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multiple-zone VAV systems

Finding the Right Balance for VAV Energy Savings

Fan pressure optimization (sometimes called critical zone reset) and supply-air-temperature reset are two prescriptive requirements from ANSI/ASHRAE Standard 90.1 that can be used to save energy and operational cost in multiple-zone variable air volume (VAV) systems. While both strategies have existed for many years, both control technology and standard requirements have changed since we first wrote about the strategies in 1991. This newsletter will cover benefits, drawbacks, and methods to mitigate the drawbacks for both strategies.

Background

Multiple-zone VAV systems have existed for more than forty years. One reason they continue to remain popular is that they save fan horsepower at part load by reducing airflow. These systems can utilize direct expansion or chilled-water cooling and serve just a few or many zones.

In VAV systems, the damper in each box modulates to vary the flow of air supplied to its zone, to match cooling capacity to the cooling load. As the space temperature deviates from setpoint, the VAV box controller responds by adjusting the position of the damper to increase or decrease airflow.

Varying the zone damper position causes the pressure inside the supply ductwork to change.

To maintain a constant static pressure in the supply duct as the airflow changes, VAV systems have historically modulated the supply fan motor speed. For example, at full load, with many of the VAV dampers wide open, the supply fan operates to provide design airflow. As the cooling load decreases, the VAV dampers modulate to reduce supply airflow and prevent overcooling. The partially-closed dampers increase the duct static pressure and if the fan is controlled to maintain a constant pressure in the duct, energy is wasted.

This situation presents an opportunity to optimize the system.

Implementing energy-efficient fan-capacity control strategies while resetting the supply-air (SA) temperature are strategies that can save energy in these systems.

Fan speed control. The supply fan in a VAV system must vary airflow based on the amount of air needed to condition the individual zones. Today, most systems are installed with direct digital controls (DDC) to enable control of the supply fan based on the static pressure measured at a single location in the duct. There are multiple ways for the fan to vary airflow including "riding" the fan curve, inlet guide vanes, electronically commutated motors (ECM), and variable speed drives.

The most common method to vary SA volume is to change the speed at which the supply fan rotates. This is achieved by applying a variable-speed drive to modulate the motor and fan's rotational speed. A unit controller can vary the supply fan speed to maintain a desired setpoint based on signals from a static pressure sensor within the supply duct.

Static pressure sensor placement. The static pressure sensor can be placed within the duct system or at the outlet of the fan. Traditionally, the pressure sensor was located two-thirds of the distance down the longest main supply duct. The balancer would determine the static pressure setpoint needed at this location to ensure that each zone can receive its design airflow. The setpoint was often kept constant, regardless of load conditions. This combination typically yielded sufficient airflow at both design and part-load conditions.

Alternatively, manufacturers offer options to install this static pressure sensor at the fan discharge. This allows the sensor to be installed in a factory environment and tested before unit shipment.

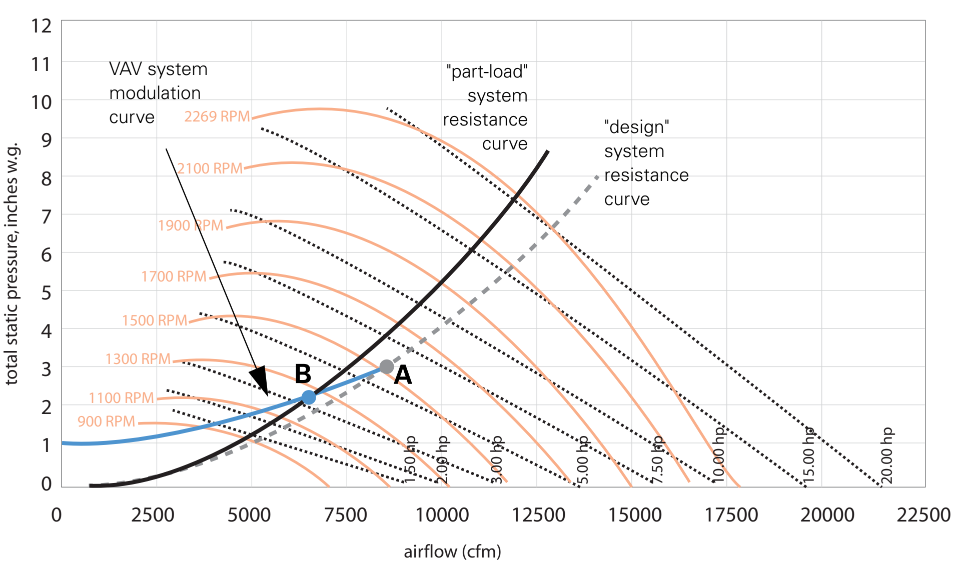
Regardless of sensor placement, the static pressure in the duct system increases as VAV dampers close. The unit controller responds by slowing the fan speed to reduce the duct static pressure back down to the desired setpoint.

