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Designing Mega-AHUs

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The advent of fan arrays along with the increased cost competitiveness in the custom air-handling unit (AHU) market has given rise to a new air-handling unit design option: very large air-handling units, or mega-AHUs, designed for over 100,000 cfm (50 000 L/s). This month's column discusses the advantages and disadvantages of mega-AHUs vs. multiple floor-by-floor AHUs for high-rise buildings and reviews design considerations and options.

Industry Drivers

Fan Arrays

One of the most significant innovations in air-handling unit design is the concept of using an array of small single-width, single inlet direct-drive plenum fans (*Photo 1*) in lieu of the more conventional design that includes one or two large plenum or housed centrifugal fans. Fan arrays can be used for supply, return, and relief fan assemblies and they offer several significant advantages vs. conventional fan system designs:

- Reduced AHU length;
- Reduced sound power, especially on the discharge side;
- Improved redundancy;
- Reduced fan energy if sound attenuators or system effect are eliminated;
- Easier motor and fan replacement; and
- Easier to install in retrofit applications.

Disadvantages include higher (but ever falling) first costs and increased weight for the fan section. These are minor relative to the advantages.

Custom Air Handlers

Another significant change in the industry has been improved competitiveness of custom AHUs. Until recently, the cost premium for custom AHUs versus modular commercial AHUs was a factor of 5 or so. But improvements in manufacturing processes and lower labor rates in adjacent countries have caused the premium to be reduced to a factor of 1.5 or 2 from about 20,000 cfm (10 000 L/s) to 50,000 cfm (25 000 L/s). This premium can be offset by installation cost savings with the ability to make the AHU almost any desired dimension and aspect ratio and include any desired features. For AHUs above about 50,000 cfm (25 000 L/s), there is no cost premium for custom AHUs—this market sector is dominated by custom AHU manufacturers.

Mega-AHUs

The combination of fan arrays and affordable custom AHUs has also made it practical to design very large mega-AHUs. Our firm has designed several projects with AHUs in the 100,000 cfm (50 000 L/s) to 200,000 cfm (100 000 L/s) range serving large variable air volume (VAV) distribution systems. We have two high-rise office building projects in the design phase that have partially field-built VAV AHUs designed for 240,000 cfm (120 000 L/s) and 585,000 cfm (275 000 L/s), respectively.

Application Drivers

Air Economizers

One of the biggest drivers leading to mega-AHUs in large high-rise office buildings is that central AHUs can

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more easily and practically incorporate air economizers (aka airside economizers). This is of particular significance in very mild climates. For instance, in Oakland, Calif., an air economizer can meet the entire cooling load for about 50% of daytime operating hours and provide partial (integrated) operation for 95% of daytime operating hours, i.e., the economizer is disabled only 5% of daytime operating hours in a typical year. San Francisco weather is even milder at 55% and 97% operation, respectively. Therefore, cooling energy savings from air economizers can be substantial in these mild climates. With the additional indoor air quality improvement provided by air economizers,[1] incorporating economizers in our designs is a very high priority.

But economizers require a means to supply 100% outdoor air to each air handler and a means to relieve excess outdoor air to control building pressure. This can be very difficult for high-rise buildings if air handlers are provided on each floor. If outdoor air and relief is provided vertically in shafts, excess space is required for the shafts along with AHU mechanical rooms. Providing intake and relief horizontally to AHUs in center-core mechanical rooms is usually impractical because outdoor air and relief ducts are large and would compete for valuable ceiling space with other ductwork and utilities, not to mention the large louver areas required are seldom acceptable architecturally. For side-core mechanical rooms, air economizers are more feasible although sometimes not allowed by fire ratings that limit openings along property lines. This pushes AHUs to the roof where outdoor air and relief air openings are more easily accommodated, and for large buildings, that leads to the need for large AHUs.

Cost Savings

A major advantage of mega-AHUs is reduced first costs vs. multiple floor-by-floor AHUs. The installed cost of one large AHU will be less than multiple AHUs and chilled water distribution is usually a fraction of the cost since the chiller plant and mega-AHU can be located adjacent to each other. Control system costs are significantly lower because the cost of controls for each AHU is about the same regardless of AHU size. There are also significant savings from other trades, such as lower electrical, plumbing, and architectural (mechanical room) costs.

