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Making VAV Great Again

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Variable air volume (VAV) systems were "the next best thing" when they were developed in the 1970s and soon became the de facto system of choice for commercial buildings and the baseline system for energy standards such as ASHRAE Standard 90.1[1] and California's Title 24.[2] Over the following decades, new system types were created in an effort to surpass the energy efficiency and comfort control performance of VAV systems and become the "next, next best thing." These systems include underfloor air distribution, chilled beams, variable refrigerant flow, and in-slab radiant.

My engineering staff and I have studied these systems in depth, and designed and installed many of them, but for most building types, we have yet to find any that perform better on a life-cycle cost basis than a "well-designed" VAV system, which we find is almost always less expensive and usually more energy efficient, at least in the mild climates where we practice. "Well-designed" is in quotes because one significant negative aspect of VAV systems is that they are easily designed poorly, rendering their performance on par with the constant volume systems they replaced in the 1970s. But two recent ASHRAE publications, discussed in this month's column, make it much easier to design high performance VAV systems, perhaps making VAV "the next best thing" once again.

Guideline 36

The first edition of ASHRAE Guideline 36, *High-Performance Sequences of Operation for HVAC Systems*[3] was published in June 2018. The Guideline was created to publish and maintain "best in class" sequences for HVAC systems. This first edition includes optimized control sequences for VAV air handlers and VAV terminal units.* Guideline 36 will ultimately be expanded to include sequences for heating and cooling plant and hydronic systems,[4] dedicated outdoor air systems,radiant heating and cooling systems, etc., whether developed from research projects or recommended by engineers, manufacturers, and contractors. Controls manufacturers are expected to preprogram the sequences into their controllers and verify the programming is correct with factory-performed functional tests. Then control contractors and dealers can simply use the programming directly with minimal configuration, significantly reducing programming and commissioning time.

Standardized advanced control sequences for common HVAC applications will reduce the cost of designing and installing control systems for all parties (design engineers, controls contractors, and commissioning agents), reduce maintenance costs through automatic fault detection, and, most importantly, improve HVAC system thermal comfort and energy performance and ensure compliance with energy and indoor air quality standards. Guideline 36 is truly a win-win-win for the building industry. See Hydeman, et al.,[5] for more details.

This edition of Guideline 36 is almost 100 pages long, so a complete discussion of the sequences included is not practical in this column. But listed below are examples of some of the more significant sequences.

Dual Maximum VAV Logic

Dual Maximum VAV logic[6] has been required by

*Air-handling system types include single zone VAV, multiple zone VAV, and dual-fan/dual duct VAV. VAV terminal types include cooling-only, single duct reheat, constant and variable volume parallel fan-powered, constant and variable volume series fan-powered, and four types of dual duct boxes.

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Standard 90.1 and Title 24 for VAV reheat terminal units for a decade, but neither document provides details for how to implement the logic. Guideline 36 provides detailed sequences enhanced with advanced logic for optimum start (warm-up or cool-down), demand limiting, occupancy sensor status, window switches, and CO_2 demand-controlled ventilation. *Figure 1* shows the mode setpoint table† and control diagram from Guideline 36. This logic has been shown to both reduce energy use and to improve thermal comfort in ASHRAE Research Project 1515[7] when combined with low minimum airflow setpoints.

Figure 2 shows the prevalence of airflow expressed as a percentage of design flow for each zone in the RP-1515 test buildings during summer months using conventional logic with 30% minimums and Dual Maximum logic with low minimums. (There is more discussion on how to determine minimum setpoints below.) Note the significant reduction in airflow rates, which results in lower fan energy, lower cooling energy, and significantly lower reheat energy use.

