HVAC Fans and Ductwork: Sizing and Selection

An Online Continuing Education Course for Engineers

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HVAC Fans and Ductwork: Sizing and Selection

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The Heating, Ventilating, and Air Conditioning (HVAC) system has been a mainstay of society since its invention in the early 1900s. Without HVAC systems, most buildings would be cold in the winter and warm in the summer, suffer potentially dangerous indoor air quality issues, and be just plain unbearable. In fact, if not for the modern convenience of HVAC systems, many southern states would probably have populations near zero!

The heart of the HVAC system is the fan. A good fan selection can mean the difference between an energy-efficient and quiet system that stealthily blends into the background or an expensive, noisy, unreliable maintenance headache generating frequent occupant complaints. To avoid the nightmare scenario, careful selection of fans by engineers designing HVAC systems is critical to overall HVAC system efficiency, performance, occupant comfort and productivity.

This course comprises three sections. Section 1 - Fans, Section 2 - Ductwork, and Section 3 - Fan Control. Section 1 encompasses the engineering tools at our disposal to understand and document fan behavior as well as the many types of fans and their applications. Section 2 explains the calculation of ductwork friction and fitting losses. The reader should understand that duct design is an involved subject that is beyond the scope of this course and is better offered as a separate discussion. Calculating duct losses, a subset of duct design is included in this course to facilitate fan sizing since the resistance “felt” by a fan must be measured or calculated before the proper fan can be selected. Section 3 illustrates the various methods of fan control and the control equipment and devices used. After all, a perfectly sized fan in the right application can still be problematic with a poorly operating control system. Finally, example problems are provided throughout the course to reinforce the concepts learned.

Mechanical and controls engineers working in HVAC design or operations and maintenance in the commercial or industrial market will benefit from this course. The concepts introduced will not only provide a solid foundation of knowledge, but also arm the student with the tools necessary to specify the right fan for new installations as well as troubleshoot any type of existing fan issue encountered.

Section 1 – Fans

Fans are rotating machines designed to move large quantities of air (or any gaseous fluid desired), usually for the purposes of ventilation, odor removal, particulate removal, and heat exchange. An electric motor provides shaft power to either a belt-driven or direct-driven impeller where the motor is directly coupled to the fan shaft. The rotating impeller adds potential energy and kinetic energy to the fluid. Some fans may generate more potential energy (static pressure) than kinetic energy (velocity pressure) and vice versa. Fan impellers come in a wide variety of sizes and styles for many different applications. The two main types of fans found in HVAC are centrifugal and axial. Hybrids of these types are also available. Centrifugal fans are the most prevalent due to their ability to provide the required flow rate at low noise levels, working against the resistance caused by ductwork, fittings, filters, heat exchangers, and dampers. While some axial fans are capable of higher pressures, most axial fans are used in high-volume, low-pressure ventilation applications where some noise can be tolerated.

Volumetric and Mass Flow Rate

Fans are constant volume devices. This means that a fan will deliver the same volume flow rate of a gas regardless of the gas density and water vapor fraction present (Lindeburg, 2001, p. 20-10). In other words, the volumetric flow rate is constant, but the mass flow rate and density will vary depending on altitude. Mass flow rate and volumetric flow rates are related by the density equation:

$$\rho = \frac{m}{V}$$

Density, represented by the Greek letter rho (ρ), is equal to mass m divided by volume V (upper case). Rearranging the above equation to solve for mass and dividing both sides of the equation by units of time gives:

$$\dot{m} = \rho \cdot \dot{V}$$

Mass m and volume V with a dot above represent mass flow rate and volumetric flow rate, respectively. In HVAC, the volumetric flow rate is typically expressed in cubic feet per minute (CFM), and the mass flow rate is expressed in units of pounds mass per minute (lbm/min). A low-pressure fan moving 10,000 CFM of air at standard sea level density of 0.075 lbm per cubic foot in Orlando, FL, would still move 10,000 CFM of air in Denver, CO, but the density of the air would be approximately 0.063 lbm per cubic foot. The same fan's mass flow rate in Orlando is 750 lbm/min, while the mass flow rate in Denver would be 630 lbm/min.

The HVAC industry uses volumetric flow rate almost exclusively, but mass flow rate can be used in industrial process systems. For example, in systems that supply gaseous nitrogen (GN2) from liquid nitrogen (LN2) dewars or tanks, it is more convenient to use mass flow rate versus volumetric flow rate. Keeping track of the many pressure changes that occur in nitrogen systems can result in calculation errors when using a volumetric flow rate, but the mass flow rate is constant (Mass flow rate in equals mass flow rate out).

