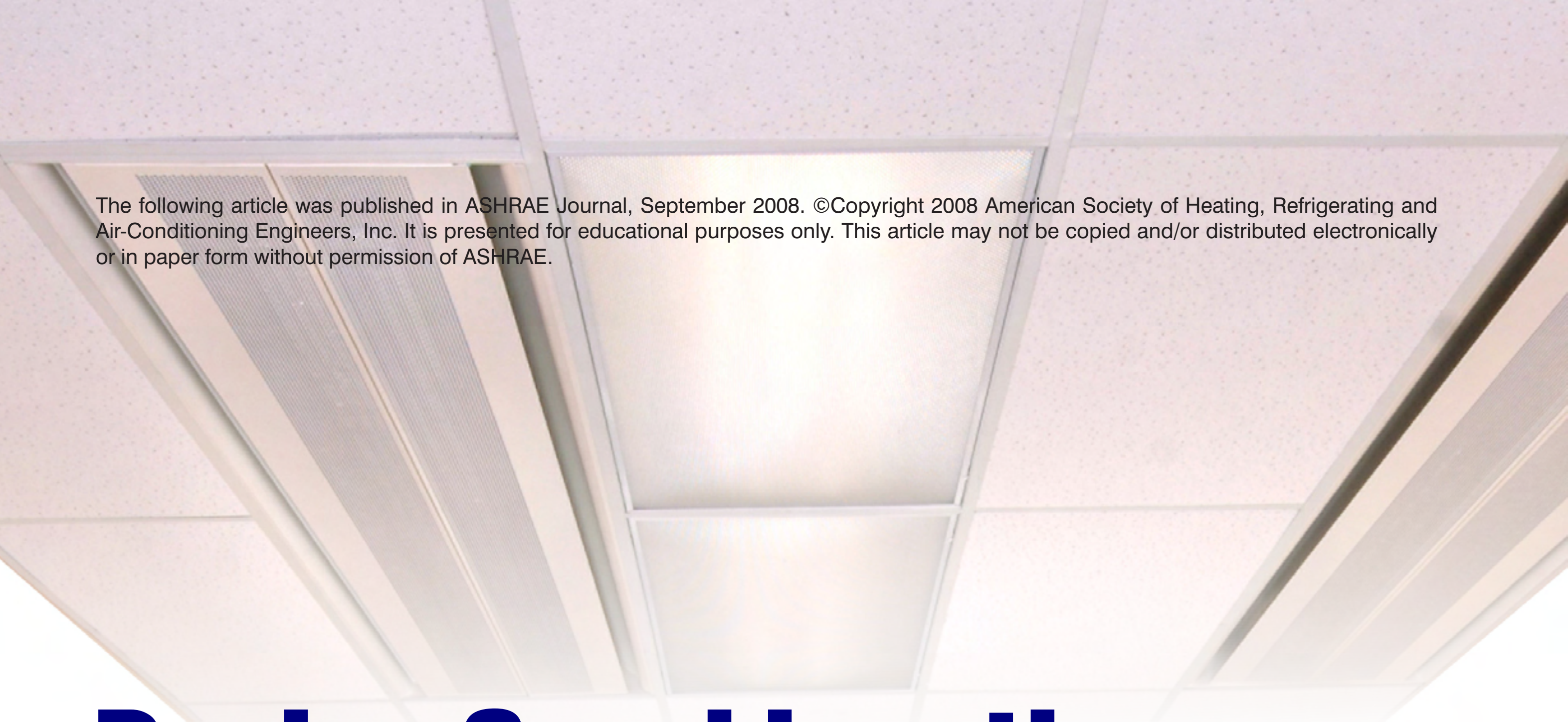

Design Considerations For Active Chilled Beams

By Darren Alexander, P.Eng.; and **Mike O'Rourke**

Active chilled beams (ACBs) are becoming popular with design consultants as a means of managing large sensible cooling loads with excellent energy performance and low acoustic signatures. This type of active chilled beam is generally installed within a T-bar ceiling grid and is often supplied in 1 ft or 2 ft (300 mm or 600 mm) widths, and lengths ranging from 2 ft to 10 ft (0.6 m to 3.0 m). Active chilled beams provide the advantage of a substantial sensible cooling effect, often by using as little as only the required ventilation air.