The improvement in thermal comfort is primarily due to reduced overcooling as demonstrated in *Figure 3*: when the actual airflow required to meet the cooling load is relatively low (the red line in *Figure 3*), conventional VAV logic pushes the zone into heating, resulting in space temperatures near the heating setpoint, e.g., 70°F (21°C) even in summer months when occupants are wearing lightweight clothing. Conversely, for the same cooling load, Dual Maximum logic results in temperatures near the cooling setpoint, e.g., 75°F (24°C), a much more comfortable temperature for occupants in summer clothing. RP-1515 found that cold complaints dropped 14% to 22% when Dual Maximum logic was implemented.

FIGURE 1 Guideline 36 VAV reheat setpoint and control diagram.

SETPOINT	OCCUPIED	COOL-DOWN	SETUP	WARM-UP	SETBACK	UNOCCUPIED
Cooling Maximum	$V_{cool\text{-}max}$	$V_{cool\text{-}max}$	$V_{cool\text{-}max}$	0	0	0
Cooling minimum	V_{min}*	0	0	0	0	0
Minimum	V_{min}*	0	0	0	0	0
Heating Minimum	Max ($V_{heat\text{-}min}$, V_{min}*)	$V_{heat\text{-}min}$	0	$V_{heat\text{-}max}$	$V_{heat\text{-}max}$	0
Heating Maximum	Max ($V_{heat\text{-}max}$, V_{min}*)	$V_{heat\text{-}max}$	0	$V_{cool\text{-}max}$	$V_{cool\text{-}max}$	0

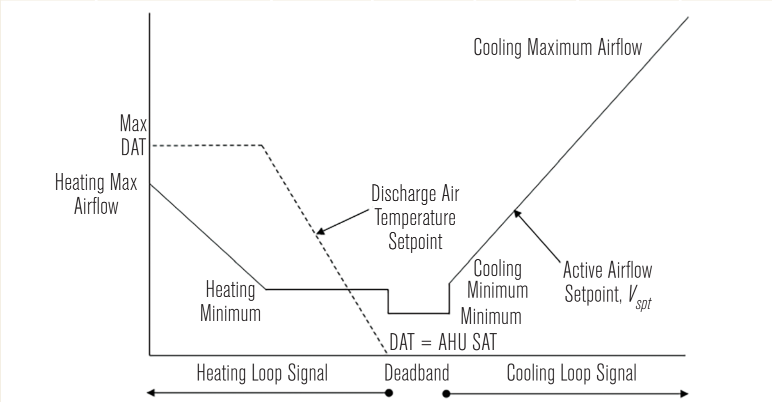
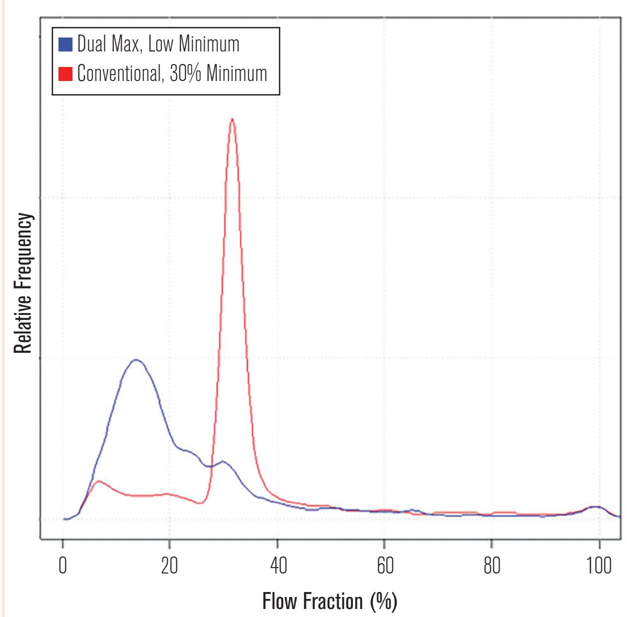


FIGURE 2 RP-1515 airflow ratio distribution, warm season.

