The Relationship Between CO_2 Levels and Ventilation for DCV Applications

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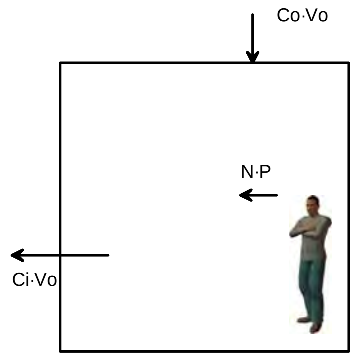
INTRODUCTION

Carbon dioxide (CO_2) levels inside occupied building spaces are often used to reset outside airflow rates (ventilation air) in an effort to reduce the energy consumption of a facility. Unfortunately, most designers do not understand the relationship between CO_2 and ventilation. This paper will clarify the relationship between CO_2 levels and ventilation rates. It will also present serious shortcomings of using CO_2 levels to reset ventilation rates on multi-zone recirculating air systems.

ASHRAE Standard 62.1

Up until 2004, the ventilation rate tables in ASHRAE Standard 62 were stated as a fixed airflow rate per person (i.e. CFM/person or LPS/person). As a result, the indoor CO_2 level could be used to estimate the outside airflow rate per person. The steady-state, mass balance equation for this relationship is illustrated in figure 1.

Figure 1



Co = Outside air CO_2 level (scfm CO_2/scfm Air)
Ci = Inside CO_2 level (scfm CO_2/scfm Air)
Vo = Outside air flow rate (scfm)
N = [scfm CO_2/min]/person
P = Number of people
R = Rate (scfm OA/person)

Mass Balance Equation

In = Out
$Co \cdot Vo + N \cdot P = Ci \cdot Vo$

Simplifies to:
$N / (Ci - Co) = Vo / P = R$ scfm/person

The model's ability to accurately predict the source airflow rate per person, R, is dependent on the CO_2 production rate of the individual, which can vary significantly with activity and age. For average adults with an activity level associated with office work, the equation for I-P units can be rewritten as follows:

$$R = 0.010951 / (Ci - Co)$$

Additional measurement uncertainty of the breathing zone and source CO_2 levels will also affect model performance. A transient term can be added to improve the prediction of the source airflow rate per person when either the source airflow rate or population varies rapidly. Unfortunately, many implementing this technique do not understand the relationship between CO_2 levels and air quality. Many falsely interpret CO_2 to be a contaminant and that a level of CO_2 approximately 700 ppm greater than outside levels (approximately 1,100 ppm inside) would result in acceptable indoor air quality. This misconception was partially a result of ambiguous text in ASHRAE Standard 62 prior to 2004 which stated:

> 6.1.3. Ventilation Requirements
> "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."

On single zone systems, a 700 ppm rise in the CO_2 level results in an outside airflow rate/person, R, that is equal or greater to approximately 15 CFM; the minimum ventilation rate required to dilute body odor. Nonetheless, many today still assume that the CO_2 level is directly related to the contaminants, and that CO_2 levels greater than 1,200 or 1,300 ppm are harmful. In fact, that is not true. Compliance with Standard 62.1-2010 in high occupant density meeting rooms will result in steady-state CO_2 levels in excess of 2,000 ppm when the required outside air is provided!

{example of meeting room needed}

Ventilation Rate Procedure (determines V_{bz})

Standard 62.1-2010 has not changed significantly since 2004 when the breathing zone outside air requirements where adjusted to include a floor area component. Today, the breathing zone outside airflow rate, V_{bz}, is calculated based on table values as follows:

$$V_{bz} = R_p \, P_z + R_a \, A_z$$

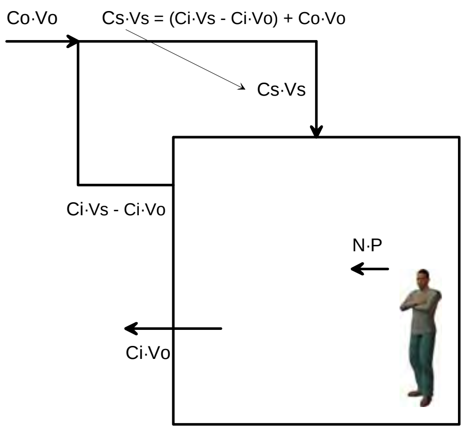
where,

R_p = Outside air rate/person
P_z = Number of persons
R_a = Outside air rate/floor area
A_z = Floor area

As a result, a constant CO_2 setpoint will no longer result in specified ventilation rates unless the setpoint is calculated at the lowest expected occupancy (i.e. when the ventilation rate per person is at its highest).

This dilemma can easily be compensated for on single zone systems by solving the steady-state model for the actual occupancy, calculate V_{bz} based on that occupancy. All that is required is the addition of an outside airflow measurement device. The resulting steady-state mass balance equations for estimating the population are shown in figure 2 (recirculating system) and figure 3 (dedicated outside air system – DOAS). Note that the equations are identical for recirculating and DOAS systems.

