Is CO_2 Demand-Controlled Ventilation the Answer?

Trying to serve the twin masters of ASHRAE 62 and optimal system efficiency, the author examines DCV in both general and more nuanced terms. That overview leads to a comparison with the performance of a dedicated outdoor air system using a sample building.

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CO_2-based demand-controlled ventilation (DCV) is arguably the hottest ventilation control topic in the industry today. The DCV control strategy is aimed at verifiably meeting the ventilation requirements of ASHRAE Standard 62-1999[1] while simultaneously minimizing the energy utilized to condition the ventilation air. The three goals of this article are:

- Present the background that has brought the industry to where it is currently with regard to ventilation.
- Explore CO_2-based DCV in sufficient detail to appreciate some of the major issues surrounding it.
- Compare all-air vav systems utilizing CO_2 DCV to dedicated outdoor air systems (DOAS), on the basis of energy utilization, economic, and IAQ issues.

BACKGROUND

Adequate ventilation of buildings for human occupancy has long been an important engineering design consideration in the industry. However, during the fossil fuel shortages of the 1970s and the subsequent emphasis on energy conservation, new IAQ problems confronted the occupants of buildings. ASHRAE responded with a much-revised ventilation standard: Standard 62.

Engineers rather quickly adopted the ventilation rate procedure portion of the standard, which prescribes a fixed minimum ventilation rate per person, based upon building type. The author's experience has been that the engineering community much less rapidly accepted the multiple spaces portion of the standard, specifically the multiple spaces equation 6.1.

Simply put, the multiple spaces procedure recognizes that the ratio of unvitiated ventilation air to supply air in the main supply ductwork must equal the ratio of required ventilation to supply air for the most critical zone (designated Z_c in ASHRAE Standard 62, equation 6.1). Since this virtually always means that the non-critical zones are overventilated, the overventilation air in the recirculation air can be credited as unvitiated OA at the AHU.

As a result, the fraction of OA (drawn into the AHU directly from outside) to total supply air (designated Y in ASHRAE Standard 62, equation 6.1) is always less than the fraction of OA required at the critical zone (Z_c), so long as the critical zone OA to supply air ratio is less than unity. Even with this credit procedure, the quantity of OA drawn directly into the AHU exceeds the product of cfm/person times occupants. Frequently the required OA is 20% to 70% greater than the simple product.

In the latter 1980s, the author began to recognize many of the problems associated with all-air vav systems. His research findings led to numerous articles[2, 3, 5]. And his approaches became increasingly complex, culminating in a real-time, online opti-