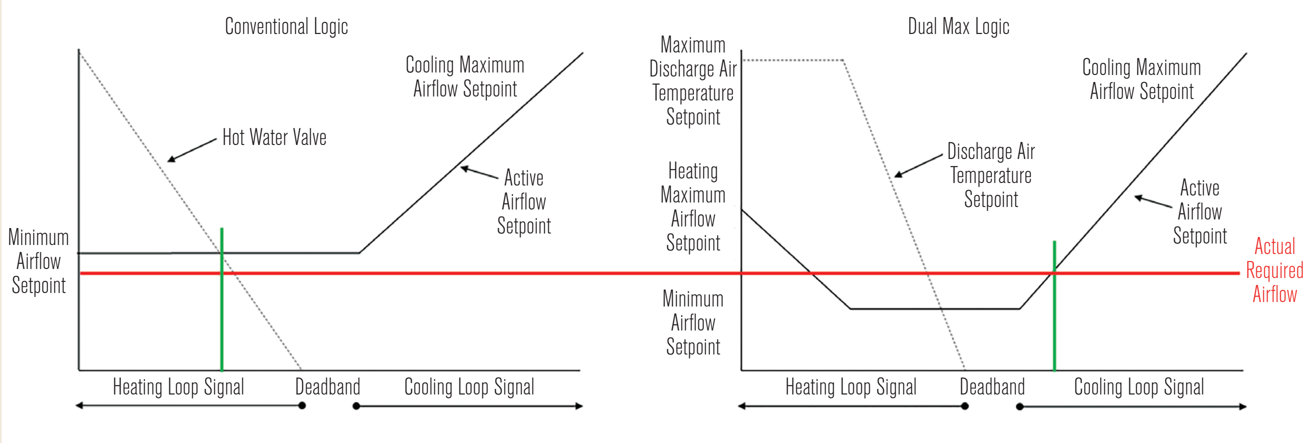


Static Pressure Setpoint Reset

Static pressure setpoint reset has been required by Standard 90.1 and Title 24 for VAV systems for decades, but once again neither document provides details for how to implement the logic. Guideline 36 uses Trim & Respond logic[8] to reset static pressure setpoint based on VAV box damper position. The logic trims the setpoint to try to keep the most open VAV box damper fully open,

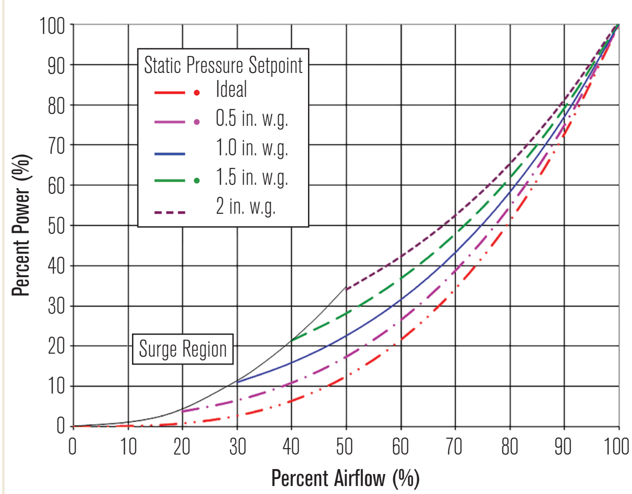
†Setpoint definitions in this table: $V_{cool\text{-}max}$ = cooling maximum, $V_{heat\text{-}max}$ = heating maximum, V_{min}* is the occupied minimum setpoint adjusted for dynamic parameters such as window switches, occupancy sensors, and CO_2 DCV.

FIGURE 3 Thermal comfort impact of dual maximum logic.



i.e., the setpoint is as low as it can be to satisfy all zones. *Figure 4* shows the impact of static pressure setpoints on fan power, including "ideal" reset from damper position. "Ideal" reset is not possible with real systems due to modulating VAV dampers varying system geometry, non-simultaneous variations in zone loads, and other factors. Nevertheless, field studies and simulations have demonstrated that damper position reset can reduce fan energy on the order of 30% to 50% compared to fixed setpoints.[9,10,11]

FIGURE 4 VAV fan performance as a function of static pressure setpoint (Design SP = 4.5 in. w.g.).



