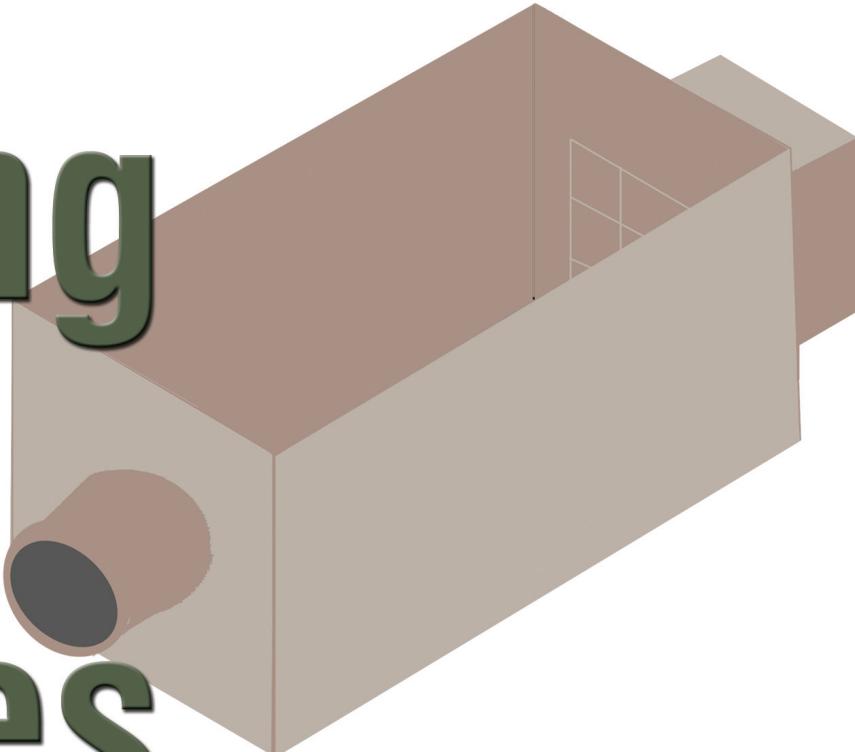


Sizing VAV Boxes



By Steven T. Taylor, P.E., Fellow ASHRAE, and Jeff Stein, P.E., Member ASHRAE

Selecting the inlet size of a variable air volume (VAV) terminal box requires the consideration of five factors: (1) pressure drop across the box; (2) ability of the VAV box controller to measure and control the desired minimum and maximum airflow setpoints; (3) first costs of the VAV box, its installation, and controls; (4) noise generation; and (5) space constraints.

The first three considerations affect energy costs and first costs and ideally should be balanced to minimize life-cycle cost (LCC). The last two considerations represent installation and application constraints that can limit the LCC optimum selection. This article summarizes a detailed analysis of VAV box control and selection¹ and provides VAV boxes sizing criteria that will minimize LCC in typical applications.

VAV Controls and Airflow Setpoints

Figure 1 shows a single duct VAV box

using pressure independent control logic. Pressure independent controls use two cascading control loops. The first loop controls space temperature; its output is an airflow setpoint limited to a range between the minimum airflow setpoint (V_{min}) and the maximum airflow setpoint (V_{max}). This setpoint is then sent to the second control loop, which modulates the VAV damper to maintain the box airflow rate at setpoint.

V_{max} and V_{min} are shown in Figure 2, a control schematic for a typical VAV reheat (VRH) box, and Figure 3, a control

schematic for a parallel fan-powered VAV (FPV) box. For both box types, V_{max} is typically the design cooling airflow rate. For VRH boxes, V_{min} is typically selected to be the largest of the following:

1. The airflow required to meet the design heating load at a supply air temperature that is not too warm, e.g., $\leq 90^{\circ}\text{F}$ ($\leq 32^{\circ}\text{C}$). Warmer temperatures tend to result in poor temperature control due to stratification and short circuiting.²

2. The airflow required to prevent “dumping” and poor distribution. This limit depends on the diffuser style and sizing. Thirty percent is a common rule-of-thumb but some research has shown that lower rates are satisfactory.⁶

3. The minimum required for ventilation. Depending on the code one is designing to, determining this rate can be

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simple (e.g., California's Title 24³) or it can be complex due to varying supply air rates and outdoor air percentage (e.g., ANSI/ASHRAE Standard 62, *Ventilation for Acceptable Indoor Air Quality*⁴).

