Reliable DCV methods - Meeting ventilation requirements while minimizing energy

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Overview

Spaces with high occupant densities and variable populations present a unique challenge to designers struggling to meet the requirements of both ASHRAE Standards 62.1-2010 and 90.1-2010, plus the 2009 International Mechanical Code on Ventilation. Energy, rather than occupant health and productivity, has become the focus of most owners and engineers with respect to HVAC design. Can systems using demand controlled ventilation (DCV) strategies to conserve energy comply with today's ventilation standard for acceptable indoor air quality (IAQ) and our national energy standard? This paper will demonstrate the potential uncertainties associated with several methods of demand controlled ventilation, including: traditional CO_2-based DCV, DCV using population estimates from CO_2 and direct occupancy counting systems.

ASHRAE 62.1-2010 Requirements

Standard 62.1-2010 specifies outdoor air ventilation rates based on both floor area and population. This requirement is a result of a wholesale change to the *Ventilation Rate Procedure* (VRP) by addendum "*n"* to 62-2001 in 2003 with ANSI approval in 2004.[1] Prior to addendum 62*n*, the required outdoor air ventilation rate was based exclusively on CFM per person.

Although the calculations in the VRP may appear cumbersome, the theory is quite simple: provide the required outdoor air at the breathing zone based on the population size and floor area. Although multi-zone systems may appear to be more complex, the requirement at the breathing zone is the same as with single zone systems. Multiple-zone system calculations simply provide a credit of the unused outdoor air from the zones that are not critical. DCV for VRP compliance should modify the outdoor air required at the air handling unit (AHU) based on actual conditions. On single zone systems, the population and floor area is required to establish the specified minimum ventilation rate.[2] Multiple-zone systems additionally require that the primary supply airflow and any recirculated return or transfer airflow, if provided to any of the zones. Air distribution effectiveness at the zone level also must be taken into account for both single and multiple zone spaces

ASHRAE 90.1-2010 Requirements

Section 6.4.3.9 *Ventilation Controls for High Occupancy Areas* requires DCV for all ventilation systems with design outdoor air capacities greater than 3,000 cfm serving areas larger than 500 ft^2 and having an average density exceeding 40 people/1000 ft^2 (90 m^2). It takes a broad brush to the ventilation control requirements and by definition requires that the system automatically reduce intake rates "when the actual occupancy of spaces served by the system is less than design occupancy" for spaces with high occupant densities. The requirement is limited to specific areas and system capabilities.[3]

DCV is defined by the 90.1 standard differently than in 62.1. Std. 90.1 says it is *"a ventilation system capability that provides for the automatic reduction of outdoor air intake below design rates when the actual occupancy of spaces served by the system is less than design occupancy."*

While 62.1 defines DCV as *"any means by which the breathing zone outdoor airflow (V_{bz}) can be varied to the occupied space or spaces based on the actual or estimated number of occupants and/or ventilation requirements of the occupied zone."* Standard 62.1 broadens the application to any 'ventilation requirement' including other reasons that the minimum rates could be adjusted downward; for example, to take advantage of periodic availability of greater efficiencies in air distribution effectiveness or higher fraction of outdoor air in the air supply.

Unfortunately, this definition also allows "estimating" P_z for the current population of the zone, whereas 90.1 and IMC Chapter 4 require that the population for ventilation determination be based on the "actual" occupancy. The problem stems from 62.1 not providing guidance on the tolerance in population determination allowed for compliance with the minimum rates. Only that V_{bz} shall never be below the amount required for floor area component of the total rate, which cannot be determined by CO_2 concentration inputs.

