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VAV System Duct Main Design

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There is a dearth of detailed advice in common HVAC design handbooks describing how to design ductwork for VAV systems. Chapter 21 of *ASHRAE Handbook—Fundamentals*, for instance, provides three suggestions for duct sizing friction rates but does not suggest when to use each and does not distinguish between constant volume and variable volume systems with respect to design techniques or friction rates. In this month's column, I will provide detailed advice and a simple procedure for sizing "medium-pressure"* duct mains† in VAV systems.

Duct Design Methods

Ideally, ductwork should be sized based on life-cycle costs, balancing first costs with life-cycle energy costs, with constraints due to noise and space considerations. This is readily done with pipe sizing[1] leading to ASHRAE Standard 90.1[2] limits on pipe sizing that vary depending on whether the system is variable flow or constant flow. But life-cycle costing for duct sizing is simply not practical, primarily because:

- There are no standard sizes or standard fittings for ductwork, as there are for piping. This makes cost estimating much more difficult.
- Duct system effects due to consecutive fittings make up a very large portion of fan system pressure drop but they are not readily calculated. In fact, the ASHRAE Duct Fitting Database[3] does not include any data on consecutive fittings and the SMACNA *HVAC Systems Duct Design*[4] manual has pressure drop data on just one, consecutive elbows in different planes without turning vanes. This is not a common application, but it demonstrates the impact of duct system effect: the pressure drop of the consecutive elbows is ~40% higher than that of two individual elbows with long straight ducts entering and leaving. Piping, on the other hand, has negligible or even below-unity system effects due to consecutive fittings.[5]

Tsal developed a life-cycle cost-based duct design method called the T-method[6] in the 1980s, but its simplified techniques for calculating both first costs and energy costs were deemed to be so inaccurate, the T-method was removed from Chapter 21 in 2013.

Instead, Chapter 21 lists two duct sizing methods:

- Equal Friction (EF). Each duct section is sized to have the same friction rate loss, in. w.g. per 100 ft (Pa/m).
- Static Regain (SR). Each duct section is sized so that

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* The term "medium pressure" is not strictly defined by ASHRAE or SMACNA but is commonly used to describe ductwork upstream of VAV boxes. It is typically selected for SMACNA pressure class from 2 in. w.c. to 4 in. w.c. (500 to 1,000 Pa) inclusive with velocities up to about 4,000 fpm (20 mps). Low pressure systems are typically selected for less than 2 in. pressure (500 Pa) class and less than 2,000 fpm (10 mps) velocity.

† Duct "mains" are defined here as ductwork upstream of the taps to VAV boxes. Toolbox column "VAV Box Duct Design" in the July 2015 ASHRAE Journal addresses sizing of the inlets and outlets to VAV boxes. Branch lines from VAV boxes to outlets are typically sized as low-pressure ductwork using equal friction method at 0.08 in. w.c. to 0.10 in. w.c. per 100 ft [0.65 to 0.8 Pa/m].

the static pressure loss due to friction in that section is offset by the static pressure regain resulting from a reduction in duct velocity at the beginning of that section.

Neither method has a strong rationale for why it should be used to size ducts!

Clearly, there is no intrinsic value to having the same rate of pressure loss due to friction in each duct section. In the author's opinion, the EF method offers only this benefit: it is readily understandable and repeatable. Two engineers given the same desired friction rate will design ducts roughly the same size. But there is no way to relate friction rate to life-cycle costs other than designing for lower friction rates will almost always result in higher first costs and lower energy costs.

The SR method results in the static pressure at each tap to be roughly constant, arguably making the system self-balancing. But true self-balancing is seldom possible because of duct size limitations‡ and, moreover, having the same static pressure at taps seldom provides self-balancing in real systems§ since taps very seldom require the same pressure from that point to supply the desired airflow through the tap, through the branch ductwork, through terminal devices, then through the final air outlet. The SR method is also more difficult to use than EF because iteration is required; it cannot be readily done by hand. The SR method generally results in larger downstream ducts (and lower energy costs) than the EF method when starting with the same initial duct size.

