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VAV System Optimization
Critical Zone Reset

Variable air volume (VAV) systems are very popular in many modern buildings. One important benefit that VAV systems offer is low operating cost at part-load conditions. In a VAV system, air volume delivery rate varies directly with the cooling or heating load. Less air is needed at part-load conditions, so less fan horsepower is required. Mechanical cooling requirements also vary directly with the cooling load.

The key to maximizing part-load horsepower savings is proper control of fan capacity and mechanical cooling capacity. How can a VAV system be controlled to maximize part-load energy savings without sacrificing zone comfort? Is there a way to optimize fan capacity and cooling capacity, and at the same time, make the VAV system more reliable, easier to design and install, without adding cost? Let's find out.

A Simple VAV System

Let's start with a very simple cooling system as we try to answer these questions. An elementary VAV air delivery system with only a single zone is shown in Figure 1. Although unrealistic, this simple system serves to illustrate VAV system operation. Air from the occupied zone enters the return duct system, then returns to the central variable air volume supply fan mounted in a rooftop air conditioning unit.

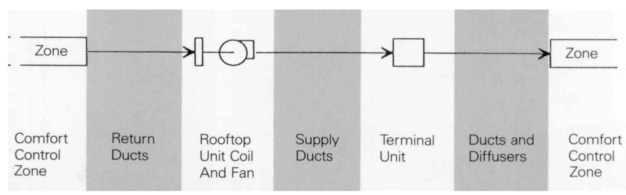

Figure 1. Single-Zone Air Delivery System

The fan adds mechanical energy to the air stream, increasing its total pressure, while the cooling coil removes heat from the air stream. The amount of energy added by the fan is variable, and is usually modulated with fan inlet vanes or a variable-speed drive on the fan motor.The amount of heat removed by the cooling coil is also variable, and is usually modulated in response to the supply air temperature. Supply air is delivered to the VAV terminal unit via the supply duct system. The VAV terminal unit adjusts the volume of air delivered by modulating the position of a damper or air valve. Finally, the air travels from the terminal unit through the downstream ducts and diffusers, and once again enters the occupied zone.

The fan curve, brake horsepower curves for 100-percent-open inlet guide vanes, and the duct system resistance curve for our simplified system are shown in Figure 2A. Figure 2B shows the static pressure gradient throughout the entire air path. (At partially closed vane positions, the horsepower curves actually shift downward, but this effect is ignored in the following discussion. Consequently, all energy saivngs values calculated are somewhat conservative.) The fan, a dual-inlet 20×20 FC fan with inlet guide vanes, operates at 1,000 rpm and is mounted in a 40-ton rooftop unit. Duct system resistance is determined by the supply and return ducts, as well as the coils and filters in the rooftop unit, and the VAV terminal unit.

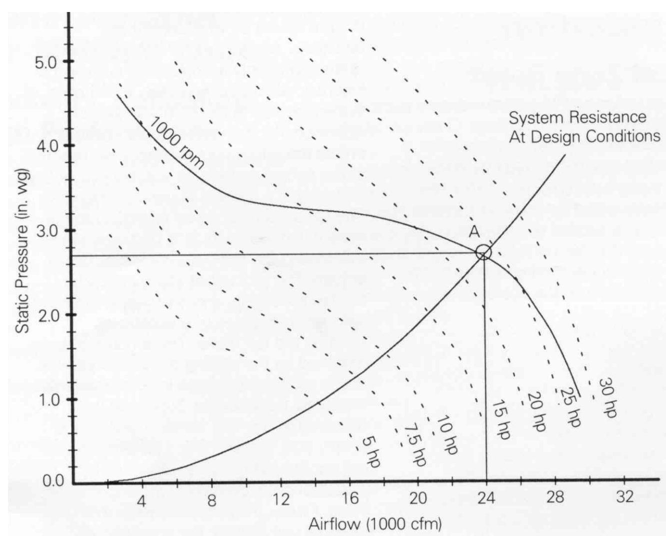

Figure 2A. System Performance with 100-Percent-Open Inlet Guide Vanes

For this discussion, we'll assume that the static pressure drop through the system is 2.70 in. wg at the design flow of 24,000 cfm. At design flow, the VAV terminal unit at the zone is fully open, as are the fan inlet guide vanes. The fan operates at the intersection of the fan curve and system resistance curve, Point A, using approximately 23 brake horsepower (bhp). The various system components reduce the static pressure as shown in Figure 2B. The fan static pressure is 2.70 in. wg, while the duct static pressure—measured with respect to the ambient pressure—is 1.40 in. wg.