For example, consider a small VAV air handler designed to deliver 8500 cfm of SA at 3.0 in. w.g. to several zones at design cooling conditions.
Figure 1 shows the performance of the 25-inch direct-drive plenum fan at these design conditions (A). The system resistance curve at design has also been plotted. At these conditions, the fan uses about 5.8 horsepower.

Figure 1 illustrates system performance with a variable-speed drive modulating fan speed to reduce the supply air volume, with the duct static pressure control setpoint fixed at 1.0 inch w.g. As the zone cooling loads decrease, the dampers in most or all of the VAV boxes modulate toward a closed position. This restriction increases the pressure drop through the system, reducing supply airflow and causing the (part-load) system resistance curve to shift upwards (black curve in Figure 1).

In response, the fan begins to "ride up" the constant-speed (rpm) performance curve, from the design operating point (A), attempting to balance with this new system resistance curve. As a result, the fan delivers less airflow at a higher static pressure. The duct static pressure sensor measures this higher pressure and the controller responds by reducing the speed of the supply fan. This shifts the operation of the fan downward until the system balances at an operating point (B) bringing the duct static pressure back down to the 1.0 inch w.g. setpoint. This response, over the range of system supply airflows, causes the supply fan to modulate along a VAV system modulation curve (the blue curve in Figure 1). This fan, when paired with a variable-speed drive and operating to provide 6600 cfm, observes a power reduction from 5.8 to 3.2 horsepower.

Figure 1. System performance with a variable-speed drive



Fan pressure optimization

Reducing fan pressure reduces fan energy consumption, but it takes communicating controllers on the VAV boxes to do it. It's possible to optimize this static-pressure control function to provide just enough pressure in the duct to satisfy the most wide-open box.

This is a dynamic process where the system controller periodically polls the VAV box controllers to learn the damper positions. The controller resets the static pressure setpoint upward or downward by a small amount (e.g. 0.1 or 0.2 inches w.g.). For example, if all dampers are partially closed, the static-pressure setpoint can be adjusted downward. As a result, the supply fan speed can be lowered even further, saving energy. During this process, total supply airflow remains constant because the damper in each zone opens to maintain its required airflow, but static pressure in the supply duct is reduced.

In response to this lower pressure in the duct, the VAV boxes open further to provide the airflow needed to maintain zone temperature. The goal of this strategy is to identify the *critical zone*—the zone that needs the most pressure—and reduce the duct pressure to the point where its damper is nearly fully open. The supply fan generates the minimum amount of static pressure needed to push the conditioned air through the critical box reducing fan energy.

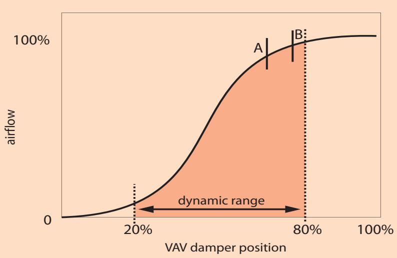
With fan pressure optimization, fans operate much closer to their theoretical

Damper High- and Low-Limits

Note that VAV dampers do not operate in a linear fashion. As shown in Figure 2. Most airflow variation occurs between 20 and 80% open. For stable operation,a more-linear portion of the curve should be used for control.