PHOTO 1 Large plenum fan array (Courtesy of Huntair, Inc.).

Space Savings

The overall area required for one large AHU will be less than that of multiple floor-by-floor AHUs in part because the latter has duplicated service and installation clearances. The difference in floor space required for shafts and mechanical rooms depends on how outdoor air is delivered to the floor-by-floor AHUs and whether they have air economizers. If all outdoor air and relief is delivered horizontally through side walls, e.g., for mechanical rooms in side-cores, the space required by floor-by-floor mechanical rooms will roughly equal the shaft area required for mega-AHUs at about 20 stories; below that, the floor-by-floor mechanical rooms will take up more space and above that, they will take up less space.* Some mega-AHU shaft space savings are possible by stepping back shafts at lower floors. For buildings taller than 20 to 30 stories, mega-AHUs may not be practical unless there are multiple mechanical room floors, e.g., one near the bottom with AHUs feeding up as well as one at the top with AHUs feeding down, or a floor in the middle of the building with AHUs feeding both up and down.

Maintenance Savings

Maintenance costs will be lower than for multiple floor-by-floor AHUs since there are fewer devices to maintain and they are all centralized and readily

*The issue of "rentable" vs. "usable" floor area always comes up when discussing mechanical room vs. shaft area required. BOMA Standard Methods of Measurement (ANSI/BOMA Z65.1-2017) designates mechanical room space as rentable, including central mechanical room space (e.g., the area used by the mega-AHU) as well as mechanical room space on each floor. But shaft area is not rentable. However, neither mechanical rooms nor shafts are usable space and sophisticated tenants will look at cost per usable area in lease negotiations, so the discussion is largely academic.

accessed. Mega-AHU system reliability is both better and worse than floor-by-floor AHUs; the system is much more resilient to a fan failure, which can cripple an entire floor with floor-by-floor AHUs, but has increased exposure to a single control system failure or cooling coil failure.

Design Considerations

Variable Speed Drives

Variable speed drive (VSD) options for fan arrays, listed in order of increasing costs, include:

1. One VSD for all fans (1X cost). This is seldom the best choice for mega-AHUs because it creates a single point of failure and thus does not take advantage of the inherent redundancy offered by the fan array. This option does not allow fan staging, discussed further below.
2. One VSD for every three to five fans, minimum two per AHU (1.3 to 1.5X cost). This is usually the best balance of cost and redundancy benefits. It can be used with and without backdraft devices on fans, discussed further below. With backdraft devices, this option allows fan staging, also discussed further below.
3. Redundant VSDs (2.2X cost). This option includes two full size VSDs with some hardware and programming that allows lead/standby changeover from one to the other on a scheduled basis for even wear and should the lead VSD fail. This option is usually only used for very critical applications that need to have full capacity available at all times, but need variable speed capability as well such that a bypass starter is not sufficient. This option does not allow fan staging, discussed further below.
4. One VSD per fan (2.5 to 3X cost). This option is the most expensive but offers the most robust redundancy. If backdraft dampers are provided, greater fan staging is also possible, discussed further below.

Option 2 is usually the best option for mega-AHUs because it offers redundancy at a reasonable cost and fan staging for more efficient low-load operation. The efficiency benefits of fan staging are discussed further below.

Another recent innovation is the "EC fan," a combination of a plenum fan and electrically commutated motor (ECM). ECMs are inherently variable speed and now available with the electronics to provide many of the same features as VSDs, such as a network connection to the building automation system. The availability of EC fans in the sizes required by mega-AHUs is currently limited but they could dominate the fan array market in the near future as ECM costs fall. Because each fan is variable speed, EC fans offer the same benefits as Option 4 above but at potentially lower costs.

Quantity of Fans

Increasing the number of fans in the array improves redundancy, reduces sound power levels, and it makes fans and motors smaller so they are more easily replaced. For mega-AHUs, limiting fans to about 7 hp† (5 kW) is recommended so that the motors are relatively easy to handle by mechanics and easily transported from the loading dock to the AHU. The reduction in sound power offered by more, smaller fans can allow sound attenuators to be eliminated, reducing space required and partially or fully offsetting the added fan cost; before adding sound attenuators, always look at adding more fans first.