For the FPV box, only the last issue typically applies because the parallel fan operation ensures sufficiently high supply air rates in the heating mode and at the diffuser. California's Title 24³ and the latest version of ASHRAE Standard 62⁴ allow the designer to take credit for the dilution offered by the transfer air supplied by the FPV fan. This allows the minimum primary airflow to the zone, V_{min} , to be reduced to very low levels, even to zero in some cases depending on the details of the design.

The above three factors determine the lowest required value of V_{min} . On the high side, V_{min} is limited by energy codes to minimize reheat energy losses. Both California's Title 24³ and ASHRAE Standard 90.1⁵ limit V_{min} to the largest of:

- 30% of V_{max} ;
- The minimum required for ventilation;
- 0.4 cfm/ft² (2 L/s per m²) of conditioned floor area of the zone; and
- 300 cfm (142 L/s).

V_{min} can have an impact on VAV box sizing because pressure independent controllers have a limit to how low their setpoint can be. The lowest non-zero setpoint is a function of the characteristics of the flow probe located at the box inlet (Figure 1) and the accuracy of the transducer/controller (see sidebar). Different box sizes using the same flow probes and transducer/controllers will have approximately the same minimum controllable velocity. Since the minimum velocity is the same, the larger the VAV box, the higher the minimum airflow setpoint. For FPV systems that can meet ventilation codes at very low primary airflow rates, the minimum setpoint allowed by the controller can be higher than that required for ventilation. Thus, a larger box serving a given zone may need a higher minimum setpoint, which will result in higher central fan energy, reheat energy, and possibly cooling energy (for systems without economizers).

This limitation typically does not affect VRH systems with digital controls because the minimum setpoint for proper heat-

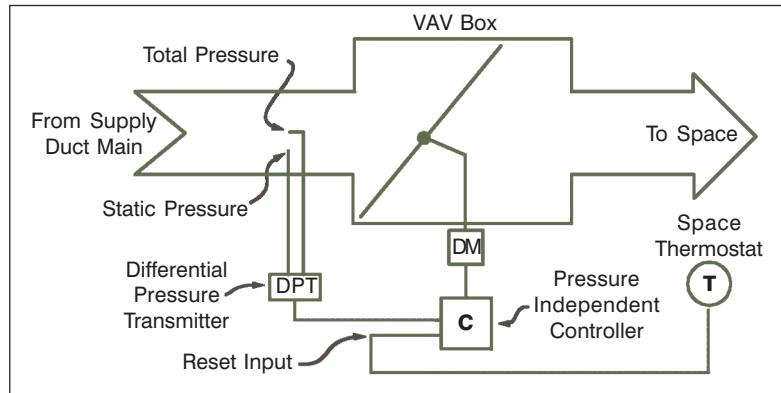


Figure 1: Typical VAV box controls.

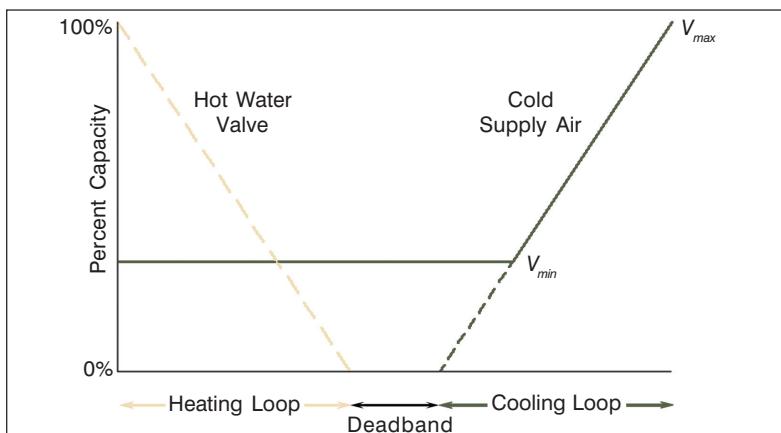


Figure 2: VAV reheat control diagram.

