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4-Pipe VAV vs. Active Chilled Beams for Labs

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Variable air volume (VAV) laboratory HVAC systems, including VAV fume hoods, are now standard practice and dramatically improve energy efficiency compared to the constant volume systems they replaced. To further improve efficiency, modern laboratory HVAC designs focus on two primary goals: minimizing the energy used to condition outdoor air and minimizing terminal unit reheat energy. In this regard, several guides and articles[1–5] encourage using active chilled beams (ACB) in lab zones. But ACBs have many disadvantages both from a cost and efficiency perspective. This month's column discusses an alternative design, 4-pipe VAV (4PVAV) systems, which cost less and are usually more efficient.

The 4PVAV system is not a new concept. It has been used in many labs and is discussed in the Labs21 Best Practice Guide *Minimizing Reheat Energy Use in Laboratories* referenced above, where the system is called "ZC" for zone cooling coils. But the design has been losing favor relative to ACBs in the literature and in many recent high performing labs. In humid climates, where active dehumidification is typically necessary with all HVAC systems, and in predominantly load-dominated labs, a well-designed and controlled ACB system may have better energy efficiency. But that is not the case for ventilation- and hood-dominated labs and not the case in mild, dry climates. Furthermore, because of the need to prevent condensation on the chilled beams, ACB systems are more complicated with respect to optimized control logic. These issues are discussed in more detail below.

Lab Types

Labs can generally be broken into three categories:

- Ventilation-dominated, labs where the minimum air changes per hour (ACH) required for safe dilution of lab process emissions is greater than hood exhaust rates and rates required by the cooling load;
- Hood-dominated, labs where the hood exhaust rate exceeds that required by the cooling load or minimum ventilation; and
- Load-dominated, labs where the airflow needed by the cooling load exceeds the hood exhaust and minimum ventilation rates.

Labs may operate in all three categories at different times. For instance:

- When ventilation requirements are reduced from

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FIGURE 1 UC Davis lab plug loads. (From Labs21 Minimizing Reheat Energy Use in Laboratories. The upper and lower ends of the lines represent maximum and minimum. The upper and lower ends of the boxes represent 99th and 1st percentiles of the measurements.)

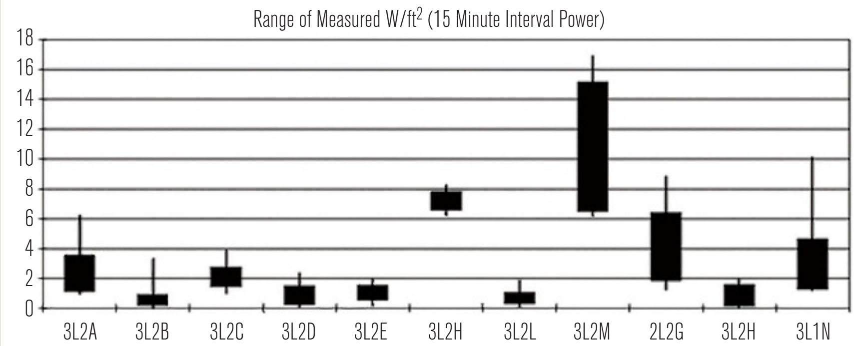


TABLE 1 Equivalence of ACH to plug loads assuming a 9 ft (2.7 m) ceiling and 55°F (13°C) supply air temperature, 75°F (24°C) space temperature (not including loads from envelope, lighting, and people).

ACH	LOADS W/FT^2
2	1.9
4	3.9
6	5.8
8	7.7
10	9.7
12	11.6
14	13.5

high occupied rates (e.g., 6 to 8 ACH) to lower unoccupied rates (e.g., 2 to 4 ACH), a ventilation-dominated lab could become load-dominated.

- When hoods are not in use and their sashes are closed, a hood-dominated lab could become ventilation- or load-dominated.
- As cooling loads fall due to reductions in internal and envelope loads, a load-dominated lab could become ventilation-dominated.

Only zones that are load-dominated benefit from active chilled beams. In these labs, the use of ACBs reduces outdoor airflow rates because the induction effect of the ACBs increases cooling capacity vs. supplying primary outdoor air alone. The design and energy impacts are discussed further below.