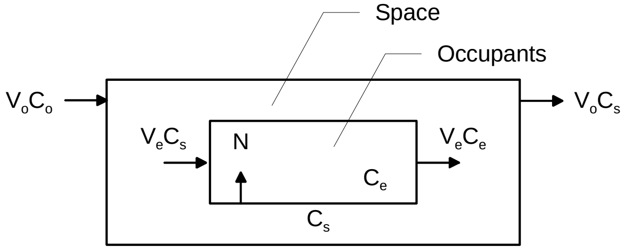
It is interesting to note that the high and low density requirements (and the use of CO_2-based DCV) for *Outdoor Air Delivery Monitoring* in the 2012 LEED Rating System draft, have been completely removed from the rating document, based on language in the Public Review version. The definition and references to DCV in 90.1-2010 also no longer mention CO_2 or any specific method. Only "DCV" is mentioned in its more generic form, as is appropriate. All this tells us that the shine of CO_2-based methods is wearing thin, and standard writers are being cautious in recognition of the numerous control issues, difficulties reported in start-up validation and operation, questionable reliability, cost effectiveness and sensor inaccuracy.

We understand that over ventilation is not prohibited by either ASHRAE Standard 62.1 or 90.1 for compliance with the established minimums. However, should that allow the standard to ignore prudent engineering practices required for compliance to both Standards?[5] Should not design practice attempt to satisfy ventilation minimums at the lowest energy cost – not just the minimum required in the code?[6] If over ventilation is not a significant energy concern, why devote so much attention to DCV and make it a minimum requirement in the energy code?

Whether your designs include CAV or VAV air distribution systems, serve single or multiple-zones; the uncertainty in control must be known. Compliant control methods must have an expectation of providing satisfactory results and be sufficiently effective to justify an implied recommendation within standards and model code documents.

The History and Rationale behind CO_2-based DCV

Before CO_2 DCV was used in HVAC systems, industrial hygienists were monitoring CO_2 levels inside and outdoor of buildings to determine if ventilation rates were sufficient to adequately dilute body odor. These spaces typically had near constant occupancy and constant outdoor airflow setpoints. As a result, the steady-state, two chamber CO_2 model could be applied to estimate the outdoor air CFM per person. The steady-state model, discussed in *Informative Appendix C* of Standard 62.1, is illustrated below.



