

## energy-saving control strategies for Rooftop VAV Systems

Rooftop variable-air-volume (VAV) systems are used to provide comfort in a wide range of building types and climates. This system consists of a packaged rooftop air conditioner that serves several individually-controlled zones. Each zone has a VAV terminal unit that is controlled by a temperature sensor in the zone.

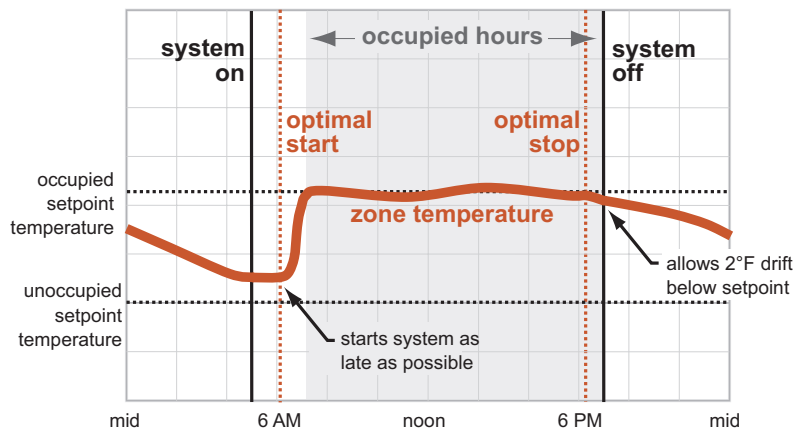
This EN discusses HVAC system control strategies that can be used to save energy in rooftop VAV systems.

**Optimal Start/Stop.** In some buildings, a simple time clock or time-of-day schedule is used to start and stop the HVAC system. During hours when the building is expected to be unoccupied, the system is shut off and the temperature is allowed to drift away from the occupied setpoint. The time at which the system starts again in the morning is typically set to ensure that the indoor temperature reaches the desired occupied setpoint prior to occupancy on either the coldest or warmest morning of the year. As a result, for most days, the system starts much earlier than needed. In turn, this increases the number of operating hours and system energy use.

An alternative approach is a strategy called *optimal start*. This strategy utilizes a building automation system (BAS) to determine the length of time required to bring each zone from current temperature to the occupied setpoint temperature. The system waits as long as possible before starting, so that the temperature in each zone reaches occupied setpoint just in time for occupancy (Figure 1). This optimal starting time is determined using the difference

between actual zone temperature and occupied setpoint. It compares this difference with the historical performance of how quickly the zone has been able to warm up or cool down.

**Figure 1. Optimal start and optimal stop**



The optimal start strategy reduces the number of system operating hours and saves energy by avoiding the need to maintain the indoor temperature at occupied setpoint even though the building is unoccupied.

A related strategy is *optimal stop*. As mentioned earlier, at the end of the occupied period, the system is shut off and the temperature is allowed to drift away from occupied setpoint. However, the building occupants may not mind if the indoor temperature drifts just a few degrees before they leave for the day.

Optimal stop uses the BAS to determine how early heating and cooling can be shut off for each zone, so that the indoor temperature drifts only a few degrees from occupied

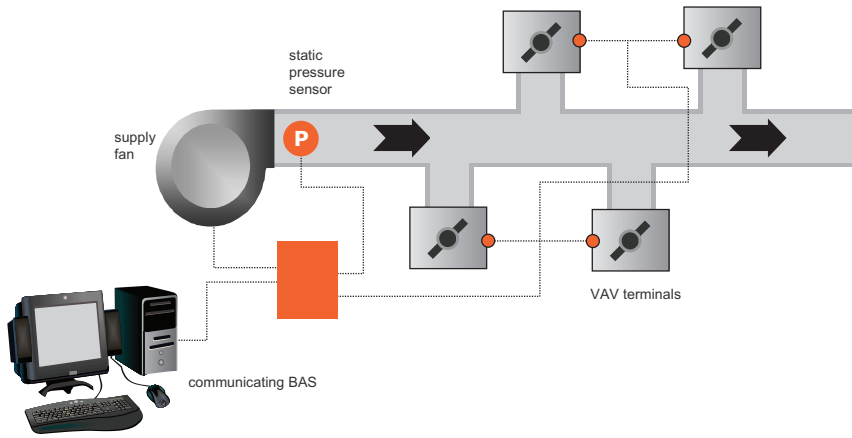
setpoint (Figure 1). In this case, only cooling and heating are shut off; the supply fan continues to operate and the outdoor-air damper remains open to continue ventilating the building.