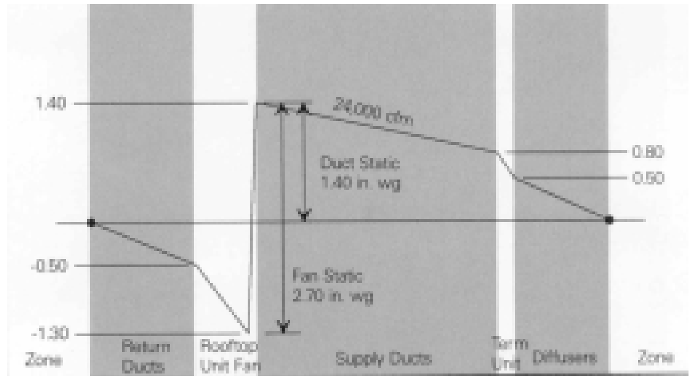

Figure 2B. Pressure Profile with 100-Percent-Open Inlet Guide Vanes

As the cooling load in the zone decreases, less airflow is needed. As shown in Figure 3A, if no fan modulation is used, the terminal unit closes to reduce the airflow and a new system resistance curve results. The fan operates at the intersection of this new system curve and the fan curve, Point B. In our simple system, closing the terminal unit to reduce airflow from 24,000 cfm to 18,000 cfm, a 25 percent reduction in airflow, increases fan static pressure to 3.15 in. wg, increases duct static pressure to 2.42 in. wg and decreases fan brake horsepower to 18. As Figure 3B shows, pressure drop through the ducts, fittings, and rooftop unit decreases, while the pressure drop across the VAV terminal unit rises from 0.30 in. wg to 1.80 in. wg.

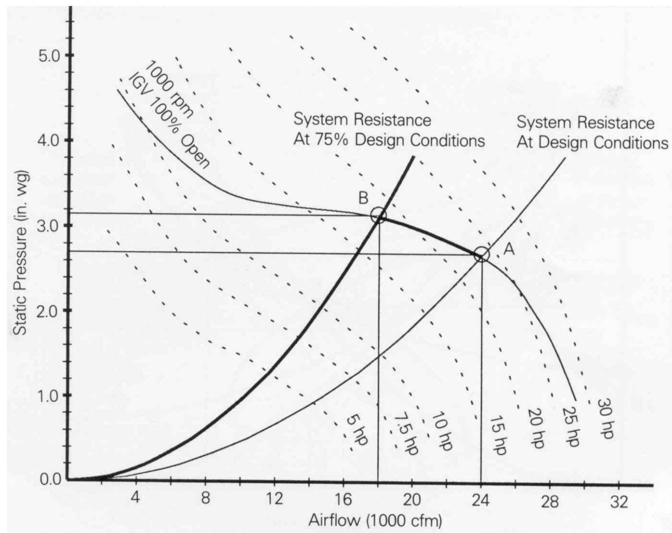

Figure 3A. System Performance without Fan Modulation

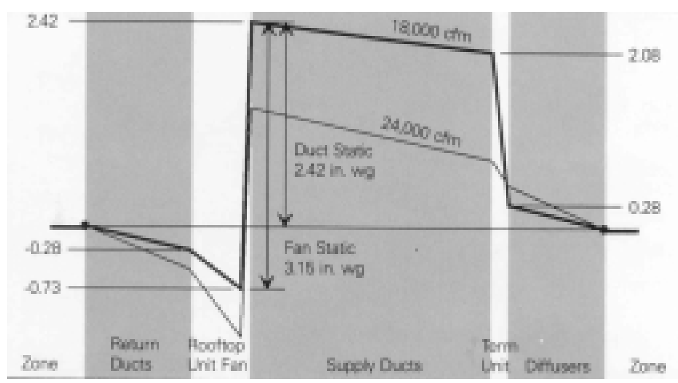

Figure 3B. Pressure Profile without Fan Modulation

Fan Capacity Control

When inlet guide vanes are used to modulate fan capacity, as in our simple example system, fan static pressure is reduced at part-load airflow and additional horsepower reduction is possible. The magnitude of the fan static pressure and horsepower reductions depends upon the method used to position the inlet guide vanes and thereby control fan capacity. Note that as fan capacity is reduced, airflow through the coil is reduced and less mechanical cooling is needed to maintain the supply air temperature set point.