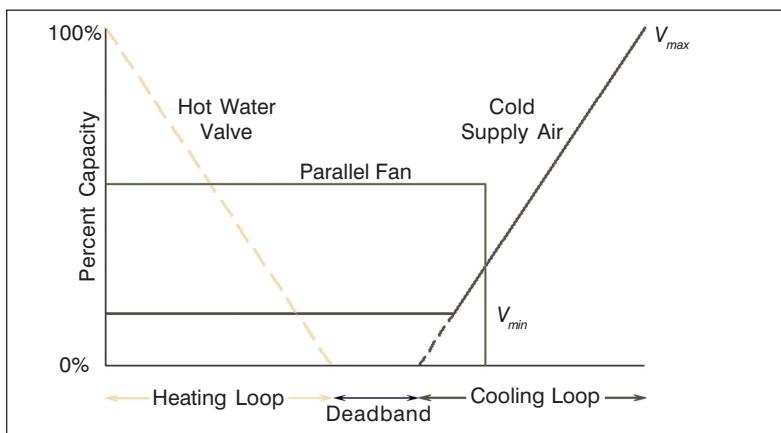


Figure 3: Parallel fan-powered VAV control diagram.

ing diffuser performance (e.g., 30% of V_{max}) is generally much higher than the lowest controller setpoint (see table in sidebar) unless the box is significantly oversized. It can be a limitation for VRH systems with pneumatic controls, which have relatively high minimum setpoints, or with digital controls when a "dual maximum" control strategy is used (see Reference 1 for a complete description of this strategy).

Pressure Drop and Fan Energy

The pressure drop across the VAV box at the zone design

airflow rate will affect the design pressure required by the supply air fan, provided the box is in the “critical path” or “index run,” which is the airflow path that has the highest overall pressure drop. Assuming this to be the case (more on this later), the greater the pressure drop across the box, the greater the fan power. VAV boxes with smaller inlets will have higher pressure drops and, hence, will result in higher fan energy.

VAV box pressure drops can be expressed in terms of both static pressure drop and total pressure drop, which are related by *Equation 1*:

$$\begin{aligned}\Delta TP &= \Delta SP + \Delta VP \\ &= \Delta SP + \left[\left(\frac{v_{in}}{4005} \right)^2 - \left(\frac{v_{out}}{4005} \right)^2 \right] \\ &= \Delta SP + \left[\left(\frac{4Q}{4005\pi D^2} \right)^2 - \left(\frac{Q}{4005WH} \right)^2 \right]\end{aligned}\quad (1)$$

where

ΔTP is the total pressure drop

ΔSP is the static pressure drop

ΔVP is the velocity pressure drop

v_{in} and v_{out} are the inlet and outlet velocities

Q is the airflow rate

D is the box inlet diameter

W and H are the inside (clear) width and height of the box outlet (outside dimensions less insulation thickness)

The static pressure drop across standard commercial VAV boxes is always lower than the total pressure drop since the velocity at the box inlet is much higher than the outlet velocity, resulting in static pressure regain. But the total pressure drop is the true indicator of the fan energy required to deliver the design airflow through the box since the fan has to generate both the pressure and velocity at the box inlet. Therefore total pressure drop, not static pressure drop, should be used to evaluate and select VAV boxes. Using static pressure drop can be misleading since VAV boxes from different manufacturers may have different outlet dimensions, and, hence, different outlet velocity pressures. Unfortunately, most VAV box manufacturers do not list total pressure drop in catalogs. If not, it can be calculated using *Equation 1*.

Simulations

The previous discussion established the fundamentals of how VAV box selection affects energy usage. To calculate the magnitude of the impact, a prototypical Oakland, Calif. office building was simulated using the DOE-2.2 computer program. Local utility rates were modeled with resulting blended rates on the order of \$0.13/kWh and \$0.59/therm.

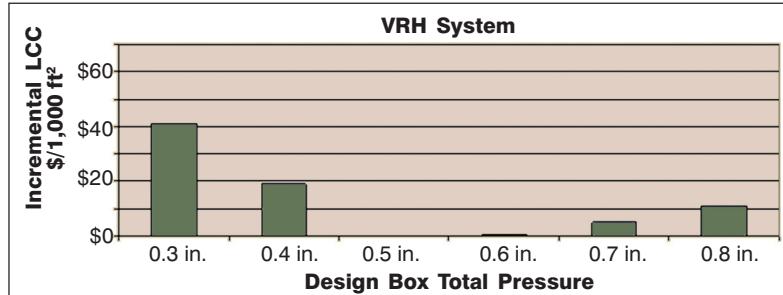


Figure 4: Incremental life-cycle cost for VRH system as a function of VAV box total pressure drop.