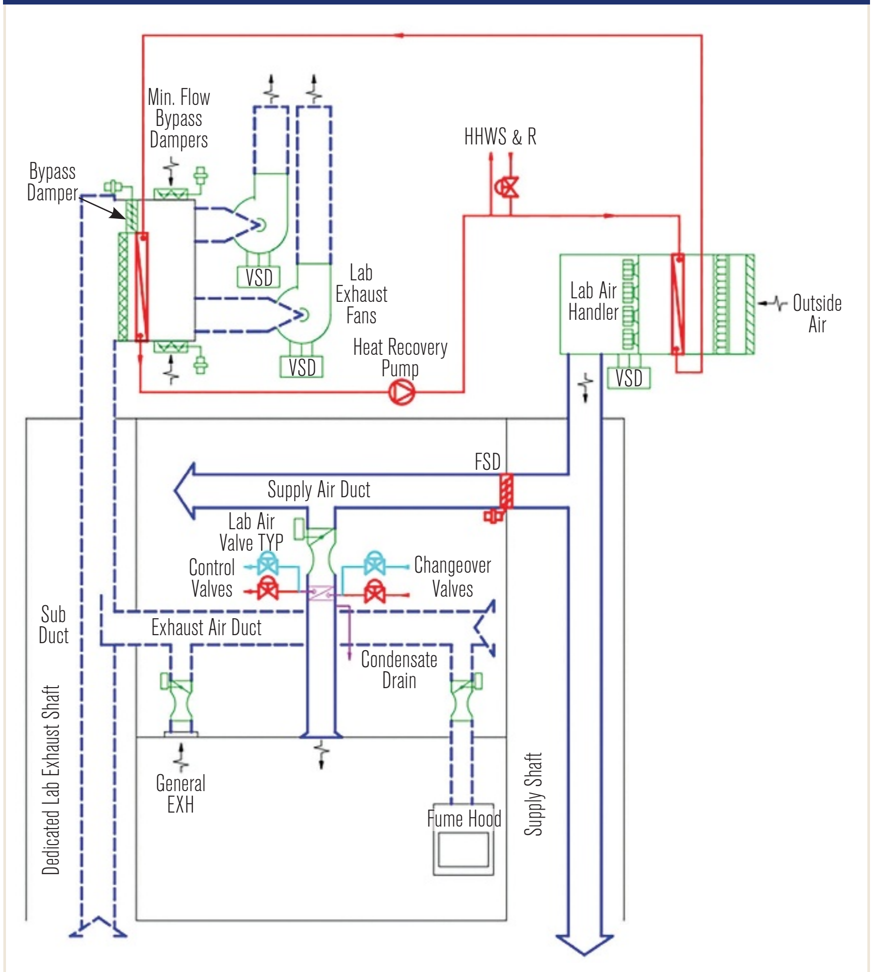
So how prevalent are load-dominated labs? The answer varies significantly from lab to lab but, in the author's experience, seldom are loads as high as those lab users and lab consultants claim them to be. *Figure 1* shows an example from one university lab. Not including loads from envelope, lighting, and people, the peak airflow required to meet these loads is mostly less than 4 ACH (*Table 1*). If 6 ACH (corresponding to 5.8 W/ft^2 [62 W/m^2]) is the minimum required for ventilation, only three labs operate predominantly as load-dominated, and thus might benefit from ACBs. The majority of labs in this example are ventilation-dominated during almost all operating hours. (Some may be hood-dominated as well—data on hood rates from this study are not known.) Loads tend to be particularly low in typical university and high school labs.