Economizer High Limits

Standard 90.1 and Title 24 stipulate the outdoor air conditions at which outdoor air economizers must be shut off. Unfortunately, it is common for engineers and building operators to overlook these requirements, typically setting high limits too low which causes economizers to be unnecessarily disabled for many hours per year. To minimize the chance for errors, Guideline 36 determines the setpoints automatically from the current standards (e.g., *Table 1* for Standard 90.1) based on the climate zone and high limit type specified by the designer. This is similar to some packaged unit economizer controllers where setpoints are determined automatically by the user simply entering ASHRAE climate zone number or zip code.[12]

Addendum 62.1*f*

Addendum *f* to Standard 62.1-2016,[13] approved in May 2018, created a Simplified Procedure for determining outdoor air rates for multiple zone recirculating air-handling systems that includes a simple prescriptive requirement for calculating air-handling system ventilation efficiency (which in turn is used to determine the air handler minimum outdoor air rate) as well as minimum setpoints for VAV zones. The following paraphrases the new procedure:

6.2.5.3 Simplified Procedure

6.2.5.3.1 System Ventilation Efficiency. System Ventilation Efficiency (E_v) shall be determined in accordance with Equation 6.2.5.3.1A or B as a function of occupant diversity, *D*.

$$E_v = 0.88 \times D + 0.22 \text{ for } D<0.60 \quad (6.2.5.3.1A)$$

$$E_v = 0.75 \text{ for } D \geq 0.60 \quad (6.2.5.3.1B)$$

6.2.5.3.2 Zone Minimum Primary Airflow. For each zone, the minimum primary airflow ($V_{pz\text{-}min}$) shall be determined in accordance with equation 6.2.5.3.2 based on zone minimum outdoor airflow rate, V_{oz}.

$$V_{pz\text{-}min} = V_{oz} \times 1.5 \quad (6.2.5.3.2)$$

This Simplified Procedure may be used in lieu of the more comprehensive procedure that uses the so-called Multiple Spaces Equation (MSE). To determine VAV zone minimum setpoints using the MSE is very complicated, involving many assumptions about occupancy and airflow rates and requiring multiple iterations to find the critical zone, adjust the system outside air rate and/or zone minimum, and repeat until the perceived lowest energy solution is reached. This complexity and uncertainty is now eliminated with this addendum.

TABLE 1 Standard 90.1-2016 economizer high limits.

CONTROL TYPE	ALLOWED ONLY IN CLIMATE ZONE AT LISTED SETPOINT	REQUIRED HIGH-LIMIT SETPOINTS (ECONOMIZER OFF WHEN): EQUATION	DESCRIPTION
Fixed Dry-Bulb Temperature	0B, 1B, 2B, 3B, 3C, 4B, 4C, 5B, 5C, 6B, 7, 8	T_{OA} > 75°F	Outdoor Air Temperature Exceeds 75°F
	5A, 6A	T_{OA} > 70°F	Outdoor Air Temperature Exceeds 70°F
	0A, 1A, 2A, 3A, 4A	T_{OA} > 65°F	Outdoor Air Temperature Exceeds 65°F
Differential Dry-Bulb Temperature	0B, 1B, 2B, 3B, 3C, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, 8	T_{OA} > T_{RA}	Outdoor Air Temperature Exceeds Return Air Temperature
Fixed Enthalpy With Fixed Dry-Bulb Temperature	All	h_{OA} > 28 Btu/lb[a] or T_{OA} > 75°F	Outdoor Air Enthalpy Exceeds 28 Btu/lb[a] of Dry Air[a] or Outdoor Air Temperature Exceeds 75°F
Differential Enthalpy With Fixed Dry-Bulb Temperature	All	h_{OA} > h_{RA} or T_{OA} > 75°F	Outdoor Air Enthalpy Exceeds Return Air Enthalpy or Outdoor Air Temperature Exceeds 75°F

Table 2 shows the VAV box minimums for a few common occupancy types with these options:

TABLE 2 Zone VAV box minimum $V_{pz\text{-}min}$ (cfm/ft^2).