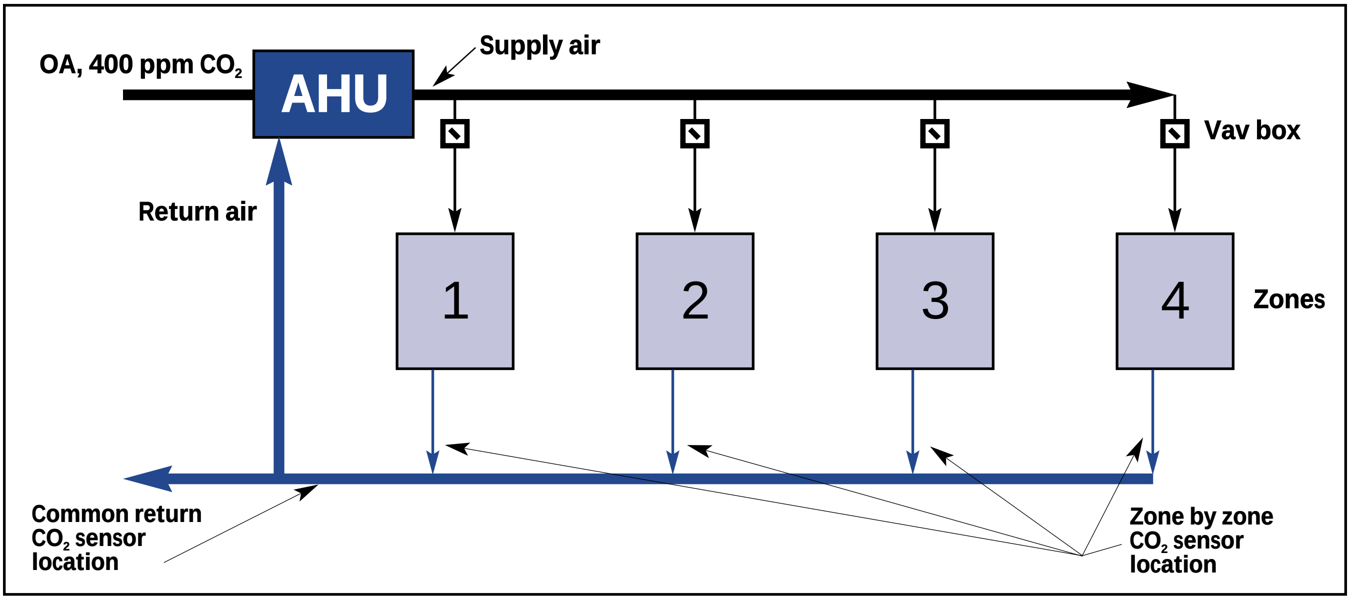

FIGURE 1. An example a four zone system, which is based on applying the ASHRAE Standard 62 multiple spaces equation 6.1 to a shut off vav box system that experiences no short circuits, infiltration, exhaust, or transfer.

Occupancy	Case 1	Case 2	Case 3	Case 4	Case 5
Zone 1	4	2	4	1	1
Zone 2	50	25	50	12	11
Zone 3	150	75	36	38	25
Zone 4	24	12	24	6	20
Total Occupancy	228	114	114	57	57
Supply air (cfm)					
Zone 1	700	675	710	665	665
Zone 2	7,500	7,220	7,500	7,070	7,060
Zone 3	16,000	15,150	14,700	14,725	14,580
Zone 4	800	665	800	600	755
Total supply air	25,000	23,710	23,710	23,060	23,060

Case 1: Design occupancy;
Case 2: Each zone's occupancy reduced to 50% of design occupancy, or uniform occupancy reduction;
Case 3: Occupancy of Zone 3 reduced by 114, making the building occupancy 50% of design, a very nonuniform occupancy reduction;
Case 4: Each zone's occupancy reduced to 75% of design occupancy, or uniform occupancy reduction;
Case 5: Nonuniform zone occupancy reduction so the building design occupancy was 75% of design.

TABLE 1. Occupancy and supply air quantities used in the example for the five cases.

mization control[3] to minimize energy consumption and demand while meeting the ventilation requirements of ASHRAE Standard 62-1989. Some of those concepts have since been adopted by industry and articulated at a manufacturer's[4] website as follows:

“Ventilation Reset dynamically resets the amount of outdoor air in the supply air based on real-time system operating parameters to assure that each zone is properly ventilated at all times. The DDC/VAV terminals continually measure the amount of supply air delivered to each zone.”

“The design ventilation rate for each VAV zone is known by the DDC/VAV terminal controller or the BAS. Knowing the current zone supply airflow and the zone design ventilation rate, a ventilation fraction can be calculated for each zone. As the BAS polls the VAV terminals, it continually identifies the zone with the critical (highest) zone ventilation fraction.”

“By summing the airflow from the VAV zones and knowing the ventilation fraction of the critical zone (Z), the BAS system can determine the exact amount of outdoor air that is needed at the air handler. The BAS sends the new outdoor airflow (cfm) set point to the air handler, which repositions the OA damper to satisfy that specific operating condition. The result: a VAV system that fully complies with the ventilation requirements of ASHRAE Standard 62-1989 and minimizes costly overventilation.”

