Design Considerations For Dedicated OA Systems

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Dedicated outdoor air systems (DOAS) decouple the heating, cooling, dehumidification and humidification of outdoor air from the space air-conditioning system. Common HVAC systems such as water (ground) source heat pumps, variable refrigerant flow (VRF), fan coils and chilled beams require a DOAS to meet ventilation requirements. But DOAS is a system, not a piece of equipment.

In some parts of the world, a DOAS may not be any more complicated than a supply fan and an exhaust louver. For many locations, conditioning (heating, cooling, humidifying and dehumidifying) will be necessary. Often, the DOAS unit performing this work is one of the highest energy consumers in the HVAC system.

DOAS Design

The DOAS's main function is to provide ventilation air to achieve acceptable indoor air quality. One advantage of using a DOAS is that the ventilation air can be directed and balanced to point of use. This is harder to achieve with all air multi-zone systems. The most common way to establish ventilation airflow is to follow ASHRAE Standard 62.1.

In addition to ventilation, the DOAS can also be called upon to deliver outdoor air to offset local exhaust such as bathroom exhaust, provide building pressurization and, with chilled beams or radiant cooling systems, provide dehumidification (latent cooling) and primary air to make the beams function properly.

For a typical office application, the ventilation air will likely be around 0.11 to 0.15 cfm/ft^2 (0.55 to 0.75 L/s·m^2). Centralizing the DOAS to a single unit means connecting every occupied space in the building back to a single location with ductwork. This can be costly but it also impacts fan power requirements and thus energy usage. In Europe, it is far more common to decentralize the DOAS into smaller local systems and thus lower the design external static pressure requirement.

Figure 2 shows the potential energy and cost savings (see sidebar) from decentralizing the DOAS and reducing the required external static pressure. Reducing the external static pressure by 0.75 in. w.c. (187 Pa) reduces the DOAS unit fan energy use by 20%, while also requiring smaller main ducts (smaller ceiling plenum) by using multiple, smaller DOAS units. It does require locations for smaller DOAS units closer to point of use.

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Integrating the psychrometrics of the DOAS with the main HVAC system requires some consideration. Not cooling the outdoor air at all in the Chicago example (in the sidebar at right) will shift 473 kBtu/h (139 kW) of cooling load to the terminal units. If the main HVAC system is made up of WSHPs, then it would increase the model size of all the units by one. Many terminal units are on-off control. During off cycles, outdoor humidity will be directed to the space, resulting in high humidity levels and unsatisfactory space conditions. For most locations, not cooling or dehumidifying the outdoor air in some form is problematic.

At a high level, designing the DOAS for "neutral room air" such as 75°F (24°C) db and 50% RH seems like a good starting point; however, it is not actually an easy condition to achieve. It will likely require reheat in most locations. It also assumes that some other system or piece of equipment is offsetting latent gains from infiltration or zone latent loads.[1] The best designs will integrate the DOAS design conditions into the main HVAC system. This is a topic all by itself; the following are some suggestions.

- Some main HVAC systems (chilled beams, radiant cooling) require the building latent load be decoupled from the zone cooling system. For these systems the DOAS unit must be designed to provide all of the building latent cooling requirements because the zone systems cannot handle condensation.
- Cooling the outdoor air to 75°F (24°C) db makes the outdoor air neutral on dry-bulb temperature but will have removed almost no humidity. This will shift a significant latent load (depending on location) to the terminal units, likely beyond what they are designed to deliver.
- Cooling the outdoor air to 55°F (13°C) db makes the outdoor air neutral on humidity ratio, but much colder than the space condition. This can be advantageous as the primary air can be used to provide space sensible cooling and reduce the size of the terminal units. Care should be taken to make sure the space will not be overcooled by the ventilation air at part-load conditions.
- Using a total energy recovery device such as an enthalpy wheel without additional mechanical cooling may cool and dehumidify the outdoor air enough that when mixed with return air to the terminal units, no other mechanical cooling of the outdoor air is required. For example, using 15% outdoor air, the mixed air condition for the Chicago example is 76°F (24.4°C) db, 64°F (17.8°C) wb, which is well within the cooling capacity of WSHPs, GSHP, fan coils and VRF terminal units. While this approach is (capital) cost effective, there will be part-load conditions (70°F [21.1°C] and raining for example) that can be problematic. Further analysis is warranted before applying.