The optimal stop strategy also reduces the number of system operating hours, saving energy by allowing indoor temperatures to drift early.

**Fan-Pressure Optimization.** As cooling loads change, the VAV terminals modulate to vary airflow supplied to the zones. This causes the pressure inside the supply ductwork to change. In many systems, a pressure sensor is located approximately two-thirds of the distance down the main supply duct. The rooftop unit varies the capacity of the supply fan to maintain the static pressure in this location at a constant setpoint. With this approach, however, the system usually generates more static pressure at part load than necessary.

When communicating controllers are used on the VAV terminals, it is possible to optimize this static-pressure control function to minimize duct pressure, and save fan energy. Each VAV unit controller knows the

**Figure 2. Fan-pressure optimization**



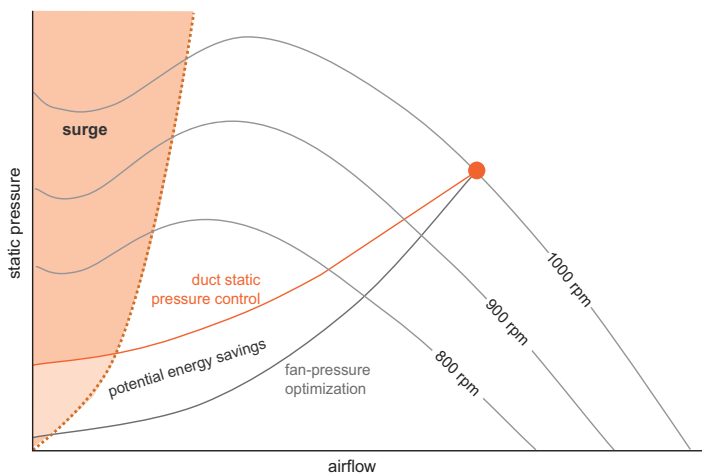
current position of its air-modulation damper. The BAS continually polls these individual controllers, looking for the VAV terminal with the most-open damper (Figure 2). The setpoint for the supply fan is then reset to provide just enough pressure so that at least one damper is nearly wide open. This results in the supply fan generating only enough static pressure to push the required quantity of air through this "critical" VAV terminal unit.

This control strategy, sometimes called fan-pressure optimization, has several benefits:

- **Reduced supply fan energy use.** At part-load conditions, the supply fan is able to operate at a lower static pressure and consume less energy (Figure 3).

- **Lower sound levels.** The supply fan does not generate as much static pressure and will typically generate less noise. In addition, with lower pressures in the supply duct, the dampers in the VAV terminals will be more open, resulting in less regenerated noise.
- **Reduced risk of fan surge.** By allowing the fan to operate at a lower pressure when delivering reduced airflow, the fan operating point is kept further away from the surge region (Figure 3).
- **Flexibility of sensor location.** Since this strategy uses the position of VAV dampers to reset the pressure setpoint, the static-pressure sensor can be located anywhere in the supply duct. It can even be located at the discharge of the fan, allowing

**Figure 3. Benefits of fan-pressure optimization**



it to be installed inside the rooftop unit and tested at the factory. In this location, it can also serve as the duct high-pressure sensor, protecting the ductwork from damage in the event of a fire damper closing.

**Supply-Air-Temperature Reset .** In a VAV system, it is tempting to raise the supply-air (SA) temperature at part-load conditions to save compressor and/or reheat energy. Increasing the supply-air temperature reduces compressor energy because it allows the compressor to operate at a warmer suction temperature. The corresponding higher suction pressure reduces the compressor lift, reducing the power required.

In addition, supply-air-temperature reset makes an airside economizer more beneficial. When the outdoor air is cooler than the SA temperature setpoint, the compressors are shut off, and the outdoor- and return-air dampers modulate to deliver the desired supply-air temperature. A warmer SA temperature setpoint allows the compressors to be shut off sooner and increases the number of hours when the economizer is able to provide all the necessary cooling.

For zones with very low cooling loads, when the supply airflow has been reduced to the minimum setting of the VAV terminal, raising the supply-air temperature also decreases the use of reheat at the zone level.

However, because the supply air is warmer, zones that require cooling will need more air to satisfy the cooling load. This increases supply fan energy.

Finally, in non-arid climates, warmer supply air means less dehumidification at the coil and higher humidity levels in the zones. If dehumidification is a concern, use caution when implementing this strategy.