Next came a realization that the limitations of ASHRAE Standard 62 multiple spaces approach were rather severe. The four limitations are:

- It does not accommodate systems with fan-powered vav boxes where local recirculation occurs;
- It does not accommodate local exhaust or infiltration;
- It does not accommodate interzonal transfer; and

- It does not explicitly address short circuit flow between entry and exit points in the zone.

These limitations, addressed in the ASHRAE literature[5], led many in the industry to realize that all-air vav systems, as controlled at the time, could not verifiably demonstrate compliance with ASHRAE Standard 62. That realization may be what has placed DCV at the forefront today. However it is not without reservation. A manufacturer's website[4] makes the following comment:

"The acceptability of CO_2-based demand controlled ventilation remains controversial. To date, ASHRAE has published four interpretations dealing with the use of measured zone CO_2 levels to control the amount of OA introduced into the system. In three of the interpretations, ASHRAE concludes that controlling CO_2 levels below 1000 ppm alone, through either dilution or treatment, does not assure acceptable indoor air quality and does not meet the requirements of Standard 62-1989. The fourth and most recent interpretation (IC-62-1989-27) allows the use of CO_2-based demand-controlled ventilation to reduce outdoor air supply during periods of reduced occupancy however, there are many other stringent system and control provisions which must also be met.

"The interpretations should be carefully studied before a CO_2-based demand control ventilation control strategy is adopted. Using CO_2 levels measured in the zone to control zone ventilation levels can however, improve comfort and reduce system operating energy costs in applications where contaminant levels result primarily from people."

Like the paragraph above, the technical literature on DCV recognizes the fact that not all contaminants are occupant based. The literature[6] recommends that when DCV is used, the ventilation should not be reduced below 20% of design ventilation rates. By maintaining this minimum ventilation flow rate, sufficient ventilation air is supplied to dilute building contaminant sources, even at very low occupancy levels.

UNDERSTANDING DCV WITH ALL-AIR VAV SYSTEMS

DCV is intended to resolve the traditional conflict between operating cost and maintaining ventilation for acceptable IAQ. In order to achieve this objective, the system must be properly implemented. Many variables are important in proper implementation, but only one of those, CO_2 sensor placement, will be addressed explicitly in the example that follows. If properly applied, DCV can be expected to provide the following benefits:

- Reduced energy operating costs, compared to all-air vav systems operating with a fixed minimum OA, are realized from reduced overventilation of critical zones when such zones are partially occupied. That does not mean that most of the zones are not still overventilated.
- It is not particular about where the OA is coming from or going to, so long as

proper CO_2 concentrations are being read. If the zone air is not well mixed, the CO_2 sensor located either in the zone or the zone return will not provide representative readings, leading to either overventilation or underventilation of the critical zone.

- The desired ventilation rate per person is more easily maintained than most other all-air vav approaches designed to accommodate variable occupancy.

Often, when DCV is considered, questions concerning sensor placement arise. In order to reduce first cost, maintenance cost, and complexity, a single sensor in the common return to the AHU is favored. The alternative is to place sensors in every zone (or at least enough so that the critical zones are monitored), and use a discriminator to select the one with the highest CO_2 reading. Based upon the highest reading, the OA dampers are adjusted accordingly.

To develop an understanding of a system's energy and IAQ performance based upon one of the two general sensor locations, consider a simple four-zone example, which is based on applying the ASHRAE Standard 62 multiple spaces equation 6.1 to a shutoff vav box system that experiences no short circuits, infiltration, exhaust, or transfer.

The individual zones are assumed to be well mixed. Outdoor air loads are based upon an assumed 75˚ db/50% zone condition and outdoor air design condition of 95˚ db/78˚ wb. Operating parameters will be used to illustrate the operating conditions for full, 50% and 25% of design occupancy. Occupancy reductions will be both uniform and nonuniform. The simple four-zone schematic for the five cases is presented in Figure 1.