Figure 2 – Single Zone Recirculating System



Co = Outside air CO_2 level (scfm CO_2/scfm Air)
Cs = Supply air CO_2 level (scfm CO_2/scfm Air)
Ci = Inside CO_2 level (scfm CO_2/scfm Air)
Vo = Outside air flow rate (scfm)
Vs = Recirculated supply air (scfm)
N = [scfm CO_2/min]/person
P = Number of people

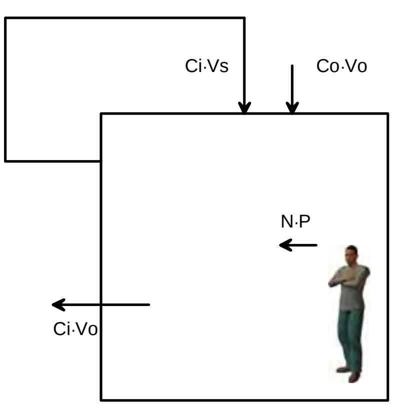
Mass Balance Equation

In = Out
(Ci·Vs - Ci·Vo)+ Co·Vo + N·P = (Ci·Vs - Ci·Vo) + Ci·Vo

Simplifies to:
P = Vo·(Ci-Co)/N

Figure 3 – Single Zone DOAS System

Shown with a recirculating system for the sensible load (the sensible load could also be handled by radiant panels, chilled beams, etc.)



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Vo = Outside air flow rate (scfm)
Vs = Recirculated supply air (scfm)
N = [scfm CO_2/min]/person
P = Number of people

Mass Balance Equation

In = Out
Ci·Vs + Co·Vo + N·P = Ci·Vs +Ci·Vo

Simplifies to:
P = Vo·(Ci-Co)/N

Estimating accurately or determining the real-time actual population, P_z (required for ventilation rate determination by IMC §403.5) is the challenge for an energy efficient VRP compliance. The historical alternative has always over ventilated when space occupancy varied lower than design maximum. Modulating the position of one intake damper based on changes in interior CO_2 can only satisfy V_{bz} if you are lucky or you intentionally over ventilate at all times.

The CO_2+airflow rate counting method:

- Is best suited for large places of assembly with multiple, large entry doors.
- Uses the CO_2 relationship to CFM/person to estimate the population.
- Requires a CO_2 sensor in each zone or a CO_2 sampling system to determine the ΔCO_2 (SA to space) of variable occupancy zones.
- Is still subject to numerous errors associated with CO_2 DCV but may be the only practical approach on certain types of spaces.

Changing ventilation rates based solely on interior CO2 concentration levels is too unreliable to allow predictable and repeatable results in multiple zones, across climates, system designs, over time and varying occupant densities.

A single common element is available that can improve operating performance and reliability – population size determination.

Possible alternatives in determining P_z, with less uncertainty than CO_2–based methods, include the use of:

- Direct counting devices
- Occupancy schedules
- Design occupancy , when
  - the AHU is in occupied mode.
  - the zone is occupied (binary detection)
- CO_2+airflow rate counting method

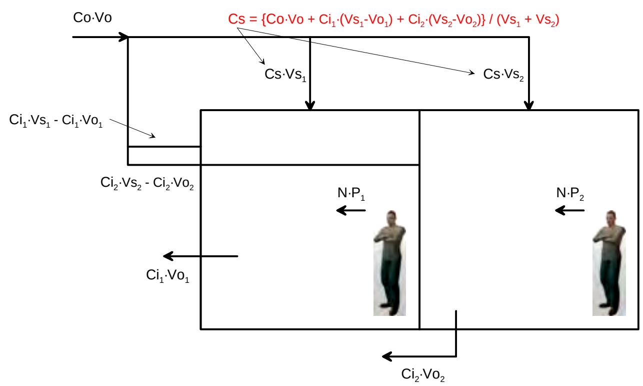
Some or all of these may allow you to operate multizone DCV systems effectively and more efficiently.

Complications with Multi-zone Systems

CO_2 DCV is routinely applied on multi-zone systems. Unfortunately, there are significant flaws if one assumes that the steady-state model shown in the previous figures is valid on multi-zone systems.

Figure 4 shows the steady-state model for a multi-zone recirculating system.

Figure 4 – Multi-zone Recirculating System



Co = Outside air CO_2 level (scfm CO_2/scfm Air)
Ci = Inside CO_2 level (scfm CO_2/scfm Air)
Cs = Calculated return air CO_2 level (scfm CO_2/scfm Air)
Vo = Outside air flow rate to zone (scfm)
Vs = Recirculated supply air rate to zone (scfm)
N = [scfm CO_2/min]/person
P = Number of people

Mass Balance Equation (zone 1)

In = Out
$Cs \cdot Vs_1 + N \cdot P_1 = Ci_1 \cdot Vs_1 - Ci_1 \cdot Vo_1 + Ci_1 \cdot Vo_1$

Simplifies to:
$P_1 = [Vs_1 \cdot (Ci_1 - Cs)] / N$

62.1 VRP compliance with CO_2 can be achieved for multizone recirculating systems, in theory, through the following calculations for population estimation and reseting ventilation rate setpoints.