System Schematics

The 4PVAV option is shown in *Figure 2*. Comments on design details:

- The 4-pipe changeover coils (discussed in August 2017 Engineer's Notebook column[6]) at each zone are shown to have four 2-way valves but for simplicity and reduced costs, 6-way valves would be used in all except very large zones where 6-way valves are not currently available.
- A run-around exhaust energy recovery system is shown, although not usually part of our lab designs in coastal California. There are many operational concerns with these systems, such as how to change filters upstream of the exhaust coil given possible contamination, but energy recovery is encouraged by Labs21[7] and cost effective in many climates. However, we do not use energy recovery in coastal California (ASHRAE Zone 3c) because it is not cost effective based on studies performed for the California Energy Commission,[8] which found it to have a *negative* net energy savings because the added fan energy due to the pressure drop of added coils and filter on the exhaust fan side offsets the heating and cooling savings due to the mild climate. Accordingly, energy recovery is not a requirement in either ASHRAE/IES Standard 90.1[9] and California's Title 24[10] for labs (or any other occupancy type) in this climate zone.
- Note that the run-around heat recovery piping is shown with a hot water connection and there is no separate HW coil in the air handling unit (AHU)—one coil does both duties. This also allows the HW system makeup water and expansion tank to serve the heat recovery loop as well, further reducing first costs. While heat recovery alone generally provides warm enough supply air in cold weather, the HW connection can also provide emergency heating in case the exhaust heat recovery coil is inoperative. If heat recovery

FIGURE 2 4-pipe VAV system.



is not provided, this coil would be a standard HW coil for preheat. It can be deleted entirely in climates, such as San Francisco's, where outdoor air temperatures seldom fall below ~40°F (4.4°C).

- There is no cooling coil at the AHU. This is only possible in relatively dry* climates, such as those on the western and southwestern United States. In ventilation- and hood-dominated labs, the supply air temperature to the space needed to handle cooling loads can be as high as 70°F [21°C], resulting in no dehumidification and high space humidity if outdoor air humidity is high.
- The CHW supply temperature for this system generally uses standard temperatures, e.g., 42°F to 45°F [5.6°C to 7.2 °C] in order to handle the cooling load of load-dominated labs. This necessitates a condensate pan and drain at the coil assembly.
- Only lab zones are shown in the schematic. Most labs also include office areas, which can be served by the same AHU, separate AHUs, or hybrid AHUs that include a common mixed air plenum as described in reference *1*. The latter option is the most efficient.
- Also not shown in *Figure 2* is supplemental recirculating cooling-only fan-coils that would be provided in labs with very high load densities, such as lab 3L2M in *Figure 1*. These are often DX or variable-refrigerant-flow fan-coils since the chiller plant does not run in cold weather and these fan-coils may need to in order to meet loads. Note that all load-dominated labs could be provided with fan-coils so that they no longer were load-dominated from the perspective of the outdoor air system, but this adds to first costs and it can increase energy costs since the fan-coils would have to run in cold weather (more discussion on energy impacts below.)

Sizing the outdoor air system for the loads in load-dominated labs also improves flexibility – hoods could be added to the lab in the future with nothing more than setpoint changes to the outdoor air supply system.

The ACB system is shown in *Figure 3*. It is almost identical to the 4PVAV system with these exceptions:

1. Instead of a HW/CHW coil downstream of the supply air valve for the 4PVAV system, this system uses active chilled beams. ACBs are low pressure induction units, in this case with a single coil used for both heating and cooling. The same change-over valve assembly that is used in the 4PVAV system can also be used with ACBs.
2. The CHW supply to the ACBs must be tempered water, e.g., 55°F to 58°F [12.8°C to 14.4°C] supply temperature (vs. 42°F to 45°F [5.6°C to 7.2°C] for the 4PVAV

* "Dry climates" in this context are those where high humidity levels, above about 63°F (17°C) corresponding to 75°F (24°C) and 65% RH, are not sustained for many hours or days consecutively. Microbial growth will not generally be sustained unless high humidity levels are sustained.