Traditionally, inlet guide vane position is determined by a static pressure control loop consisting of a duct static pressure sensor, static pressure controller and inlet guide vane actuator. Duct static pressure is sensed at some location in the duct system and transmitted to the controller. The controller compares the sensed pressure to a set point pressure and modulates the inlet guide vane actuator to maintain a constant duct static pressure at the sensor location. The location chosen for the sensor and operation of the controller determine the system first cost, installed cost, and overall reliability, as well as fan static pressure and operating cost.

Let's examine and compare three static pressure control methods:

- Fan outlet static control
- Supply duct static control
- Critical zone reset

Fan-Outlet Static Control

It is often convenient to mount the duct static pressure sensor at the supply fan outlet, and set the static pressure controller to maintain the static pressure required at design flow. The sensor can either be mounted cost effectively and reliably at the factory, or in the field at a somewhat higher cost and without benefit of a factory run test. Reliable sensor installation and operation entails proper static pressure sensing and signal routing. If fire dampers are included in the supply ducts, fan outlet sensing assures that the static pressure sensor is on the fan side of the fire dampers so that ducts are protected from high pressures. Also, depending on the design and layout of the duct system, this method may eliminate the need for multiple duct-mounted sensors.

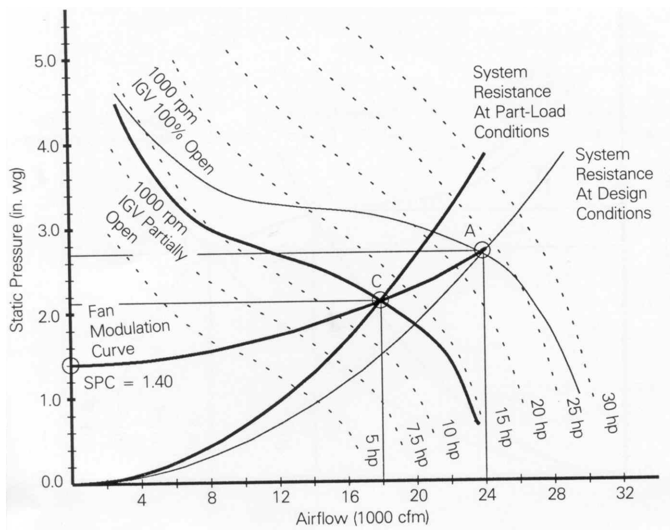

Figure 4A. System Performance with Fan-Outlet Static Pressure Control

When the duct static pressure sensor is located at the outlet of the fan, the static pressure controller, SPC in our system example, must be set to 1.40 in. wg so that the pressure at the inlet of the VAV terminal unit is 0.80 in. wg at design airflow. Figure 4A shows the system resistance curves, fan modulation curve, and the new fan curve at part-load flow. They indicate that at zero airflow, fan static pressure is the duct static pressure set point, SPC = 1.40 in. wg. At our part-load airflow, the inlet guide vanes are repositioned and a new fan curve is created so that 18,000 cfm is delivered and the duct static pressure at the fan outlet is constant at 1.40 in. wg.

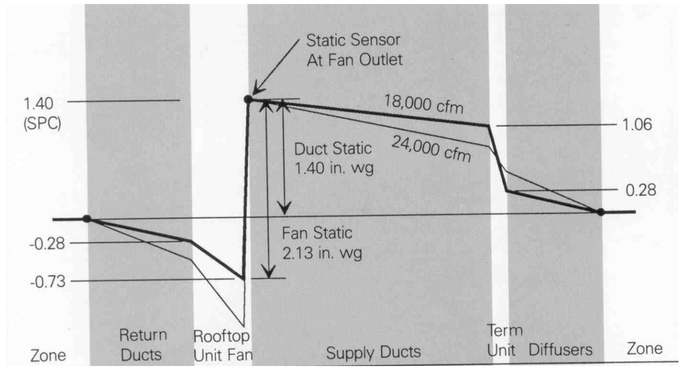

Figure 4B. Pressure Profile with Fan-Outlet Static Pressure Control

The fan now operates at the intersection of the fan modulation curve and new fan curve, Point C. As the pressure gradient curve in Figure 4B shows, fan static pressure drops to 2.13 in. wg, duct static pressure is constant at 1.40 in. wg, and the static pressure at the inlet to the terminal unit rises to 1.06 in. wg. The terminal unit must close to introduce a 0.78 in. wg pressure drop, but fan brake horsepower is reduced to 13 bhp.