The system controller polls the VAV box controllers to determine the critical zone based upon the farthest-open VAV damper. If this damper is less than 65% open (point A), the duct static pressure setpoint is decreased; if it's more than 75% open (point B), the setpoint is increased; and if it's between 65% and 75% open, the duct pressure setpoint remains unchanged.

Figure 2. VAV damper position versus airflow



best performance (predicted by the affinity laws) as shown in Figure 3. When operated with a constant duct pressure setpoint, the fan consumes 3.2 horsepower at part-speed to deliver 6600 cfm (B). When the same fan is operated with fan pressure optimization to deliver the same volume of air, it operates at a lower pressure and consumes 2.5 horsepower (B'). In addition to reducing the energy consumed by the supply fan during part-load operation, there are other benefits.

Surge avoidance. When running at reduced speed and generating lower static pressure, the fan operates farther from the surge region compared to traditional duct static pressure control.

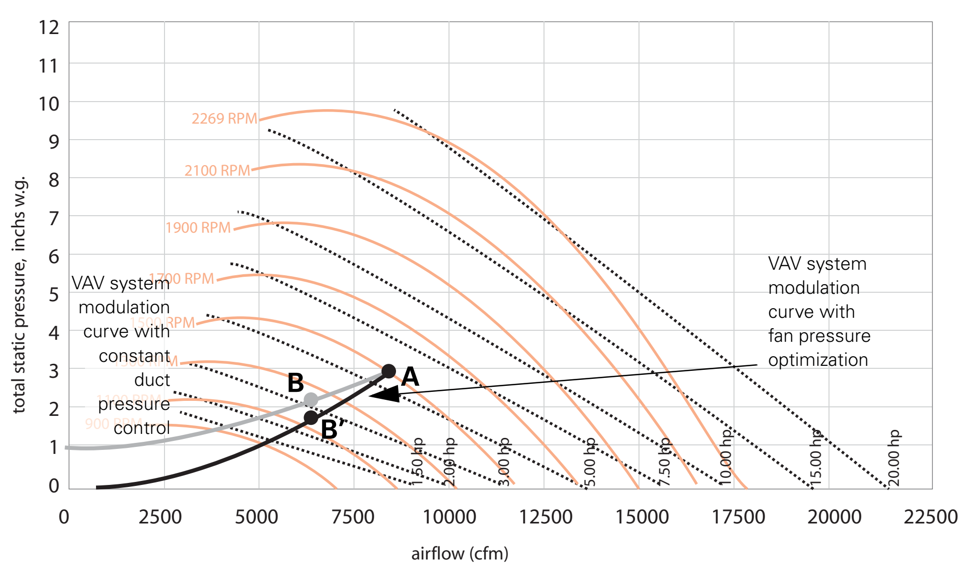
Acoustics. The fan itself generates less noise at lower speed and the further-open dampers produce less noise in each box.

Reliability and lower installed cost. The position of the supply static pressure sensor matters less when the system is run with fan pressure optimization because its setpoint is continually reset. This allows the sensor to be factory-tested and installed at the outlet, which reduces installed cost and increases reliability.

Proper operation. Fan pressure optimization and DDC control allow the system and operators to identify, correct, and/or ignore *rogue zones*. A rogue zone can prevent the duct static pressure from being reset downward because it requires nearly constant airflow. Sometimes, this indicates one of several possible problems:

- undersized VAV box,
- obstruction in supply duct to zone (such as crimped flex duct),
- improperly located or malfunctioning zone sensor.

