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Air-Distribution Design for Comfort in High-Performance Air Systems

By **DAN INT-HOUT**,
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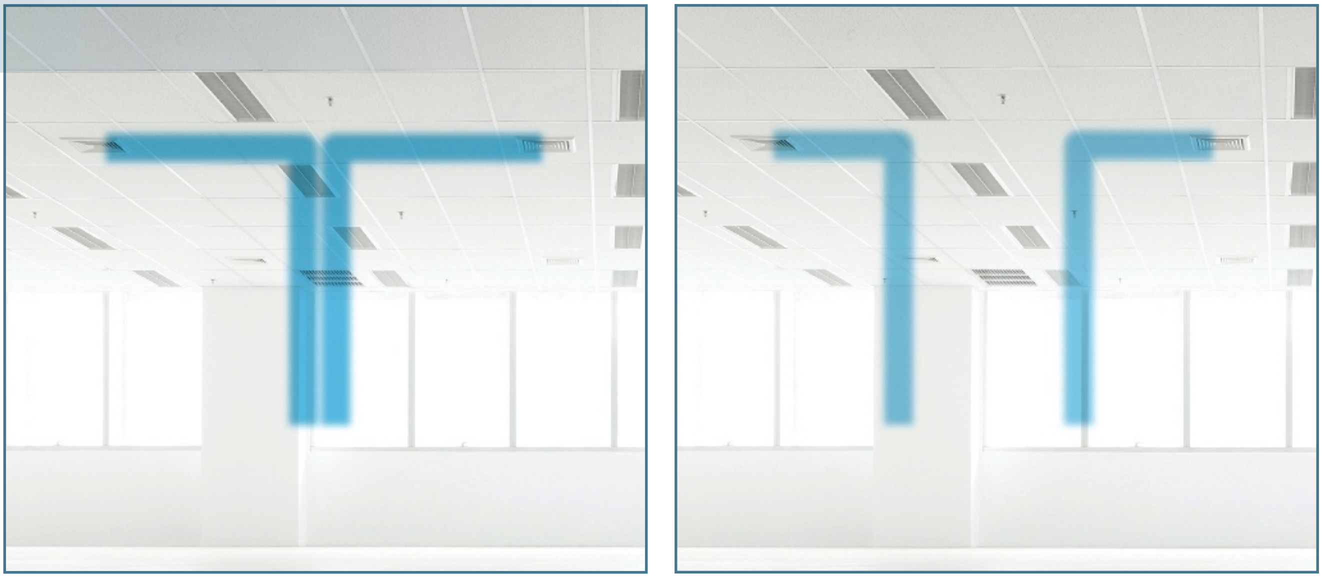
HVAC-equipment selection, location, and operation can have a significant impact on occupant comfort and, thus, the cost of running a business. How do you determine the suitability of a device for a given application and where to place devices for effective delivery of required parameters?

Amid growing concerns about climate change, resource scarcity, and carbon emissions, it can be easy to lose sight of the biggest challenge of HVAC-system design: to provide an environment acceptable to the occupants of a space. This is especially true with commercial buildings. With the cost of employing people likely several orders of magnitude greater than the cost of operating the HVAC systems in such spaces—employee salary costs are at least 200 times greater than energy costs in almost every type of building[1]—it makes sense to base selection, location, and operation of HVAC components on what will provide the greatest occupant comfort.

As discussed in the 2018 edition of *AMCA inmotion*,[2] a high-performance air system (HPAS) is an excellent means of cost-efficiently providing comfort and ventilation in commercial spaces. This article will discuss how to determine the suitability of a device for a given application and where to locate devices for effective distribution of required parameters, including temperature and outdoor air.

More importantly, the article will discuss how to determine the effectiveness of room air distribution during design. Using air diffusion performance index (ADPI) for open offices (no enclosed rooms or walled cubicles) and jet mapping for other spaces, we can be assured we are providing a comfortable environment.

The discussion will focus on variable- and constant-volume



PHOTOS 1A AND 1B. Based on the ratio of isothermal throw at 50 fpm (0.25 m/s) to the midpoint between diffusers, ADPI aids design for comfort. An ADPI of 80 percent or greater indicates a space is well-mixed and that drafts and stratification are unlikely. If ADPI is less than 80 percent, occupant discomfort and complaints can be expected. Above, on the left, is an illustration of optimal ADPI; on the right is an illustration of poor ADPI.