	$V_{pz\text{-}min}$ WITHOUT DCV		$V_{pz\text{-}min}$ WITH DCV	
OCCUPANCY CATEGORY	OVERHEAD HEATING E_z=0.8	OTHER E_z=1.0	OVERHEAD HEATING E_z=0.8	OTHER E_z=1.0
Auditorium Seating Area	1.52	1.22	0.11	0.09
Classrooms (Age Nine Plus)	0.88	0.71	0.23	0.18
Conference/Meeting	0.58	0.47	0.11	0.09
Corridors	0.11	0.09	0.11	0.09
Office Space	0.16	0.13	0.11	0.09
Sales	0.44	0.35	0.23	0.18

- Demand Controlled Ventilation (DCV): With DCV, the minimums are based solely on the area (building) component of ventilation rate. CO_2 sensors are used to adjust the occupant component dynamically. These calculations are built into the Guideline 36 sequences.
- Overhead Heating: When warm air is supplied from overhead at a temperature more than 15°F (8°C) above the room temperature, the zone air distribution effectiveness (E_z) drops to 0.8, according to Standard 62.1. E_z for cooling and heating are variables in Guideline 36 sequences entered by the designer based on the air-distribution design. The adjustments for E_z are made dynamically based on real-time supply air and room temperatures.

Standard 90.1 currently allows VAV box minimum setpoints with Dual Maximum logic to be as high as 20% of the design supply air rate. Outdoor air rates are much lower than 20% of the maximum rate in many occupancy types, but designers often use 20% anyway to ensure they meet the MSE requirements. Moreover, using percentages to determine minimums is problematic because VAV boxes are almost always oversized due to conservative load assumptions for occupants, lights, plug loads, etc. It is not unusual for boxes to be sized three or more times larger than they need to be, as was found to be the case in ASHRAE RP-1515: *Figure 2* shows that airflow rates with conventional logic, even in summer months, seldom exceeded 40% and was predominantly at the 30% minimum setpoint—the VAV boxes were essentially sized ~three times larger than they needed to be. This is not atypical. *Figure 2* shows that even if the minimums were set to 20% instead of 30%, excess air would have been supplied for most hours. The "low minimums" for the Dual Maximum logic in *Figure 2* were based on the Title 24 ventilation rate for offices of 0.15 cfm/ft^2 (0.75 L/s·m^2), which is a bit higher than the Simplified Procedure rate for offices in *Table 2*. So, setting minimums to the new Simplified Procedure rates would have further reduced airflow and associated HVAC energy use.

No doubt, some readers are thinking: VAV boxes cannot control to setpoints that low! Not so. Here are the facts:

- Do not believe the setpoints in VAV box manufacturer's catalogs unless the VAV controller is provided by the same manufacturer. The VAV box typically includes an amplifying velocity pressure (VP) sensor only; the controller, which includes a transducer to convert VP to an analog electrical signal and an analog-to-digital converter, is usually provided by the controls manufacturer who is providing controls for the rest of the building. The VP sensor from almost all manufacturers have similar performance, e.g., they provide a very linear VP signal with an amplification factor above 2.0 for each box size. The most critical elements in determining how low the setpoint can be are the transducer and A/D converter. Given neither are provided by the VAV box manufacturers, how can they know what the minimum setpoint can be? They cannot. Instead most assume the minimum VP signal is very high, e.g., 0.03 in. w.g. (7.5 Pa), while some provide a range of airflow minimums as a function of a few VP readings, as low as 0.015 in. w.g. (3.7 Pa). In actuality, most VAV controllers can control to 0.004 in. w.g. (1 Pa) velocity pressure reading and VAV box VP sensors are stable and linear at this low pressure.[14,15] So, in almost all cases, the controllable minimums listed in VAV box manufacturer catalogs are much higher than they need to be.