Also known as high induction diffusers, ACBs recirculate room air through a unit-mounted coil, driven by ventilation air (primary air) with mixing ratios as high as 6:1 (discharge air to primary air). The coil is provided chilled water, which is maintained above the dew point of the primary air to prevent condensation from forming on the coil. The driving force in dehumidifying a space is the mixing of moist room air with drier primary air. By decoupling the ventilation load from the space load, perpetual fan energy savings are created when compared to VAV and other types of all-air systems.

Although the low air volume advantage may be reduced when addressing higher latent loads, ACBs offer the benefit of warmer chilled water temperatures for cooling, and cooler hot water temperatures for heating (low exergy systems) to provide high levels of controlled comfort within the occupied zone. This allows for consideration of additional system options in the design process, and offers a new world of possible solutions to the total HVAC system design process. A system advantage in terms of improving the chilled water temperature range is open to sites that use a dedicated outdoor air system (DOAS)* evaporator return water to service part of the secondary chilled water loop, minimizing the total pumping requirements. Fin-enhanced, closed-circuit fluid coolers allow for ACB water-side economization, and mixed mode ventilation can be used to great effect to further reduce the carbon footprints of new and existing buildings.

In addition to their relatively shallow depth (generally less than 12 in. [300 mm] clearance requirements), ACBs offer

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an attractive solution to retrofit type applications as the mechanical service space requirements are exceedingly modest in comparison to systems such as variable air volume (VAV), constant air volume (CAV), or fan coil applications. In new construction, this reduction in clearance above the ceiling height could offer lower construction costs for buildings with lower floor-to-floor height. Essentially, active chilled beams are used to remove the sensible heat from the occupied zone via chilled water in lieu of air. Given the high specific heat of water, and the reduction in total fan energy, it is easy to understand why active chilled beams offer substantial water and fan energy savings over all-air type systems. Capital cost savings are often available due to a potential reduction in floor-to-floor height, ducting requirements, and air-handling unit sizes.

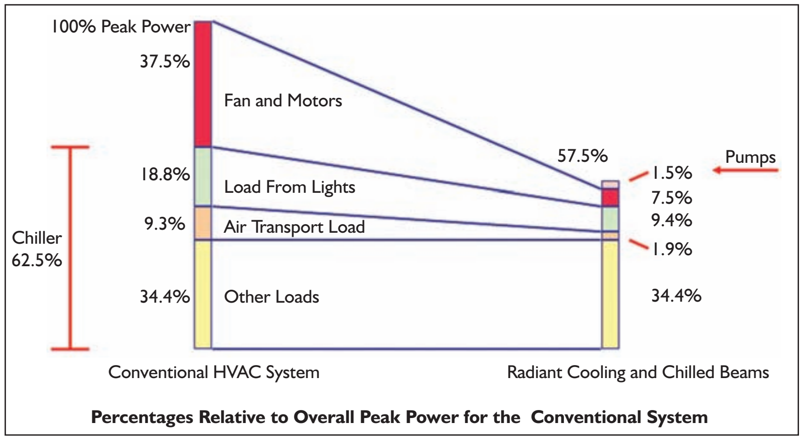

Figure 1: Typical fan and motor savings for office building dedicated outdoor air systems (DOAS) vs. conventional HVAC systems.[2]

Capacity and Energy Savings

Active chilled beams have the ability to reduce the total air handled by the ventilation system because they typically require as little as 99 cfm/ton to 250 cfm/ton (13 L/s per kW to 33.6 L/s per kW) of sensible cooling as it relates to the volume of primary air delivered to the beam plenum for dehumidification, creating the induction effect within the ACB. Potentially, for an office type building, this could translate into a reduction in the amount of total air processed at the air-handling unit to between 25% to 50% of that which is required by an all-air system. Consequently, by using the fan laws, one can quickly calculate the potential fan energy reduction compared to all-air systems when using DOAS equipment.