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ducted HVAC systems. Supply of system air includes both applied (chilled water) and unitary (compressor-equipped units) systems. The delivery of hot and cold air to building occupants is the focus of the article.

ADPI and Jet Mapping

ADPI is a single-number rating of temperature and air speed in the occupied zone of a space. It can be measured using ANSI/ASHRAE Standard 113, *Method of Testing for Room Air Diffusion*. In a sense, ADPI is a measure of how well-mixed a zone is (photos 1A and 1B). It is limited to open spaces with multiple diffusers and an 8-to-10-ft (2.4 to 3.0 m) floor-to-ceiling height, such as a typical open office. It is not applicable to perimeter or closed (walls extending to the ceiling) offices or to heating evaluations.

An ADPI prediction considers air-outlet type, diffuser spacing, throw of 50 fpm (0.25 m/s) at the desired airflow (usually based on sound generation), and room load. One then enters data from the ADPI table in ASHRAE Handbook—Fundamentals,[3] usually using manufacturer software. An ADPI of 80 percent or greater is recommended for most office-type spaces and can be used to prove compliance with ANSI/ASHRAE 55, *Thermal Environmental Conditions for Human Occupancy*'s vertical-temperature-stratification limit of 5.4°F (3°C).

Once a diffuser's performance at a design load and spacing is determined, the lowest possible airflow rate that will result in a calculated ADPI greater than 80 percent can be determined. From that, the optimum separation distance and minimum recommended flow rate easily can be determined.

It is important to note that most acoustical specifications require a noise-criteria (NC) level of 35. ASHRAE recommends increasing published NC levels by 5 to account for real-world room acoustics and less-than-ideal inlet conditions. For a given airflow through a four-way outlet, the separation distance simply is the square root of the sum of the airflow divided by the airflow/unit area. Note that this calculation is independent of any performance parameter

What Is a HPAS?

Usually consisting of a chiller, an air handler, and terminal units or a chiller and fan coils, a modern high-performance air system (HPAS) provides advantages such as individual temperature zoning and high-efficiency filtration of 100 percent of both outside air and recirculated air. It radically improves energy efficiency with features including aggressive supply-air-temperature and chilled-water-temperature reset, demand-control ventilation, integrated economizing with heat recovery, separation of return-air and outside-air treatment in humid climates, exhaust energy recovery where appropriate, and heat-pump-chiller buildingwide heat recovery and optional 100-percent electric operation.

PHOTO 2. Air distribution differs between perimeter spaces (left) and interior spaces (right).
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of a diffuser except sound. The ADPI parameter *L* is half the separation distance.

Knowing the separation distance, one can use ADPI to determine the lowest acceptable airflow rate. Note that for some ceiling air outlets, turndown may not be possible.

One also can use manufacturer data to determine throw for any outlet and look at jets directly. An alternative to using ADPI is to ensure the 50-fpm throw does not cause collisions at the midpoint between diffusers. The midpoint should not exceed the separation distance plus the distance from the ceiling to the top of the comfort zone, usually 3 ft (0.9 m).

Changing Loads

Rules of thumb. During the mid-1980s, variable air volume (VAV) was becoming more and more electronically controlled and lighting was becoming stabilized at levels far below those during the 1960s, when many designs were established. As a rule of thumb, a flow-rate set point of 1 cfm per square foot (0.47 l per second [l/s]) of interior space was established, making VAV design much easier. A second rule of thumb concerned acoustics, as NC 35 became the seemingly universal maximum desired noise level in specifications for interior spaces. Lastly, with pneumatic controls having a finite ability to resolve low flow, VAV boxes began being set with a 30-percent minimum flow, which became another rule of thumb.

Of course, nothing stays the same forever. Lighting loads now are less than 1 W per square foot (10.8 W per meter squared [W/m^2]), as modern computers and screens draw far less current than older office equipment did and office spaces are more spread out. What's more, VAV-box probes have shown linearity well below any controller's ability to resolve low flow. The result is that interior-zone loads likely are far less than the 22 Btuh (6 W per square foot [64.6 W/m^2]) that results with 1 cfm per square foot at 55°F (12.8°C). When VAV boxes are set at 30-percent minimum flow, there is a likelihood the minimum flow will exceed the space load and the space will become subcooled.

