Multiple-Zone VAV Systems in Buildings

Applying Demand-Controlled Ventilation

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Demand-control ventilation (DCV) provides "automatic reduction of OA intake below design rates when the actual occupancy of spaces served by the system is less than design occupancy."[1] CO_2 sensing can be used to estimate the strength of occupant-related contaminant sources.[2] This type of control approach is called CO_2-based DCV. With a single-zone system, the breathing zone CO_2 concentration can be used to directly control the outdoor air (OA) damper.

With a multiple-zone variable air volume (VAV) system, each zone in the system requires a different fraction of OA, but the primary air delivers the same fraction of OA to all zones. To ensure proper ventilation that satisfies the ventilation requirement of ASHRAE Standard 62.1-2013, the critical zone should be properly ventilated, while all others are overventilated. And, the unused OA from the noncritical zones is accounted for in the recirculated air. As a result, the system OA intake can be modulated to ensure the critical zone is maintained at no less than the current required minimum zone OA rate.

This article presents three options of CO_2-based DCV that are Standard 62.1-2013 compliant in multiple-zone recirculating air-handling systems. The intent of these proposed DCV control strategies is to provide a method to introduce the proper outdoor airflow rate satisfying Standard 62.1-2013, while minimizing the energy used to condition outdoor air.

The challenges of complying with ASHRAE Standard 62.1-2013 when developing DCV logic are:

- Unlike versions of Standard 62.1 prior to 2004, the current version requires that the occupant- and building-related components of the minimum ventilation rate are additive, which results in the corresponding zone steady-state CO_2 concentration having a nonlinear relationship with the number of occupants. Therefore, a fixed CO_2 setpoint cannot be used.
- Another challenge is how to account for the real-time system ventilation efficiency (E_v). System ventilation efficiency is defined as the efficiency with which the system distributes air from the OA intake to the breathing zone in the ventilation-critical zone. This is driven

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by the zone that requires the largest fraction of OA in the primary airstream (aka the critical zone).

- With recirculation paths in the HVAC system, one more challenge is related to properly estimating bioeffluent load in each zone and the corresponding ventilation demand in each zone.

Option 1: CO_2-Based Dynamic Reset (DR)

The CO_2-based dynamic reset (DR) strategy dynamically calculates the required setpoint for the system OA rate and then modulates dampers to maintain the OA flow rate at the new setpoint. The current zone primary airflow and the zone CO_2 concentration (or occupancy) state are sensed to calculate the required OA rate for zones with CO_2 sensors and/or zones with occupancy sensors. Zones without any sensors are assumed to be always occupied at the design population. Details of this control strategy are presented in Lin and Lau.[3]

This control strategy can be applied to any HVAC system with direct digital control (DDC) at the zone level and at the air-handling system level that can solve the equations and reset the OA intake airflow setpoint. An airflow measurement device and modulating OA control dampers are also required.

This control accounts for two changes of operation: the variation of occupant number in one or more individual zones in the system; and the variation of system ventilation efficiency.

For application of CO_2-based DR in a single-fan, single-duct VAV system with terminal reheat, the CO_2 concentrations in breathing zones and/or occupancy states are measured. The zone primary airflow rate to each zone is also measured to dynamically calculate system ventilation efficiency on a real-time basis.

The system outdoor airflow setpoint is determined by the following (no less than the larger of):

- The amount of outdoor airflow required to the building to maintain an appropriate pressure.
- The amount of outdoor airflow required by the economizer control logic. If a system operates in economizer mode, a certain amount of outdoor airflow rate will be introduced to maintain system mixed-air temperature or system supply-air temperature;
- The amount of outdoor airflow required by the demand-controlled ventilation logic.

OA measuring and control devices must be included to implement this approach. Equations[3] can be used to dynamically reset the OA intake rate setpoint. The control system must be capable of calculating these equations to obtain the required system OA rate setpoint and then to modulate dampers to adjust the OA rate to the new setpoint.

The variables in the CO_2-based dynamic reset approach for this system are obtained as follows:

- The CO_2 concentration in each breathing zone with a CO_2 sensor and system primary;
- Zone primary airflow rate; and
- Values of zone parameters are determined as described in Standard 62.1-2013.

The advantage of this control logic is that it calculates the real-time system ventilation efficiency by considering both the varying occupancy as well as the varying primary airflow rate due to change in thermal load. This logic uses the difference in CO_2 concentrations between zone primary air and breathing zone air, as well as the zone primary airflow rate, to calculate the breathing zone ventilation rate (V_{bz}).