Note: the CO_2 sensors are either in every zone or in the common return. The four zones represent somewhat different use zones in an approximately 30,000-sq-ft-building. The design occupancy is 228 people. The occupancy and supply airflow rates for each zone under the five cases is presented in Table 1. All of the results are based upon steady-state conditions. Critical zone CO_2 concentrations are presented in Figure 2.

It was assumed that the OA CO_2 concentration was 400 ppm, the desired cfm/person was 20, and that the CO_2 generation rate per person was 0.0105 cfm (typical for light work). These conditions result in a steady-state zone leaving CO_2 concentration of 928 ppm. The set of simultaneous equations necessary to compute the required OA flow rate and all of the CO_2 concentrations were solved by holding either the common return CO_2 concentration at 928 ppm or the critical zone CO_2 concentration at 928 ppm.

The bars in Figure 2 labeled sensor/zone are for the situations where the critical zone ppm was maintained. The bars labeled sensor/return are for a constant common return concentration of 928 ppm. In all five cases it may be noted that holding the common return at 928 ppm resulted in underventilation of the critical zones, (i.e., concentrations about 300 ppm to high).

Also shown in Figure 2 are the critical zone CO_2 concentrations for the DOAS approach. In the DOAS approach, the supply air quantity is not modulated, so in two of the cases, the critical zone CO_2 concentrations are quite low, indicating that the zones are overventilated. The energy implications of the DOAS approach will be addressed later in the article.

The critical zone cfm/person is illustrated in Figure 3. When the CO_2 sensor is placed in the common return, the critical zones are extremely underventilated. Instead of the design flow rate of 20

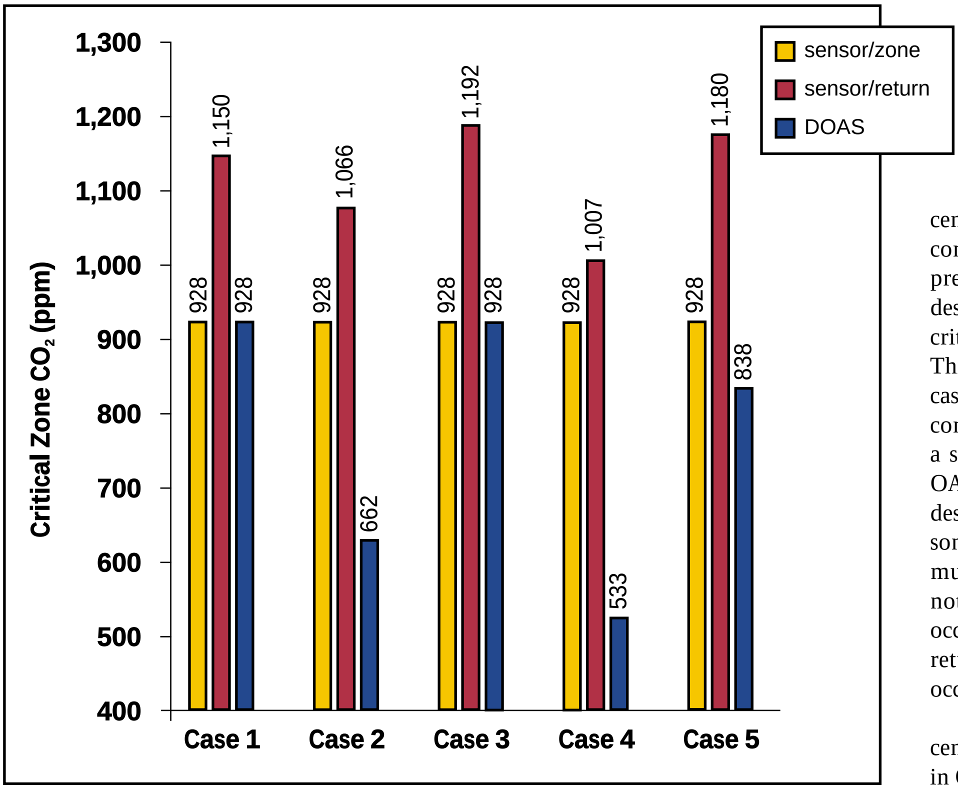

FIGURE 2. CO_2 concentrations in the critical zones.