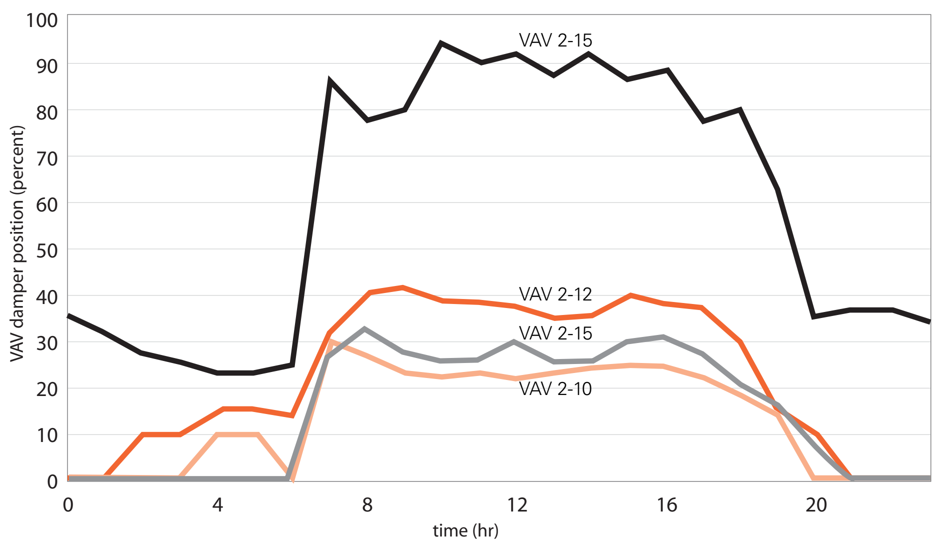
Figure 3. VAV system modulation curve comparison



During operation, the system controller gathers data about the damper position. Over time, this data can be plotted to help the building operator identify any potential rogue zones. For example, consider the damper positions (shown in Figure 4) plotted as a function of time for a system serving an office building. The damper position for VAV 2-15 shows that it is open more often and spends much of the occupied hours nearly fully open.

Identifying such a zone notifies the building operator that inspection for malfunction or placement of the zone sensor might be in order. It's likely that this VAV box has prevented fan pressure optimization from realizing its expected energy savings, so the operator can remove this rogue zone from the optimization calculation until the problem has been resolved.

Figure 4. VAV damper position as a function of time



Supply-air-temperature reset

The supply-air temperature in a VAV system has historically been controlled to a constant temperature, such as 55°F. *Supply-air-temperature reset* raises the SA temperature setpoint of the system at part-load conditions. This strategy is used to save compressor or reheat energy and increases the benefit of an airside economizer.

When the outdoor air is cooler than the SA setpoint, the compressors are shut off and the outdoor- and return-air dampers modulate to deliver the desired SA temperature to satisfy the cooling load. A warmer SA temperature setpoint allows the compressors to operate at reduced capacity (or shut off) and increases the number of hours when the economizer provides "free cooling."

When it's warm outside, the outdoor air provides little or no cooling benefit for economizing. In this case, the cooling load in most zones is likely high enough that reheat is not required to prevent over-cooling. Keeping the air cold (no reset) allows the fan to turn down which results in energy savings from reducing the airflow. Additionally, the colder SA temperature allows the system to provide sufficiently dry air to the zones, improving part-load dehumidification.

When the outdoor temperature is cooler, the controls begin to reset the SA temperature setpoint upward. At mild or cold outdoor temperatures, reset enhances the benefit of the economizer. At these cooler temperatures, the supply fan has most likely unloaded significantly, so the incremental energy use of having to deliver a little more air is lessened.

For zones with very low cooling loads, where the supply airflow has been reduced to the minimum setting of the VAV box, raising the SA temperature also decreases the use of reheat energy.

But, when the SA temperature is reset upward, zones with large cooling loads will require more airflow compared to the design SA temperature. And, warmer discharge air temperatures reduce the amount of dehumidification done by the cooling coil and the resulting space humidity levels may increase. If dehumidification is a concern, this strategy should be used with caution in climates with humid seasons.

There are several different methods used to reset SA temperature. This reset strategy should attempt to minimize overall system energy use which requires considering the tradeoff between compressor, reheat, and fan energy, and the impact on space humidity levels.