Options 2 & 3: CO_2-Based DR With Zone Level Control

Although the dynamic reset at the system level can ensure each zone in the system satisfies the requirement of Standard 62.1-2013, the potential for further energy savings still exists if the minimum primary airflow rate to zones can be modulated to increase the system ventilation efficiency (E_v). Therefore, two options of control strategy are further developed to dynamically reset the minimum zone primary airflow setpoint to maintain a system either at a target OA rate or a target system ventilation efficiency (and named CO_2-based *DR+ZDR_*V_{ot} or CO_2-based *DR+ZDR_*E_v, respectively). The details of these control strategies are presented in Lin and Lau.[4]

The key concept of the proposed DCV control strategies is to modulate the zone primary airflow rate first before modulating the system OA rate. For example, if one conference room in a large building requires a large amount of OA, then it is more energy efficient to increase the primary airflow rate to this specific conference room, rather than to increase the system level OA rate (V_{ot}).

A higher primary airflow rate in that room will provide a sufficient amount of OA, even though the fraction of OA in the primary airflow remains the same. Any added reheat energy to the zone to prevent overcooling would take less energy than conditioning a larger outdoor air rate to the entire system just to satisfy the ventilation needs for this one zone.

This control logic can be broken down into two levels: system level and zone level. The system level is the same as CO$_2$-based dynamic reset. At the zone level, the zone primary airflow rate minimum setpoint is reset to reduce the system OA rate. The zone level of the proposed control logic resets the critical zone primary airflow minimum setpoint upward to decrease the primary outdoor air fraction (Z_{pz}) and increase E_v to decrease the current outdoor airflow rate V_{ot} as a target V_{ot} (V_{ot_target}). This resetting reduces the system OA rate by increasing the zone primary airflow rates for the zones that require more OA. This option is called CO$_2$-based *DR+ZDR_*V_{ot}.

The alternative option of the proposed DCV control strategy is similar. The main difference is that the aim of zone primary airflow minimum setpoint reset is to maintain the value of system ventilation efficiency greater than or equal to a certain value (E_{v_limit}). E_{v_limit} is a design system ventilation efficiency that can be achieved by modulating the zone primary airflow rate. This option is called CO$_2$-based *DR+ZDR_*E_v.

The zone level control increases the zone primary airflow minimum setpoint upward to decrease the zone primary outdoor fraction (Z) and increase system ventilation efficiency (E_v) to increase the current system ventilation efficiency E_v to a target E_v. The objective of resetting the primary airflow rate minimum setpoint is to obtain a higher E_v without being penalized by a large amount of reheating energy.

The value of the minimum zone primary airflow rate should be designed based on different DCV control strategies. The minimum zone primary airflow rate design setpoint for systems with CO$_2$-based dynamic reset with zone level control can be designed lower than that for systems with control strategies without zone level control. This setting reduces the energy consumption for the system supply fan as well as the energy consumption for terminal reheating.

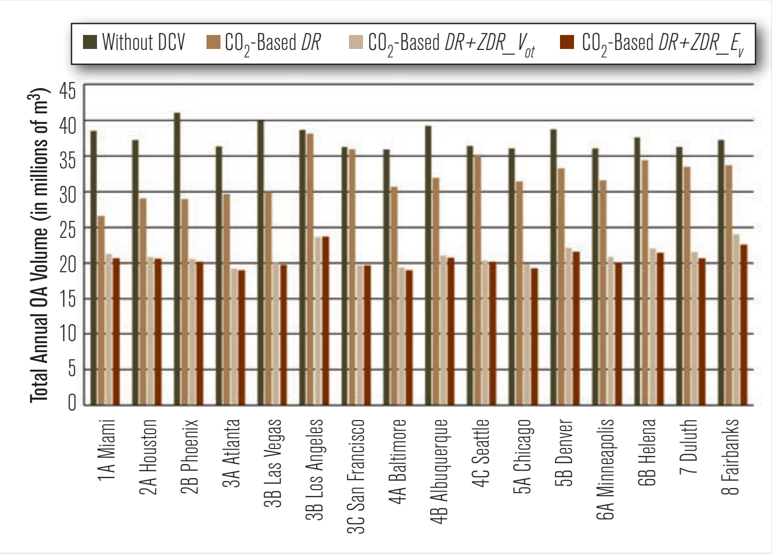

FIGURE 1 Annual system OA rate for different control strategies by climate zone.