A study of comfort and energy at the Sunnyvale, Calif., campus of Internet-access provider Yahoo![4] showed that, at 30 percent of 1 cfm per square foot, spaces were being subcooled and employees were quite dissatisfied with a 68°F (20°C) workplace every afternoon. Reducing the minimum setting resulted in a measured load equivalent to about 0.22 cfm per square foot (0.011 l/s per m^2), very close to ventilation minimums in California. This has tremendous implications, as the interior load in Sunnyvale, Calif., is

PHOTO 3. Round diffusers installed in an open ceiling. *tavizta/Shutterstock*

PHOTO 4. Square diffuser installed in a closed ceiling. *imnoom/Shutterstock*

very similar to the one in Saskatoon, Saskatchewan.

What to do. Some engineers are lowering design interior airflow to more realistic levels, while others are reducing it to code-minimum values. Although this is helping to reduce incidents of subcooling, issues with air-outlet performance and objectionable drafts remain. We, therefore, need to look at air outlets.

Diffusers

Selection and location. A common question concerning open-plan offices the author has encountered over the last 40-plus years is, "Where do I place my air outlets?" The answer, of course, is, "It depends"—on cost, performance, and aesthetics.

Often, there is a trade-off between cost and performance, as, typically, the lower the (first) cost, the poorer the performance (noise, pattern control, durability, etc.). An understanding of the actual performance characteristics of air outlets can lead to better selection and value.

Interior vs. perimeter. Air distribution differs between interior offices and perimeter offices (Photo 2). With interior offices, only interior loads need to be considered. When at least one of an office's walls is an outside wall, both interior and perimeter loads need to be considered, which affects both diffuser selection and diffuser location.

Interior zones. Spaces more than 15 ft (4.6 m) from a perimeter surface usually are considered "interior." For the most part, interior spaces are independent of outside temperature and humidity, except for the conditioning of ventilation air.

Additional recirculated air typically is provided to take care of sensible loads, including lighting loads. When VAV first was employed in the early 1970s, lighting loads were quite high—as high as 6 W per square foot. With increasing energy costs and the addition of computers, necessary lighting levels have dropped.

Ceiling air-outlet performance. Open-plan offices have been conditioned from the ceiling, with ceiling returns, for many years. Ceiling air outlets, properly referred to as air diffusers (photos 3 and 4), are designed to distribute cool air along a ceiling surface, mixing room air by means of induction (a jet of air has lower static pressure than the slower air around it) and preventing cold air from falling into the occupied zone through reliance on the Coanda effect. Performance is characterized by throw distance, generated noise, and pressure required over a range of airflow. ADPI can be calculated using the throw, diffuser-spacing, and load data and tables in ASHRAE Handbook—Fundamentals.[3]

Open vs. closed offices. In closed offices, air typically is distributed with a single centrally located diffuser. ADPI generally is not useful at design loads in single-outlet closed offices, as the throw will hit the walls. If such a space has a window, however, ADPI needs to be considered. When designing air distribution for an open-plan office, jet collisions at high flow and excessive drop at low flow have to be considered. If the suspended ceiling is near

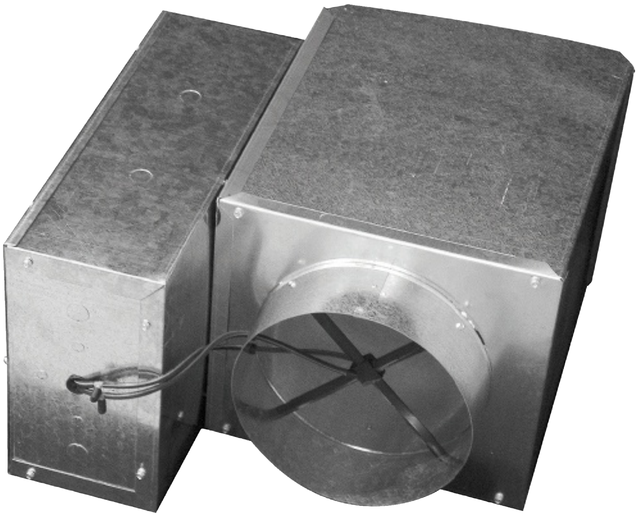

PHOTO 5. Single-duct terminal unit.

Photo courtesy of Krueger

9 ft (2.7 m) from the floor, ADPI will be a good tool.

ADPI graph. Using device throw performance and data in ASHRAE Handbook—Fundamentals[3] correlating throw to ADPI, one can determine the effective range (ADPI greater than 80 percent) of an air outlet as a function of flow rate, flow rate per unit area, and location in an array.