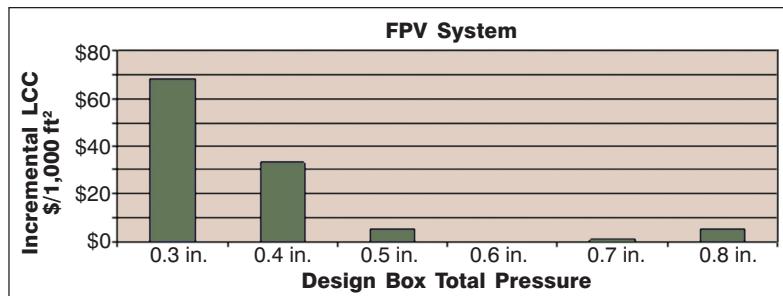


Figure 5: Incremental life-cycle cost for FPV system as a function of VAV box total pressure drop.

VAV systems with variable speed supply fans were modeled using the two VAV box types shown in *Figures 2* and *3*. For FPV boxes, V_{min} was set to the larger of 0.15 cfm/ft² (0.8 L/s per m²) and the lowest box setpoint (see sidebar), which varies by box inlet size. V_{min} was set to 30% for VRH boxes. First costs were determined by averaging contractor costs for VAV boxes from two popular manufacturers and adding a 25% contractor markup. Installation costs were assumed to be the same for all boxes. The cost differences for inlet reducers and discharge plenums were ignored, mainly because there was no easy way to account for them. Life-cycle costs were calculated over a 15-year life using a discount rate of 8% and 0% escalation rates for both electricity and gas.

Results

The incremental life-cycle cost impact of VAV boxes sized for 0.3 in. w.g. to 0.8 in. w.g. (75 Pa to 200 Pa) ΔTP at design airflow rates are shown in *Figures 4* and *5* for VRH and FPV systems, respectively. The results indicate that for optimum life cycles costs, VRH boxes should be sized for 0.5 in. w.g. to 0.6 in. w.g. (125 Pa to 150 Pa) total pressure drop while FPV systems should be sized for 0.6 in. w.g. to 0.7 in. w.g. (150 Pa to 175 Pa) total pressure drop. However, LCC differences among the options and systems are quite small, only a few cents per square foot per year. This is because first costs favor smaller boxes while energy costs favor bigger boxes, and both effects are small. Energy savings are small because the design pressure drop only occurs at peak conditions; pressure drop and fan energy drop quickly (nearly with the square and cube of flow, respectively) at part-load conditions. Life-cycle costs for FPV systems favor smaller

boxes than VRH systems because sizing affects the minimum airflow setpoint as well as pressure drop, so reheat energy increases when boxes are oversized.

To test the sensitivity of modeling assumptions, parametric runs were made with varying sizing assumptions (undersizing and oversizing), controller minimum setpoint, weather, occupancy schedule, internal loads, supply air temperature, utility rates, and window area. In all cases, the LCC optimum pressure drops were very similar to those shown in *Figures 4 and 5*.

Table 1 shows performance data for a particular VAV box manufacturer based on total pressure drops of 0.5 in. w.g. and 0.6 in. w.g. (125 Pa and 150 Pa), including the pressure drop across a hot water reheat coil. At these total pressure drops, noise is not likely to be an issue for this particular line of VAV boxes for most applications, as indicated by the NC levels from radiated noise predicted by the selection software. For other manufacturers, higher design pressure drops, and for noise sensitive applications, this may not be the case.

Sizing of Non-Critical Zones

As noted previously, box pressure drop only affects fan energy if the box is in the “critical path,” the airflow path requiring the most fan pressure. Arguably then, the sizing criteria suggested by *Figures 4 and 5* apply only to these zones, while VAV boxes closer to the fan hydraulically, where excess pressure is available, could be sized for a greater pressure drop. However, we recommend that a consistent pressure drop sizing criterion be used for all boxes regardless of location for following reasons.