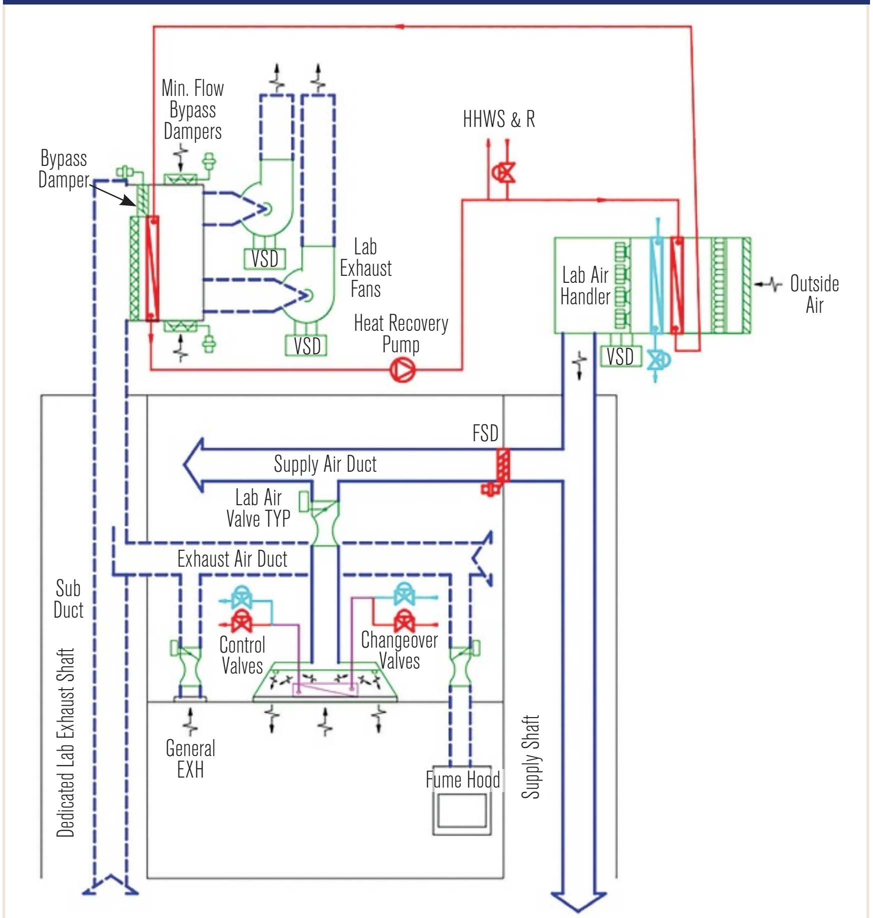
system) to ensure that condensation does not occur on the chilled beam surfaces. Using tempered water eliminates the need for condensate drains and also can improve chiller efficiency as discussed below.

3. A cooling coil must be provided at the AHU to dehumidify outdoor air, again to prevent condensation on chilled beams. The cooling source for this coil should be separate from that serving the ACBs, e.g., a separate DX system or a dual temperature plant,[11] in order for the tempered water required by the ACBs to improve chiller efficiency. This is discussed further below.

4. The size of the AHU and ductwork serving the ACBs will be smaller than that for the 4PVAV system because the supply air needed for load-dominated labs is lower. A typical ACB at typical design conditions[†] can deliver about 2.5 times the sensible load that primary outdoor air can provide alone. So a lab that requires from 6 ACH (a typical occupied minimum for ventilation) up to 15 ACH of supply air from the 4PVAV system to meet cooling loads would require only 6 ACH with the ACB system. This reduction in the outdoor air rate is the key "selling point" of the ACB system in the literature. The significance of this reduction on costs and space requirements depends on the size and quantity of load-dominated labs.

5. The ACB system in *Figure 3* suggests that all labs have ACBs. But ACBs are very expensive and offer no value to ventilation-dominated and hood-dominated labs, and it is sometimes impossible to use them in hood-dominated labs because there is not enough ceiling space to house all of the ACBs. So non-load-dominated labs are often served instead by 4-pipe terminal units and standard diffusers, just like the 4PVAV system. The capacity of the terminal in an ACB system is less than the typical 4PVAV system because the available tempered CHW results in warmer supply air temperature, so the terminal may have to be upsized somewhat for some zones.

FIGURE 3 ACB system.