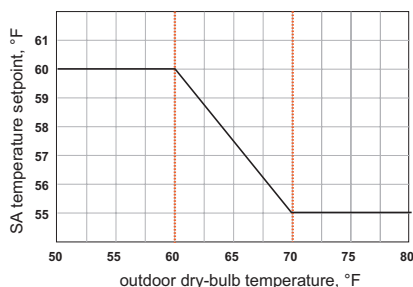
Supply-air-temperature reset should be implemented so that it minimizes overall system energy use. This requires considering the trade-off between compressor, reheat, and fan

energy, as well as the impact on space humidity levels. Table 1 contains some general guidance to determine when this strategy might provide the most benefit.

These competing issues are often best balanced by first reducing supply airflow, taking advantage of the significant energy savings from unloading the fan. Once fan airflow has been reduced, raise the supply-air temperature to minimize reheat energy and enhance the benefit of the airside economizer. While one could dream up numerous control schemes, the simplest approach is probably most common. Figure 4 shows an example of a supply-air-temperature reset strategy based on the changing outdoor dry-bulb temperature.

When the outdoor temperature is warmer than 70°F, no reset takes place and the SA temperature setpoint remains at the design value of 55°F. When it is this warm outside, the outdoor air provides little or no cooling benefit for economizing. The cooling load in most zones is likely high enough that reheat is not required to prevent overcooling. In addition, the colder (and drier) supply air allows the system to provide sufficiently dry air to the zones, improving part-load dehumidification.

**Figure 4. Supply-air-temperature reset based on OA temperature**



When the outdoor temperature is between 60°F and 70°F, the SA temperature setpoint is reset at a 2-to-1 ratio. That is, for every 2°F change in outdoor temperature, the setpoint is reset 1°F. In this range, supply-air-temperature reset enhances the benefit provided by the economizer

**Table 1. Supply-air-temperature reset**

Conditions that favor using supply-air-temperature reset	Comments
Mild climates that have many hours when outdoor dry-bulb temperature is below 60°F	In this type of climate, the economizer-related benefits typically outweigh the impact on increased supply fan energy.
Systems with VAV terminals that have minimum airflow settings higher than 30% of design airflow	Higher minimum airflow settings increase the likelihood that reheat will be needed to avoid overcooling the zones.
Efficient air distribution system design	Low pressure losses result in less of a fan energy penalty for the higher airflows that result from raising SA temperature.
Systems with interior zones that have varying cooling loads	The variable loads might allow these zones to still be satisfied with a warmer supply-air temperature.
Conditions that reduce the potential to save energy with supply-air-temperature reset	Comments
Hot climates that have relatively few hours when the outdoor dry-bulb temperature is below 60°F	In this type of climate, the economizer-related benefits are minimal.
Systems with efficient part-load fan modulation	Using a VFD on the supply fan, and/or the fan-pressure optimization control strategy, may make it more advantageous to reduce supply airflow to save fan energy, rather than increase airflow and save compressor energy.
Inefficient air distribution system design	High pressure losses result in a significant fan energy penalty for the higher airflow that accompanies a warmer supply-air temperature.
Systems that serve some zones that have nearly-constant cooling loads	These zones will require near-design airflow during all occupied hours, limiting the ability to raise supply-air temperature. Investigate using a separate system to serve these zones.

Source: California Energy Commission, Advanced Variable Air Volume System Design Guide, 2003.

and it is likely that some zone-level reheat can be avoided.

Finally, when the outdoor temperature is colder than 60°F, no further reset occurs, and the SA temperature setpoint remains at 60°F. Limiting the amount of reset to 60°F allows the system to satisfy the cooling loads in interior zones without needing to substantially oversize VAV terminals and ductwork.

Alternatively, some systems reset the SA temperature setpoint based on the temperature in the "critical" zone. This is the zone that is most nearly at risk of overcooling, which would require activating local reheat. A building automation system (BAS) monitors the temperature in all zones, finding the critical zone that is closest to heating setpoint. The rooftop unit then resets the SA temperature setpoint to prevent this critical zone from needing to activate reheat.

When considering using supply-air-temperature reset in a rooftop VAV system:

- First analyze the system to determine if the savings in compressor and reheat energy will outweigh the increase in fan energy.
- If higher space humidity levels are a concern, consider either disabling reset when it is humid outside, or providing one or more humidity sensors to override the reset function whenever humidity in the zone exceeds some maximum limit.
- For interior zones with near-constant cooling loads during occupied periods, calculate design airflows for those zones based on the warmer, reset supply-air temperature (60°F in the example from Figure 4). While this may require larger VAV terminals and ductwork, it allows the use of supply-air-temperature reset during

cooler weather, while still providing the necessary cooling to those weather-independent, interior zones.