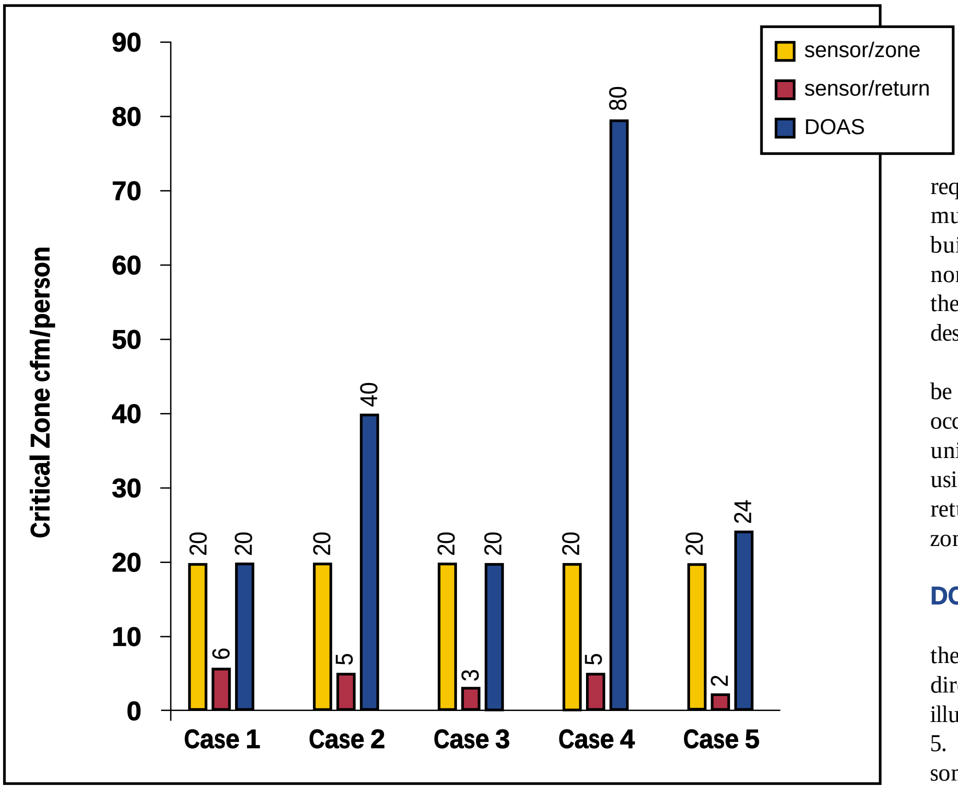

FIGURE 3. Cfm/person for the critical zone in the five cases.

cfm/person, they are in the 2 to 6 cfm/person range. And the constant volume DOAS unit overventilates the critical zones on two occasions, one by 100% and one by 400%.

In order to meet the required CO_2 concentrations at either the critical zone or the common return, the outdoor airflow rates presented in Figure 4 were required. At design, in order to properly ventilate the critical zone, 7,830 cfm of OA was required. This is the flow rate that was used in each case with the DOAS system. When the common return CO_2 sensor was used with a setpoint of 928 ppm, only 4,560 cfm of OA was required at design. The product of design occupancy of 228 times 20 cfm/person equals 4,560 cfm (this indicates that the multiple spaces concept of Standard 62 has not been met). At the 50% and 25% design occupancy, the required OA with common return sensing were also the products of occupancy times 20 cfm/person.