Chicago DOAS Example

A BIN weather model of a 100,000 ft^2 (9290 m^2), five-story office tower in Chicago is used to help demonstrate the concepts discussed in this article.

The DOAS design is based on 11,000 cfm (5190 L/s) outdoor air and 10,000 cfm (4720 L/s) exhaust air. Summer design conditions are 91.4°F (33°C) db, 74.3°F (23.5°C) wb (Peak dewpoint design is 83.7°F (28.7°C) db, 74.7°F (23.7°C) wb) and winter design is –1.5 °F (–18.6°C). Design space conditions are 75°F (23.9°C) db and 50% RH summer and 72°F (22.2°C) db and 20% RH winter.

Mechanical cooling is provided by a water-cooled chiller plant with variable primary flow and heating is provided by a 90% efficient hot water boiler. The building is occupied 4,015 hours/yr. Electrical costs are based on $0.10/kWh and gas costs are based on $0.50/therm.

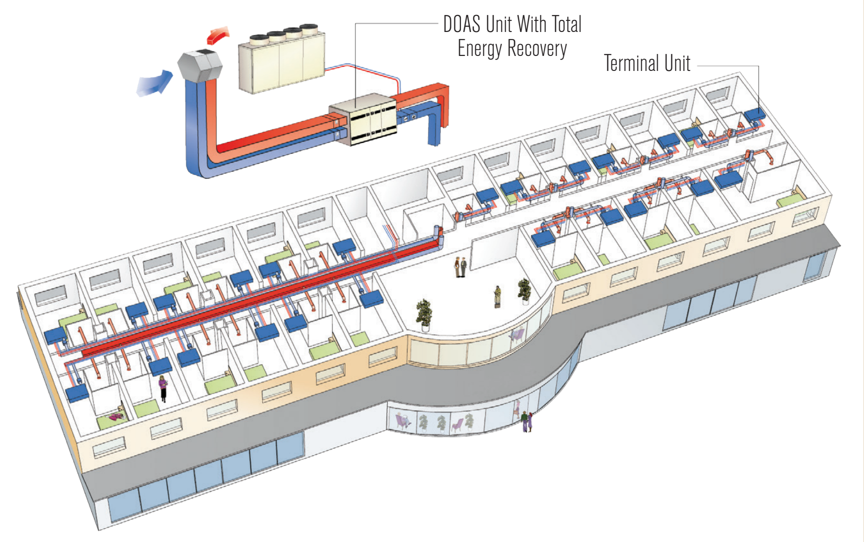

FIGURE 1 Basic DOAS with energy recovery.

- Provide a DOAS unit with passive reheat (hot gas reheat for DX systems, wraparound heat pipe, sensible energy recovery devices such as a wheel or plate) so the outdoor air can achieve 75°F (24°C) db and 50%.

Energy Recovery

For most locations ventilation air represents a significant portion of the total HVAC load. ASHRAE/IES Standard 90.1-2013, Section 6.5.6, covers in detail when exhaust air energy recovery is required. The need for energy recovery is based on location, hours of operation and the size of the system. For many DOAS applications, energy recovery is a requirement and even when it is not mandated, it can be one of the best ways to improve the building's energy efficiency.

When exhaust air energy recovery is required, Standard 90.1 requires 50% total effectiveness*(ASHRAE/USGBC/IES Standard 189.1 requires 60% total effectiveness).