Reset based upon outdoor air temperature. Perhaps the simplest method is to reset the SA temperature based upon the current outdoor air dry-bulb temperature. When the outdoor temperature is high, the SA temperature is at design. As the outdoor air temperature decreases, the SA temperature is slowly reset upward.

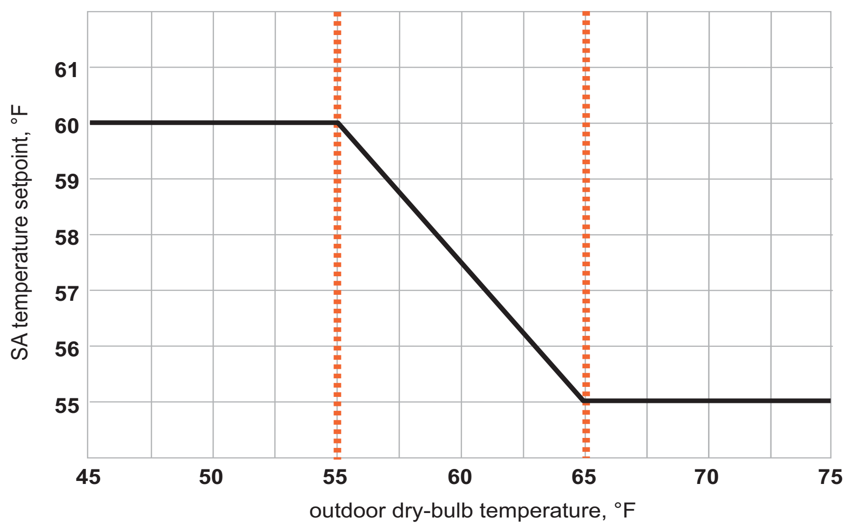
Using the example in Figure 5, when the outdoor air temperature drops below 65°F, the SA temperature is gradually reset upward from a design temperature of 55°F to 60°F. When the outdoor air temperature starts to increase—above 55°F in this case—the SA temperature is gradually reset back downward until it reaches the design SA temperature of 55°F. No reset takes place when the outdoor air dry-bulb temperature is higher than 65°F.

If an economizer with dry-bulb temperature control is used, the upper limits for SA temperature reset and the high-limit shutoff temperature are often the same.

In this example the amount of reset is capped at 60°F. Limiting the amount of reset allows the system to satisfy cooling loads in interior zones without needing to substantially oversize VAV terminal units and ductwork.

While this strategy is easy for the building operator to understand, it doesn't account for the cooling demands of individual zones or space humidity levels. Some zones may require a large amount of cooling, regardless of the outdoor air temperature. Designers should consider sizing the duct and VAV boxes serving those zones for higher SA temperatures and volumes to ensure proper comfort.

Figure 5. Supply-air- temperature reset based upon outdoor air dry-bulb temperature



Reset based upon VAV damper position. Another option uses the VAV damper position, just like fan pressure optimization. The system identifies the farthest-open VAV damper and resets both the SA temperature and the duct static pressure setpoints. Typically, this strategy will reduce the duct static pressure setpoint first, in an effort to save fan energy, then reset the SA temperature upward to save compressor or reheat energy.

As the zone cooling loads decrease, the VAV dampers begin to close, causing the system controller to reset the duct static pressure setpoint downward. Once the static pressure setpoint is at its minimum, the system controller begins to increase the SA temperature setpoint. As the cooling load increases and the VAV box dampers open, the system controller first lowers the SA temperature back to its design value, and then increases the duct pressure setpoint.

This strategy maximizes fan energy savings because the duct static pressure setpoint is reset *before* the SA temperature. However, the SA temperature may rarely be reset upward. This is because all zone cooling loads must be low enough such that all VAV dampers are partially closed when the duct static pressure setpoint is at its minimum before the SA temperature setpoint is reset at all.