However with the critical zone CO_2 concentration held at 928 ppm, the reduction in OA was strongly dependent on how uniform the building occupancy was reduced. For example, when the occupancy was uniformly reduced by 50%, the required OA was only 40% of design while reducing it nonuniformly, the required OA was 60% of design flow.

In the case of a uniform 75% reduction in occupancy, the 1,342 cfm of required OA dropped below the 20% minimum recommended (1,570 cfm) to dilute building contaminant sources. With a nonuniform 75% reduction in occupancy, the required OA was 30% of the required design flow rate.

Clearly, from these results, two things can be observed. First, the reduction in OA with occupancy is strongly influenced by how uniform the occupancy reduction is. Second, using a single CO_2 sensor in the common return set at 928 ppm will result in critical zones that are unacceptably underventilated.

DOAS

The DOAS discussed in this article supply the design minimum ventilation outdoor air directly into every zone of the building. An illustration of a DOAS is presented in Figure 5. The OA generally is preconditioned to some extent. The extent of the preconditioning[8] needed is dependent on;

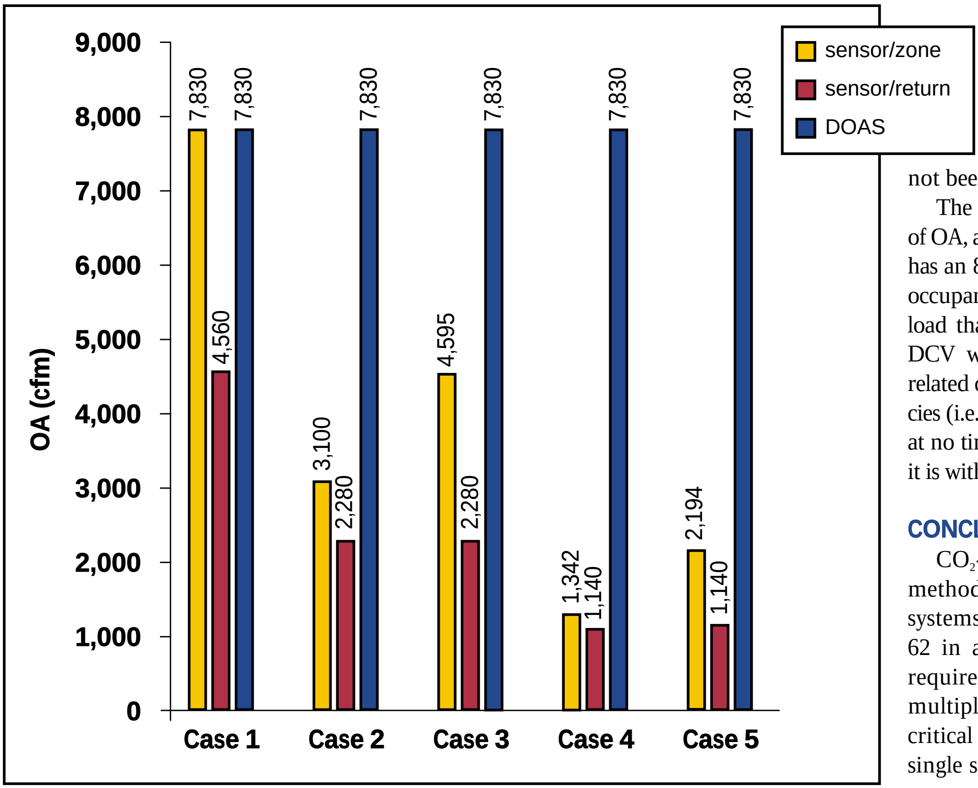

FIGURE 4. Outdoor air required for the five cases.

- The parallel system used to meet the zone loads;
- How the OA is introduced into the zone; and
- The extent of energy recovery utilized.