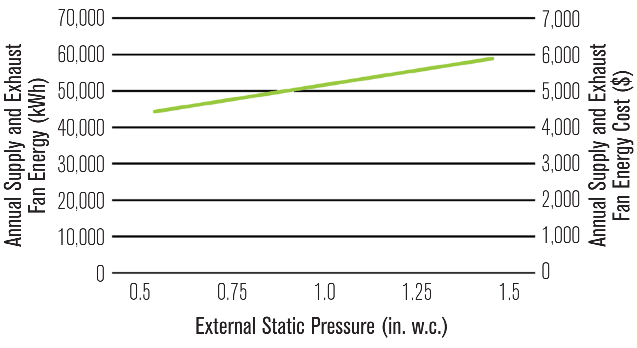

FIGURE 2 Fan energy and cost vs. external static pressure.

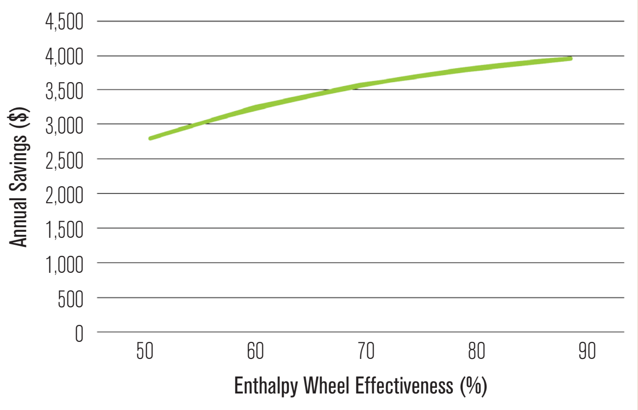

FIGURE 3 Annual cost savings vs. enthalpy wheel effectiveness.

Figure 3 shows the annual savings for the Chicago example vs. enthalpy wheel effectiveness. The operating savings is about $1,000/year between a 50% and 80% wheel. Using a 50% effective recovery device lowered the required design mechanical cooling size by 43% (from 34 tons [120 kW] to 19 tons [67 kW]). Upgrading to an 80% effective device decreases the mechanical cooling load by 73% (34 tons [120 kW] to 12 tons [42 kW]). Considering that the cost difference between a 50% and 80% wheel is relatively small compared to the total DOAS energy recovery system cost (supply and exhaust ducting, dual path AHU, controls, etc.) and the additional savings from reducing the mechanical cooling, a more effective energy recovery device is a good idea.

Not all projects require mechanical humidification. The Chicago example (based on an 80% effective enthalpy wheel) reduced the humidifier size by 45% (capital savings) and annual output by 16,700 lbs (7575 kg). For an electrical humidifier the savings are $489/year and for a gas humidifier the savings are $104/year.

The impact of controls must not be underestimated. In the Chicago example, 25% (1,158 hours) of the operating hours occur where operating the recovery device would actually raise the cooling load, not lower it. It is a Standard 90.1 requirement that the energy recovery device be shut down or bypassed during these operating conditions.

Another example is frost control. A common method to control an enthalpy wheel is to modulate the wheel speed. Most frost control algorithms are based on modulating the wheel speed to maintain the exhaust dry-bulb temperature above freezing (call this dry-bulb control). This effectively flat lines the heat transfer once the exhaust air reaches around 35°F (1.7°C). This is safe and easy to execute. However, an enthalpy wheel lowers the humidity ratio of the exhaust air as it cools it sensibly. For many operating conditions, this means the exhaust air can be cooled below 32°F (0°C) without frost forming. Maximizing the energy transfer by getting the exhaust air as close to the dew-point line as possible (call this dew-point control) will increase the annual energy savings.

In the Chicago example, switching from dry-bulb control to dew-point control increased the annual heat

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*ANSI/ASHRAE Standard 84, *Method of Testing Air-to-Air Heat/Energy Exchangers,* defines effectiveness as the actual transfer of moisture or energy/maximum possible transfer between airstreams.

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savings by 15.8%. The investment in ducting, DOAS unit, energy recovery devices is identical; how well the DOAS will work will ultimately come down to the controls.