Figure 1 is an approximate representation of the possible energy savings associated with DOAS ventilation systems. Although the primary means of heat transfer is radically different, radiant chilled ceilings and ACB projects using DOAS offer the potential fan energy savings of this type of air-distribution system for many conventional building types including offices, schools, etc. Lab spaces may require additional airflow to provide prescribed air change rates, or for fume hood makeup, but have used ACBs to manage the sensible loads within the space with great success.[1] The energy savings associated with the load from lights may not be available to ACB installations, as this graphical representation assumes that the sensible heat gain from the lighting load would be transported from the building envelope via the plenum, and that this heat gain would not be added to the space load, as it would in the conventional HVAC system and ACB installations.

Enthalpy wheels and heat pipes can be added inexpensively to makeup air-handling units as the total air volumes managed by DOAS equipment is much smaller than that required for VAV or CAV systems. There is an additional cost that must be considered for ducted return systems, which is unnecessary if there is no heat reclaim option included with the DOAS unit. However, an energy model will quickly and clearly identify if the added expense is justifiable.

Suitability for Various Spaces

Active chilled beams should not be considered a silver bullet in terms of addressing high sensible cooling requirements in all spaces. Certain spaces are well suited to chilled beam use, and others are not appropriate for this technology.

Areas that may not be suitable for active chilled beams may include, but are not limited to:

- Large vestibules/atriums: latent load is difficult to control and could be addressed via other design strategies;
- High latent cooling requirements: kitchens, pools, locker rooms, spas, gymnasiums, etc.;
- Hospitals: Class I and Class II areas where recirculated room air is not permitted;† and
- High ceilings: room air movements should be for ceilings in excess of 14 ft (4.3 m).

Many spaces lend themselves well to the use of active chilled beams. These may include, but are not limited to, offices, schools, labs computer rooms (i.e., desktop farms as opposed to rack rooms), and low-ceiling height building retrofits (i.e., <10 ft [<3 m] and other space that provides little clearance for mechanical services).

Duct Design and Working Static Pressures

Active chilled beams are dependent on pressure for driving the induction engine. One must consider reviewing the duct design to ensure that the pressure is efficiently delivered to the beam plenum. Although not a requirement, it is generally preferable to consider a low-velocity downstream ducting strategy. The main ducts may be sized as they would normally for offices at 1,200 fpm to 2,400 fpm (6 m/s to 12 m/s), favoring lower duct velocities or less where possible to mitigate duct frictional losses. However,

*For additional information on dedicated outdoor air systems, see http://doas-radiant.psu.edu/.

†Class I and II areas as defined by CSA Standard Z317.2, Table 1, Ver. 01, 2001.

when considering the branch ducts to the beam plenums, a slight oversizing of the ductwork helps avoid duct pressure losses, which can be used more effectively at the beam plenum to enhance the ACB capacity. In the strategy of avoiding downstream pressure losses, one can ensure more pressure is available to operate the beam, and improve its capacity, resulting in a reduction in the number of beams required on a project, and consequently, lowering the initial capital costs for this type of system. One must be aware that higher operating static pressures increases the acoustic signature of the ACBs. A balance between acoustic requirements and capital cost must be evaluated.