$$Vo = N/(C_s\text{-}C_o)$$

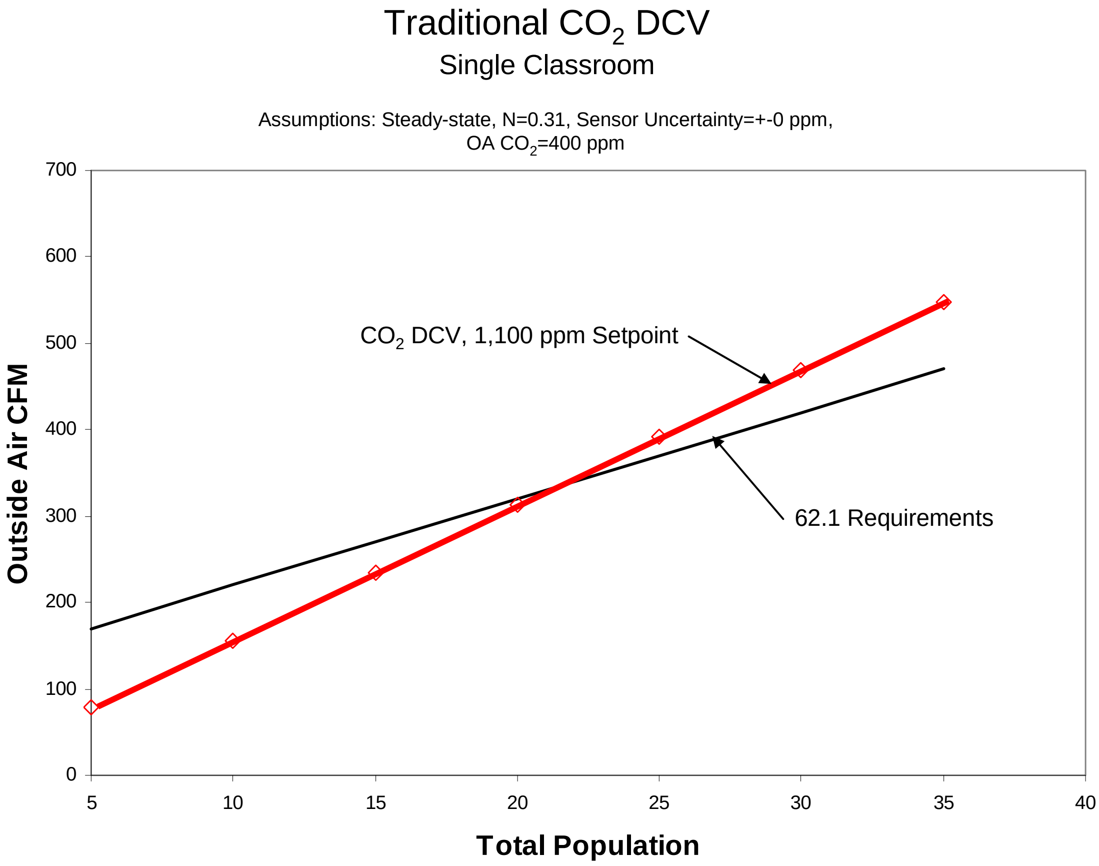
where

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

ASHRAE Standard 62-1989 presented the first real challenge to designers of variable occupancy spaces. Enterprising individuals recognized that the relationship between CO_2 and the ventilation rate per person could potentially be used to modify outdoor air ventilation rates as conditions or occupancy changed, in order to save energy. Although the relationship had large potential errors from its assumptions, the technique gained considerable popularity over the years.

Addendum 62*n*, incorporated into 62.1-2004 and now the current 62.1-2010 parent document complicated the use of CO_2-based DCV since it resulted in a variable ventilation rate per person and potentially a variable CO_2 setpoint. Since a given CO_2 level, at best, can only estimate the outdoor airflow rate per person, the correct CO_2 setpoint would require that the population was known, should one of your objectives be to maintain intake airflow at the lowest minimum allowable value. With this goal in mind, we create a somewhat circular argument; if you know the population, you do not need to know the CO_2 level.

As a result, using traditional CO_2 DCV and expecting to minimize energy while doing so, may be very problematic for Standard 62.1-2010 compliance. Figure 2 shows the ventilation rates associated with a fixed CO_2 setpoint and that required by Standard 62.1. Note that traditional CO_2 DCV will either under or over ventilate the classroom. In this simple illustration steady-state conditions are assumed and all of the occupants are generating CO_2 at a fixed and constant rate. It is also assumes that the CO_2 sensors have negligible error and the outdoor CO_2 level is actually monitored (outdoor levels are typically assumed at a fixed level).



CO_2-based DCV Uncertainties

There are a number of compounding uncertainties when using CO_2 to modify the outdoor airflow rate.[8] Steady-state conditions seldom occur in spaces where the population and outdoor airflow rate is variable. This is significant if the performance of your system is based on the assumptions in the Steady state Equation being valid. The CO_2 production rate changes considerably with the activity level and the measurement error of space CO_2 can be quite large.[8]