Backdraft Devices

Even without backdraft devices at each fan in a fan array, the system will still provide partial capacity with a failed fan or VSD, especially on large arrays. For offices and other applications where full capacity is seldom required, manual blank-off plates can be provided; if a fan or VSD fails, building operators can temporarily install the plates at each failed fan inlet until the failed devices can be repaired. The plates can simply be stored on the floor of the fan inlet plenum until needed. While obviously not as robust as backdraft dampers, the plates are low cost, offered by all manufacturers, and have zero pressure drop. But where fan staging is desired (see discussion below) and in critical applications, automatic backdraft devices are required. Installing standard control dampers right at fan inlets is not recommended due to the resulting high pressure drop and fan system effects. A plenum would have to be created to separate the dampers from the fan inlets by 18 in. (450 mm) or so. Some manufacturers offer patented "near-zero pressure drop" backdraft dampers that take no additional space, but specifying them

†Fan arrays are usually composed of direct-drive fans that use non-standard motor sizes, so a typical fan motor might be 7 hp (5 kW) rather than 7.5 hp (5.6 kW).

reduces competition, possibly leading to higher first costs.

Partial Occupancy Operation and Fan Staging

One obvious concern with a mega-AHU is how well it can perform when the building is partially occupied, such as serving a single tenant that operates longer hours than others. ASHRAE/IES Standard 90.1-2016[2] includes a mandatory requirement to ensure efficient operation for large air handlers[‡] during partial occupancy:

> 6.4.3.3.4 *HVAC systems* serving zones that are intended to operate or be occupied nonsimultaneously shall be divided into isolation areas. Zones may be grouped into a single isolation area provided it does not exceed 25,000 ft^2 of *conditioned floor area* nor include more than one *floor*. Each isolation area shall be equipped with *isolation devices* capable of and configured to automatically shut off the supply of conditioned air and *outdoor air* to and exhaust air from the area. Each isolation area shall be controlled independently by a device meeting the requirements of Section 6.4.3.3.1. For central *systems* and plants, *controls* and devices shall be provided to allow stable *system* and *equipment* operation for any length of time while serving only the smallest isolation area served by the *system* or plant.

In modern buildings, zone isolation is provided by VAV box direct digital controls at no added cost other than programming. The required control sequences are outlined in proposed ASHRAE Guideline 36, *High Performance Sequence of Operation for HVAC Systems*,[3] where isolation areas are called Zone Groups. To meet Standard 90.1-2016, each floor of a high rise served by a mega-AHU would be its own Zone Group and must be capable of operating independently of other floors as if each floor had its own air handler.

Figure 1 shows the part-load performance of a large fan array with six VSDs each serving multiple fans with backdraft dampers. The curves include the impact of "good but not perfect"[§,4] static pressure setpoint reset[5] as well as the significant drop in VSD and motor efficiency at low loads.[6] The green curve showing the performance with all six fans running tapers off below about 30% of design airflow due to very low VSD/motor efficiency at low loads. The curve is shown to stop at about 20% of design flow because the imperfect static pressure setpoint reset causes the fans to enter the surge region at that point. The other curves in *Figure 1* show that as VSDs are staged off, fan energy and minimum flow before surge continue to fall. With one VSD operating at about 10% speed,[#] the system can operate stably and efficiently at less than 2% of AHU design flow and less than 1% of design power.

Figure 1 demonstrates that for an air handler serving Zone Groups requiring no less than about 30% of the total AHU capacity, there is little value to fan staging. But for mega-AHUs, which almost surely will have to serve small Zone Groups at times, the energy savings offered by fan staging can be substantial.

Figure 1 also demonstrates a perhaps counterintuitive point: a mega-AHU can have lower fan energy than a floor-by-floor air-handling system when serving only a few floors. For instance, if half the floors of the building were occupied, the mega-AHU will use about 40% of the fan power of floor-by-floor AHUs.[II] This is because the pressure drop through the common elements of the AHU (coils, filters, riser, etc.) falls as the square of the flow. With fan staging, even when serving a small Zone Group, such as one floor of a 20-story building, the fan energy required for a mega-AHU will be about the same as that of a single AHU of a floor-by-floor AHU system.