Fan Work

One of the key strengths of decentralized HVAC solutions is that energy is moved throughout the building in water or refrigerant, which have much lower transport costs than air. Now a DOAS unit is, by purpose, an air moving system so close attention to fan system design is warranted, especially with energy recovery, which requires both a supply and exhaust air fan.

Figure 4 shows the annual operating cost for different types of fans. The savings in energy and operating cost is about 20% from worst to best. Permanent magnet synchronous motors (EC motors) offer excellent motor efficiency (93% plus) and can have variable speed, allowing direct drive fans (no belts to service or belt transmission loss).

When the DOAS unit includes fans with speed control (i.e., VFDs), supplemental controls can be included to compensate for air density changes (this can be significant in DOAS units), filter loading, etc. It is also a key building block in designing a demand-controlled ventilation (DCV) DOAS that will be discussed shortly.

Plenum fans are popular because of their small space requirements, particularly in direction of airflow and their real-world versatility regarding system effects. A scrolled fan is more efficient under ideal conditions.

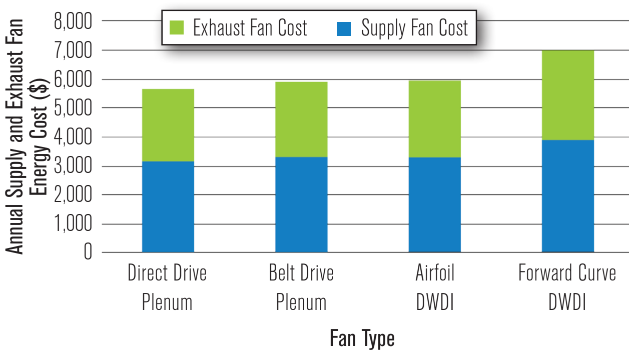

FIGURE 4 DOAS unit fan cost vs. fan type.

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However, to achieve the additional performance requires the fan, DOAS unit and DOAS duct design be carefully designed and integrated. Introducing an elbow into the duct within 2 ft (610 mm) of the scrolled fan discharge can add 0.7 in. w.c. (174 Pa) static pressure in system effect. That is an additional 20% in fan work.

Demand Control Ventilation

There is no better way to improve energy performance than to not use it in the first place. The DOAS will be sized based on design conditions at full occupancy. Von Neida, et al., and Maiccia, et al.,[2] found daytime occupancy between 6 a.m. and 6 p.m. was 40% for break rooms, 26% for classrooms, 20% for conference rooms, 33% for single person offices and 33% for restrooms.

Figure 5 shows actual ventilation airflow data and energy usage for an office building in Sweden. The system was sampled every hour for a year and never exceeded 76% of design airflow. For 80% of the time it averaged less than 45% of design airflow. Standard 90.1 (6.4.3.8) requires DCV in high density applications such as classrooms. ASHRAE Standard 62.1-2013 (6.2.7) allows DCV providing the minimum ventilation rate is no less than building component (area outdoor air rate, R_a × floor area).

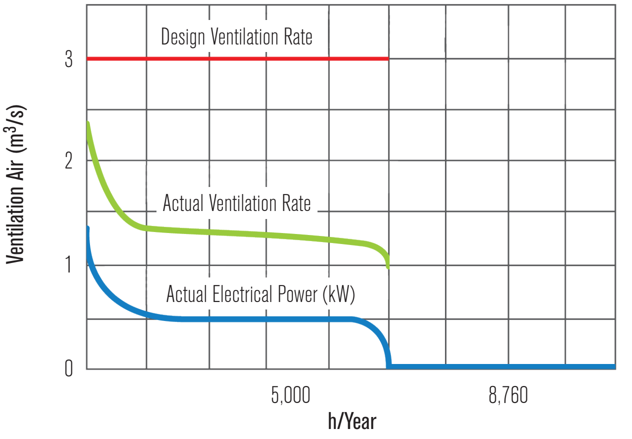

FIGURE 5 Measured airflow log with DCV for one year.[3]