Example Energy Comparison

An EnergyPlus model was created for a lab in Oakland, CA to compare the 4PVAV and ACB systems. The systems are as shown in *Figure 2* and *Figure 3* except there is no heat recovery system. Minimum ventilation during occupied periods was 6 ACH, while 4 ACH was maintained during unoccupied hours. Both systems include air-to-water heat pumps to provide both hot water and chilled water. They are not the heat recovery type because the 4PVAV system has no hours where there is simultaneous heating and cooling, and, if well controlled as discussed below, the ACB system has few hours, not enough to justify the added expense. Since the cooling system is air-cooled, there is no waterside economizer on the ACB system. Labs were a mixture of ventilation-dominated and load-dominated to varying

† Room temperature 75°F/50%, primary supply air 57°F, 58°F CHW supply temperature for the ACB system vs. 55°F supply air temperature for the 4PVAV system.

degrees; none were hood dominated, an assumption that favors the ACB system in any comparison.

One of the complexities of ACBs is how to control the AHU supply air temperature. If it is too warm, supply air dew point will be too high and condensation will occur on the chilled beams. If it is too cold, cooling and reheat energy significantly increase. Many designers simply supply outdoor air at the tempered CHWS temperature, or a few degrees lower for safety, but that is overly conservative and significantly increases energy use. The ideal control logic is to reset supply air temperature as required to ensure condensation just barely occurs on the CHW supply piping to each zone. Pipe-mounted condensation sensors are available that can detect a microscopic deposit of condensate, then close a contact that can be used as an input to the control system to reset the AHU supply air temperature setpoint (e.g., using Trim & Respond logic[12]). Sensors should be provided in each lab since there are often local moisture producing activities, such as boiling liquids and Bunsen burner use.

Unfortunately, the ideal logic cannot be modeled with EnergyPlus without significant additional work developing control plug-ins. So we modeled four supply air temperatures: 55°F, 58°F, 60°F, and 65°F [12.8°C, 14.4°C, 15.6°C, and 18.3°C]. The actual performance will be somewhere in between these extremes. Performance cannot be as good as the 65°F [18.3°C] model since that will result in condensation at times, even in Oakland's mild weather. But it could be close with an aggressive reset strategy based on condensation sensors.

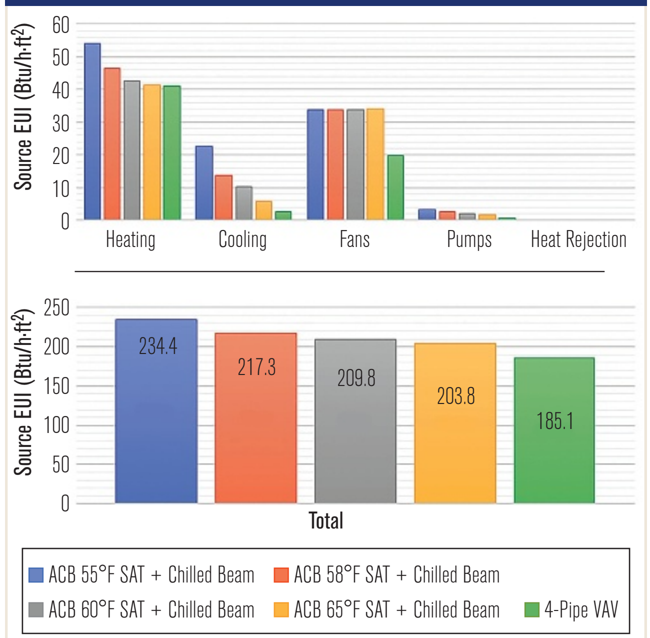
The 4PVAV system in this case has only a heating coil at the air handler—all cooling is done at the zone level—so the system is not sensitive to AHU supply air temperature setpoint. The supply air temperature setpoint may be simply fixed at the design cooling supply air temperature, 55°F [12.8°C] in this case.

Estimated loads from the EnergyPlus model are shown in *Table 2*. The 4PVAV system has the highest AHU airflow rate, as expected, but the lowest cooling loads. Higher cooling loads for the ACB system are due to the overcooling of supply air by the ACB AHU for ventilation-dominated zones; even at design cooling conditions, these zones require reheat with the ACB system. Because all cooling is at the zone level with the 4PVAV system, there is no reheat and no overcooling.