Because of the simplicity of the EF method, it is by far the most popular method for sizing all types of HVAC systems, including both constant volume and variable volume. But what is the "right" friction rate for each system? Chapter 21 states that friction rates typically range from 0.05 to 0.20 in. w.c. per 100 ft (0.4 to 1.6 Pa/m) for low-pressure ductwork and has duct size tables for three rates: 0.08, 0.2, and 0.6 in. w.c. per 100 ft (0.65, 1.6, and 5 Pa/m) friction rates. But it offers no advice about when to use any of these rates. The chapter includes an example where the friction rate (0.67 in. w.c. per 100 ft [5.5 Pa/m]) is determined by the duct size that maximizes the acoustically allowable velocity (3,000 fpm [15 mps] in the example); this friction rate is used to size all the downstream ductwork. During my ~40 years designing and peer reviewing duct systems, I have never heard of anyone using this approach to size ductwork!

The SMACNA *HVAC Systems Duct Design* manual suggests starting with friction rates and velocities in the shaded area of *Figure 1*. This is, of course, a huge range so not very useful advice. The manual does suggest that a friction rate of 0.1 in. w.c. per 100 ft (0.8 Pa/m) is a typical EF design value for low-pressure ducts.

Friction Rate Reduction Method

While ASHRAE and SMACNA Handbooks offer little concrete advice on sizing medium-pressure VAV duct mains, the EDR *Advanced VAV System Design Guide*[7] outlines a relatively simple duct sizing technique called the Friction Rate Reduction Method. The procedure is as follows:

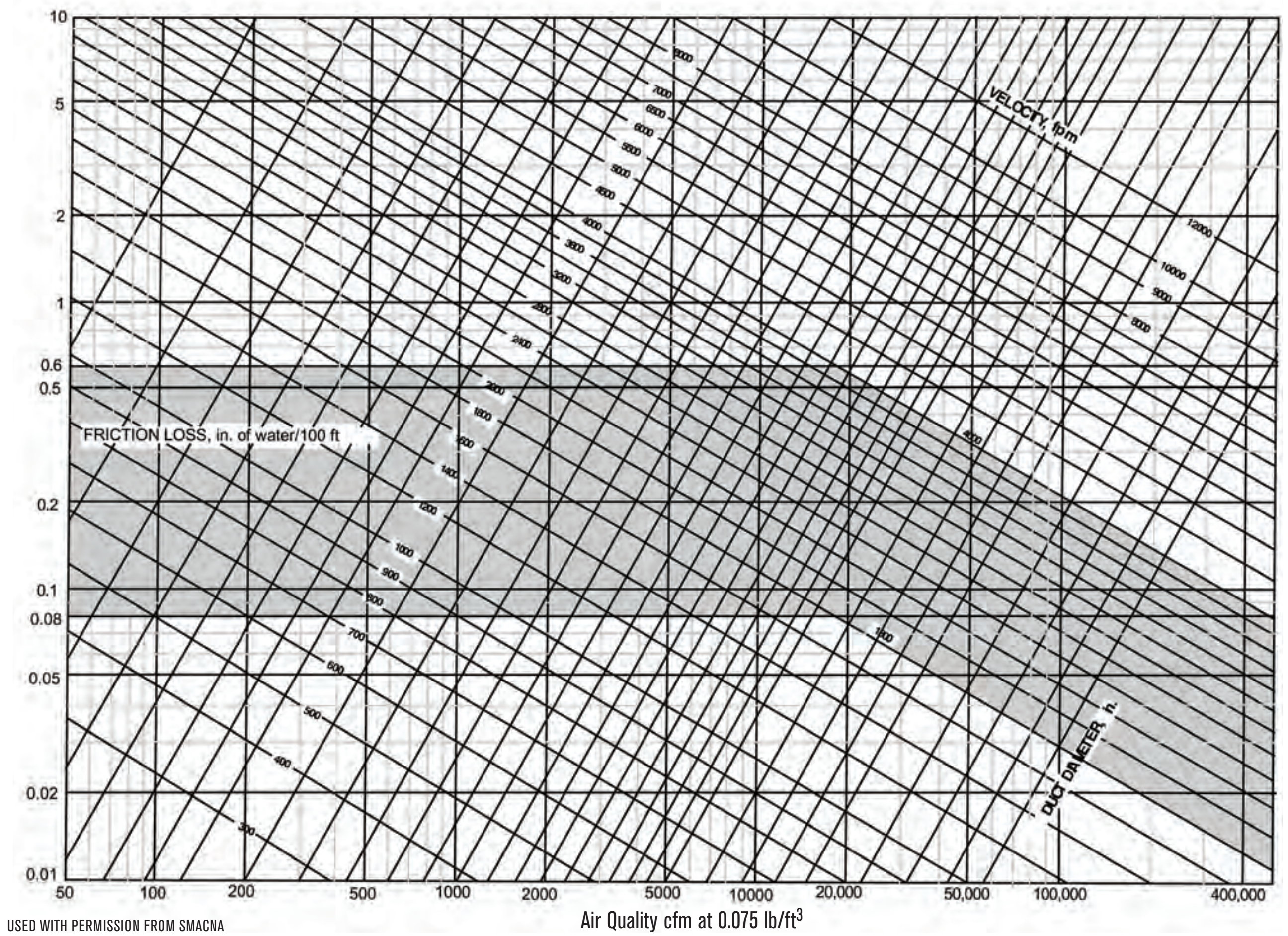
1. Starting at the fan discharge, choose the larger duct size from among both of the following design limits:
   a. Maximum velocity (to limit noise). Velocity limits are commonly used as a surrogate for limiting duct noise generated by the airflow itself (as opposed to that generated by the fan). In fact, research[8] has demonstrated that noise created by airflow in straight ducts is negligible compared to other sources, such as noise generated by fans and by turbulence at fittings. It is possible that a high velocity duct system with smooth fittings may make less noise than a low velocity system with abrupt fittings. Nevertheless, limiting velocity to limit noise is a common practice. Chapter 21 recommends the velocity limits shown in *Table 1*.** Velocity limits for flat-oval duct are not listed but can be estimated