Figure 6 shows a DOAS designed for DCV. In addition to all the components present in a constant airflow (CAV)

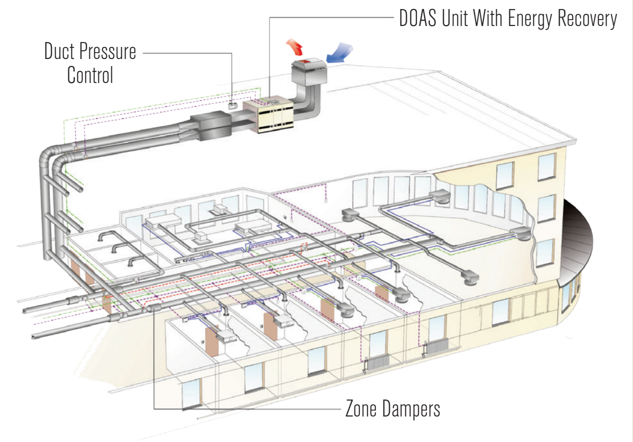

FIGURE 6 **DOAS with DCV.**

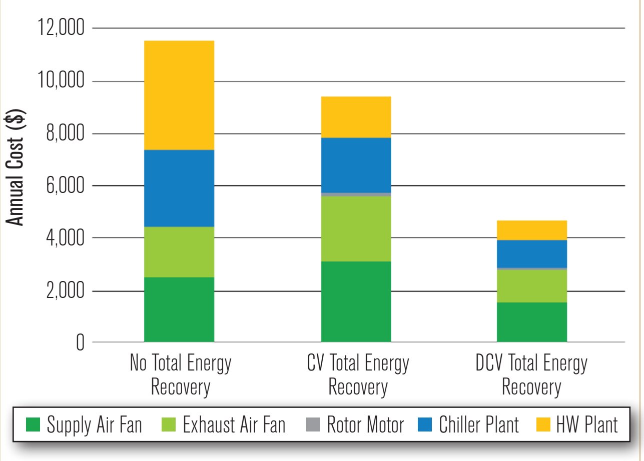

FIGURE 7 **Demand control ventilation cost vs. constant volume DOAS cost.**

application, the supply and exhaust fans need to be variable flow (add VFDs and controls), and there are now isolation dampers to serve the individual zones.

For main HVAC systems where the purpose of the DOAS is ventilation air (WSHP, GSHP, fan coil, VRF), the ventilation airflow control is based on indoor air quality. The most common methods of control are CO_2 sensors or occupancy sensors or both. For small zones, an occupancy sensor is reliable and cost effective. The isolating damper can be an on-off type. For larger zones with a wide range of occupancy, a CO_2 sensor allows for modulating ventilation airflow.

For HVAC systems where the DOAS unit is supplying air for ventilation, latent control and possible zone sensible cooling, the airflow control will need to include sensors and control algorithms for latent and sensible temperature control, as well as IAQ control.

The DOAS unit will require variable airflow, which is typically achieved with VFDs and duct pressure control similar to a conventional VAV system.

Figure 7 shows the annual costs for the Chicago example between a CAV DOAS unit with no energy recovery, a CAV system with energy recovery and a DCV system with energy recovery. It is based on 50% average occupancy during operating hours and 55°F (12.8°C) summer supply air temperature reset to 65°F (18.3°C) in winter. From worst to best is a 72% energy savings and a 59% cost savings.

Economizers and DOAS

Integrating an economizer strategy into a DOAS is worthy of some thought. First step is to determine what is meant by “economizer”? In an all-air HVAC system, economizer means increasing the outdoor airflow (above the minimum required for ventilation) to gain “free cooling” when outdoor air conditions allow. Since a DOAS is a 100% outdoor air unit that is typically sized to deliver the minimum outdoor airflow required for ventilation, it cannot economize by increasing outdoor airflow. (While it is technically possible to oversize a DOAS to provide more airflow for “free cooling,” it likely is not a good investment.) But the DOAS unit can provide some level of economizing by not operating cooling or heating components when outdoor conditions allow for the air to be delivered without any conditioning.