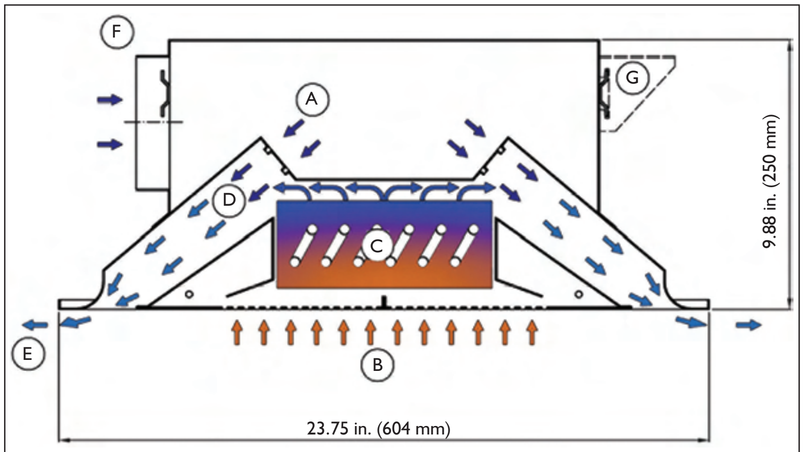

Figure 2: Schematic operation of an active chilled beam.

Active chilled beam projects often are installed using round spiral downstream ducting. A slight increase in the internal diameter of the duct network would result in little impact on the capital cost, and the associated labor to hang the larger ducting (i.e., 6 in. [150 mm] diameter round duct versus 4 in. [100 mm] diameter). A good rule of thumb would be to restrict the branch ducting to less than 600 fpm (3 m/s). An extended plenum design is the ultimate goal of the downstream duct design for ACB applications. The cross-sectional area required to achieve this design is not always available or possible due to restrictions in height and/or costing restraints. The duct optimization will remain a design issue tailored to each project.

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When zoning the ductwork, consider a duct ring around the glazed perimeter of buildings. In this way, the loads can be managed independently of one another. The perimeter ring may be equipped with a duct-mounted heating coil to address the skin losses that are not present within the core of the building. Increasing the primary air temperature to the exterior zone, via this offset during the heating season, allows the ACBs to yield the greatest heating output, without sacrificing internal cooling comfort capability. Although four-pipe ACBs are available, the aforementioned strategy typically requires less capital investment at the cost of individual room temperature control.

Manufacturers' data suggests that increasing the end-of-run operating static pressure from 0.4 in. w.c. to 1.0 in. w.c. (100 Pa to 250 Pa) will increase the active chilled beam capacity by more than 55%, at a fan brake horsepower penalty of only 14.1%.[‡] Typical operating static pressures range from 0.3 in. w.c. to 1.2 in. w.c. (75 Pa to 300 Pa) at the pressurization plenum of the beam. This trend would hold true with all active chilled beam manufacturers. While an exhaustive study is not included here, it is reasonably easy to make a case for higher beam plenum pressures as this strategy ultimately requires fewer beams to satisfy the sensible cooling load, and little in terms of a fan energy penalty. A slight increase in the cross-sectional area of the primary air ductwork also helps to mitigate any additional fan power, and could be accomplished with little premium in terms of material or labor. However, the additional static pressure at the beam plenum generally adds more sound pressure to the space. The effect is typically considered inconsequential.

Higher frequency acoustic content, which is typical of beams, generally dissipates quickly once the room attenuation effect is factored into the analysis. At 1 in. w.c. (250 Pa), the acoustic signature of a single active chilled beam in a typical room could be as low as 29.5 dBA,[§] assuming no other sound sources within the space, and no room attenuation effect. As a result, a small increase in system working pressures would seem to remain essentially innocuous from a perspective of a total systems impact. Supercharging beam applications by considering working static pressures between 0.75 in. w.c. to 1 in. w.c. (185 Pa to 250 Pa) is fundamentally a sound approach from an optimization perspective in terms of first costs. As the sound source for an active chilled beam is the nozzle, and since these sound sources are added logarithmically, once the acoustic signature of a single beam is known, with dozens of nozzles per beam, the acoustic signature of the space is also known (as it relates to the beam's contribution).