- First and foremost, it is much simpler. Designers would not have to determine where boxes are located along the duct mains before sizing them. Automated sizing programs or spreadsheets could then be used much more easily.

- “Undersizing” boxes to absorb excess pressure is limited by noise constraints. As pressure drop increases, noise generation increases.

- Energy codes^{3,5} require that static pressure setpoints used for fan capacity control be reset to satisfy the box requiring the most static pressure, and as loads shift throughout the day and year the most demanding box will change.

Figures 6, 7, and 8 are images of VAV box zone demand at different times of day for an office building in Sacramento, Calif. All three images are taken on the same day, Aug. 5, 2002. At 7 a.m., Zone 14 on the southeast corner of the build-

Inlet Size (in.)	Outlet Width (in.)	Outlet Height (in.)	Total Pressure Drop = 0.5 in. w.g.				Total Pressure Drop = 0.6 in. w.g.			
			Static Pressure Drop (in. w.g.)*	Velocity pressure drop (in. w.g.)	Max cfm	Radiated NC	Static Pressure Drop (in. w.g.)*	Velocity pressure drop (in. w.g.)	Max cfm	Radiated NC
4	12	8	0.08	0.42	230	24	*	*	*	*
5	12	8	0.15	0.35	333	24	0.18	0.41	360	24
6	12	8	0.24	0.25	425	24	0.29	0.31	470	25
7	12	10	0.25	0.25	580	23	0.30	0.30	640	24
8	12	10	0.33	0.17	715	23	0.36	0.24	790	24
9	14	13	0.27	0.23	930	20	0.32	0.28	1,030	23
10	14	13	0.32	0.18	1,100	23	0.38	0.22	1,210	25
12	16	15	0.32	0.17	1,560	23	0.39	0.21	1,720	24
14	20	18	0.31	0.19	2,130	22	0.37	0.23	2,350	23
16	24	18	0.32	0.18	2,730	25	0.39	0.21	3,010	26

* For the 4 in. inlet size, 230 cfm is the maximum rate allowed by the manufacturer's selection program.

Table 1: VAV reheat box maximum airflow rates.

ing has the most demand. Later that morning at 9 a.m., Zone 36 in the interior of the building experiences the most demand. At 5 p.m., the high demand has shifted to Zone 30 in the northwest corner. Throughout the period monitored (the better part of a year), the peak zone changed throughout the floor plate, including both interior and perimeter zones. Hence, the zone requiring the most static pressure could vary throughout the day. If fan static pressure is reset to meet the requirements of only the zone requiring the most pressure, and if boxes close to the fan are undersized to dissipate excess pressure that is available at design conditions, then fan pressure and fan energy would increase when these boxes become the most demanding during off-design conditions.

Conclusions

Life-cycle costs over a wide range of economic and operating assumptions were found to be minimized when VRH boxes (and other box types with high minimum volume setpoints) were sized for a maximum total pressure drop of 0.5 in. w.g. to 0.6 in. w.g. (125 Pa to 150 Pa). Similarly, life-cycle costs for FPV boxes (and other box types with low minimum volume setpoints) were minimized when boxes were sized for a maximum of 0.6 in. w.g. to 0.7 in. w.g. (150 Pa to 175 Pa) total pressure drop. It is important to note that these sizing criteria apply to the total pressure drop, not the static pressure drop, across the box including reheat coils.

Acknowledgments

The research for this article was funded by a Public Interest Energy Research (PIER) grant from the California Energy Commission. The authors would like to acknowledge the input and work of other members of our research team, including Cathy Higgins of the New Buildings Institute, Mark Hydeman of Taylor Engineering, and Erik Kolderup and Tianzhen Hong of Eley Associates.

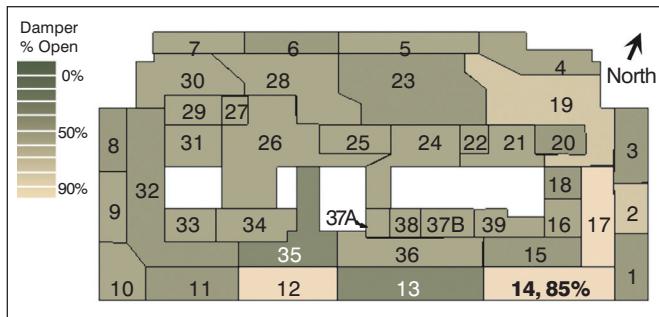


Figure 6: Site 3 VAV box demand (7 a.m., Aug. 5, 2002).