Supply-Duct Static Control

The most commonly recommended static pressure sensor location is a point in the supply duct at which the duct static pressure at design flow is approximately two-thirds of the duct static pressure drop from the fan outlet to the terminal unit inlet. The sensor is field-installed and the controller is set to maintain the duct static pressure at the value required at design flow conditions. Of course, field installation and adjustment of one (or possibly several) static pressure sensor not only raises first cost and installation cost, but may lower system reliability as well. An additional high-pressure sensor is usually needed, too, if fire dampers are used in the duct system. However, even though first cost and installation cost are higher, and installation/operation reliability may be compromised, the operating cost of this method is decidedly lower than that of fan outlet static control.

In our simple example system, since we only have one terminal unit, supply-duct static-pressure control is best implemented by locating the supply-duct-static-pressure sensor in the inlet to the terminal unit itself, rather than “two-thirds down the duct.” This is the “critical terminal unit,” that is, the terminal unit that always requires the highest pressure. With the sensor at the terminal unit inlet, the controller must be set to 0.80 in. wg (SPC = 0.80 in. wg), the required terminal inlet pressure at design airflow. Figure 5A shows the system resistance curves, fan modulation curve, and fan curves. At our part-load airflow, the inlet guide vanes are repositioned, creating another new fan curve. The fan operates at the intersection of the new fan curve and the fan modulation curve, Point D, to deliver part-load airflow of 18,000 cfm.

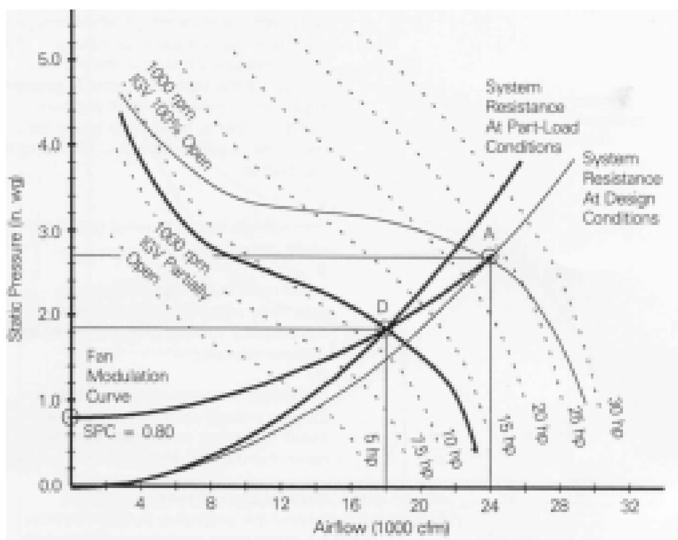

Figure 5A. System Performance with Supply-Duct Static Pressure Control

As the pressure gradient in Figure 5B shows, fan static pressure at this point is reduced to 1.85 in. wg, duct static pressure is reduced to 1.12 in. wg, and the static pressure at the terminal unit inlet is held constant at 0.80 in. wg. The terminal unit must close to introduce a 0.50 in. wg pressure drop. The fan now requires only 12 bhp (approximately) to deliver 18,000 cfm at 1.85 in. wg.

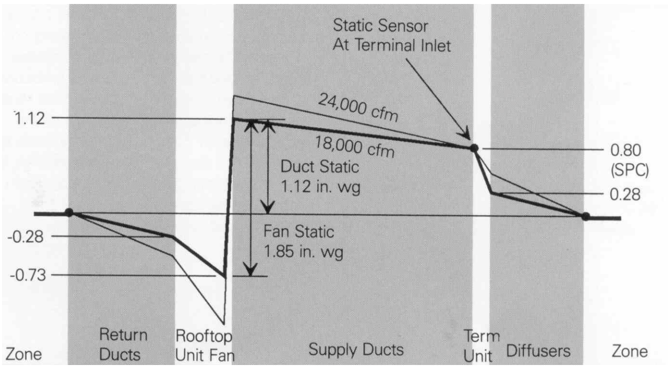

Figure 5B. Pressure Profile with Supply-Duct Static Pressure Control

Of course, an actual VAV duct system has many terminal units and the critical terminal unit is difficult to identify. Furthermore, it is most likely not the same terminal unit at all flow conditions throughout the day and throughout the year. Therefore, to properly implement supply-duct-static-pressure control—that is, to properly locate the duct-static-pressure sensor—the designer must either:

1 Find a single critical terminal unit, which is seldom possible. Or ...

2 Install multiple sensors, one at each potentially critical terminal unit, and a discriminator circuit, which adds cost and reduces reliability. Or ...