Sealant materials and workmanship become important issues with pressurized ductwork. However, smaller ducting typically servicing ACB systems is easier to leak test, particularly when leaks in the duct network are easily identified by a whistling

[‡]Primary air volume = 4,000 cfm (1887 L/s) at 2.4 in. w.c. (600 Pa) increased to 3.0 in. w.c. (750 Pa). Total sensible capacity increase provided by active chilled beam = 50%. Increase in fan bhp = 14.1%. 15 in. SISW AFPF, 9-blade, Arr.3., CLII.

[§]Acoustic sound pressure levels determined using selection program data from Twa Panel Systems, Inc. (MAC Beam software Ver. 11).

		Case A	Case B
Total Number of Active Chilled Beams		156	99
Total Primary Air Capacity	MBh (kW)	42.4 (12.4)	42.5 (12.5)
Total Secondary Air Capacity	MBh (kW)	33.1 (96.9)	32.5 (95.3)
Total Sensible Cooling Capacity	MBh (kW)	37.3 (109.4)	36.7 (107.8)
Total Airflow	cfm (L/s)	3,990 (1882)	4,001 (1887)
Total Water Flow	gpm (L/s)	207.5 (13.1)	131.7 (8.3)
Total Latent Cooling Available	Btu/h (kW)	28.9 (8.48)	29.0 (8.50)
Total Cooling Effect	Btu/h (kW)	40.2 (117.8)	39.6 (116.3)
Input Data/Beam	Module	2 ft by 6 ft	2 ft by 6 ft
Nominal Active Coil Length	ft (m)	6 ft (1.8)	6 ft (1.8)
Nozzle Type	A, B, C, D	A	A
Room Air Design Setpoint	°F (°C)	75.0 (23.9)	75.0 (23.9)
Room Relative Humidity	%	50.0	50.0
Supply (Primary) Airflow Rate	cfm (L/s)	25.6 (12.1)	40.4 (19.0)
Supply (Primary) Air Temperature (DB)	°F (°C)	65.0 (18.3)	65.0 (18.3)
Inlet Water Temperature	°F (°C)	57.0 (13.8)	57.0 (13.8)
Water Flow Rate (Min. = 0.5 gpm/Circuit)	gpm	1.33	1.33
Duct Connection Size		5 in. dia.	5 in. dia.
Calculated Data			
Supply (Primary) Air Capacity	Btu/h (W)	272 (79.7)	429 (126)
Water Capacity (Two-Row Cooling Coil)	Btu/h (W)	2,120 (621.3)	3,286 (963.1)
Total Sensible Capacity	Btu/h (W)	2,392 (701.1)	3,715 (1088)
Water Outlet Temperature	°F (°C)	60.2 (15.7)	61.9 (16.6)
Water Pressure Drop	ft w.c. (kPa)	4.0 (12.0)	4.0 (12.0)
Plenum Static Pressure	in. w.c. (Pa)	**0.40 (99.0)**	**1.00 (249)**
Sound Pressure Level	dBA	< 22	29.5
Sound Values (Excluding Room Attenuation)	NC	<18	25.5

Table 1: Comparing 0.4 in. w.c. and 1.0 in. w.c. working static pressures for active chilled beams.

noise generated at any breach in the seal. The goal in the downstream duct design is to efficiently deliver the pressure to the beam plenums through the use of low velocity ducting.

Beam Placement and Room Air Distribution

A high induction ratio provides discharge air normalization as it relates to discharge temperatures. As a result, a lower approach exists between the beam's discharge air temperature and the room air temperature. Consequently, the occupants can tolerate higher average room air velocities (30 fpm [0.15m/s]), and remain in compliance with ANSI/ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy,* for the design setpoints of 75°F (24°C) and higher, which is common criteria for ACB projects. Typical discharge temperatures from ACBs range between 64°F to 66°F (18°C to 19°C), and ultimately yield lower overall space temperature variations. Comfort levels are improved over conventional methods and occupant comfort complaints are reduced.