For an open-plan office with four-way or circular-pattern outlets, separation distance can be determined using a simple equation:

$$\text{Separation distance} = (q/r)^{0.5}$$

where:

q = flow at desired NC, cubic feet per minute

r = flow rate per square foot

Minimum flow rate. Next, using the flow and half of the separation distance, we can consult the ADPI table in ASHRAE Handbook—Fundamentals[3] to determine the minimum rate of flow.

Open ceilings. Most manufacturers provide data for throw measured along a surface. With an open ceiling, however, throw is shortened by about 30 percent.

An open-plan space with open ceiling is best served with round diffusers on spiral-duct drops. The larger the diameter of the supply duct, the more uniform the discharge from a short drop. Most round diffusers have a slightly upward discharge pattern with an open ceiling, usually compensating for the lack of Coanda effect to avoid an excessive amount of cold air falling into the occupied zone.

Linear diffusers. In defining the area to be served by linear diffusers, end-to-end spacing needs to be considered. At lower design airflows (less than 1 cfm per square foot), a spacing of 8 ft (2.4 m) is typical with 4-ft (1.2 m) linear diffusers, resulting in a 12-ft- (3.7 m) wide zone. Dividing this into (q/r) will yield the length of the space to be conditioned. For one-way discharge, this is the distance to the next outlet. For two-way discharge, it is halfway to the next diffuser (but the same total distance apart). ADPI for linear slot diffusers uses 100-fpm (0.51 m/s) terminal velocity (instead of the 50 fpm used for everything else), but the analysis is similar.

Grilles. Grilles seldom are used in open-plan offices. When they are used, ADPI typically is not a valid calculation, as the ceiling usually is much higher than 9 ft and often there is no suspended ceiling. As with linear slot diffusers, the spacing between outlets is used to determine the area served at a given design flow rate. Grille throws can be shortened by increasing the spread, while excessive drop can be controlled by adjusting horizontal blades.

To avoid drafts, throws to 100 fpm from opposing grilles never should be allowed to meet.

Perimeter zones. Perimeter loads are far less today than they were when overhead heating was introduced in the 1970s. Nevertheless, data indicate effective overhead heating requires that room-to-discharge delta-T never exceed 15°F (9.4°C). What's more, the downward convective airflow generated by the cold surface of a window is best treated by being mixed with warm (not hot) air directed down the window. ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*, says that, if discharge delta-T exceeds 15°F or a 150-fpm (0.76 m/s) throw does not come to within 4.5 ft (1.4 m) of the floor, ventilation air will short-circuit into ceiling returns and additional ventilation air will be required. ASHRAE Handbook—Fundamentals[3] indicates excessive vertical stratification also will result, preventing compliance with ANSI/ASHRAE Standard 62.1.

Perimeter diffusers. Air outlets in a perimeter zone need to be close enough that a 150-fpm throw at the heating airflow rate will project down a window. Ideally, slot diffusers will be located a couple feet from the window and have two-way discharge. ADPI does not really work for heating. As a result, there are proposals to develop rating methods based on recent research. It is important that the responsibility for adjusting linear-slot-diffuser pattern controllers be clearly identified at the design stage and verified after construction. This is best done by the installing contractor.

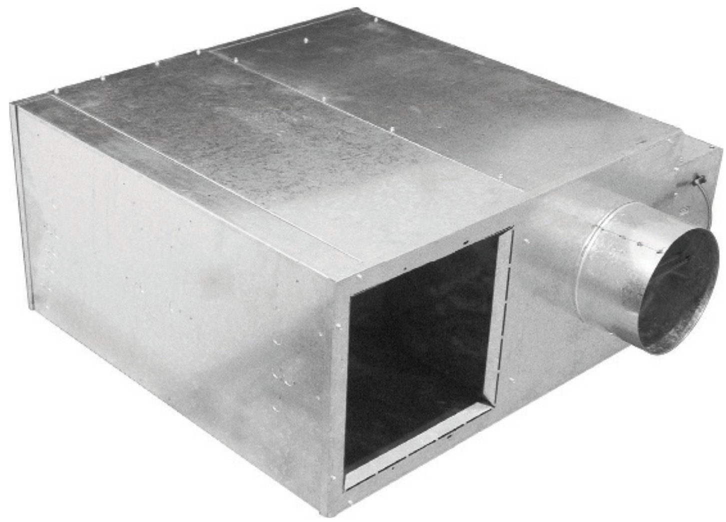

PHOTO 6. Fan-powered terminal unit.