Reset based upon outdoor air temperature and VAV damper position. The third method combines the previous two strategies to reset SA temperature as a function of both outdoor air temperature and VAV damper position. The SA temperature setpoint reset is based upon outdoor air dry-bulb temperature, as previously described.

However, the VAV damper positions are monitored to ensure that no zones are overheating. This is especially useful when it's cool outside and warm SA temperatures cannot provide sufficient cooling to an interior zone, like a conference room. A wide-open damper indicates that additional cooling is needed and the SA temperature may not be cool enough. When a wide-open damper is reported, the system can determine if it has reset too much and respond by again lowering the SA temperature setpoint.

This strategy is illustrated in Figure 6. The design SA temperature setpoint is 55°F but can be reset upward by as much as 5 degrees to 60°F during cooler outdoor temperatures. When the outdoor air temperature is above 65°F, no reset occurs and the system delivers 55°F air. The temperature at which reset begins (below 65°F) can be adjusted to suit the climate and installation.

Considerations for supply-air-temperature reset. The economizer high-limit shutoff setpoint temperature is often used as the setpoint to begin SA temperature reset.

The amount of reset can vary as well. Systems serving zones that require more cooling year-round (e.g. interior conference rooms) should limit the amount of reset, while systems that serve zones with a mixture of heating and cooling typically benefit from higher SA temperatures.

Some designers might choose to monitor indoor space humidity levels as well. When space humidity rises above a specific threshold, say 60 percent RH, the SA temperature is reset downward to increase the dehumidification performed by the cooling coil. Similarly, designers may choose to monitor outdoor dew-point temperature to limit or disable reset during humid weather. For example, when the outdoor air dew-point temperature is greater than 60°F, the SA temperature might not be allowed to reset upward to avoid adding humid air to the spaces.

The ability to automatically disable supply-air-temperature reset during humid outdoor or indoor conditions should alleviate concerns about its implementation negatively affecting occupant comfort.

What do others say about supply-air- temperature reset? The California Energy Commission (CEC) published the "Advanced VAV System Guideline" in October 2003. In it, different SA temperature reset methodologies were evaluated using energy modeling. Based on the results, they stated: "it appears that it is best to reset the supply air temperature upwards until the outdoor air temperature exceeds 65°F or 70°F, then reduce the supply-air temperature to [the minimum] in order to minimize fan energy and rely on the chiller for cooling." [2]

This is reinforced by earlier research from Texas A&M University. In a study, they found that resetting the SA temperature upward during mild weather (below approximately 72°F) was optimal for a VAV system serving a 3-story building [3]. The optimal SA temperature schedule from the study is reproduced as Figure 7.

In both cases, it was found that keeping the SA cold (rather than resetting upward) during warmer weather was more efficient. The CEC guideline concludes that "the recommended control sequence is to lead with supply temperature setpoint reset in cool weather where reheat might dominate the equation and to keep the chillers off as long as possible, then return to a fixed low setpoint in warmer weather when the chillers are likely to be on. During reset, employ a demand-based control that uses the warmest supply air temperature that satisfies all of the zones in cooling."

Figure 6. Supply-air-temperature reset based upon outdoor air temperature and VAV damper position

