of CO_2 downward (control set point for an increase in per-person ventilation rates). This can be seen most prominently by those state codes that establish requirements for interior CO_2 limits for ventilation control (e.g. Commonwealth of Massachusetts and California Title 24-Sec. 6). This may be perceived as a hedge against negative error potential, but contradicts the energy efficiency original justification for employing CO_2-based methods. To them, small differential CO_2 set points mean more ventilation and therefore more safety in the numbers selected to exceed the minimum required. By reacting this way, we are increasing the inefficiency of the air system and contradicting the reason DCV was justified in the first place. When added to the tendency of CO_2 -based DCV to over ventilate, we can expect to use more energy than with other, more precise methods of ventilation reset control.

We can see this bias to over ventilate from the ventilation rate's non-linear response to changes in populations that result from control error in the differentials in measured CO_2. A simple example (below) shows the calculated result from incremental ±25 ppm changes in CO_2. Given the numerous sources of measurement uncertainty, it is not difficult to expect that differential CO_2 measurements will be in error at least by ±200 ppm for some period during normal operation and before sensors can be recalibrated. [Dougan, D.S. and L.A. Damiano, *CO_2-DCV: Do Risks Outweigh the Rewards?*. ASHRAE Journal, Oct. 2004; Damiano, L.A. *Reduction of Errors in Ventilation Rate Determinations.* ASHRAE Transactions, p. 54-69. Jan. 2010]

Even after calibration, ±50 ppm is the best performance we are told to expect from commercial CO_2 sensors, while ±75 ppm is more typical in published performance, without consideration of recent studies criticizing the unreliability of most CO_2 sensors. [NBCIP/IEC 2009 and LBNL 2006] Differentials between the assumed (fixed) outdoor air concentration and the actual concentration can easily add another ±50 ppm (350 – 450 ppm) during relatively short cycles – hours or days. Based on recent published research, we also know that barometric pressure can add error to CO_2 measurement outputs. +150 ppm for altitude (sea level to Denver) and +80 – 100 ppm due to weather (low to high readings). This can conservatively add another ±50 ppm. If our assumption of a fixed CO_2 generation rate is flawed, changes in the occupant-group's diet or changes in work activity can add another ±150 ppm error.

This totals ±300 ppm in additional uncertainty. The RSS value (Root-sum-of-the-squares) establishes the statistical probability of error rates from multiple components in the determination. RSS calculates to ±173.2 ppm – a more realistic yet significant amount of control uncertainty.

At 175 ppm above actual, the CO_2 steady-state formula calculates that V_o will be about -24%, below our assumed set point of 20 CFM per person using a fixed 0.31 L/min generation rate. When we look at the opposite extreme (-175 ppm from actual), we calculate that V_o **will be 46% greater than the variable being controlled (intake CFM)**, using all of the same conditions.

Overnight sensor reset (similar to "auto-zero" for daily drift) will not overcome all of the sources of error and makes the assumption that overnight indoor concentrations equal those of outdoor ambient levels and that it will be the same from one night to another.

Vo %chg	Vo CFM/ person	Solve for: **Vo L/s/ person**	fixed N L/min	Cs - Co L-co2/L-o2	delta Cs - Co ppm	fixed Co = 400 Cs	Cs - Co %chg	given Cs - Co error
-37.14%	12.51	5.90	0.31	0.000875	875	1275	59.09%	325
-35.29%	12.88	6.08	0.31	0.000850	850	1250	54.55%	300
-33.33%	13.27	6.26	0.31	0.000825	825	1225	50.00%	275
-31.25%	13.69	6.46	0.31	0.000800	800	1200	45.45%	250
-29.03%	14.13	6.67	0.31	0.000775	775	1175	40.91%	225
-26.67%	14.60	6.89	0.31	0.000750	750	1150	36.36%	200
-24.14%	15.10	7.13	0.31	0.000725	725	1125	31.82%	**175**
-21.43%	15.64	7.38	0.31	0.000700	700	1100	27.27%	150
-18.52%	16.22	7.65	0.31	0.000675	675	1075	22.73%	125
-15.38%	16.84	7.95	0.31	0.000650	650	1050	18.18%	100
-12.00%	17.52	8.27	0.31	0.000625	625	1025	13.64%	75
-8.33%	18.25	8.61	0.31	0.000600	600	1000	9.09%	50
-4.35%	19.04	8.99	0.31	0.000575	575	975	4.55%	25
Target	**19.91**	9.39	0.31	0.000550	550	950		
4.76%	20.85	9.84	0.31	0.000525	525	925	-4.55%	(25)
10.00%	21.90	10.33	0.31	0.000500	500	900	-9.09%	(50)
15.79%	23.05	10.88	0.31	0.000475	475	875	-13.64%	(75)
22.22%	24.33	11.48	0.31	0.000450	450	850	-18.18%	(100)
29.41%	25.76	12.16	0.31	0.000425	425	825	-22.73%	(125)
37.50%	27.37	12.92	0.31	0.000400	400	800	-27.27%	(150)
46.67%	29.20	13.78	0.31	0.000375	375	775	-31.82%	**(175)**
57.14%	31.28	14.76	0.31	0.000350	350	750	-36.36%	(200)
69.23%	33.69	15.90	0.31	0.000325	325	725	-40.91%	(225)
83.33%	36.49	17.22	0.31	0.000300	300	700	-45.45%	(250)
100.00%	39.81	18.79	0.31	0.000275	275	675	-50.00%	(275)
120.00%	43.79	20.67	0.31	0.000250	250	650	-54.55%	(300)
144.44%	48.66	22.96	0.31	0.000225	225	625	-59.09%	(325)