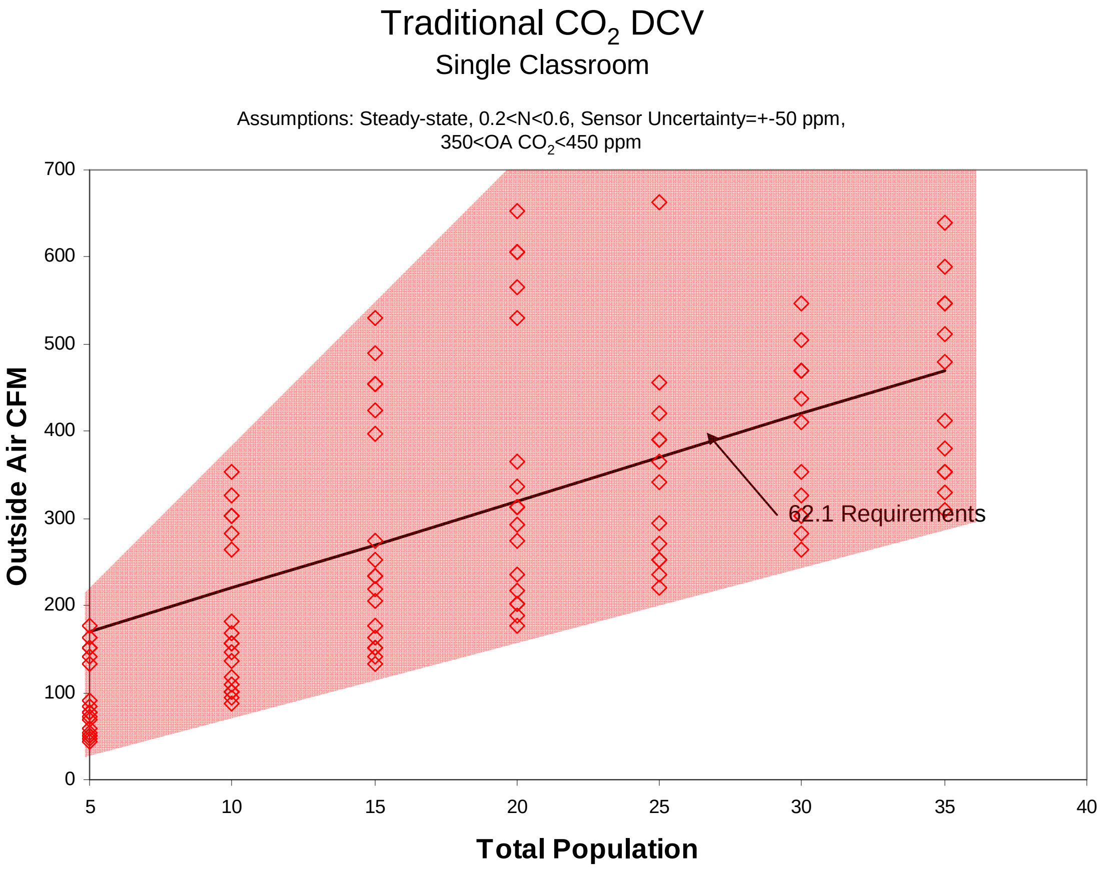
The outdoor CO_2 level is typically not measured due to cost implications and temperature limitations in CO_2 sensor technology. When the uncertainties of this assumption are considered, the potential deviation from Standard 62.1 requirements is alarming with a single CO_2 setpoint. The resulting area of uncertainty is shown in figure 3. The use of variable CO_2 setpoints within system-specific algorithms has been proposed as an alternative method of control but its analysis is beyond the scope of this paper.[11, 13] It should be sufficient to point out that these methods are mostly theoretical and as yet have not been tested to determine their realistic ability to “maintain” ventilation at rates “not less than” those minimums required by codes and standards.

Calculating Potential CO_2 DCV Uncertainty

Figure 3 data assumes steady-state to simplify calculations. The steady-state model from figure 1 is biased by the CO_2 production rate, sensor error and outdoor air CO_2 level for each combination of uncertainties at various population levels. Uncertainties in this analysis are conservative and consider population activity levels ranging from sleeping to walking ($0.2 < N <$

0.6 L/min) and a space CO_2 uncertainty of ±50 ppm and an outdoor air uncertainty of ±50 ppm from a nominal level of 400 ppm. In practice, the space CO_2 uncertainty will be much greater due to sensor drift and location.

One should note that the flow rate uncertainty above full design requirements can be minimized by setting a maximum limit on the position of the outdoor air damper. However, it should also be noted that wind, stack and mixed air plenum pressure variations (VAV systems) will affect the outdoor air intake flow rate[12] and still result in the potential for significant over-ventilation.



Improving CO_2 Based DCV

CO_2-based DCV can be improved by one of the following methods:

- Setting an upper and lower outdoor airflow limits (Threshold Method), or
- Using CO_2 to estimate the population (CO_2 Count Method)

Threshold Method

The Threshold Method (TM) uses an airflow measuring station in the outdoor air to “clamp” the range of airflow rates provided by traditional CO_2 DCV. The upper limit is based on full design ventilation requirements and the lower limit is established by analysis of IAQ risk or the minimum outdoor airflow rate required for pressurization.