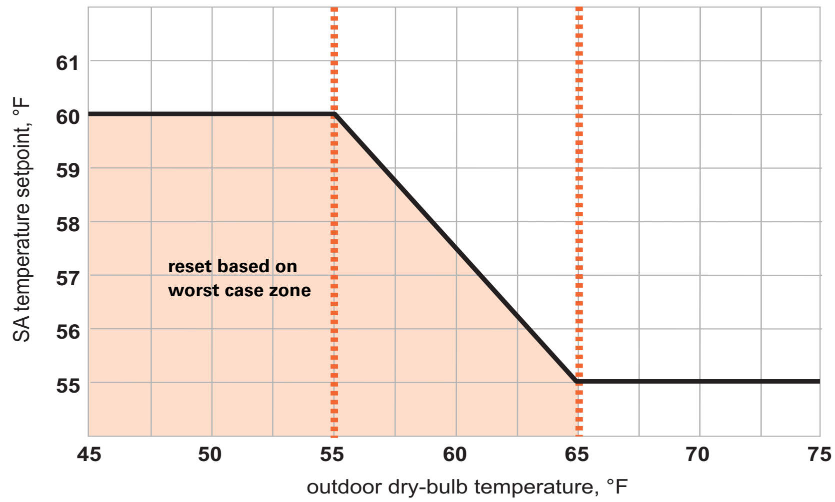
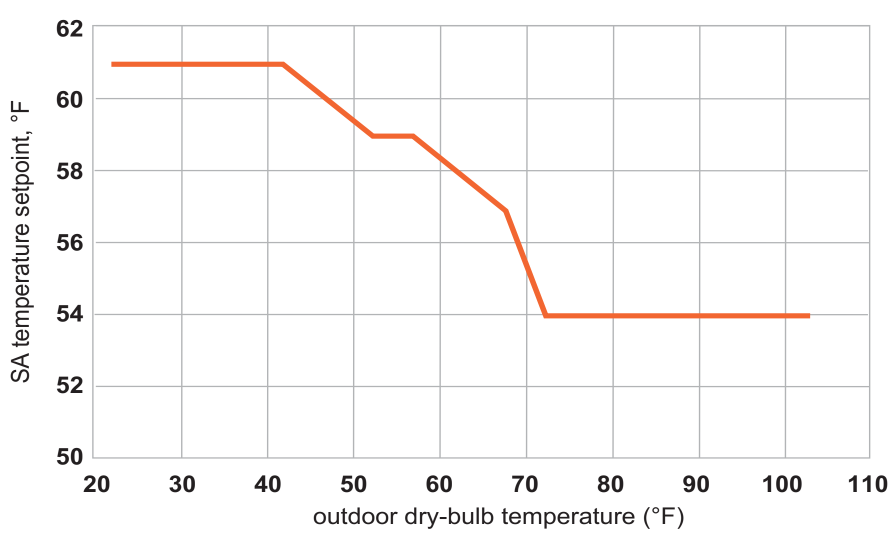


Figure 7. Optimal SA temperature schedule from Texas A&M University



ASHRAE's Proposed Guideline 36

In January 2014, ASHRAE authorized the creation of Proposed Guideline 36, *High Performance Sequences of Operation for HVAC Systems*, with the purpose to "provide uniform sequences of operation for heating, ventilating, and air-conditioning (HVAC) systems that are intended to maximize HVAC system energy efficiency and performance, provide control stability, and allow for real-time fault detection and diagnostics."

The proposed guideline would provide "detailed sequences of operation" for systems and "functional tests that when performed will confirm implementation of the sequences of operation."

The first public review draft suggested that during the occupied mode, the highest SA temperature for a VAV system should be 65°F in mild and dry climates and 60°F in humid climates. The authors warn that SA temperatures greater than 65°F "may lead to excessive fan energy that can offset the mechanical cooling savings from economizer operation."

The authors suggest when reset should occur for typical outdoor air dry-bulb temperatures:

- The minimum (coldest) SA temperature should be delivered whenever outdoor temperatures are warmer than 70°F.
- The maximum reset SA temperature should be delivered whenever outdoor temperatures are cooler than 60°F.

The proposed guideline also includes a description and example of trim and respond setpoint reset logic. This logic allows requests to reset the SA temperature or static pressure setpoints to be sent to the central controller. Each zone and request type can be assigned an importance multiplier greater than one to increase the rank of the specific zone within the algorithms. Rogue zones are identified using the request-hours data point. The default logic triggers an alarm indicating a rogue zone when a specific zone has run hours exceeding 40 and request-hours greater than 70 percent.

This is consistent with reset based upon outdoor air temperature and VAV damper position, as shown in Figure 6.

This same approach is recommended in the public review draft of ASHRAE Guideline 36 (see sidebar).