For buildings the size used in the example or larger (i.e., design OA flow rates over 7,000 cfm) ASHRAE Standard 90.1[9] requires the use of total energy recovery. For much of the USA, the design wetbulb temperatures are sufficiently high that Standard 90 requires the use of an enthalpy wheel. For the example illustrated in this article, an enthalpy wheel effectiveness of 80% has been assumed. Such a wheel is capable of preconditioning the OA to within 20% of the zone conditions (drybulb and humidity ratio) — resulting in a huge reduction in the outdoor air cooling and dehumidification, or heating and humidification loads.

To learn more about DOAS, visit the following website: *http://doas.psu.edu/papers.html.* The result of total energy recovery is that the OA cooling and dehumidification loads are reduced by 80% for 100% of the operating hours. And heating of OA is virtually eliminated, as is the need for winter humidification.

LOAD AND ENERGY CONSEQUENCES OF USING DCV VS. DOAS

When the OA flow rates illustrated in Figure 4 are used, and the return and OA conditions of 75° db/50% and OA conditions of 95° db/78° wb are assumed, the results presented in Figure 6 are obtained. At design ventilation flow of 7,830 cfm without energy recovery, the OA load is 39 tons. When the CO_2 sensor is placed in the common return, the ventilation airflow rate is reduced to 4,560 cfm and the OA load is 23 tons, but Standard 62 has not been met.

The DOAS, supplying a constant 7,830 cfm of OA, and utilizing a total energy recovery, only has an 8-ton OA load. This is true for all of the occupancy cases considered. This is the same load that a vav system would experience with DCV when operating to overcome building-related contaminates at extremely low occupancies (i.e., at 20% of design OA flow). Notice that at no time is the OA load lower with DCV than it is with DOAS.

CONCLUSIONS

CO_2-based DCV appears to be a necessary method to verifiably ensure that all air vav systems are able to meet ASHRAE Standard 62 in an energy-efficient fashion. This will require a properly designed system using multiple CO_2 sensors to make sure all of the critical zones are monitored. Employing a single sensor in the common return will lead to ventilation problems in at least the critical zones if not other zones.

While the energy savings are better than with an all-air system supplying a fixed minimum ventilation rate, it can not come close to matching the energy savings potential of the DOAS. Additional reasons that DOAS is superior to an all-air system using DCV are:

- The chiller plant demand is reduced from almost 40 tons to 8 tons in a 7,830 cfm of an OA system.
- A first cost savings for the chiller and a lifetime reduction in kilowatt demand charges are realized.
- The constant OA supply maintains the design OA cfm/person without energy penalty, thus improving overall sense of health and well-being in the occupied zones.
- Building-related contaminants can never build up to unacceptable levels at low occupancies.
- The OA can be preconditioned so that all of the OA sensible and latent loads are accommodated as well as all of the zone latent loads. When the zone sensible and latent loads are decoupled, potential microbial problems in the building are either reduced or eliminated.
- Lawrence Berkeley Laboratories estimates that by avoiding microbial problems, businesses could save an estimated $258 billion/year.[10]
- By using high-aspiration diffusers with DOAS, opportunities for short circuit paths between the supply and return are virtually eliminated.
- Finally, since the DOAS is a 100% OA system, local infiltration, exhaust, and interzonal transfer do not impact IAQ like they do vav systems, with or without DCV.