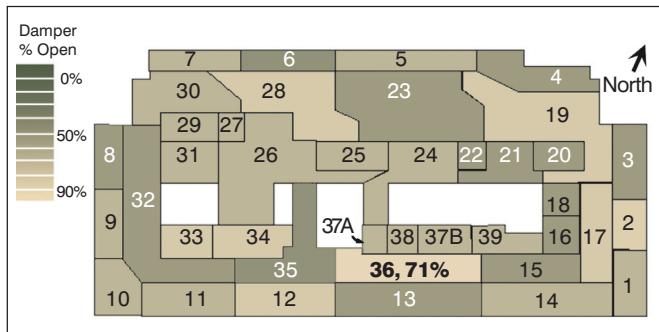


Figure 7: Site 3 VAV box demand (9 a.m., Aug. 5, 2002).

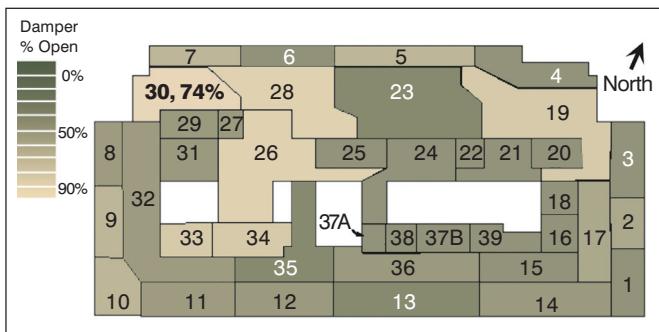


Figure 8: Site 3 VAV box demand (5 p.m., Aug. 5, 2002).

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Determining Minimum Airflow Setpoint

One limitation on the minimum airflow setpoint for the VAV box is the controllability of the box. VAV box manufacturers typically list a minimum recommended airflow setpoint for each box size and for each standard control option (e.g., pneumatic, analog electronic, and digital). However, the actual controllable minimum setpoint is usually much lower than the box manufacturer's scheduled minimum when modern digital controls are used.

The controllable minimum is a function of the design of the flow probe and the accuracy and precision of the digital conversion of the flow signal at the controller.

The flow probe is installed in the VAV box inlet or outlet and provides an air pressure signal that is proportional to the velocity pressure of the airflow through the box. Flow probes, which are typically manufactured and factory installed in the VAV box by the box manufacturer, are designed to provide accurate signals even when inlet conditions are not ideal (e.g., an elbow close to the inlet) and to amplify the velocity pressure signal to improve low airflow measurement. The amplification factor varies significantly by VAV box manufacturer and, to a lesser extent, by box size. The greater the amplification factor, the lower the controllable minimum. The VAV box manufacturer must balance this benefit with other design goals such as minimizing cost, pressure drop, and noise.

The box controller must convert the velocity pressure signal from the probe to a control signal. To make this conversion, digital controls include a transducer to convert the velocity pressure signal to an analog electronic signal and an analog-to-digital (A/D) converter to convert the analog signal to "bits," the digital information the controller can understand. For stable control around a setpoint, the controller must be able to sense changes to the velocity pressure that are not too abrupt. One controller manufacturer recommends a minimum setpoint equating to at least 14 bits for stable control.

The steps to calculate the controllable minimum airflow rate (V_m) for a particular combination of VAV box and VAV box controller are as follows:

1. Determine the velocity pressure sensor setpoint,

VP_m in inches of water that equates to 14 bits. This will vary by manufacturer. For several manufacturers who were contacted, VP_m can be as low as 0.004 in. w.g. (1 Pa). This will require a 10-bit (or higher) A/D converter and a 0 to 1 in. w.g. (0 to 250 Pa) or 0 to 1.5 in. w.g. (0 to 375 Pa) range transducer. Use of an 8-bit A/D converter or a transducer with a wider range can result in a stable control setpoint 0.01 in. w.g. (2.5 Pa) or higher.