Combining supply-air-temperature reset and fan pressure optimization. Some designers might choose to minimize fan power by resetting duct pressure downward first, then raising the SA temperature setpoint later, as discussed in "Reset based upon VAV damper position."

Others might choose to reset both SA temperature and static pressure setpoints simultaneously, as discussed in "Reset based upon outdoor air temperature and VAV damper position." In this case, both SA temperature reset and fan pressure optimization might use the same control point—VAV damper position—to determine operation. Some SA temperature reset strategies use the position of the VAV dampers to determine when to end reset and return the SA temperature to the design setpoint. On the other hand, fan pressure optimization attempts to keep at least one VAV damper nearly wide open to reduce fan energy. These two control loops using the same data could result in some conflicts during operation, so careful programming of the control loops is essential.

Determining when to reset and optimize one system variable before another is complex. The decision could be based upon weather conditions, building loads, HVAC system type, and so on. Designers should consider evaluating options through energy modeling, then coordinate strategies with the controls vendor, programmer, and building operators.

Conclusion

Fan pressure optimization and supply-air temperature reset are both energy conservation measures, prescriptively required by ASHRAE Standard 90.1 (see sidebar). They can be implemented relatively easily with modern controls. Both have been used simultaneously to significantly reduce the energy usage and operational cost of multiple-zone VAV systems. Not using one or both should be the exception. Too often energy savings is left on the table.

By Eric Sturm, applications engineer, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/EN. To comment, send e-mail to ENL@trane.com.

ASHRAE Standard 90.1 Requirements - Supply Air Temperature Reset

ANSI/ASHRAE/IES Standard 90.1 has prescriptively required SA temperature reset for multiple-zone systems for many years. The requirements allow SA temperature to be automatically reset in response to either building load or outdoor air temperature.

Section 6.5.3.4 of the 2013 version of the standard requires the SA temperature be reset by at least "25 percent of the difference between the design SA temperature and the design room air temperature." The standard also permits control of reset based upon zone humidity. Finally, it suggests zones with constant internal loads be designed for the reset SA temperature instead of the design SA temperature.

There are three exceptions to this requirement:

1. Installations in hot and humid climate zones 1A, 2A, and 3A
2. Systems that prevent reheating, recooling, or mixing of heated and cooled SA
3. Systems that source at least 75 percent of the annual energy used for reheat from site-recovered or site-solar energy

So for instance, consider an installation at Flamborough Head on the Yorkshire coast of England where the climate is cool and humid. Here, the design SA temperature is 55°F and the space cooling setpoint temperature is 75°F. The amount of reset needs to be at least 5°F, which is 25 percent of the difference of 20°F. In this case, the controller should be programmed to reset from 55°F to at least 60°F to comply. Because this is a coastal location, the designers may choose to monitor indoor humidity and discontinue reset when indoor relative humidity surpasses a threshold- perhaps 60 percent RH.

ASHRAE Standard 90.1 Requirements - Fan Pressure Optimization

ASHRAE Standard 90.1 has prescriptively required the static pressure setpoint to be reset for VAV systems when the system uses DDC controls and a central/system controller for many years. Section 6.5.3.2.3 of the 2013 version also requires:

- System controls must monitor damper position or "other indicator of need for static pressure"
- Automatic detection of rogue zones and notification of these to the system operator
- Ability for the system operator to remove zones from the reset algorithm

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[1] Stanke, D., "VAV System Optimization Critical Zone Reset," Trane *Engineers Newsletter,* vol. 20, no. 2, 1991.

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[3] G. Wei, M. Liu and D. Claridge, "Optimize the Supply Air Temperature Reset Schedule for a Single-Duct VAV System," in Proceedings of the Twelfth Symposium on Improving Building Systems in Hot and Humid Climates, San Antonio, 2000.

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- **CVHS Library Trane Series S CenTraVac™ chiller is now available as cooling equipment library in the program.** This can be found in the water-cooled chiller category. Remember, you can still import Trane equipment selections from TOPSS® into TRACE.

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