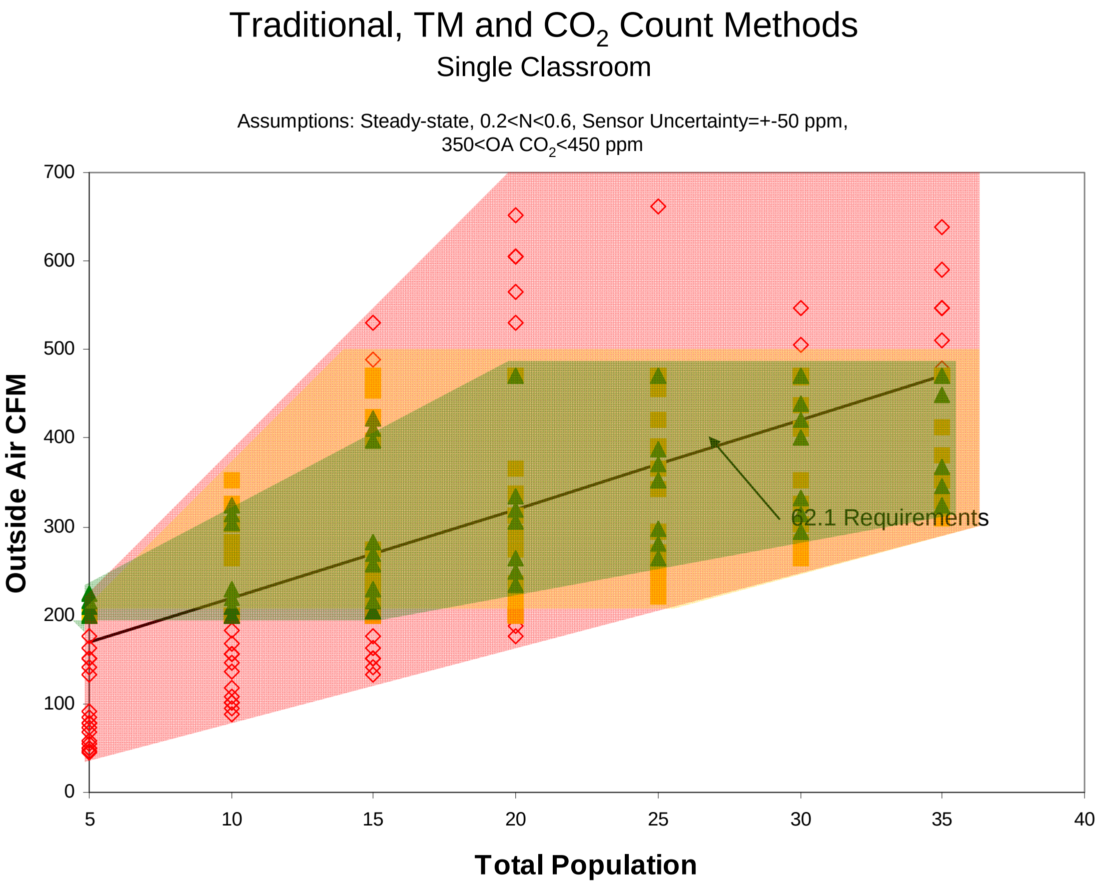
CO_2 Count Method

Using CO_2 and intake flow rate inputs to calculate or “count” the number of space occupants would take advantage of the relationship between CO_2 and ventilation rates (i.e. CFM/person) and solve for “persons”. When combined with airflow measurement, the population can be estimated using an appropriate CO_2-DCV model. This method may also use the non steady-state CO_2 model to improve population estimates when populations change significantly. [10]

The CO_2 Count Method can be used on both single and multi-zone systems. On single zone systems, the zone CO_2 level and the outdoor airflow rate is required to estimate the population. A straight line approximation of this method was presented by Stanke that simplifies the calculations for adaptation on simple setpoint controllers. [13]

On multiple zone recirculating systems, the outdoor airflow rate along with the zone supply airflow rate and CO_2 level of each DCV zone is required.