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‡This mandatory requirement applies to large dedicated outdoor air system (DOAS) units as well, an often-overlooked requirement that necessitates the use of pressure independent controls at ventilation zones.

§"Perfect" static pressure setpoint reset means at zero flow, zero static pressure would be required. "Good" reset assumes at zero flow, 0.5 in. w.g. (125 Pa) is required. This is more representative of real systems. The detailed curve fits are developed in Reference 4.

#Yes, VSDs and motors can run at 10% speed indefinitely without damage. Most or all VFD-ready motors list 10-to-1 minimum turndown; some are 20-to-1. There is an unfortunate old wives' tale in the industry that motors will fail at low speeds. That is not the case for fans and pumps because motor power (and motor losses) fall roughly as the cube of the speed. The energy impact of operating VAV fans at less than about 30% speed is small, but low speeds prevent excess duct pressures at low loads and they either eliminate fan operation in surge or reduce the noise and vibration caused by surge to negligible levels.

IIThis assumes full load fan power per cfm (L/s) is about the same for the mega-AHU and floor-by-floor AHU. Whether this is true or not depends on the details of each design. For instance, floor-by-floor AHUs often require sound attenuators due to their proximity to occupied spaces and usually include smaller fans that have lower efficiency. On the other hand, central AHUs will have the added pressure drop of the duct riser and fire/smoke dampers, but large risers tend to have low friction rates due to velocity limits often imposed for acoustical reasons. Accordingly, in the author's experience, fan power per unit flow tends to be about the same in both applications.

Minimum Outdoor Air Control

Control of minimum outdoor air is a challenge with mega-AHUs because of the wide range of minimum outdoor air setpoints possible when serving small Zone Groups. If a single outdoor air damper and outdoor airflow measuring station (OAFMS) bank were used, the velocity would be too low to accurately measure when serving a small Zone Group. The solution is to break the economizer dampers and OAFMS into multiple stages, usually of unequal sizes so the smallest stage is small enough for the OAFMS to be able to accurately measure the minimum outdoor air setpoint of the smallest Zone Group. Using an OAFMS that can measure low velocities (e.g., 150 fpm [0.762 m/s]) can minimize the number of stages required. The control system then enables the stages based on the ability of the active AFMS being able to measure the current minimum outdoor airflow setpoint. Usually, only the two smallest stages require OAFMS; the other stages are used only when the economizer is enabled and minimum outdoor air control is not an issue. For control stability and improved mixing, return air dampers should also be staged. *Figure 2* is a control schematic of a mega-AHU with three stages of

FIGURE 1 Part-load curves with fan staging.