Table 1 – *Ventilation rates/person based on steady-state CO_2 calculations for incremental errors (25 ppm).*

When the CO_2 generation rate increases to 0.40 L/min, the comparison requires a shift to a higher set point to achieve the targeted 10 L/s/ person or 20 cfm/person (which equates to 700 ppm from 550 ppm differential). The result from a ±175 ppm error does not provide the same percentage changes as previously shown, due to the higher concentration level it is being compared with. Outdoor CO_2 is still assumed (incorrectly) to be fixed. As we have seen, even small differences in the concentration differential can mean a large deviation in the actual intake rate.

Vo %chg	Vo CFM/ person	Solve for: **Vo L/s/ person**	fixed N L/ min	Cs - Co L-co2/L-o2	delta Cs - Co ppm	fixed Co = 400 Cs	Cs - Co %chg	Cs - Co error
20.00%	16.14	7.62	**0.40**	0.000875	875	1,275	25.0%	**175**
Target	**20.18**	9.52	**0.40**	0.000700	700	1100		
33.33%	26.91	12.70	**0.40**	0.000525	525	925	-25.0%	**(175)**

Table 2 – *Ventilation rates/person at 0.40 L/min generation rate, based on steady-state CO_2 calculations for 175 ppm errors only.*

The many limitations, considerations and uncertainties in measurement have been explored in a number of studies. One of the more recent studies was published by Lawrence Berkeley National Labs' Indoor Environment Division in 2008.

> *"…this method [CO_2] is subject to several sources of error which are described in detail elsewhere (Persily 1997, Mudarri 1997, ASTM D 6245-98) and summarized below: ……*
>
> - *Concentrations of carbon dioxide in outdoor air vary with location and time, and significant error may result if assumed outdoor concentrations are used in calculations.*
> - *The number, weight, activity and diet of the occupants affect the indoor carbon dioxide generation rate and each of these parameters can only be estimated.*
> - *Indoor carbon dioxide concentrations may be spatially non-uniform and measurements at a few locations may not accurately represent the average concentration in the exhaust air.* [Author's Note: CO_2 stratification and/or sampling error.]
> - *Use of the peak CO_2 instead of actual steady state values may produce erroneous ventilation rate estimates, off by a factor of 2 at low ventilation rates, and less at higher ventilation rates (Persily and Dols 1990)."*
>
> [*Ventilation Rates and Technologies: How are CO_2 concentrations related to ventilation rates?* LBNL-IED, http://eande.lbl.gov/IED/viaq/v_rates_3.html, downloaded 07/15/08.]

Without considering other sources of error or improved methods of implementing DCV, and without using an additional input to validate and feedback actual intake rates; we still appear to be taking unnecessarily large risks for noncompliance with code minimums or for making zero energy buildings more difficult to achieve.