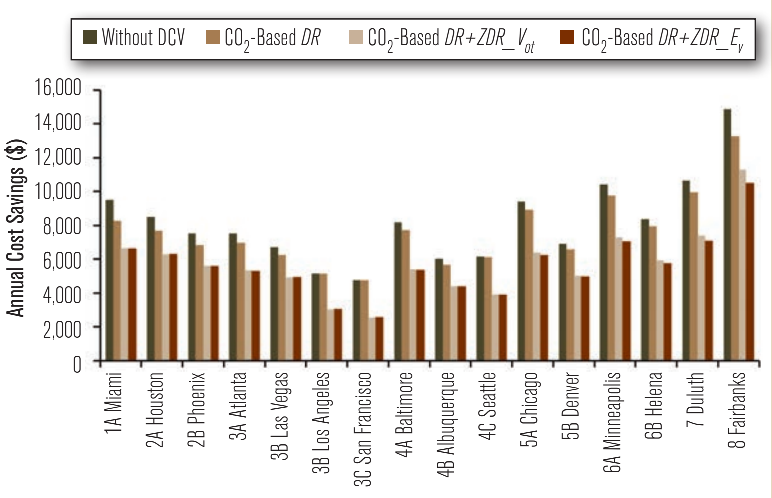

FIGURE 2 Cost savings of different control strategies by climate zone.

Potential Issues with DCV or Dynamic Reset

The above DCV control strategies calculate the required outdoor airflow rate setpoint based on the CO$_2$ concentrations in the system supply air and in zones, and based on zone airflow rates. Then, the outdoor airflow rate is measured and the outdoor air damper is modulated to maintain this calculated setpoint. Here are the potential pitfalls of DCV application if the following issues are not addressed properly.

Building Pressurization

Most buildings are installed with exhaust systems that are separated from the main/central air-handling units (AHU). Air exhaust is necessary for some special zones, such as restroom, kitchen, trash room, copy room, etc. Building pressurization involves balancing between outdoor air intake and exhaust. Both supply fans, return fans, exhaust fans, and mixed-air dampers will impact the overall building pressure. Typically, it is suggested that the outdoor airflow rate should be higher than the exhaust airflow rate during humid weather to maintain a slightly positive pressure inside a building. If an application of DCV is not addressing the needs for exhaust air, a DCV controller must not reduce the outdoor airflow rate to a level that results in improper building pressure.

Locations and Installation of Sensors and Their Accuracy

The readings of CO_2 sensors should reflect the actual CO_2 concentrations in the breathing zones. Sensors should not be located in the return air duct since short-circuiting of supply air can cause unrepresentative CO_2 readings. Also avoid locations near doors and operable windows.

CO_2 sensors are subject to calibration drift and accuracy issues over time. A field study on a campus building with CO_2-based DCV found that differences between the commercial CO_2 sensors used in buildings are significant.[5] Periodic maintenance is essential to keep the readings of CO_2 concentration accurate over time. Since the difference between primary air and zone air CO_2 concentrations may be very small, sensor accuracy is critical. A system that uses a single sensor with multiple air-sampling ports would likely result in the most accurate CO_2 readings, provided sampling times are reasonably short. A system with separate zone air and primary air sensors would likely result in the least accurate CO_2 readings.

Since these proposed control strategies require an outdoor airflow monitoring station, a potential challenge includes the accuracy of the airflow station, which often requires long, straight, outdoor air ducts. However, many cost-effective products still satisfy these requirements in the current market.

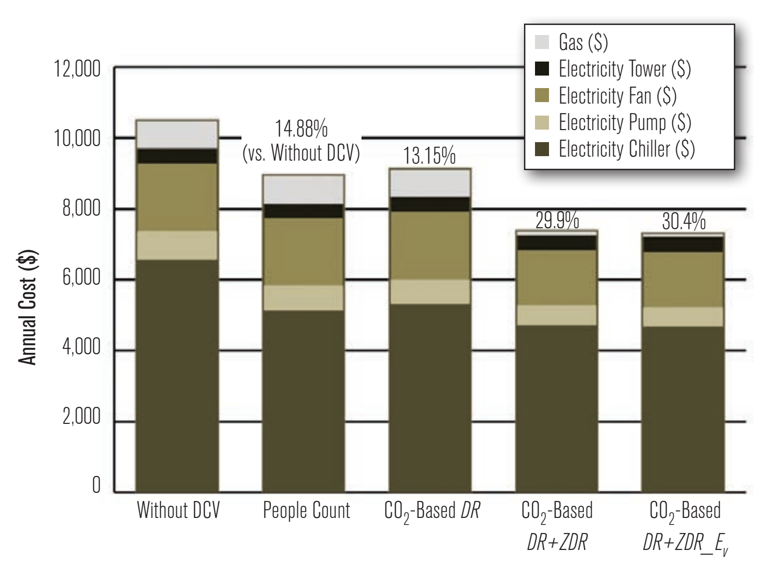

FIGURE 3 Energy cost breakdown for different DCV strategies: Climate Zone 1A-Miami.