- With Guideline 36, there is no need for the designer to determine what the controllable minimum is anyway! The Guideline places the burden of determining the controllable minimum on the installing controls contractor who knows best what the controllable VP signal is (because they are supplying the controller) and what the VP amplification factor is (because the VAV box manufacturer will be selected by this time and can provide these data). So, design engineers should not consider controllable minimum when setting VAV box minimums.
- Even if the designer had the information needed to determine the controllable minimum in the design phase, there is still no reason to consider it when determining minimum setpoints. This is because Guideline 36 includes sequences, called Time-Averaged Ventilation (TAV), that will allow supply air rates to be maintained that are below the controllable minimum. Standard 62.1 allows ventilation to be averaged over the nominal time constant of the space:

$$T = 3v/V_{bz} \text{ (I-P)} \qquad (6.2.6.2\text{-}1)$$

$$T = 50v/V_{bz} \text{ (SI)} \qquad (6.2.6.2\text{-}2)$$

where

T = averaging time period, min

v = the volume of the ventilation zone, ft^3 (m^3)

V_{bz} = the breathing zone outdoor airflow, cfm (L/s)

T is on the order of 5 hours for the typical office space and 1.5 hours for a densely occupied space like a conference room. Conservatively, the Guideline 36 TAV sequence pulses the VAV box minimum from zero to the controllable minimum every 1.5 minutes and ensures average minimum is maintained over a 15-minute window. A recent study[16] found TAV reduced fan energy 20%, cooling energy 23%, and reheat energy 41% when implemented on a project with conservative box manufacturer recommended controllable minimums.

Conclusions and Recommendations

The publication of Guideline 36 and Addendum 62.1*f* (forthcoming) greatly simplifies the design of high performing VAV systems. The designer can simply:

- Specify that all VAV system control sequences be in accordance with Guideline 36. The control sequence specification section need only say, "All control sequences shall be in accordance with Guideline 36."[‡]
- In VAV box schedules, list both area and occupant based outdoor air requirements.[§] The zone air distribution effectiveness, E_z, could also be listed in the schedule or just by a general note if they are the same for each zone. The minimum airflow setpoint is then simply calculated using Equation 6.2.5.3.2 above.** Again, there is no need to consider controllable minimums—Guideline 36 sequences fully address this issue. An example partial VAV box schedule is shown in *Table 3*.

VAV systems designed using these two procedures are Making VAV Great Again.

[‡]There are some control sequence options the designer will have to designate, but these could be determined later in the construction process via request for information from the controls contractor. A form is also being developed as an informative appendix to Guideline 36 for use by designers to indicate sequence options. Note also that there is no need to copy-and-paste Guideline 36 sequences into control specifications—simply refer to them. That also makes it easier on the controls contractor who would have a hard time knowing if any of the sequences had been edited.

[§]In addition to adjusting minimum airflow rates at the zone level, zonal outdoor air rates are also used to reset the air handler outdoor air rates to just that needed by occupied zones.

TABLE 3 Example partial VAV box schedule.

VAV BOX SCHEDULE									
TAG	INLET SIZE	DESIGN CFM			MIN OA CFM		ZONE E_z		CO_2 DCV?
		COOL	MIN	HEAT	AREA	PEOP	COOL	HEAT	
VR-101	6	300	102	120	18	50	1.0	0.8	Y
VR-102	8	540	90	270	16	44	1.0	0.8	Y
VR-103	12	1200	255	255	120	50	1.0	0.8	N

References

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**An addendum to Guideline 36 is being developed that would eliminate the need for the designer to calculate and schedule minimum setpoints; these setpoints instead would be dynamically calculated using the scheduled outdoor air rates adjusted for occupancy sensors, E_z, percentage of outdoor air, etc. This will further simplify the design process and further increase energy savings.

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