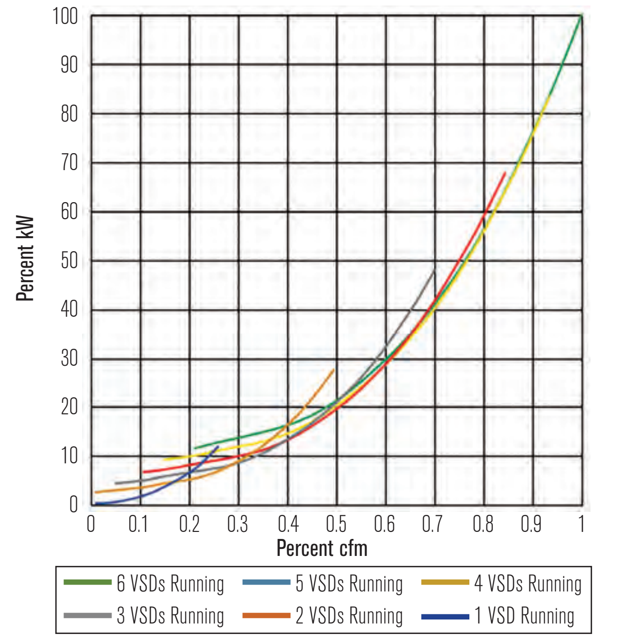
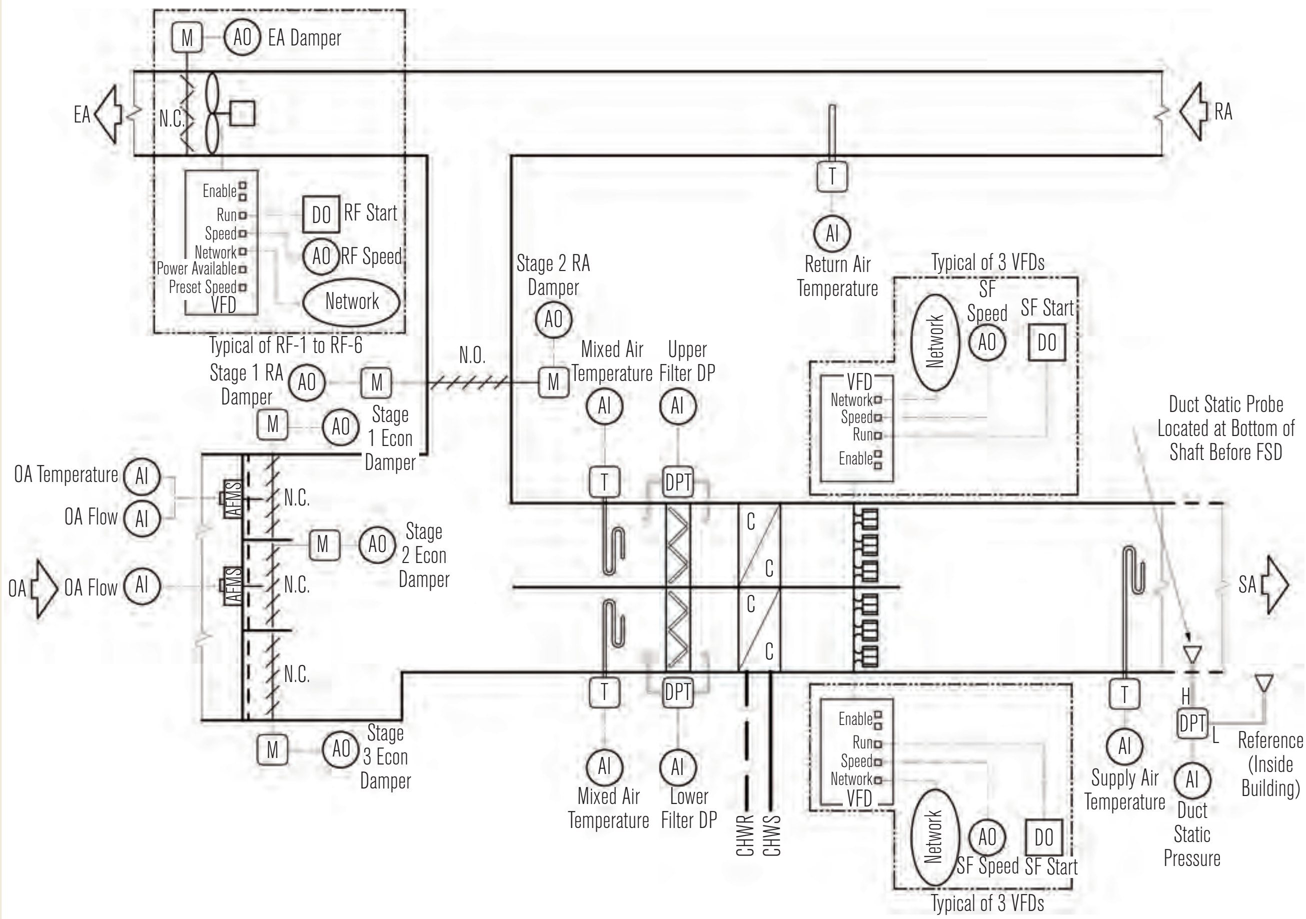


FIGURE 2 Mega-AHU control schematic. Note that life safety smoke controls are not shown.



outdoor air damper control, two with OAFMS, and two stages of return air damper control.