We can summarize the simple truths of CO_2:

- CO_2 varies with population changes, *unrelated to floor area or occupancy type.* No longer can a single CO_2 set point satisfy ventilation for changing populations, without massive over ventilation during operation.
- For a given population, the CO_2 level will represent a fixed outdoor air rate per person only, ignoring the fixed rates required for building generated contaminants.
- CO_2 levels will change with variations in intake flow rates.
- CO_2 levels will change with differences in occupant metabolism.
- Using any variation of the Steady-State formula will tend to over ventilate, while the only assurance that minimum populations will not be under ventilated requires that worst-case population estimates be used.
- Systems that maintain constant CO_2 levels will typically provide waste energy and more outdoor air than desired.
- CO_2 Sensor Errors add to the uncertainty of OA set point determination and control. ± 75 ppm = +15% / -13% V_{ot}
- Outdoor CO_2 concentrations can vary significantly increasing outdoor airflow rate set point errors. ± 50 ppm =+11% / -7% $V_{ot.}$
- CO_2 (interior or differentials) by itself cannot determine the population (P_z) of a space, THE key variable for reset control of ventilation rates (V_{ot} or V_{bz}).

How can we respond more precisely to actual population changes and reduce the errors in MOA set point control?

1. We can start by **directly monitoring the variable that we are trying to control – airflow rates and space population**. More precise determination of both variables is needed in order to make ventilation changes to reflect the needs of a specific population.
   a. Direct measurement limits uncertainty to the one method used to determine the variable. Avoiding indirect determinations which will contain the largest uncertainties. We can require that outdoor intake rates be continuously validated with permanently installed meters, similar to what Standard 189.1 and LEED have done. Many venues have separate means of determining populations, either for billing, market research, security or ticketing. Large conference or meeting rooms can be fitted with purpose-built counters tied directly to HVAC ventilation control. Several methods using CO_2 can be employed to 'count' indirectly, but with higher error rates. Known occupancy schedules or timers can also be effective in many situations. KISS.
   b. A five-year verification minimum frequency for units providing >2,000 CFM (ASHRAE 62.1 §8.4) or even semi-annual balancing is insufficient to maximize operational efficiency. Adjustments are unpredictable and may be needed on a daily, weekly or even seasonal basis.
   c. Permanently installed airflow meters are primarily intended to provide immediate feedback on changes in outdoor airflow rates or volumetric differentials for pressurization. They may be used additionally for system set up, commissioning, FDD as well as continuous control.
   d. Systems using CO_2 -based DCV methods, may be combined with direct volumetric airflow measurement to establish and enforce a min/max intake control range, to count populations and improve reset precision.

2. The dynamic reset provision in our 62.1 standard should be emphasized to reflect the **true common denominator for variability in ventilation requirements: space population (P_z) and its relationship to dynamic reset.** All methods of DCV and ventilation code compliance are dependant upon knowing or estimating this sometimes dynamic variable for the worst case expected.
   a. Surrogate and indirect control variables or tenuous logic should be prohibited.
   b. Methods should not be selected merely because they are easier or serve other interests.

3. The MOA control error potential we have discussed here applies to Constant Volume air handlers as well as Variable Volume systems. Many **CAV designs are now required to have multi-speed or variable supply fans** (90.1 §6.5.3.2.1 Fan Airflow Control and CA Title 24, Part 6, 2013) which produce similar and dramatic changes in intake rates as shown in VAV systems.
   a. When climatic conditions support the economic justification, DOAS systems could overcome this deficiency, but there would be application limits.
   b. Smaller FC fans (within 5-10 ton AHUs) are more prone to capacity fluctuations due to filter loading, dirty coils, wind and stack pressure effects.
   c. Fan speed alone will not ensure constant output. "*Note that a fixed-speed, outdoor-air fan without control devices will not maintain rates within the required accuracy*" [User's Manual for ASHRAE 62.1-2010, VAV p.31]
   d. Many more air systems in the future will include variable supply controls and therefore variable and uncontrolled intake and pressurization flow rates.

4. We should **re-examine the first cost for the additional instrumentation** relative to the price for the average DDC controls contract or the entire HVAC mechanical components use. We should also **check the economic impact on: system selection, sizing, reliability, temperature control, humidity control, occupant health, reduction in sick time lost and energy savings**, etc. before making a short-sighted decision on first costs alone.

Several velocity meters can now also provide basic ventilation control functions or alarms, which can be used to great effect with smaller air handlers in systems which normally have only the simplest thermostatic binary control. Improvements in airside economizer operation, reliability and fault detection are a byproduct if not a primary objective of these hardware developments.

The combined state of our minimum standards and first-cost motivations in our contracting culture retard the advancements we have identified as a societal imperative. It's time to make the simple changes that can make so much difference in the quality of our lives and sustainability of our children's futures. Increasing and validating the performance requirements for control components on air systems will be reflected in both future operational cost savings and improvements in the indoor environment.