3 Compromise operating cost savings by locating a single static-pressure sensor closer to the fan; two-thirds of the way down the duct, for instance.

Critical Zone Reset

Both of the preceding control methods, fan outlet static control and supply duct static control, have advantages and disadvantages. Fan outlet pressure control is reliable and first-cost effective, but cannot minimize operating costs. Supply-duct-pressure control is less reliable and has a higher first cost. It reduces operating cost, but cannot minimize operating cost because the terminal unit must always close somewhat to introduce a pressure drop at part load. The “critical zone reset” method, on the other hand, has all the advantages of both previous methods with none of the disadvantages. In addition, it lowers operating costs to the absolute minimum by keeping the critical zone terminal unit fully open at all load conditions.

The critical zone reset method combines the location-related benefits of fan outlet static control with operating cost savings that exceed those possible with supply-duct-static-pressure control. The single static-pressure sensor is located at the fan outlet, and the static-pressure controller is set to control the design flow static pressure. But the **actual** static presure set point is continually adjusted (reset) so that at least one terminal unit in the system—the terminal unit serving the critical zone—is wide open. The static-pressure controller monitors the position of each terminal unit and resets the duct-static-pressure set point based on the maximum terminal position. (This can be accmplished at virtually no cost penalty when implemented using factory-installed DDC/VAV terminal unit controls.) First cost and installed cost are reduced, reliability is increased, and fan operating cost is at the absolute minimum.

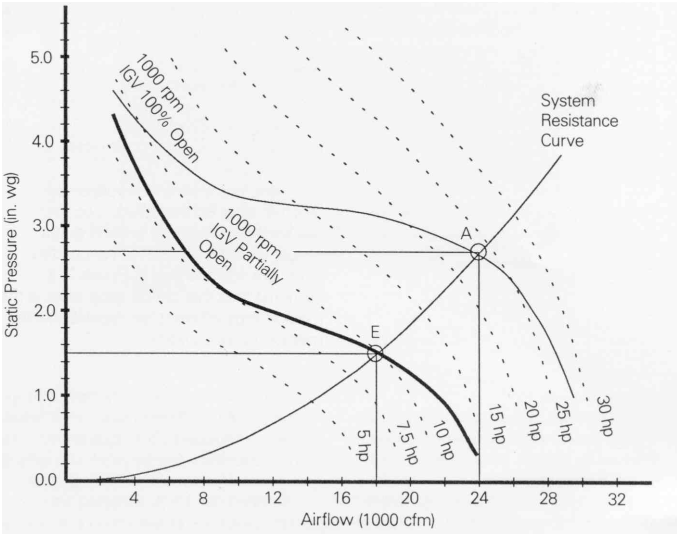

Figure 6A. System Performance with Critical Zone Reset

When critical zone reset is used, duct static pressure at any flow condition can be controlled so that the pressure at the inlet to the critical terminal unit **precisely** matches the pressure drop through the wide-open terminal unit and the downstream ducts and diffusers. The fan unloads following the design system resistance curve, rather than a new system resistance curve created by partially open terminal units. In other words, the fan modulation curve is identical to the design system resistance curve. Fan static pressure and horsepower are always at the minimum required level and duct static pressure never exceeds the level required to keep the critical terminal unit wide open.