‡ Round duct diameters are typically limited to multiples of 1 in. (25 mm), and to multiples of 2 in. (51 mm) in large diameter ducts (actual break point varies by manufacturer). While rectangular duct making machines can readily make any duct dimension, standard practice is to use multiples of 1 in. (25 mm).

§ One example where SR is useful is the design of stair pressurization fan ductwork. These systems are required by most codes for high rise buildings to protect exit stairs during a fire. Duct sizing need not consider energy use or noise since these fans operate only for fire emergencies. Hence, initial velocity can be high, e.g., 4,000 fpm (20 mps), which provides sufficient velocity pressure for substantial regain to occur at taps for supply air grilles. The taps are also usually identical so the benefit of equal static pressure at each tap that the SR method provides has the benefit of making the system relatively self-balancing. Using the SR method for this application typically results in the duct remaining the same size down to the last one or two sections.

** Table 12 from Chapter 21 was extracted from *A Practical Guide to Noise and Vibration Control for HVAC Systems*, 2nd Edition, 2011, which includes no references to research to support the velocity limits. They were likely created by the authors based on experience. For this reason, and because turbulence is the driving factor, not speed, they should not be considered hard limits.

FIGURE 1 Duct Friction Loss Chart from SMACNA's *HVAC Systems Duct Design*, Figure A-1.



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to be between those for rectangular and round but closer to rectangular due to the flat bottom surface of the flat-oval duct.

b. Maximum friction rate (to limit fan power). A reasonable starting friction rate for VAV systems is 0.25 in. to 0.30 in. per 100 ft (2 to 2.5 Pa/m). The rationale for this range is shown in the sidebar, *Design Friction Rates for VAV Systems*, on page 58.

2. At the end of the duct main, choose a minimum friction rate, typically 0.10 in. w.c. to 0.15 in. w.c. per 100 ft (0.8 to 1.2 Pa/m)

3. Decide how many transitions will occur along the hydraulically longest duct main (the so-called "index run," the run with the highest pressure drop that will determine the design pressure drop and fan power) from the fan to the most remote VAV box. Typically, a transition should not be made any more frequently than every ~20 ft (6 m) since the cost of the transition will generally offset the cost of the sheet metal savings. The

TABLE 1 Recommended Maximum Airflow Velocities to Achieve Specified Acoustic Design Criteria (Table 12 from *ASHRAE Handbook—Fundamentals*, Chapter 21).