Mixing Plenum Design

The economizer mixing plenum of large AHUs is commensurately large so adequate mixing of outdoor air and return air can be a concern in two cases:

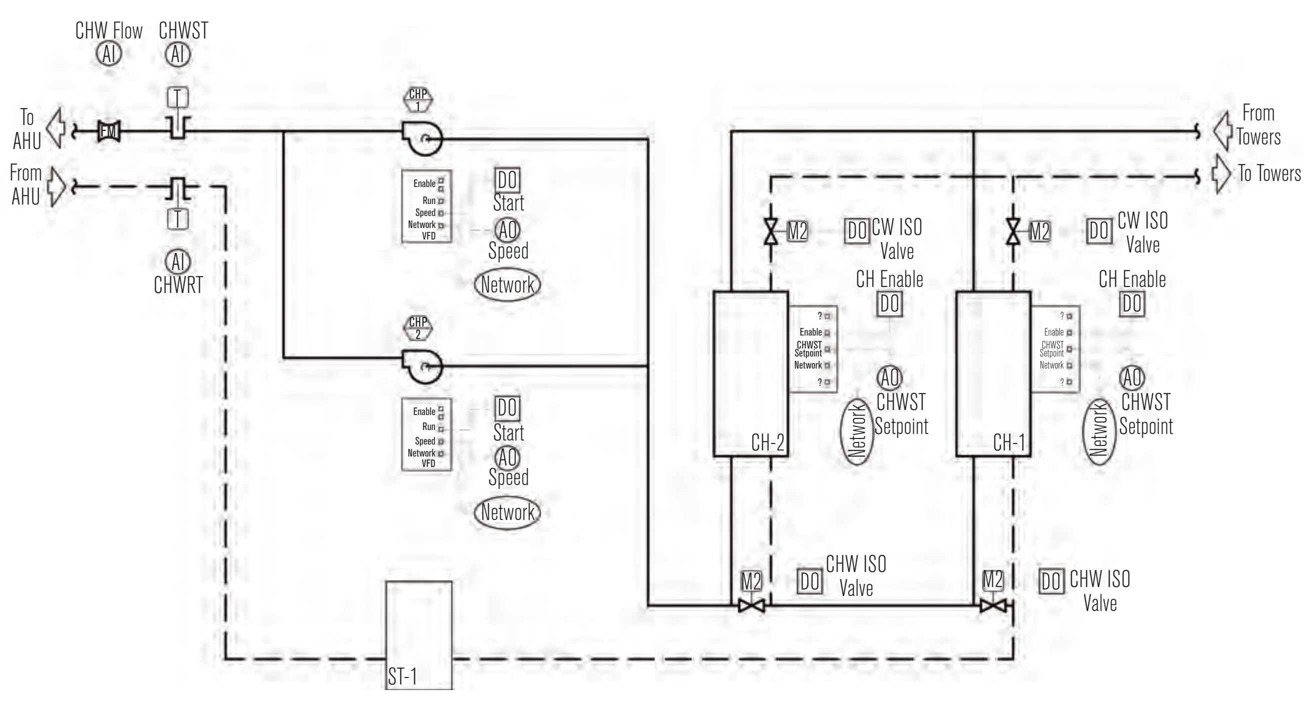
- In any climate where coil freezing is possible; and
- If the AHU has more than one supply air discharge duct such that imperfect mixing can cause supply air ducts to supply air at different temperatures when operating on economizer.

One mitigation is to place the lowest stage outdoor air damper and OAFMS adjacent to the return air dampers and orient the damper blades to direct outdoor air and return air into each other to encourage mixing. This has proven to be adequate in mild climates, but in colder climates, better mixing may be needed. Because of the very large size of the mixing plenum, air blenders may not be effective. Instead, consider installing propeller fans inside the mixed air plenum to stir the air before it enters the filter bank. A computational fluid dynamics analysis may be used to properly design and orient the mixing fans.

Building Pressure Control

In the mild climates, the impact of stack effect on building pressure control is small so controlling relief/return fans using a single building pressure control point is usually effective. Building pressure can range from slightly negative to as high as 0.1 in. w.c. (25 Pa) at exit doors to ensure door closers work without excessive door-opening forces. The pressure can be even higher at upper floors until airflow through stair and elevator doors becomes an issue with whistling noises and door jamming. Using automatic smoke dampers at elevator shaft vents, or eliminating the vents entirely where allowed by code, minimizes these issues and allows even higher pressures near the top of the building, making a single pressure control point near the bottom of the building feasible.

FIGURE 3 Chiller plant control schematic.