For example, if energy recovery is added to the DOAS unit, then ensure its controls will stop the energy transfer by the recovery device when it is counterproductive. For example, allowing the energy recovery device to work when it is 55°F (13°C) outdoors and the exhaust air is 75°F (24°C) will actually add heat to the outdoor air and cooling load to the main HVAC system. To economize, there must be controls to stop energy transfer during economizer opportunities. It is a good idea to rotate wheels periodically during economizer cycles to minimize dust buildup on the wheels.

Adding DCV to the DOAS can reduce this economizing benefit. DCV will reduce the outdoor airflow rate during periods of partial occupancy, which greatly reduces the “free cooling” potential of the DOAS during mild weather. During favorable economizer conditions, the controls should “override” DCV and increase outdoor airflow to gain more “free cooling” but this will add fan work.

TABLE 1 DCV economizer performance.

OUTDOOR TEMPERATURE DB (°F)	CHILLER PLANT SAVINGS (KWH)	INCREASED FAN ENERGY (KWH)	TOTAL SAVINGS (KWH)
65 to 70	948	2,886	–1,938
60 to 65	3,094	3,666	–572
55 to 60	3,310	2,661	650
50 to 55	4,510	2,850	1,660
45 to 50	4,537	2,779	1,758
40 to 45	4,051	2,448	1,603
35 to 40	7,603	4,529	3,074
30 to 35	7,318	4,293	3,025

Table 1 compares the cooling plant savings at full DOAS design airflow during favorable outdoor conditions to the increased DOAS fan work. In this example, the additional fan work costs more than the cooling savings until the outdoor air temperature gets close to 55°F (13°C). Compare this to an all-air HVAC system with economizer, which will see energy savings as soon as the enthalpy of the outdoor air is less than the enthalpy of the exhaust air. (Note: the all-air system airflow rates do not change due to economizer operation.)

At ambient air temperatures below 55°F (13°C), the energy recovery device in the DOAS unit can be used to raise the supply air temperature up to 55°F (13°C) and provide zone cooling if required. At these conditions, the cooling energy savings are greater than the additional fan work. However, at some point, supplying outdoor air at 55°F (13°C) to all the zones may not be desirable as it shifts heating load to the terminal device and during zone terminal off cycles may cause drafting. There is energy to be saved here, but the controls can be complex.

Summary

- Many common HVAC systems require a DOAS. Since the DOAS is critical to IAQ and can be a large energy draw (even though the overall HVAC solution can be very efficient), special consideration of the DOAS design, how it integrates with the main HVAC system and the subsequent controls are justified. Here is a summary of the key points:
- It's important to know if the purpose of the DOAS is to provide ventilation air, offset infiltration and local exhaust (WSHPs, GSHPs, fan coils, VRF), or if the DOAS also needs to manage zone latent and sensible loads (chilled beams and radiant cooling).
- Give careful thought to how the DOAS will psychrometrically integrate with the main HVAC system. Consider the cooling capabilities of the terminal units, local design conditions, capital investment and especially control algorithms of both the terminal units and the DOAS unit.
- DOAS units and energy recovery go hand in hand. In many cases it is mandatory. Consider exceeding minimum design efficiencies as it will likely be paid for by the cooling plant savings and will definitely reduce operating cost.
- Energy recovery DOAS unit fans consume 60% of the unit energy input. Pick good fans and motors and consider real-world issues such as system effect.
- DCV is the single best thing to reduce the operating cost of the DOAS unit. It adds complexity and first cost but almost always shows an acceptable payback. In spaces with high ventilation rates due to occupant density, it is mandated by Standard 90.1.
- DOAS units do provide some level of economizing. Make sure the energy recovery control algorithms support free cooling. Integrating economizer logic with DCV logic requires some thought. There is energy to be saved, but the controls can be complex.
- Develop and specify an integrated performance-based control system, detailed steps for commissioning and requirements for operational verification.

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