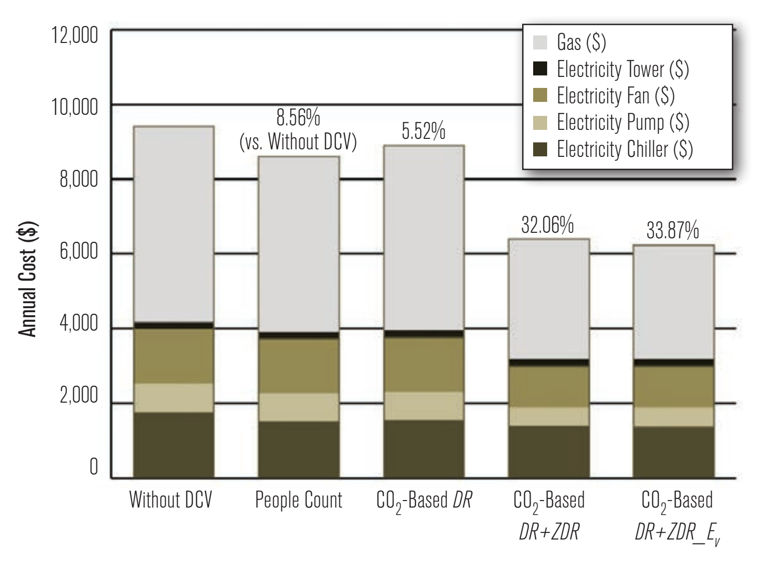

FIGURE 4 Energy cost breakdown for different DCV strategies: Climate Zone 5A-Chicago.

Energy-Saving Performance of DCV With Dynamic Reset

ASHRAE RP-1547, "CO_2-Based Demand Controlled Ventilation for Multiple Zone HVAC Systems,"[6] included a case study of an example university building to compare the performance of these proposed DCV control strategies, plus a reference case (Without DCV) in terms of annual system OA rate and annual energy cost.

Figure 1 (Page 32) shows that the OA rate for CO$_2$-based DR is lower than the OA rate for Without DCV. However, there are two exceptional situations. For Climate Zone 3B (Los Angeles) and Climate Zone 3C (San Francisco), the OA rates for these three DCV strategies are similar due to the operation of economizer mode most of the time. The OA rates for both options of CO$_2$-based dynamic reset with zone primary air minimum reset (i.e., $DR+ZDR\_V_{ot}$ and $DR+ZDR\_E_v$) are very similar, and are both lower than the OA rates for all other DCV strategies. By averaging over 16 locations, the average annual system outdoor airflow rate for CO$_2$-based DR is 14.6% less than Without DCV. The average annual system outdoor airflow rates for two options of CO$_2$-based *DR+ZDR* are 44.1% and 45% less, respectively, than for Without DCV.

The annual energy cost for different DCV control strategies were also analyzed. The simulation results presented in *Figure 2* (Page 32) showed that for CO$_2$-based DR, the annual savings increase from warmer climates and colder climates to mild climates. For CO$_2$-based *DR+ZDR*, the annual saving percentage decreases from mild climates to warmer and colder climates due to the lower total energy cost in the milder climates. DCV control strategy CO$_2$-based *DR+ZDR* saves significant energy cost from gas consumption (for heating) and fan energy compared to both baselines cases, as showed in *Figures 3* and *4* (Page 34).

Conclusions

This article discusses the application of three CO$_2$-based DCV control strategies in multiple-zone HVAC systems. To implement these control strategies, direct digital control (DDC) at the zone level and at the air-handling system level is required to solve the equations and reset the OA intake airflow setpoint. An airflow measurement system and modulating OA control dampers are also required. The CO$_2$ concentrations in breathing zones and primary air at one location at the central AHU, and the zone primary airflow rate to each zone, must be measured.

ASHRAE RP-1547 results show that significant energy savings potential can be achieved. The energy savings potential is up to a 45% reduction of annual OA rate in an example case study. The purpose of DCV is to save energy, rather than to improve indoor air quality. The quantity of energy savings depends on the following factors: occupancy profile, climate zone, and VAV box damper minimum setpoint, etc.

References

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3. Lin, X., J. Lau. 2014. "Demand-controlled ventilation for multiple-zone HVAC systems: CO$_2$-based dynamic reset (RP-1547)." *HVAC&R Research*, 20(8):875–888.

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