VAV systems are the most common HVAC system for commercial buildings, but design practices vary widely around the country and even among design firms in a given area. Some of the variation is due to local construction practices and labor costs, but most of the variation, in the author’s experience, is due simply to how engineers are taught by their mentors in their early years of practice; design techniques and rules-of-thumb are passed down through the generations like family cooking recipes with little or no hard analysis of whether they are optimum from a life-cycle cost perspective.

This month’s column compares various VAV box inlet and outlet duct design options including their impact on first costs and pressure drop. It focuses on single duct VAV reheat systems, but most of the principles apply to other VAV system variations, such as dual duct and fan-powered box systems. First cost data are based on San Francisco Bay Area contractor sell prices, which are higher than most other areas due to high labor costs. Pressure drop data were calculated using ASHRAE’s “Duct Fitting Database”1 or SMACNA’s HVAC Systems Duct Design.2

VAV Box Inlet Duct Design

Table 1 shows typical VAV box connections to the duct main with first cost premiums, estimated pressure drop for the listed example, and recommended applications.

Option A (conical tap with flexible duct) is the least expensive option, but it is not recommended for any applications for the following reasons:

• It results in the highest pressure drop, usually even higher than that shown in Table 1. The pressure drop shown in the table is for perfectly straight flex duct, which has a roughness factor of about 2.1 relative to hard sheet metal duct.2 But most real applications will have some drooping at a minimum and often will have bends or offsets due to boxes being misaligned with the main duct tap.

• Even when straight, the roughness of the flexible duct can cause errors in velocity pressure (VP) sensor readings by the boxes flow sensor, as shown in Figure 1. When flex duct is kinked, the impact is even worse.

• Flexible duct is largely transparent to breakout noise so any noise generated by partially closed VAV box dampers can be readily radiated to the space. Conversely, hard round duct is highly resistant to breakout noise.

Option B is also a low cost option. It has a higher pressure drop than Options C and D but much lower first costs. The added costs of Options C and D would only be cost effective if they were applied to only the “critical zones,” which are the zones that require the highest fan speed and pressure. All other zones will have excess pressure available and thus any pressure drop savings from using a more efficient inlet duct design will be throttled by the VAV box damper. But

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the critical zone will vary due to variations in internal loads, weather, sun angle, etc. It is possible for most systems that 50% or more of the zones can be the most critical at any given time (see Figures 6 through 8 in Taylor & Stein4). This would require that the first cost penalty of Options C or D would apply to many zones, not just one.

For example, simulations of a 60,000 cfm (28 000 L/s) VAV system serving an Oakland office building showed that adding 0.15 in. w.g. (38 Pa) to the fan design pressure for Option B versus D increased energy costs only a few hundred dollars per year. That would result in an excellent payback if one particular zone was always the critical zone and Option D were only applied to it. But if all 70 zones in the system were designed using Option D, the payback would be 75 years. To get a 15-year payback, no more than 20% of the potentially critical zones could be ducted using Option D, but the designer would have to figure out in advance which zones are potentially critical. Option C has similar economics: it is less expensive than Option D but not as efficient.

So instead of using Options C or D at all zones, they should be used in special cases only:

- Use Option C for VAV boxes that are at a 45° angle to the duct main. This eliminates the cost and pressure drop of the 45° elbow shown in Table 1.
- Use either Option C (a bit less expensive) or D (a bit more efficient) for “obviously critical” zones. This will require some engineering judgment on the part of the designer. Examples include zones that are a long distance from the main or zones that are expected to be at

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**TABLE 1 VAV box inlet ducts off rectangular main (based on 8 in. inlet box, 630 cfm, 1,500 fpm duct main velocity).**

<table>
<thead>
<tr>
<th>Application Note</th>
<th>A. Conical, Flex</th>
<th>B. Conical, Hard</th>
<th>C. 45°, Hard</th>
<th>D. Oversized Conical, Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

*Neither the ASHRAE Duct Fitting Database nor the SMACNA HVAC Systems Duct Design Manual includes this tap type. Pressure drop is estimated by author based on comparison of other similar fittings.*
high loads for many hours per year, such as those serving an equipment room.