		MAXIMUM AIRFLOW VELOCITY, FPM	
DUCT LOCATION	NC OR RC RATING IN ADJOINING OCCUPANCY	RECTANGULAR DUCT	ROUND DUCT
1	2	3	4
In Shaft or Above Solid Drywall Ceiling	45	3,500	5,000
	35	2,500	3,500
	25 or less	1,500	2,500
Above Suspended Acoustical Ceiling	45	2,500	4,500
	35	1,750	3,000
	25 or less	1,000	2,000
Duct Within Occupied Space	45	2,000	3,900
	35	1,450	2,600
	25 or less	950	1,700

Design Friction Rates for VAV Systems

Some may consider the 0.3 in. per 100 ft [2.5 Pa/m] initial friction rate to be very high for an energy conserving design. But this design condition represents a reasonable balance between first costs (including cost of sheet metal ducts plus the space required to house them) and energy costs, recognizing that VAV systems seldom operate at their design capacity.

The appropriateness of this friction rate as a design condition can be demonstrated by a simplified analysis of the life-cycle costs of a duct distribution system. Assume that the life-cycle cost (LCC) of the duct system is the sum of first costs (FC) and life-cycle energy costs (EC, equal to annual energy costs adjusted by a life-cycle present worth factor), as shown in the equation below:

$$LCC = FC + EC$$

Assuming a given static pressure class, first costs are roughly proportional to duct surface area (area of sheet metal). For round ducts, costs would then be proportional to duct diameter ***D***:

$$FC \propto D$$

Assuming that energy costs for a given fan system are proportional to duct friction rate, the friction rate in a standard duct system can be calculated from the following equation from the *ASHRAE Handbook—Fundamentals* (also used to develop friction rate nomographs):

$$f \propto D^{-1.2} V^{1.9}$$

where ***D*** represents the duct hydraulic diameter and V is the velocity.

For a round duct, the velocity for a given airflow rate is inversely proportional to the square of the diameter, so the friction rate varies with diameter as follows:

$$f \propto D^{-5}$$

Based on the equations above, the life-cycle cost as a function of diameter would be:

$$\begin{aligned} LCC &= FC + EC \\ &= K_1 D + K_2 D^{-5} \end{aligned}$$

and as a function of friction rate as:

$$LCC = C_1 f^{-0.2} + C_2 f$$

where *K* and *C* are constants for a given system.

LCC is minimized for a given friction rate when the derivative of the LCC with respect to friction rate is zero:

$$\frac{\partial LCC}{\partial f} = 0 = -0.2C_1 f^{-1.2} + C_2$$

Now assume that a constant volume system has a minimum LCC when the friction rate is 0.1 in. per 100 ft [0.8 Pa/m]. This is probably the most common design friction rate used for constant volume and low velocity duct systems and that recommended in the SMACNA manual. At this rate:

$$\begin{aligned} 0 &= -0.2C_1(0.1)^{-1.2} + C_2 \\ 3.2C_1 &= C_2 \end{aligned}$$

The LCC equation can be simplified to:

$$LCC = C_1 f^{-0.2} + 3.2C_1 f$$

Conservatively assume that a variable volume system will have an average annual airflow rate of 60%. With a variable speed drive, the system will use about 30% of the energy used by a constant volume system of the same design size. The LCC equation then becomes:

$$\begin{aligned} LCC &= C_1 f^{-0.2} + 0.3 \times 3.2C_1 f \\ &= C_1 f^{-0.2} + 0.96C_1 f \end{aligned}$$

Taking the derivative with respect to friction rate and setting to zero, it is possible to solve for the friction factor that results in the lowest LCC:

$$\begin{aligned} \frac{\partial LCC}{\partial f} &= 0 = -0.2C_1 f^{-1.2} + 0.96C_1 \\ f &= (0.21)^{-083} \\ &= 0.27 \end{aligned}$$

While this analysis is surely simplistic, it does demonstrate that sizing ducts for a higher friction rate for VAV systems than for constant volume systems is technically justified based on life-cycle cost. If 0.1 in. w.c. per 1 ft [0.8 Pa/m] is the "right" friction rate for constant volume systems, then 0.25 in. to 0.3 in. per 100 ft [2 to 2.5 Pa/m] is "right" for VAV systems. Note that with the Friction Rate Reduction Method, this rate is only used for the first section of duct, so average friction rates will be less, but still greater than that for constant volume systems.

design is more flexible to accommodate future changes and is more energy efficient with fewer transitions. It is not uncommon to have only three or four major transitions along the index run.