Step 1: calculate the SA CO2 level to reduce error
Cr=∑[(Vpz/Vps)*Cz]
Cp =Cr*(Vps-Voa)/Vps + Co*Voa/Vps

Step 2: estimate the occupancy
Vp (SA CFM/person) = 10,951/(Cz-Cp)
Pz (persons)= Vpz (SA CFM)/Vp (SA CFM/person)

Step 3: follow the modified VRP to calculate Vot

Note that the population calculation (a prerequisite to establish the required breathing zone outside air) requires the zone CO_2 and supply air CO_2 levels.

Although it is theoretically possible to measure the supply air and zone CO_2 levels, the sensor accuracy required to properly measure the small differential (usually much less than 300 ppm) is unavailable with today's CO_2 sensor technology unless a single CO_2 sensor is used to sample both the supply air and zone.

Multiple Sources of Ventilation Rate Uncertainty

Although CO2 may be a valuable tool for DCV, we should not ignore the potential impact of its application. Generally, steady-state conditions are assumed (a transient term can be added to compensate for non-steady state conditions). Therefore,

- **the outside airflow rate into the space must be constant (on DCV, that** obviously is not the case).
- **the CO2 level in the space must reach a constant level.**

Regardless of what model is used,

- **each person must generate the same and constant level of CO2 regardless of**
- their activity level, metabolism or diet.
- **the outside CO2 level must be** known and either be constant or accurately determined (it varies considerably in most areas).
- **the indoor CO2 level must be accurately determined and reflect the breathing** zone CO2 level.

If only zone CO_2 sensors are used, the relationship between the zone CO_2 level and population (hence ventilation) is codependent on surrounding zone CO_2 levels and supply airflow rates (red calculation for Cs in figure 4).

Simply stated, maintaining zone CO_2 levels on multi-zone recirculating systems <u>cannot</u> assure compliance with the Standard since a single CO_2 level can represent a range of populations and ventilation rates.

The key steps in VRP Compliance with DCV should be the following:

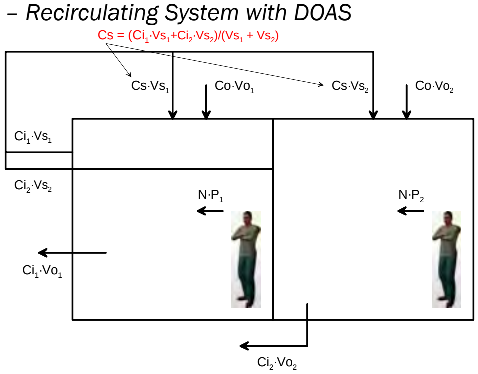
1. Zone OA rates (Voz) must be determined for all zones so that the uncorrected OA (Vou) can be determined.
   - Requires an estimate of the population (Pz) and the actual zone air distribution effectiveness (Ez) of each zone.
2. The fraction (Zp) must be determined for each zone that may go critical.
   - Requires the primary airflow rate (Vpz) and OA rate (Voz) from step 1 for each potential critical zone.
3. The total primary supply (Vps) air must be determined so that the average outdoor air fraction (Xs) can be determined using the uncorrected OA (Vou) from step 1.
4. Determine the minimum zone ventilation efficiency (Ev) and determine the OA rate required at the AHU.

All methods of **DCV should require estimated actual occupancy** since all compliance methods (VRP formulae) are based on population plus floor area. Without it, VRP compliance in multiple zone situations may not be possible.

{example needed}

The complexity is compounded on DOAS systems that have recirculating air paths to handle the sensible load (figure 5).

Figure 5 – Recirculating System with DOAS



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N = [scfm CO_2/min]/person
P = Number of people

Mass Balance Equation (zone 1)

In = Out
$Cs \cdot Vs_1 + Co \cdot Vo_1 + N \cdot P_1 = Ci_1 \cdot Vs_1 + Ci_1 \cdot Vo_1$

Simplifies to:
$P_1 = [Vo_1 \cdot (Ci_1 - Co) + Vs_1 \cdot (Ci_1 - Cs)] / N$

Recommendations & Conclusions

CO_2 is not always the best choice for a DCV strategy. In many cases, the “demand” that changes is a result of thermal load (VAV systems). In others, changes in population may be small, predictable or other means to estimate occupancy are available. It is critical that today’s designers recognize that CO_2 is not a contaminant. Its use in DCV strategies has been to adjust ventilation rates in an effort to comply with the VRP, which is rate based.

CO_2 DCV is applicable on spaces with high occupant densities that have no reasonable alternate method to estimate the population (counters, schedules). When used on single zone spaces, the outside airflow should be reset to meet the breathing zone outside air requirements for the actual population present using the relationship described in figures 2 and 3.

When multiple zone systems require population based DCV, the system becomes more complicated.

If the recirculating system is designed to serve only high occupant density spaces, population estimates can be accomplished using CO_2 sensors and airflow measurement at each zone using the equation to estimate the population in figures 4 and 5, then calculating the VRP in real time.

The best solution on multi-zone may be not to use any type of multi-zone recirculating air system. DOAS with chilled beams, radiant panels, etc. are essentially single zone systems for DCV and are much simplified when it comes to meeting the requirements of ASHRAE Standard 62.1-2010.