TABLE 2 EnergyPlus equipment loads.

	ACB 55°F SAT	ACB 58°F SAT	ACB 60°F SAT	ACB 65°F SAT	4-PIPE VAV
AHU (cfm)	39,402	39,402	39,402	39,402	61,492
HP/Chillers (tons)	196	185	178	162	105

FIGURE 4 Energy model results: source energy use intensity.



Results for source Energy Use Index are shown in *Figure 4*. Note that EUI is based on source energy, not site energy.

Energy costs for each option are shown in *Figure 5*.

The results show that a 4PVAV system outperforms the ACB options, even at its most optimistic 65°F supply air temperature setpoint. The reasons are as follows:

1. Heating energy is lowest for 4PVAV since there is literally no reheat with this design. In load-dominated labs, heating costs are greater than for chilled beam systems because of the higher outdoor air rate that must be conditioned. But the opposite is true for ventilation-dominated zone where the need for dehumidification with the ACB system significantly increases reheat energy.

2. Cooling energy is lowest for the 4PVAV system since it benefits from higher outdoor air rates in cool and mild weather due to the economizer effect of supplying cool outdoor air. The chilled beam systems in load-dominated labs have no economizer so mechanical cooling

must operate even at low outdoor air temperatures, often inefficiently because of the low loads. It is possible for chilled beam systems to at least partially offset the lack of an economizer by improved chiller efficiency due to the chiller producing warmer water, e.g., 58°F vs. 45°F [14.4°C vs. 7.2°C]. But the chillers in this model all produce 45°F [7.2°C] water and the 58°F [14.4°C] water for the ACBs is produced by blending supply water with return water. This is a common design because it is flexible and inexpensive, and for buildings connected to a campus chilled water plant, it is the only option. In order to achieve any chiller savings, the chiller plant would need to be modified to be dual temperature (e.g., one chiller plant producing 45°F [7.2°C] for the AHU while the other produces 58°F [14.4°C] for the ACBs) or a separate DX system could be used for the AHU. Both options add complexity and increase first costs, and probably are not justified in Oakland's mild climate (chiller plant energy is relatively small as shown in *Figure 5*). A water-side economizer also should be provided to reduce cool weather chiller operation, but that also increases first costs, especially for an air-cooled chiller plant such as this one.

FIGURE 5 Energy model results: energy cost index.

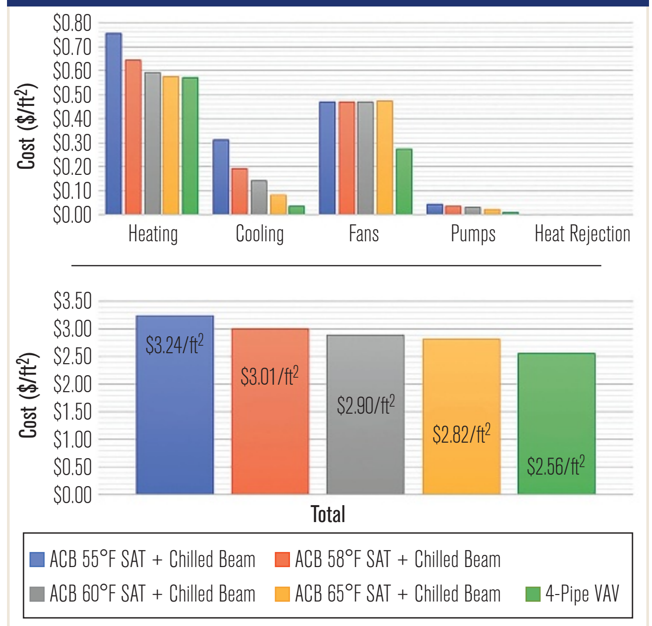
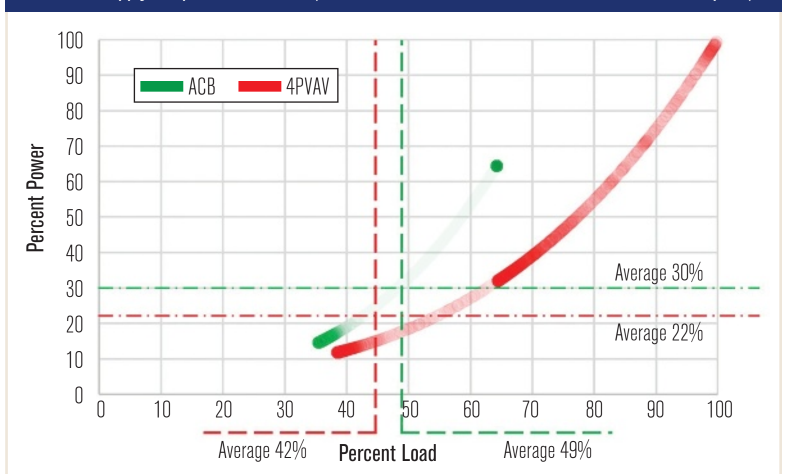