- Use Option D for zones tapping into low velocity mains. One technique for sizing duct mains is to “start fast and end slow,” as shown in the top half of Figure 2. Rather than using conservative duct design sizing techniques, such as a constant 0.1 in. w.g. per 100 ft friction rate (80 Pa per 100 m) for duct mains, this technique uses a higher starting velocity and friction rate and then keeps the duct main the same size for long distances, e.g., up to 60 ft (18 m). This results in lower first costs due to eliminated fittings but results in similar overall pressure drop. The pressure drop of the taps to VAV boxes also benefits from the lower velocities at the end of the duct main, but only to a point. As shown in Figure 3, when the duct main velocity is much lower than the velocity in the tap (less than about 60%), the pressure drop through the tap starts to increase. So VAV boxes at the end of the main should use Option D.

Note that none of the options includes a manual volume (balancing) damper upstream of the VAV box. They are never necessary in VAV systems with pressure independent controls; the VAV box controls provide continuous, dynamic self-balancing.

Note also that Option D shows a tapered reducer at the inlet to the box. Many engineers will include two or three duct diameters of inlet-sized duct between the reducer and the box to ensure that the velocity profile at the VP sensor is uniform. This is unnecessary. As shown in Figure 1, the “oversized” inlet resulted in the same VP accuracy as the straight “hard” inlet. Furthermore, in the research project upon which Figure 1 is based, the 10 × 8 reducer was only 8 in. (200 mm) long, much more abrupt than the taper shown in Option D of Table 1.

Figure 1 also shows that even having a 90° elbow directly in front of the VAV box has little impact on VP sensor accuracy. VAV box manufacturer’s installation instructions encourage using SMACNA’s recommended three duct diameters of straight duct at the inlet but also note that their VP sensors are in fact designed to allow for poor inlet conditions that frequently occur due to space constraints.

**VAV Box Discharge Duct Design**

Table 2 shows options for discharge plenums from VAV boxes. Both applications with and without 1 in. (25 mm) duct liner are shown. Duct liner is not allowed for some occupancies (e.g., hospitals) and is discouraged due to indoor air quality concerns in consistently humid climates, but it is still standard practice in many areas of the country. The cost of liner is generally close to being net first cost neutral with the same duct outside dimensions (OD) since the unlined duct must be externally insulated in the field.

Option B is the least expensive lined duct option. The OD of the discharge plenum matches the dimension of the box outlet so that a simple “S and drive”
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TABLE 2  VAV box discharge ducts. Based on 8 in. inlet box, three 210 cfm diffuser taps.

<table>
<thead>
<tr>
<th>Option</th>
<th>A. Unlined Plenum</th>
<th>B. Lined Plenum, Constant OD</th>
<th>C. Lined Plenum, Constant ID</th>
<th>D. Unlined Plenum, Oversized HW Coil</th>
<th>E. Lined Plenum, Constant OD, Oversized HW Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative First Cost</td>
<td>Base</td>
<td>$55</td>
<td>$285</td>
<td>$90</td>
<td>$145</td>
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<td>Total Pressure Drop (in. w.g.)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HW Coil</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
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<td>Liner Edge</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Plenum</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Diff. Tap</td>
<td>0.05</td>
<td>0.09</td>
<td>0.05</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>0.35</td>
<td>0.43</td>
<td>0.36</td>
<td>0.18</td>
<td>0.22</td>
</tr>
<tr>
<td>Application Note</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

1. Not recommended
2. Recommended where acoustic considerations are met without liner or liner is not allowed/desired
3. Recommended where liner is required for acoustics and allowed by code and local practice

A duct connection can be made without any fittings. This has the disadvantage of increasing plenum velocity and the liner also creates an abrupt reduction in free area right after the coil. To avoid those losses, Option C includes a 1 in. (25 mm) flange around the VAV box discharge so that the inside dimensions (ID) of the plenum matches the coil dimensions. (This could also be a standard duct transition, but the flange is usually a bit less expensive and takes up less space.) Unfortunately, the flange is expensive when shop fabricated and it is not available as an option from most VAV box manufacturers. Its costs can be offset, however, if it avoids the need for shop fabricated square-to-round taps to diffusers; the larger plenum height allows for larger standard diffuser taps.

But a better option in any case is to oversize the heating coil by using the next-size-up box and coil instead of the box and coil that comes standard with the inlet size. In this case, the box and coil are for a standard 10 in. (250 mm) VAV box but the damper and velocity pressure sensor are still 8 in. (200 mm). This is a “special” order from most VAV box manufacturers but the cost is usually the same price as the larger box; in other words, the box in this example with an 8 in. (200 mm) inlet but the box/coil of a standard 10 in. (250 mm) box costs the same as a standard 10 in. (250 mm) box. Care must be taken to make VAV box equipment schedules very clear of the design intent since this is non-standard construction. For instance, include coil size in the schedule and include a note in the “Remarks” column noting the non-standard construction.