Photo courtesy of Krueger

Terminal-Unit Selection

A number of codes affect air-distribution-system design. Some reference ASHRAE standards, while others include them. All of the standards can be considered "acceptable standards of care"; therefore, it is best to understand what they require.

ASHRAE standards 55, 62.1, and 90.1. ANSI/ASHRAE Standard 62.1 and ANSI/ASHRAE/IES 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, are referenced in most codes. ANSI/ASHRAE 55 is referenced in many codes, but seldom specified. ANSI/ASHRAE Standard 62.1 and ANSI/ASHRAE/IES 90.1 are prerequisites in the Leadership in Energy and Environmental Design (LEED) green-building rating system and, thus, must be met, while compliance with ANSI/ASHRAE 55 is optional and worth up to three LEED points. Though ASHRAE Handbook—Fundamentals[3] suggests that, if discharge temperature is high, excessive room stratification is likely, ANSI/ASHRAE/IES 90.1 limits the quantity of air that may be reheated, making comfort difficult to maintain with single-duct reheat systems in northern climates. The solution is the fan-powered terminal.

Single-duct VAV reheat terminals. The single-duct VAV box (Photo 5) has been in common use for almost 50 years. In moderate climates or buildings with supplemental perimeter heat, it can meet most occupants' comfort needs. Whereas the turndown of VAV boxes once was limited by the ability of pneumatic velocity controllers, modern direct digital controllers have greatly extended the usable range of "pressure-independent" VAV boxes.

The inlet-flow probe on VAV boxes has been improved so that VAV boxes now are able to provide both good airflow and effective temperature control. Today's VAV boxes feature a magnified probe. In a test of different probes,[5] all models exhibited linear response (to the square root of the signal) down to flows unlikely to be reproducible with a direct digital controller. Consequently, the transducer on controllers is the device that sets low-flow limits today. Some manufacturers who used to recommend a minimum signal of 0.03 in. wg (7.47 Pa) now recommend one of 0.01 in. wg (2.49 Pa).

Hot-water coils have limited reheat capabilities for reasons related to flow, turbulence, and circuitry, and their selection often is challenged by low building loads from improved thermal resistance at the perimeter of buildings. This is compounded by lower-temperature entering hot water and restrictions on return-water temperature with some boiler designs. Some new designs show enlarged water coils to reduce operating air-pressure drop.

In recent years, the industry has seen a move toward fan-assisted VAV units.

Fan-powered terminals. The fan-powered VAV device (Photo 6) has been in common use since the mid-1970s. There are two types: parallel and series.

A parallel box induces plenum air on a call for heating in coordination with a VAV damper. Airflow rates for the fan and VAV damper are independent of each other.

A series box induces plenum air, which mixes with primary air from a VAV damper before passing through the fan. The fan must never deliver less air than the VAV valve to prevent backflow into the ceiling plenum.

With a parallel box, the central-system fan delivers air to a diffuser through the box. With a series box, the central system needs only to get air to a VAV inlet, resulting in a lower system fan static-pressure requirement. The series fan, however, must run at all times during occupancy, but with constant airflow from the series terminal, diffuser turndown no longer is an issue. Which—series or parallel—then, is the better choice?

More often than not, the answer has more to do with local practice than actual data. Many building codes require summation of motor horsepower or other measures, while available building-load programs do not accurately reflect the savings that result from new technologies. ASHRAE and the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) established a joint research program to look at the system energy use of series boxes vs. that of parallel boxes and of permanent-split-capacitor (PSC) motors vs. that of electronically commutated motors (ECM).

Validation of energy use. The purpose of the ASHRAE and AHRI joint research program was to produce data enabling accurate and validated energy-use calculations. Research Project 1292 was conducted at Texas A&M University.

More than two dozen technical papers on the results of the study have been presented. Additionally, *ASHRAE Journal* published a three-part series of articles describing the purpose of the research,[6] summarizing the findings,[7] and discussing shortcomings of EnergyPlus and other energy models.[8]

Data show that, in most situations, a series box with an ECM will use less energy than a parallel box with either an ECM or a PSC motor. Additionally, if fan airflow is reduced at less than design load, rather than held constant, energy savings with a series box can be significant.

Minimum recommended airflow. When close to the primary (VAV) airflow, a series fan box with an ECM can be turned down, at which point it will use significantly less energy. The extent to which it can be turned down is largely dependent on diffuser choice and spacing.