Both methods improve CO_2 DCV but are still subject to numerous uncertainties associated with CO_2 measurement (even when the transient model is used). The resulting uncertainty for our single zone classroom example is indicated in figure 3. Although there is significant reduction of uncertainty with the improved methods, the uncertainty using CO_2, even as a counting technique, is suspect. [8, 9, 10]



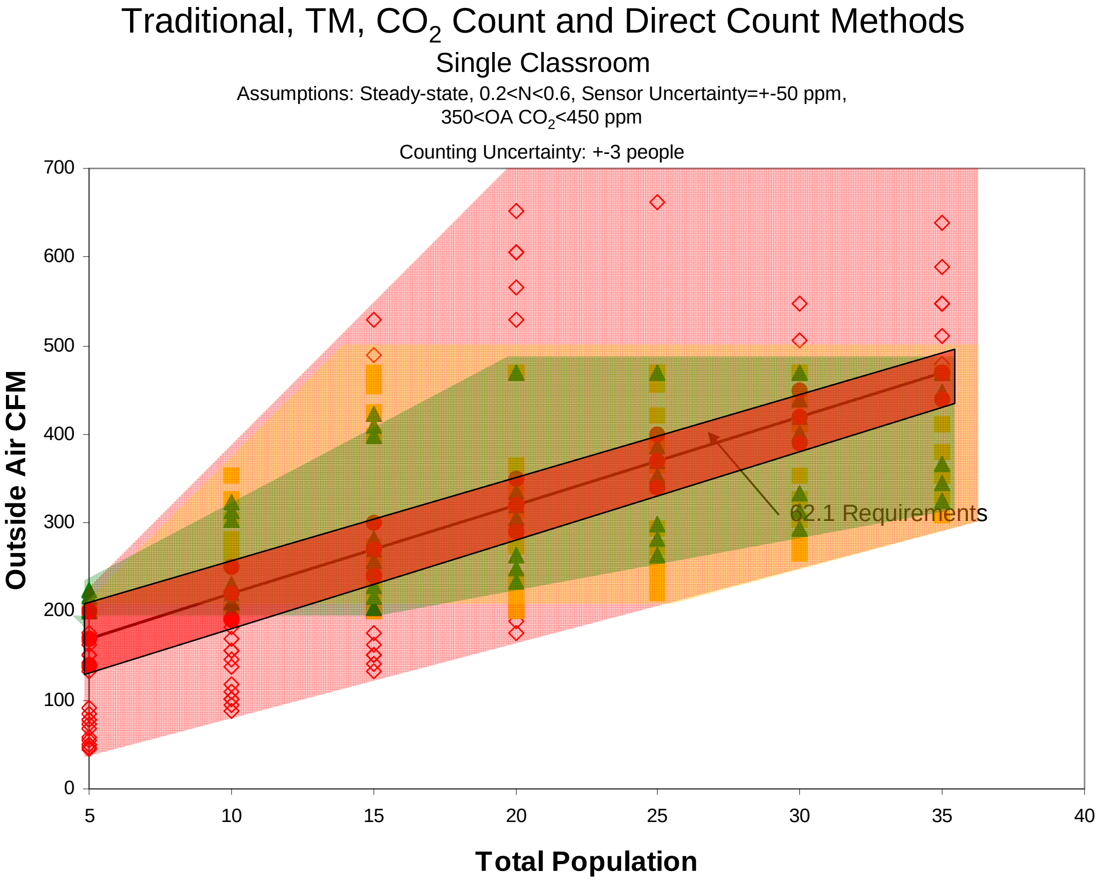
Traditional, TM and CO_2 Count Methods

Single Classroom

Assumptions: Steady-state, $0.2<N<0.6$, Sensor Uncertainty=+-50 ppm, $350<\text{OA } CO_2<450$ ppm

Direct Counting Methods

Direct counting methods eliminate the uncertainties associated with CO_2 measurement. A counting device located in each space is used to determine the actual ventilation requirements specified by ASHRAE 62.1-2010. Examples of counting devices include: video and/or thermal imaging counters, infra-red counters, radio frequency identifiers (RFIDs), turnstiles, time based schedules (if accurate) or any other device/method that can estimate the actual population of the space.[2] Multi-zone systems require that zone supply airflow is measured to calculate the multi-zone requirements of the VRP. When compared to CO_2 DCV, the performance of direct counting methods is considerably better. In our classroom example, a counting uncertainty of +/- 3 persons over the entire population range results in significantly improved performance over CO_2-based methods.