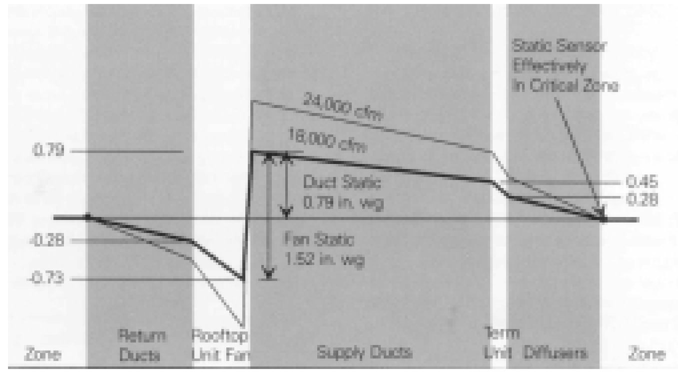

Figure 6B. Pressure Profile with Critical Zone Reset

Figure 6A shows the fan curves and system resistance curve for our simple system with critical zone reset. At 18,000 cfm, the vanes are repositioned so that the new fan curve intersects the original design flow system curve, Point E, at the lowest fan static pressure possible. As Figure 6B shows, fan static pressure is reduced to 1.52 in. wg, duct static pressure is reduced to 0.79 in. wg, and the pressure at the inlet to the terminal unit is reduced to 0.45 in. wg. The pressure drop across the wide-open terminal unit is only 0.17 in. wg, and the required fan brake horsepower is only 9.5 bhp. (Note: Although the duct static sensor is located at the fan outlet, critical zone reset has the effect of moving the sensor to the critical zone itself.)

Fan static pressure and horsepower requirements for the different control methods discussed, as applied to our simple example system at various flow rates, are summarized in Figure 7. It demonstrates that critical zone reset is the most energy-efficient fan-capacity control method for our system.

Figure 7. Comparison of Static-Pressure Control Methods

Operating Point	Control Method	Airflow (cfm)	Fan Static (in. wg)	Brake HP	Power Reduction
A	(Design)	24,000	2.70	22	—
B	No control	18,000	3.15	18	22%
C	Fan outlet	18,000	2.13	13	43%
D	Duct static	18,000	1.85	12	48%
E	Critical zone reset	18,000	1.52	9.5	59%

Critical Zone Reset Operation

The preceding discussion focused on fan capacity control. Any scheme to maximize part-load horsepower savings must also address mechanical cooling capacity control. We have assumed that fan horsepower savings are always preferred over compressor horsepower savings; for any load decrease, we save more horsepower by reducing airflow than by increasing air temperature. We have also assumed that mechanical cooling capacity in a VAV system is controlled by supply air temperature. As fan airflow decreases, or increases, cooling capacity is automatically decreased, or increased, to maintain a constant supply air temperature. When the fan is at its minimum airflow capacity, a further decrease in cooling load can only be met by resetting supply air temperature upward so that warmer air is delivered. Conversely, when the fan is at maximum airflow capacity, a further increase in cooling load can only be met by resetting supply air temperature downward so that cooler air is delivered. These supply air temperature reset strategies are included in the critical zone reset method.

Figure 8 illustrates the simple logic of critical zone reset operation. The objective is to control duct static pressure to keep at least one terminal unit wide open, so as to minimize fan horsepower. Therefore, duct static pressure at the fan outlet is sensed and controlled to a set point, but the set point is reset based on terminal unit position. If **all** terminal units are closed somewhat (less than 95 percent open, for instance), less cooling is needed. To decrease available cooling, first lower duct static pressure in small increments until minimum fan capacity is reached, then raise the supply air temperature in small increments.

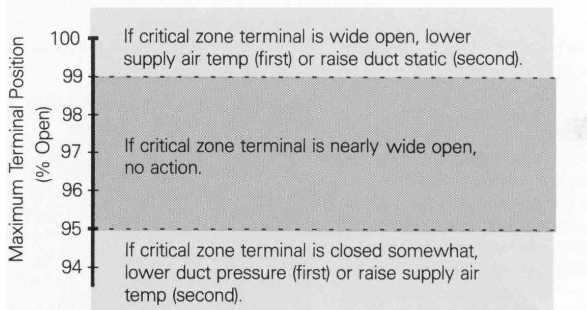

Figure 8. Operating Logic for Critical Zone Reset

On the other hand, if **any** terminal unit is wide open, (99 percent open or more, for instance), additional cooling is needed. To increase available cooling, first lower the supply air temperature in small increments until the design set point is reached, then raise the duct static pressure in small increments. (Note that the 95 to 99 percent open range is for illustration purposes. In actual practice, a wide range such as 85 to 95 percent may be required for stable system operation.)