Summary

When designing a VAV system for a large building, it is imperative to understand the role each component plays. Air handlers are used to supply air to zones. They track demand and determine the gross amount of air to provide. Terminal units are used to fine-tune the amount of air supplied to a zone and control noise. Diffusers are used to mix air within a space, ensuring comfort without drafts or stagnation. Each of these devices is equally important. All function together in a well-designed HPAS to provide an acceptable environment for occupants.

Note and References

1) Assuming the ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*, default occupancy of 150 sq ft (13.9 m^2) per person, an annual employee cost (salary, taxes, benefits, etc.) of $70,000 per person, and an annual energy cost of $2 per square foot.

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3) ASHRAE. (2017). *ASHRAE handbook—fundamentals*. Atlanta, GA: ASHRAE.

4) Arens, E., et al. (2015). *RP-1515—thermal and air quality acceptability in buildings that reduce energy by reducing minimum airflow from overhead diffusers*. Atlanta, GA: ASHRAE.

5) Paliaga, G., Zhang, H., Hoyt, T., & Arens, E. (2019, April). Eliminating overcooling discomfort while saving energy. *ASHRAE Journal*, pp. 14-28.

6) Faris, G., Int-Hout, D., O'Neal, D., & Yin, P. (2017, October). Fan-powered VAV terminal units. *ASHRAE Journal*, pp. 18-24.

7) Faris, G., Int-Hout, D., O'Neal, D., & Yin, P. (2017, November). Fan-powered VAV terminal units, part 2. *ASHRAE Journal*, pp. 20-28.

8) Faris, G., Int-Hout, D., O'Neal, D., & Yin, P. (2017, December). Fan-powered VAV terminal units, part 3. *ASHRAE Journal*, pp. 42-45.

About the Author

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High-Performance Air Systems vs. Other System Types

By **GUS FARIS**, AMCA High Performance Air Systems Committee

The following table compares in terms of key performance characteristics and capabilities high-performance air systems (HPAS) with three other HVAC-system types:

- Variable refrigerant flow (VRF)—typically, a group of non-ducted mini-splits with common condensing unit.
- Chilled beam (CB)—usually, one or more chillers, an outdoor-air handler, and chilled beams, cool-water (sensible cooling only) cooling coils built into a cabinet in which room air is blended with outdoor air before delivery to an occupied space through a diffuser. Fan coils or series fan-powered terminal units may be required for pressurization. The outdoor-air handler supplies all latent cooling prior to air being distributed to the chilled beams.
- Water-source heat pump (WSHP)—self-contained packaged unit including fan, coil, and compressor usually sized to handle a single small zone.

Performance characteristic/ capability	HPAS	VRF	CB	WSHP	Comments
Comfort control	✓				Variable-air-volume terminal units fine-tune airflow based on comfort demands, but air-handling-unit discharge-air temperature remains constant, ensuring a constant sensible-heat ratio and low humidity. Engineered duct systems terminate at high-performance diffusers that eliminate drafts and ensure proper mixing in a space.
Basic system includes outdoor air	✓				With a HPAS, outdoor air is supplied through the duct system to each zone. No additional duct systems or outdoor-air handlers are necessary.
Economizing	✓				HPAS can function with either water-side or air-side economizers. This can save significant amounts of energy with no compromise in comfort in any climate.
Simultaneous heating and cooling	✓				HPAS simultaneously heat and cool. In large single zones, mixing is adequate enough to avoid reheating and recooling.
Quiet operation	✓		✓		Centralized systems are very quiet, as their fans are located outside of occupied spaces. Additionally, there is no compressor noise in occupied spaces.
Service and maintenance	✓				With a HPAS, equipment service and maintenance usually is performed in an equipment room or outside at the chiller. Service in local zones is almost non-existent. There is no potential for condensation on ceilings.
Filtration	✓				With a HPAS, there is adequate filtration at the air handlers. Properly selected air-diffusion components deliver highly mixed air to zones and provide superior comfort, meeting both ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*, and ANSI/ASHRAE 55, *Thermal Environmental Conditions for Human Occupancy*.
Refrigerant safety	✓				With a HPAS, all refrigerant is in the chiller and out of and away from occupied spaces. Leaks are rare.
Documented performance	✓				Performance costs of HPAS are well-documented and all-encompassing, and system total energy use has been detailed in independent (ASHRAE/ Air Conditioning, Heating, and Refrigeration Institute) research.
Consistent operation	✓				HPAS operate consistently through all seasons and seasonal changes.

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