4. Take the difference between the maximum friction rate as determined in *Step 1* (whether determined by the friction limit or velocity limit) and the minimum friction rate from *Step 2* (e.g., 0.3 less 0.15 = 0.15 in. w.c. per 100 ft [2.5 less 1.25 = 1.25 Pa/m]) and divide it by the number of transitions. The result is called the friction rate reduction factor.

5. Size duct along the index run using calculated airflow with diversity†† starting with the maximum friction rate, then reduce the friction rate at each transition by the friction rate reduction factor. By design, the last section will be sized for the minimum friction

†† VAV systems should be sized based on expected loads including diversity. Solar diversity (due to the fact that the sun can only be in one position at a time) is easily determined with standard load calculation software. Diversity in other load components, such as people, plug loads, and lighting loads, is a judgment call on the part of the designer, as are the peak design assumptions for these components.

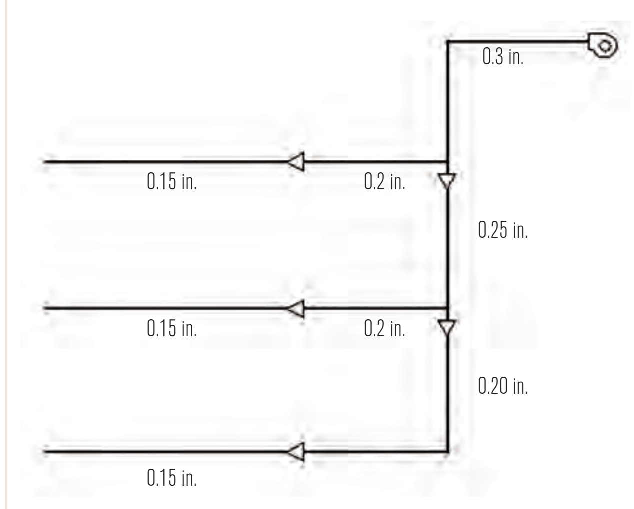
rate selected in Step 2.

The method is illustrated in *Figure 2*, which shows a riser diagram of a simple three-story building.

In this example, a maximum friction rate of 0.3 in. w.c./100 ft (2.5 Pa/m) was selected with a final rate of 0.15 in. w.c./100 ft (1.23 Pa/m) at the beginning of the last section. The index run connects to the first floor. Three transitions exist so the friction rate reduction factor is (0.3 – 0.15)/3 = 0.05 in. w.c./100 ft (0.41 Pa/m). Each section of the run is sized for ever-decreasing friction rates. The other floors should be sized for the same friction rate as the duct on the index floor (0.2 in. w.c./100 ft [1.6 Pa/m] in this example) primarily for simplicity (typical floors will have the same size ducts) and because there may be operating conditions when those floors are the index run.

This technique emulates the static regain method, resulting in somewhat constant static pressure from one end of the duct section to the other, but without complex calculations. It is not intended to be precise, but precision is not possible in most cases due to system effects and the normal changes that occur as design progresses. It is also important to realize that precise duct sizing is not necessary for proper operation because VAV boxes can adjust for a wide range of inlet pressures, generally more than what occurs in medium-pressure systems designed using the Friction Rate Reduction Method.

FIGURE 2 Example of duct sizing using the friction rate reduction method from EDR's *Advanced VAV System Design Guide.*



Conclusions

The ASHRAE Handbooks and SMACNA manuals offer no specific advice for how to size VAV system duct mains upstream of VAV box taps. Fortunately, the EDR's *Advanced VAV System Design Guide* describes a relatively simple procedure, the Friction Rate Reduction Method, that should provide a reasonable balance between first costs and energy costs.

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