Care should be exercised when placing beam discharges parallel to the exterior glazing. During shoulder seasons in colder climates, cold surfaces of glazing with poor U-values could potentially accelerate the discharge air bathing these surfaces, and cause uncomfortable room air movement in the form of drafts. Consequently, ACBs that discharge perpendicular to the exterior glazing offer a more stable and comfortable thermal environment when coupled with superior glazing that allows such placement.[3] Radiant perimeter panels or baseboard radiation also could be used at the curtain wall in the absence of high performance glazing, or for ACBs that are placed parallel to the exterior glazing.

Due to the ease at which ACBs provide ventilation effectiveness to the space, beam placement becomes relatively easy. It is not uncommon to observe air turnover rates within the space of 10 to 20 times per hour. The room air mixing within the ACBs provides a more homogeneous temperature distribution, and a ventilation effectiveness of unity is common. Manufacturers typically publish guidelines for beam locations as they relate to minimum separation distances, minimum clearances from

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walls and other full height obstructions. Shading of the exterior of the building also helps minimize the radiant effect from the floor and curtain wall, and contribute to higher occupant comfort within the space.[4]

Installation

Hanging a beam from the structure is as easy as mounting a light fixture. However, due to their typical operating weight of approximately 15 lb/ft (6.8 kg/m) for 2 ft (600 mm) wide, double deflection units, ACBs cannot be supported by a T-bar ceiling as is possible with fluorescent fixture. ACBs provide four adjustable hanging brackets that can be fastened to the concrete underfloor via threaded rod or aircraft cable. Seismic locations may require additional bracing. To reduce on-site brazing work, quick-connect flexible hoses and duct connections can be considered, decreasing the overall labor component associated with each unit, and providing a level of flexibility in unit positioning. The piping system should always be thoroughly flushed prior to the final connection of the ACBs to the distribution network, to prevent coil tube contamination.

Water-Side Control

Chilled water temperatures for ACB loops range between 55°F to 61°F (12.7°C to 16.1°C) although the space design conditions and the minimum ventilation rates dictate that the beams receive 59°F to 61°F (15°C to 16.1°C) The separation between the secondary chilled water supply temperature, and both the dew point of the primary air and dew-point design of the space, is the technique used to prevent condensation on the beam-mounted cooling coil. Overventilating slightly or increasing the temperature separation also adds a margin of safety to preventing the formation of condensate. Two position on-off control valves are typically used to provide zone control. Modulating valves may result in creating laminar flow within the ACB cooling coils. As individual space temperature control can be achieved with two-position on-off valves, and yield an acceptable proportional control band, this method of capacity control is favored over modulating water control from a first-cost perspective. LEED® compliance is satisfied for individual room temperature controls, with relatively modest expense. Additionally, ventilation and the dehumidification it offers remains, even with the majority of the cooling effect disabled via the two position on-off control valve.

Three-way mixing valves, injection pump systems, and other strategies can be used to manage loop water temperatures by floor plate or zone. This would be of particular interest for buildings with mixed mode ventilation. Dew-point sensors within zones with operable windows should be used to reset or inhibit the chilled water servicing that zone, thereby affecting dew-point control, without losing control of the secondary water loop servicing the balance of a building. Once the windows are closed and dew-point control regained, the chilled water temperature could be lowered at the mixing station servicing each floor plate or building zone.

As the relative humidity within a building envelope could fluctuate as a result of only a certain number of floors using the operable windows, dew-point sensors within the building should be used to protect the envelope from a loss of dew-point control. There is a level of sophistication required by building owners using mixed mode ventilation, as educating the occupants in the risks of opening the windows with this type of system can create problems for the building environment. However, given the advantages of free cooling afforded in certain climates, and in an effort to achieve LEED compliance, perhaps motorized operable windows could provide a control solution that offers the best of both worlds?