- Design the air distribution system for low pressure losses and use the fan-pressure optimization strategy to minimize the fan energy penalty that accompanies a warmer SA temperature.

**Ventilation Optimization .** In a typical VAV system, the rooftop unit delivers fresh outdoor air to several, individually-controlled zones. Demand-controlled ventilation (DCV) involves resetting intake airflow in response to variations in zone population. While commonly implemented using carbon dioxide (CO<sub>2</sub>) sensors, occupancy sensors, or time-of-day (TOD) schedules can also be used.

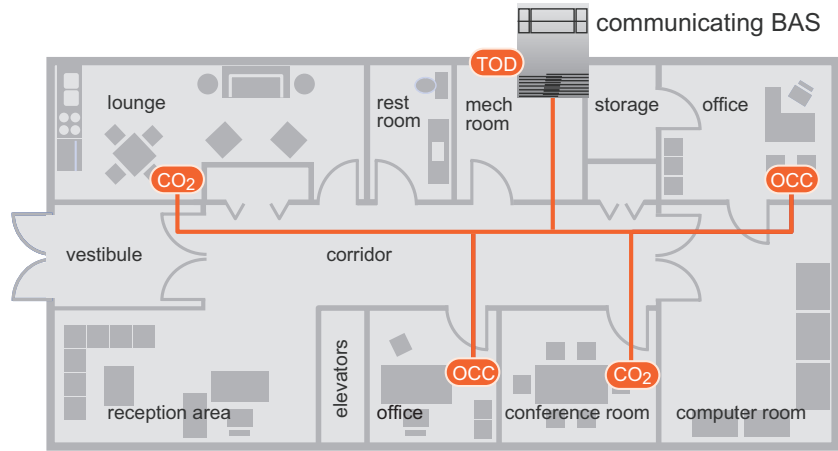
Ventilation reset involves resetting intake airflow based on variations in system ventilation efficiency.

One approach to optimizing ventilation in a multiple-zone VAV system is to combine the various DCV strategies at the zone level (using each where it best fits) with ventilation reset at the system level.

With this strategy, CO<sub>2</sub> sensors are installed only in those zones that are densely occupied and experience widely varying patterns of occupancy. For the example building in Figure 5, CO<sub>2</sub> sensors are installed only in the conference room and the lounge. These zones are the best candidates for CO<sub>2</sub> sensors, and provide "the biggest bang for the buck." These sensors reset the ventilation requirement for their respective zones based on measured CO<sub>2</sub>.

However, zones that are less densely occupied or have a population that varies only a little (such as private offices, open plan office spaces, or many classrooms) are probably better suited for occupancy sensors. In Figure 5, each of the private offices has an occupancy sensor to indicate when the

**Figure 5. Demand-controlled ventilation at the zone level**



occupant is present. When unoccupied, the controller lowers the ventilation requirement for the zone. Occupancy sensors are relatively inexpensive, do not need to be calibrated, and are already used in many zones to control the lights.

Finally, zones that are sparsely occupied or have predictable occupancy patterns may be best controlled using a time-of-day schedule. This schedule can either indicate when the zone will normally be occupied vs. unoccupied, or can be used to vary the zone ventilation

requirement based on anticipated population.

These various zone-level DCV strategies can be used to reset the ventilation requirement for their respective zones for any given hour. This zone-level control is then tied together using ventilation reset at the system level (Figure 6).

In addition to resetting the zone ventilation requirement, the controller on each VAV terminal continuously monitors primary airflow being delivered to the zone. The BAS

#### Unoccupied Humidity Control

A VAV system typically dehumidifies effectively over a wide range of operating conditions because it continues to deliver cold, dry air at part-load conditions. As long as supply-air-temperature reset is used with caution, and reheat is available for those VAV terminals that have high minimum airflow settings or experience very low cooling loads, a VAV system will typically provide supply air at a dew point that's low enough to prevent elevated indoor humidity levels during occupied periods.

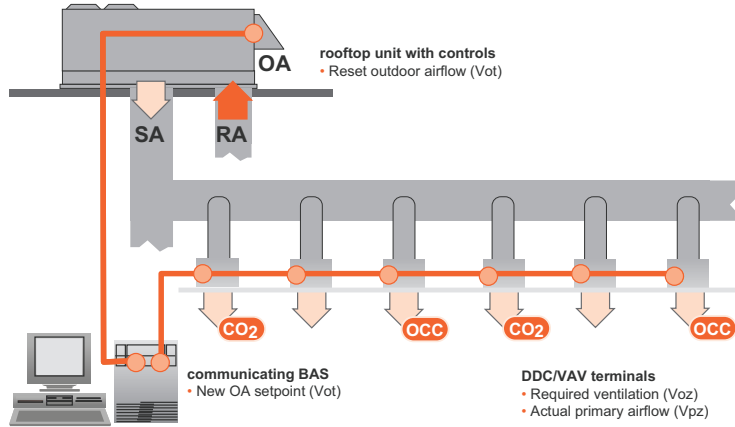
However, controlling humidity levels isn't only a priority when the building is occupied. When indoor humidity rises too high during unoccupied times, one option is to turn on the rooftop unit and dehumidify recirculated air to 55°F or so. However, there is typically very little sensible load in the zones during these