FIGURE 6 Supply fan power vs. airflow (the color darkness indicates number of hours at each point).



3. Fan energy is significantly lower for the 4PVAV system compared to the chilled beam options because of "cube law" performance of fans at part load. This may be counterintuitive but it is what we find on all DOAS vs. VAV comparisons (see Stein and Taylor[13]). The VAV system has larger ducts, filters, coils etc. due to high peak loads but operates most of the time at part load where variable speed drives reduce energy use almost cubically. The ACB AHU system is smaller but it supplies outdoor air at rates closer to the design rate, thus using closer to design fan power as shown in *Figure 6*. In this case, the lab exhaust fan exhibits similar performance because the exhaust stack design required a low minimum airflow rate; the exhaust fan savings will be smaller as the stack airflow minimum rises.

4. Pump energy is small for all options, but lowest for 4PVAV option because of the higher HW Δ*T* (~80°F [44°C]) and CHW Δ*T* (~25°F [14°C]) that is possible using large coils (4 to 6-row at zones) with 100% outdoor air. ACBs generally result in very low ΔTs, ~10°F [5.6°C] for CHW and ~40°F [22°C] for HW, due to the smaller coils and lower difference between entering air temperature and CHW/HW supply temperature.

In summary, the 4PVAV is at least 10% efficient more efficient than ACBs in this example building. It would be even more efficient comparatively if hood-dominated labs were modeled.

Other Factors

In addition to being more efficient, the 4PVAV system has other advantages over ACBs:

- First costs are lower due primarily to the very high cost of the ACBs and their installation, including the very high quantity of piping connections. These costs more than offset the cost of larger AHUs, larger ductwork, and terminal unit condensate drain piping.

- The ACB system is only effective in load-dominated labs and cannot be used on some hood-dominated labs due to insufficient ceiling space to house the ACBs.
- The 4PVAV system allows hoods to be added in the future to load-dominated labs without any modifications to the outdoor air supply system other than setpoint changes.
- Because of the large area of ACBs required in most labs, ACBs can result in air being supplied near hoods which can cause turbulence and impact hood performance.
- ACBs are less flexible to future lab reconfigurations (very common among commercial labs) given the many hard-piped connections to the ACBs. 4PVAV diffusers are more readily relocated.
- Control systems for ACBs can be complex in order to maximize efficiency without causing condensation on ACB surfaces.

However, the ACB systems has these advantages over 4PVAV:

- ACBs require less space for AHUs and duct mains, and this can be a significant advantage where labs are predominantly load-dominated. It may be possible to reduce floor-to-floor height with ACB systems, but that varies with how ducts are sized and how air is distributed, e.g., quantity of shafts. See Reference 13 for more discussion.
- ACBs eliminate the need for condensate drains at terminal units and associated piping. These drains can be problematic and require regular maintenance.

Conclusions

The 4-pipe VAV system is a proven alternative to active chilled beams in laboratories. It is usually more efficient, especially in mild, dry climates, and usually less expensive. It is also much more flexible because it can be used for all lab types, load-dominated, ventilation-dominated, and hood-dominated, and control systems are simpler. On the other hand, ACB systems have smaller space requirements, which may be a key driver on some projects, and they do not require terminal unit condensate drains.

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