Following is a detailed sequence of operation for a critical zone reset system:

- At design flow, the supply air temperature is at design set point, duct static pressure at the fan outlet is at design set point, the inlet vanes are wide open, the terminal units are open to various positions, and the critical zone terminal unit is nearly wide open (between 95 and 99 percent open).
- As the critical zone load decreases, less cooling is needed so the critical-zone terminal unit closes slightly; all terminal units are now somewhat closed. In response to the new terminal-unit positions, the duct-static-pressure set point is reset by a small amount to a lower value. The inlet vanes close slightly, creating a new fan curve with a slightly lower fan static pressure and airflow. In response to the lower duct static pressure, the critical-zone terminal reopens slightly so that it is more than 95 percent open.
- Further load decreases prompt similar reactions until the duct-static-pressure set point is at a predetermined minmum value or until the inlet guide vanes are at minimum position. In either case, if the critical zone load decreases further, causing the critical zone terminal unit to close somewhat, the supply-air-temperature set point is increased slightly, while the duct-static-pressure set point is held constant. As a result, the temperature of the supply air rises slightly. In response to the warmer supply air, the critical-zone terminal reopens slightly so that it is more than 95 percent open.
- Additional load decreases result in similar incremental increases in the supply-air-temperature set point until a predetermined maximum value is attained. At this point, the VAV system is at its absolute minimum cooling capacity and further load decreases result in no control system response.
- If the critical zone load increases, the critical zone terminal unit opens slightly. In response to this new terminal-unit position, the supply-air-temperature set point is decreased slightly, while the duct-static-pressure set point is held constant. As a result, the temperature of the supply air drops slightly. The critical-zone terminal closes slightly in response to the cooler supply air so that it is less than 99 percent, but more than 95 percent, open.
- Further load increases prompt similar reactions until the supply-air-temperature set point is at the design set point value. If the critical zone load increases further, the duct-static-pressure set point is increased slightly, while the supply-air-temperature set point is held constant at the design value. As a result, the inlet guide vanes open slightly, causing duct static pressure and supply airflow to increase. In response, the critical-zone terminal closes slightly so that it is more than 95 percent, but less than 99 percent, open.
- Additional load increases produce similar incremental increases in duct static pressure until the inlet guide vanes are fully open. At this point, the VAV system is at its maximum cooling capacity and further load increases result in no control system response.

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Real VAV Systems

Critical zone reset works in a simple one-zone system, but what about real systems?

Real VAV systems contain many zones with diverse airflow needs.
We still want to keep the critical-zone terminal wide open. But where is it? How do we select the "critical" terminal unit in a complex system? Since VAV systems have diverse load profiles, the critical terminal unit may not be the same at all times of the day or during all days of the year under all load conditions. We could calculate the theoretical critical zone for any load condition, but that would take an extensive duct system and building load model. We could "guess" at the critical zone and monitor the position of the terminal with the longest path from the fan. Or, we could monitor the position of several zones and use the position of the most wide-open zone as our critical position. But, in fact, the **best** way to select the critical zone is to monitor **all** of the terminal units and use the most wide-open position in the entire system as our critical-zone terminal position.

Real VAV systems have "bad" zones.
Bad zones are either improperly designed or inappropriately operated. In either case, the result is a zone in which the zone-temperature set point cannot be satisfied in a reasonable amount of time by design airflow at design air temperature. The zone terminal unit simply moves to the wide-open position and stays there. In a VAV system with pressure-independent terminal units, no adverse operation results when a bad zone determines the duct static pressure. The bad zone becomes the critical zone and controls duct static pressure so that design airflow is maintained in the bad zone. However, in a pressure-dependent VAV system, the bad zone terminal stays open regardless of airflow to the zone. As a result, the duct static pressure rises to the design pressure at the fan outlet. This often overpressurizes the duct system, causing noisy terminals and leaking ducts. (Incidentally, the resulting increased airflow to the bad zone may, in some cases, have the beneficial effect of actually lowering the zone temperature to set point and temporarily fixing the bad zone, at the expense of excessive duct static pressure!)

Real VAV systems are dynamic.
Repositioning the inlet guide vanes in response to terminal position could have a destabilizing effect. To avoid "hunting," the critical-zone-reset method includes an adjustable differential between increasing and decreasing the outlet-static-pressure set point. The static pressure controller can be operated so that duct static pressure is reset downward only when **all** terminal units are less than 95 percent open, for instance, and reset upward when **any** terminal unit is 99 percent open or more. If this differential does not result in stable operation, it can be increased as required with only a small operating cost penalty.