Air-Side Control

Discharge air from the DOAS is used to dehumidify the space. It is often quite common to service the makeup air unit with 45°F (7.2°C) chilled water. As such, 51°F to 52°F (10.6°C to 11.1°C) dew-point temperatures supplied to the occupied zone are relatively easy to achieve in many areas of the country by slightly oversizing the evaporator coils. Coil face velocities under 400 fpm (2 m/s) increases the coil residence time and lowers the overall fan static pressure to further decrease system operating costs. Energy wheels and wraparound-style heat pipes also can be used to enhance the dehumidification effect in more humid climates. Please note, in a draw-through configuration, it would be common to experience a 2°F to 3°F (1.1°C to 1.7°C) temperature rise as a result of fan and motor heat pickup within the DOAS unit, resulting in a duct discharge temperature of 54°F to 55°F (12.2°C to 12.7°C). Although not always necessary, primary air tempering is best provided with an energy wheel, as boiler reheat is considered wasteful, and inappropriate, given this superior option. Additionally, for areas where the primary air requirements are high, there is a risk of over-cooling the space under conditions of low load. In such cases, there is a valid argument to consider using some type of tempering device to reclaim a portion of the sensible building heat that is exhausted, or consider a VAV control strategy as it relates to zones of highly variable latent loads. Tempered primary air could be delivered to the space in a more neutral condition such as 65°F to 68°F (18.3°C to 20°C) or reset to be cooler at design conditions.

As the duct distribution network is common to other beams in other zones, it is not practical to control the duct static pressure to affect control of each beam or beam zone without the use of VAV. Static pressure control is nonlinear and gives poor control resolution. VAV control allows one to deal with highly variable latent loads such as boardrooms, classrooms, cafeterias, lunchrooms, etc., and also provides tight temperature control for variable sensible loads. Since ACBs are driven by the ventilation air, further savings can be realized at the DOAS, by minimizing airflow to spaces that do not constantly require the ventilation rate at off-peak operating conditions, assuming that the building diversity can maintain the overall envelope in terms of dew-point control.

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Traditionally, the ventilation ductwork for a VAV system is sized for maximum cooling and minimum ventilation rates. The VAV damper controlling the airflow into the occupied zone for ACBs can be sized for the greatest of either the ventilation air or the air volume required to control the latent cooling requirements. As the duct velocities are too low to support traditional VAV damper control, a more effective and stable control methodology is required. The static pressure at the chilled beam plenum can be used as the velocity pressure input signal to modulate the position of the VAV valve for fan energy savings, and is particularly effective at managing highly variable latent loads. Care must be exercised to monitor the return air CO_2 levels to ensure that the space is not underventilated. Additionally, a dew-point sensor on the chilled water supply line is necessary to give priority control of the ventilation air in the event that the latent load exceeded the limits of the dehumidification effect offered via the primary air supply.

Night setback, chilled water, hot water, and primary air reset are all effective strategies in mitigating operational costs. These should be considered a fundamental aspect of building control, given their relatively low-cost-to-benefit ratio.

Maintenance

In a properly designed ACB project, the coil surfaces will not condense. The fins of the unit mounted coils will remain dry, and will not become tacky. Although not true for every space, maintenance vacuuming can be as infrequent as once every three to five years. Additionally, since the fin surfaces of an ACB are relatively well gapped, dust and dirt particles tend not to bridge the fin surfaces. ACBs equipped with rubber nozzles may need to be replaced as a result of dry rot within their service life. Maintenance is nearly a nonissue with active chilled beams and can be used to address a variety of challenging applications.

Summary

Although they are not the solution for every space within commercial and institutional buildings, the strengths of active chilled beams are becoming a more useful tool to handle challenging spaces in today's high performance buildings. The difficulty of meeting comfort requirements with a mechanical system that is exceedingly transparent is becoming easier thanks to the growing popularity of decoupled ventilation systems and active chilled beams.

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