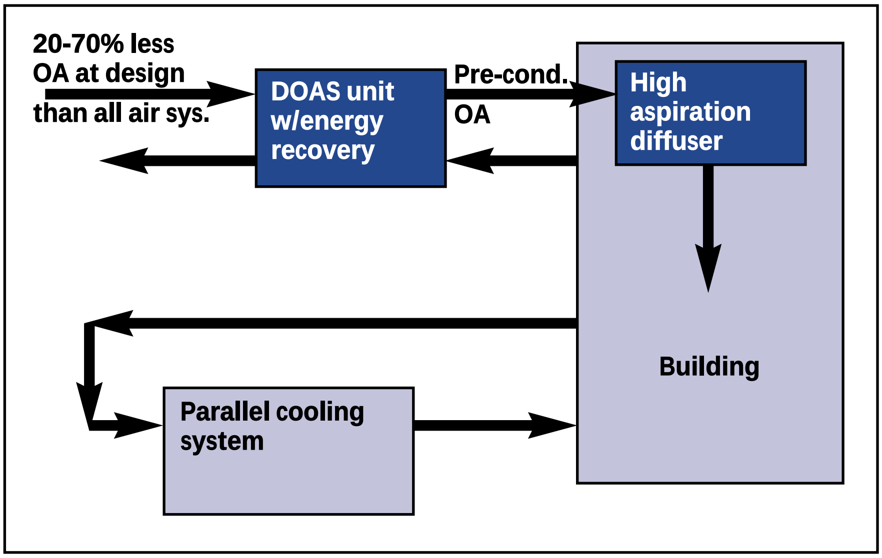

FIGURE 5. DOAS schematic arrangement.

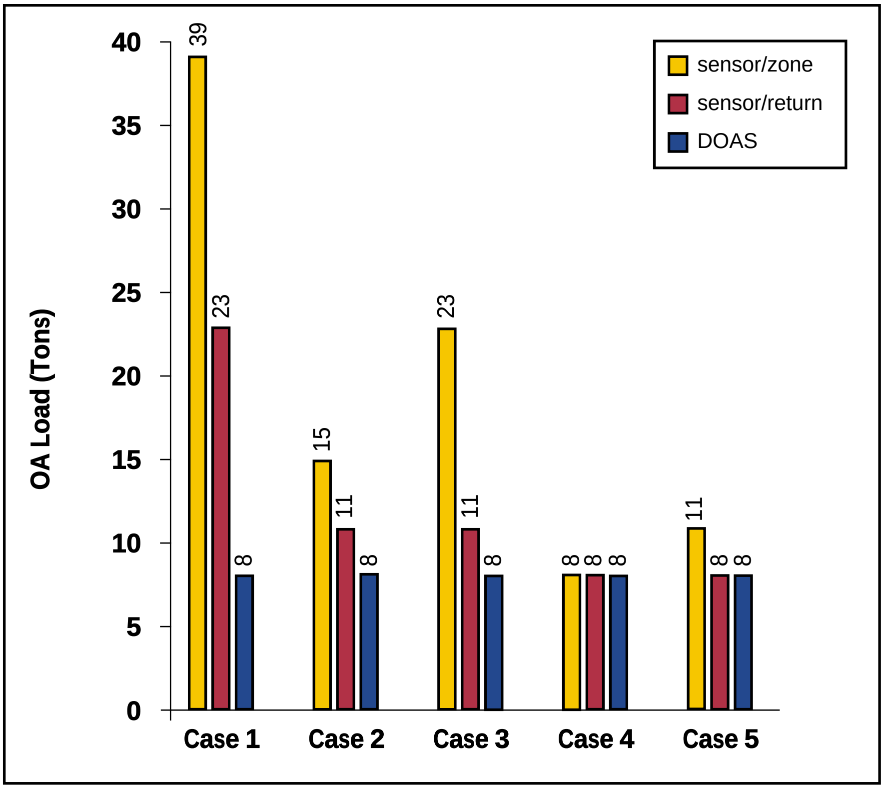

FIGURE 6. Outdoor air load for the five cases.

It is the author's opinion that the DOAS approach provides superior energy performance with less complexity and cost while improving the IAQ in the zones. DCV is a valuable new ventilation control for an all-air-vav single-supply air duct system, but it does not offer the benefits of DOAS. And integrating DCV with DOAS offers minimal additional operating cost savings and cannot compensate for the added complexity of the DCV. The engineer's best option for meeting the ventilation requirements of ASHRAE Standard 62 in an energy- and cost-effective manner is to use DOAS. **ES**

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