Real VAV systems have minimum airflow zones.
These zones require minimum airflow delivery, regardless of load conditions. If pressure-dependent terminals are used, minimum positions—not airflows—are set for each zone. When traditional duct-static-pressure controls are used, the terminal-inlet static pressure usually rises at part-load conditions (see Figure 5), so the minimum position can be set relatively low to obtain minimum flow. However, when critical zone reset is used, the inlet static pressure falls at part load (see Figure 6). Therefore, the minimum position must be set somewhat higher to assure that minimum flow is available at reduced inlet static pressure.

On the other hand, if pressure-independent terminals are used, minimum airflows are set and maintained. If reduced inlet static pressure causes a terminal unit to fully open, that unit becomes the critical zone terminal and minimum flow is maintained at minimum operating cost.

Implementing Critical Zone Reset

Critical zone reset is the best VAV static-pressure-control method, but how can it be implemented in a reliable and cost-effective manner?

Of course, the concept of critical zone reset could be implemented using traditional pneumatic controls on the VAV terminal units and a field-installed static pressure control system at the rooftop air conditioner or air handler. Some method of sensing terminal unit position and discriminating the maximum position would be needed, in addition to a duct-static-pressure sensor and controller. But field installation of many control components is costly. In fact, operating cost savings may not justify the first cost and installation cost additions required. Also, many pneumatic, field-installed control components and pneumatic tubing runs may significantly reduce the overall reliability of the system.

Critical-zone-reset control could also be implemented using analog electronic controls on the VAV terminal units and a field-installed electromechanical control system at the rooftop unit. Position-sensing transducers would be needed at each terminal unit and a discriminator circuit would be needed. Also, a duct-static-pressure sensor/transducer and controller would be needed. Installed cost would be high, and acceptable system reliability may be difficult to achieve.

The answer to implementing critical zone reset lies in direct digital control of the VAV system (DDC/VAV). A DDC/VAV system includes factory-installed DDC controllers on the VAV terminal units, factory-mounted rooftop unit or air handler controls, and an integrated building automation system that can communicate with both the VAV terminal-unit controllers and rooftop or air-handler controls. If Trane equipment and systems are used, the answer is the Trane Integrated Comfort™ system (ICS) concept of factory-mounted unit controls communicating with powerful, easy-to-use Tracer® building-automation-system products.

Using the ICS concept, terminal-unit controllers and rooftop or air-handler controllers communicate serially with the Tracer building-automation-system controller via a serial communications link. This simple wiring is already field-installed for normal building monitoring and control. The factory-installed, DDC/VAV terminal-unit controller already knows the position of the terminal unit. And this information is readily available at Tracer with no installed-cost penalty. Similarly, in many cases, the factory-installed, rooftop-unit or air-handler controller already senses duct static pressure at the fan outlet and provides for static-pressure-set-point reset via the serial communications link. The controls required for critical zone reset are largely standard, factory-installed controls so the additional cost for critical zone reset is very low. And factory-mounted controls are carefully installed at the factory and 100 percent tested to assure system reliability.

Critical Zone Reset Advantages

Low first cost. Only one duct static pressure sensor is needed for both control and high-pressure protection. Multiple static-pressure sensors, transmitters, and discriminators are not necessary, even in complex duct systems.

Low installation cost. All controls, both at the terminal unit and the rooftop unit or air handler, can be factory-installed. Field mounting and wiring or piping of controls is eliminated.

Low operating cost. Part-load energy usage is maintained at the lowest possible level. Fan energy is minimized before mechanical cooling energy is reset. Critical zone reset delivers the energy savings potential of the VAV system.

Easy to design. Since the static sensor is at the fan outlet, the best location for the sensor is already determined. And no special high-duct-pressure protection is required for installations with fire dampers. The single static sensor eliminates the need for multiple-sensor system designs.

Easy to install. Only one static sensor to mount. No long multiple sensor runs are needed. If factory-installed controls are used, field mounting of control devices is virtually eliminated.

Reliable operation. Static-pressure sensing is simplified, eliminating installation, setup, and operating errors. The duct-static-pressure sensor is always upstream of the fire dampers. If factory-installed controls are used, all controls are tested prior to shipping and installation errors are eliminated.

Quiet operation. Lower duct pressure means quiet air delivery. Open terminal units with low inlet static pressures are much quieter than nearly closed terminal units with high inlet pressures. Critical zone reset delivers quiet comfort.

Conclusion

Critical zone reset works better and costs less than traditional VAV static pressure control methods. It will become the standard control method in the future. And, with Trane Integrated Comfort systems, the future of VAV system control is available now.