Multiple Zone Recirculating Systems

All of the models presented are for single zone systems. Multiple Zone Recirculating Systems (MZRS) present another level of complexity and unanswered questions. These questions regarding the application of CO_2–based DCV methods must be answered before any theoretical method can be said to satisfy the VRP of ASHRAE 62.1.

- DCV control logic must ensure that the area (building) component of the ventilation rate is maintained regardless of CO_2 concentrations.
- Furthermore, the multiple spaces equation, which is required to be used to determine ventilation system efficiency for MZRS, has been generalized to take credit for secondary recirculation paths such as those provided by fan-powered mixing boxes or dual duct systems. This adds to the complexity of the mathematics.

- People enter or leave the portion of a building served by a particular ventilation system, or they merely move from zone to zone that are served by the same system. What system population assumptions should be used for part-load DCV operation?
- The VRP allows the outdoor air required for a zone to be based on the average population over a time constant as defined in the standard. The logic is that pollutants will not be at steady state so the time averaged ventilation rate will result in acceptable pollutant concentration. This makes sense when the ventilation rate is constant over the space's time constant, but is it appropriate when the ventilation is being varied by a DCV system?
- Similarly, the VRP allows credit to be taken for system-wide occupant diversity, allowing the design ventilation rate to be based on the system-wide average occupancy. But does this make sense when the ventilation system includes DCV in some or all of its zones? Perhaps the system can be designed using system occupant diversity at peak design conditions, but can the same diversity factor be used to solve the multiple spaces equations for the intake airflow required at part-load? Does part-load diversity apply to all zones or just those zones with no DCV capability? After all, the part-load population in DCV zones might be lower than design population but higher than diversity population.
- Can the part-load intake airflow rates be determined directly from DCV zone conditions without using the multiple spaces equation? This would greatly simplify the calculations required.

CO_2 DCV cannot be properly implemented in MZRS with the assurance that it will perform as expected, comply with Standard 62.1 and its ventilation rate procedure. Yet DCV is required by Standard 90.1 for most MZRS serving densely occupied spaces. 62.1 is a prerequisite for 90.1. This is a contradiction. Depending on the control logic, DCV strategies for MZRS may be under- or over-ventilating spaces and consequently causing indoor air quality problems and/or excessive energy usage. Its only a matter of time before they are identified.

A pending research project contract (RP-1547) is to examine theoretical solutions to the MZRS dilemma. The project assumes that static mathematical formula can be developed for 'design' purposes. Since there must be some expectation that controls will perform as designed, at least during a significant majority of the time while the building is occupied, the math may not be able to be implemented.

We have strong reservations regarding the validity of a theoretical solution, based solely on math in design, to a complex and dynamic control problem. It is possible that such a system may never perform as intended. The results of this project will be heavily scrutinized and may be an interesting one to validate in a realistic field situation with a fully instrumented building.

Conclusions

DCV is required by energy codes on high density variable occupancy spaces.[3] However, uncertainties associated with traditional CO_2-based DCV may not result in the desired result in both energy conservation and occupant well-being.

Use of direct outdoor airflow measuring devices to constrain intake flow rates between upper and lower threshold limits can improve the performance of traditional, single setpoint CO_2-DCV. The method can be improved further using the same sensors to estimate the actual population and calculate the outdoor air intake flow rates specified by ASHRAE Standard 62.1-2010. One must keep in mind, however, that these techniques are still limited by the inherent uncertainties associated with the use of CO_2.

Perhaps the most promising method of DCV may be to directly measure the population to determine the requirements of actual “real-time” requirements of 62.1-2010. Emerging, cost effective, technologies in population measurement may make this demand controlled ventilation strategy commonplace in the not so distant future.

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