periods, so delivering this cold air will result in overcooling. Reheat coils in the VAV terminals, and possibly a boiler and hot water pumps, will need to be activated.

An energy-saving alternative is to equip the rooftop unit with hot gas reheat. When after-hours dehumidification is needed, the rooftop unit turns on and diverts hot refrigerant vapor leaving the compressor through a refrigerant-to-air heat exchanger that is located in the airstream, following the evaporator coil. Sensible heat is transferred from the hot refrigerant to reheat the dehumidified air leaving the evaporator.

This strategy uses heat recovered from the refrigeration circuit to reheat centrally, and saves energy by avoiding the use of new energy to reheat remotely at the VAV terminals.

**Figure 6. Ventilation reset at the system level**



periodically gathers this data from all VAV terminals and solves the ventilation reset equations (prescribed by ASHRAE Standard 62) to determine how much outdoor air must be brought in at the rooftop unit to satisfy all zones served. Finally, the BAS sends this outdoor airflow setpoint to the rooftop unit which modulates a flow-measuring outdoor-air damper to maintain this new setpoint.

In a DDC/VAV system, this strategy is fairly easy to implement because the necessary real-time information is already available digitally. Combining DCV at the zone level with ventilation reset at the system level has the following benefits:

- Assures that each zone is properly ventilated without requiring a CO<sub>2</sub> sensor in every zone. CO<sub>2</sub> sensors are used only in those zones in which they will bring the most benefit. This minimizes installed cost and avoids the periodic calibration and cleaning required to assure proper sensor operation. For the other zones, occupancy sensors and time-of-day schedules are used to reduce ventilation.
- Enables documentation of actual ventilation system performance. The VAV controllers communicate the ventilation airflow for every zone to the BAS, even for those zones that do not have a CO<sub>2</sub> sensor. The BAS can be used to generate reports showing

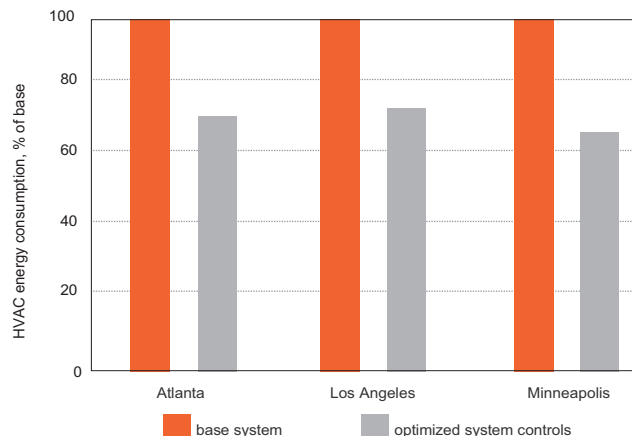
ventilation airflow (cfm) in every zone for every hour.

- Uses system-level ventilation reset equations that are explicitly defined in an industry-wide standard. Using equations from ASHRAE 62 improves the "defend-ability" of the control strategy.

**Summary.** The impact of any energy-saving strategy on the operating cost of a specific building depends on climate, building usage, and utility costs. Building analysis tools (like TRACETM 700) can be used to analyze these strategies and convert energy savings to operating cost dollars that can be used to make financial decisions.

Figure 7 shows the potential energy savings of using these various

**Figure 7. Energy-saving potential of optimized control**



strategies in an office building that has a typical rooftop VAV system. The optimized system uses the optimal start, supply-air-temperature reset, and ventilation optimization strategies discussed in this EN. In addition, the supply fan is controlled based on fan-pressure optimization, rather than on a constant setpoint in the ductwork.

The optimized rooftop VAV system reduced the HVAC energy use by about 30% for the building in both Atlanta and Los Angeles, and by 33% in Minneapolis.

There is a real potential to save energy in rooftop VAV systems through optimized system control strategies. This savings reduces operating costs for the building owner and can help in achieving points toward LEED® certification.

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