2. Calculate the velocity pressure sensor amplification factor, F , from the manufacturers measured Q at 1 in. w.g. (250 Pa) signal from the VP sensor as follows:

$$F = \left(\frac{4005A}{Q_{lin.}} \right)^2$$

where A is the nominal duct area (ft^2), equal to:

$$A = \pi \left(\frac{D}{24} \right)^2$$

where D is the nominal duct diameter (in.).

Figure 9 shows an example of a VAV box flow probe performance. The data on the right side of the graph are the airflow rates at 1 in. w.g. for various neck sizes (shown on the left). For example using this figure, this manufacturer's probe for an 8 in. (0.2 m) inlet box senses a 1 in. w.g. (250 Pa) signal at 702 cfm (331 L/s).

3. Calculate the minimum velocity v_m for each VAV box size as:

$$v_m = 4005 \sqrt{\frac{VP_m}{F}}$$

where VP_m is the magnified velocity pressure setpoint from Step 1.

4. Calculate the minimum airflow setpoint allowed by the controls (V_m) for each VAV box size as:

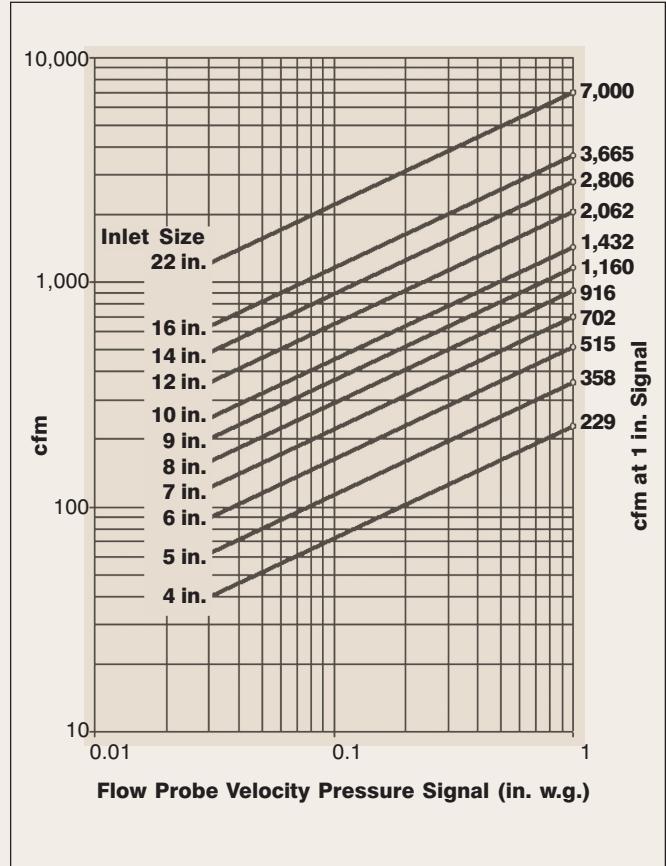


Figure 9: Sample VAV box inlet sensor performance chart, cfm vs. velocity pressure signal.

$$V_m = v_m A$$

Table 2 shows the minimum airflow setpoint for the VAV box probe depicted in Figure 9 with a controller capable of a velocity pressure setpoint of 0.004 in. w.g. (1 Pa) and 0.01 in. w.g. (2.5 Pa).◆

Nominal Inlet Diameter, in.	Area, ft^2	cfm at $Q_{1 \text{ in.}}$ Sensor Reading	Amplification factor	Min. VP Sensor Reading = 0.004 in. w.g.		Min. VP Sensor Reading = 0.01 in. w.g.	
				Minimum Velocity, fpm	Minimum Flow, cfm	Minimum Velocity, fpm	Minimum Flow, cfm
D	A		F	v_m	V_m	v_m	V_m
4	0.087	229	2.33	166	14	263	23
5	0.136	358	2.33	166	23	263	36
6	0.196	515	2.33	166	33	263	52
7	0.267	702	2.33	166	44	263	70
8	0.349	916	2.33	166	58	263	92
9	0.442	1,160	2.33	166	73	263	116
10	0.545	1,432	2.33	166	91	263	143
12	0.785	2,062	2.33	166	130	263	206
14	1.069	2,806	2.33	166	177	263	281
16	1.396	3,665	2.33	166	232	263	367
22	2.64	7000	2.28	168	443	265	700

Table 2: Sample calculation of box minimum flow.