Where finer control is required in colder climates due to stack effect, the return air floor fire/smoke dampers (FSDs) at each floor can be used to modulate return airflow based on floor pressure. This requires a modulating actuator, an option available from almost all FSD manufacturers. Damper actuator wiring must be such that the fire alarm system control takes priority over the building pressure controls. The relief/return fan system is then controlled to maintain a negative return air shaft pressure with setpoint reset to maintain at least one return air FSD wide open. Controlling the FSDs in this manner also isolates unoccupied floors during partial building occupancy.

Chiller Plant Design

Mega-AHUs usually are the only AHU in the building. This allows for a unique chilled water plant design that has no control valves; the AHU supply air temperature is controlled primarily by resetting chilled water supply temperature along with changing coil flow with chilled water pump variable speed drives. The chillers also can be readily piped in series as shown in *Figure 3*. To maximize the efficiency and minimize the cost of series-piping, coils should be selected for a large ΔT, such as 25°F (14°C), using 8-row coils.[7] The design is extremely energy efficient because chiller lift, and thus chiller power consumption, is minimized, and chilled water pump energy is very low due to the close-coupled plant and coils (low piping pressure drop), high ΔT (low flow rate), and the elimination of control valves (eliminating about 10 ft (3 m) of pressure drop). The design also maintains higher flow through the chilled water coil for more uniform supply air temperature leaving the coil.

Downsides

Potential downsides with mega-AHUs include:

Warmup inefficiency with nonuniform start times. As shown in *Figure 1*, mega-AHUs have very low fan energy use when serving small Zone Groups. But if one or more tenants has an early start time, or operates 24/7, there can be an increase in warmup energy use for single duct VAV reheat systems. Once any Zone Group is in occupied mode, the AHU supply air temperature must be controlled for comfort cooling. Thus when other Zone Groups operate in morning warmup mode, they must reheat this cool supply air temperature, increasing heating energy use compared to typical warmup scenario where the AHU supplies 100% recirculated air. This issue only occurs with single-duct VAV reheat systems; systems with separate heating fans, such as dual fan/dual duct systems or fan-powered mixing box systems, will not see any increase in warmup energy use.

More susceptible to "rogue zone" inefficiencies. "Rogue zones"[8] are zones that are undersized or have other issues that cause them to require design duct static pressure or design supply air temperature most or all of the time. This will "peg" reset strategies, causing higher energy use, particularly fan energy (see Reference 5). The solution is to identify rogue zones (which can be done automatically as discussed in References 3 and 8) and fix them. Rogue zones are possible with floor-by-floor systems as well, but they only affect the associated AHU, not the entire building.

Conclusion

Compared to floor-by-floor AHUs in high-rise buildings, mega-AHUs are less expensive, require less space, have lower maintenance costs, and generally are more energy efficient. However, mega-AHUs require additional attention to design details not typically required with smaller AHUs, and efficiency benefits can be negated by excessive warmup energy with single duct VAV systems if some tenants operate with early start times relative to others, or if rogue zones cause duct static pressure and supply air temperature reset strategies to be ineffective.

References

1. Fisk, W., O. Seppanen, D. Faulker, J. Huang. 2003. *Economizer System Cost Effectiveness: Accounting for The Influence of Ventilation Rate on Sick Leave*. Lawrence Berkeley National Laboratory, Report Number: LBNL-53192.
2. ASHRAE/IES Standard 90.1-2016, *Energy Standard for Buildings Except Low-Rise Residential Buildings.*
3. ASHRAE Guideline 36-2018, *High Performance Sequences of Operation for HVAC Systems*. Forthcoming.
4. EDR. 2007. Advanced Variable Air Volume Design Guide. Energy Design Resources.
5. Taylor, S. 2007. "VAV system static pressure setpoint reset." *ASHRAE Journal* (6).
6. Gao, X., S.A. McInerny, S.P. Kavanaugh. 2001. "Efficiencies of an 11.2 kW variable speed motor and drive." *ASHRAE Transactions*.
7. Taylor, S. 2011. "Optimizing design & control of chilled water plants part 3 pipe sizing and optimizing delta *T*." *ASHRAE Journal* (12).
8. Taylor, S. 2015. "Resetting setpoints using trim & respond logic." *ASHRAE Journal* (11). ■