This oversized box/coil option is recommended with and without duct liner. An option with a discharge flange like Option C is also possible but it is not likely to be cost effective because the pressure drop of the oversized plenum is already low.

One valuable side benefit of Options D and E is the improved waterside performance of the coil resulting from the increased heat transfer area: the coil leaving water temperature with the oversized coil is about 10°F to 15°F (5.5°C to 8°C) lower than for the standard coil. This reduces flow rates, pump size, and pipe sizes, and can improve the efficiency of condensing boilers. It can also allow low temperature water systems, such as those using condenser heat recovery, to work effectively with a two-row coil.
Table 3 shows three options for tapping the end of the discharge plenum to serve a diffuser. Many engineers forbid end taps because of perceived high pressure drops. In fact, according to the “Duct Fitting Database,” the pressure drop even for a straight tap out the end (Option A) is very low due to the low velocities in the plenum and duct to the diffuser. The straight end tap also will have a lower pressure drop than the side taps, 0.01 in. w.g. (2.5 Pa) versus 0.05 in. w.g. (12.5 Pa) in this example, so the volume damper in the end tap will have to be throttled. Regardless, end taps should be avoided unless mandated by space constraints for two reasons:

- One of the acoustical benefits of the plenum (end reflection) is at least partially lost.
- Airflow balance among the diffusers tapped out of the sides and that tapped out the end is not accurately maintained over the full range of VAV box airflow rates. This is because the pressure drop behavior of the side taps is not linear with airflow. So at low airflow rates, proportionally more air will go through the end tap than through the side taps. But the effect is very small so unlikely to cause any comfort problems.

Figure 4 shows three examples of duct design from VAV boxes, described as follows:

- Option A has a lined (or unlined) discharge plenum per Table 2. The plenum should always be 5 ft (1.5 m) long, or multiples of 5 ft (1.5 m) if added length is needed for acoustics, so that standard coil-line straight ductwork can be used to reduce costs.

Table 3: VAV box diffuser end taps.

<table>
<thead>
<tr>
<th>Option</th>
<th>A. Straight Tap</th>
<th>B. Conical Tap</th>
<th>C. Square-to-Round</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative First Cost</td>
<td>Base</td>
<td>$20</td>
<td>$80</td>
</tr>
<tr>
<td>Pressure Drop (in. w.g.)</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Application Note</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

1. Recommended where end-taps must be used due to space constraints
2. Not recommended
Taps to outlets should be near the end of the plenum to gain its full acoustical benefits and to avoid “cushion head” losses. Straight taps should be used; conical taps have negligible pressure drop benefit but add to first costs and may not always fit into the side of the plenum whose height is generally determined by the VAV box dimensions. For diffusers close to the plenum, the tap should include a volume damper; a straight tap with damper is a standard off-the-shelf item. For diffusers that are more remote from the plenum, a round branch duct is used with reducing wyes with volume dampers at each diffuser. Some contractors will find it more cost effective to duct all diffusers independently from the plenum since it eliminates fittings and gangs volume dampers in a central location for ease of balancing. With this option, all ductwork is round except for the discharge plenum. This lowers costs not only because round duct costs less than rectangular duct, but also because it is easier to make coordination offsets in the field. For instance, if the workers find a sprinkler line or cable tray in the way of a hard round duct run, adjustable elbows (with sealed joints) can be easily inserted in the field.

- Option B eliminates all rectangular ductwork. This design is often favored by contractors that do not have coil-lines for fabricating rectangular plenums. It increases the number of joints and fittings, but reducing wyes and adjustable elbows are easily obtained off-the-shelf. The one big disadvantage of this design is that it loses the acoustical benefit of the discharge plenum. The plenum is beneficial acoustically even if unlined.

- Option C is almost the opposite of Option B: it is composed of all rectangular duct except for flexible duct to diffusers. This is usually the most expensive design because rectangular duct costs more than round duct and it is less flexible to making field changes, e.g., offsetting to miss a sprinkler pipe or cable tray requires one or two shop fabricated fittings. In addition to the shop and material cost, there is usually an added labor cost to deliver the materials and possibly a time delay while it is being fabricated.

Option A is recommended for almost all applications.

**Conclusions**

This column summarizes various duct design options for VAV boxes, both upstream and downstream and makes recommendations based on lowest estimated life-cycle costs. The recommendations are generally practical and easy to implement.

**Acknowledgments**

The author would like to thank Eddie Patterson and Todd Gottshall of Western Allied Mechanical for providing the cost estimates presented in this article.

**References**

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