Pressure

Fan performance is documented by locating its operating point on a graph of flow versus pressure, which will be covered shortly. There are three types of pressure: static, velocity (or dynamic), and total pressure. Total pressure is the sum of static and velocity pressure:

$$P_{T=}P_S + P_v$$

Static pressure is the pressure exerted by any stationary fluid and is always perpendicular to the container walls. Velocity pressure is the pressure caused by the collision of fluid molecules with another object. The formula for velocity pressure is:

$$P_v = \frac{\rho \cdot v^2}{2 \cdot g_c}$$

In this course, upper case V is used to denote volume, while lower case v will be used to denote fluid velocity. Upper-case P is used for power, and lower-case p is used for pressure. The symbol g_c is known as the gravitational constant and is equal to 32.174 lbm-ft/lbf-sec^2. This term is not to be confused with the earth's gravitational acceleration constant *g,* which is numerically equal to 32.174 but has units of ft/sec^2.

Before going any further, take a small detour to discuss units. This course will use the English Engineering System of units, which requires the use of g_c to ensure units in the equations cancel appropriately, leaving the answer in terms of the correct unit. Carrying units through calculations is good discipline and will result in far fewer errors. The English Engineering System also uses pounds-force (lbf) and pounds mass (lbm). It is very important to distinguish between the two and not simply say “pounds” or use the abbreviation lb. It is also important to distinguish between gauge and absolute pressure (ex. psig/psia). Gauge pressure is usually used in HVAC unless working with a formula such as the ideal gas law, which requires absolute units of pressure and temperature.

The total pressure equation above is a simple but surprisingly useful formula. A pitot tube measures total pressure and static pressure simultaneously. Subtracting static pressure from total pressure leaves velocity pressure, which, if the fluid density and duct cross-sectional area are known, the average fluid velocity and volumetric flow rate can be determined. This formula is also the basis for calculating the energy losses that the airstream experiences when moving through ductwork and fittings (elbows, reducers, increasers). There is a gradual drop in total pressure or pressure drop from the inlet to the outlet of any section of the ductwork or across anything in the airstream that causes resistance as the fluid moves. However, there can be dramatic rises and falls in static and velocity pressure along the way through duct expansions and contractions. A venturi is an excellent illustration of this phenomenon.

The HVAC industry uses inches of water column gauge as standard units of pressure. 1 psi is equal to 27.7 inches w.g. The highest pressure encountered in a typical commercial building HVAC duct system is at the discharge of the supply fan and is usually in the 4-5 in w.g. range but can vary depending on duct length, size, and number of fittings. Specialized industrial fan systems can operate at much higher pressures using multi-stage blowers.

Incompressibility and Continuity

A gas can be considered Incompressible if its pressure does not change by more than 10% between entrance and exit with a velocity less than Mach 0.3 (Lindeburg, 2001, p. 16-3). Air at 0 psig or 14.7 psia absolute pressure would have to be more than 1.1·14.7psia=16.17psia or 1.47 psig at the entrance and 0 psig at the exit to be compressible. 1.47 psig converts to 40.7 in w.g. The Mach number is a dimensionless ratio of fluid velocity divided by the speed of sound in that fluid:

$$M = \frac{v}{a}$$

v=fluid velocity, ft/sec

a=speed of sound, ft/sec

The speed of sound in air at sea level at a temperature of 70°F is approximately 1128 ft/sec. Solving the above equation for v:

$$v = M \cdot a = 0.3 \cdot \frac{1128ft}{sec} = \frac{338.4ft}{sec}$$

338.4 ft/sec converts to 20,304 ft/min. Duct inlet pressures of 40 inches w.g. and velocities of 20,304 ft/min are much higher than nearly all HVAC applications so air is considered incompressible in the HVAC industry. For incompressible fluids, density is constant. At constant flow, the volumetric flow rate is then equal to the duct cross-sectional area times the average velocity of the fluid. This is known as the continuity equation:

$$\dot{V} = A \cdot v$$

$\dot{V}$=volumetric flow rate, ft^3/min

A=duct cross-sectional area, ft^2

v=fluid velocity, ft/min

Other useful versions of the continuity equation:

$\dot{m}_1 = \dot{m}_2$ (Mass flow in equals mass flow out)

$\dot{m} = \rho \cdot A \cdot v$

$A_1 \cdot v_1 = A_2 \cdot v_2$

Fan Curve

Many standard HVAC engineering tools are visual charts and graphs such as duct friction charts, psychrometric charts, pump curves, and fan curves. This is very helpful for HVAC engineers. For example, visualizing the psychrometric chart is a great way to understand the relationship between dry bulb temperature, relative humidity, and dewpoint (an understanding that may otherwise be lost when using tabular data or formulas).

As stated previously, a fan curve and its close relative of the pump curve are graphs of flow versus pressure with flow on the X axis and static pressure on the Y axis. An example of a typical centrifugal fan curve is shown in Figure 1 below:

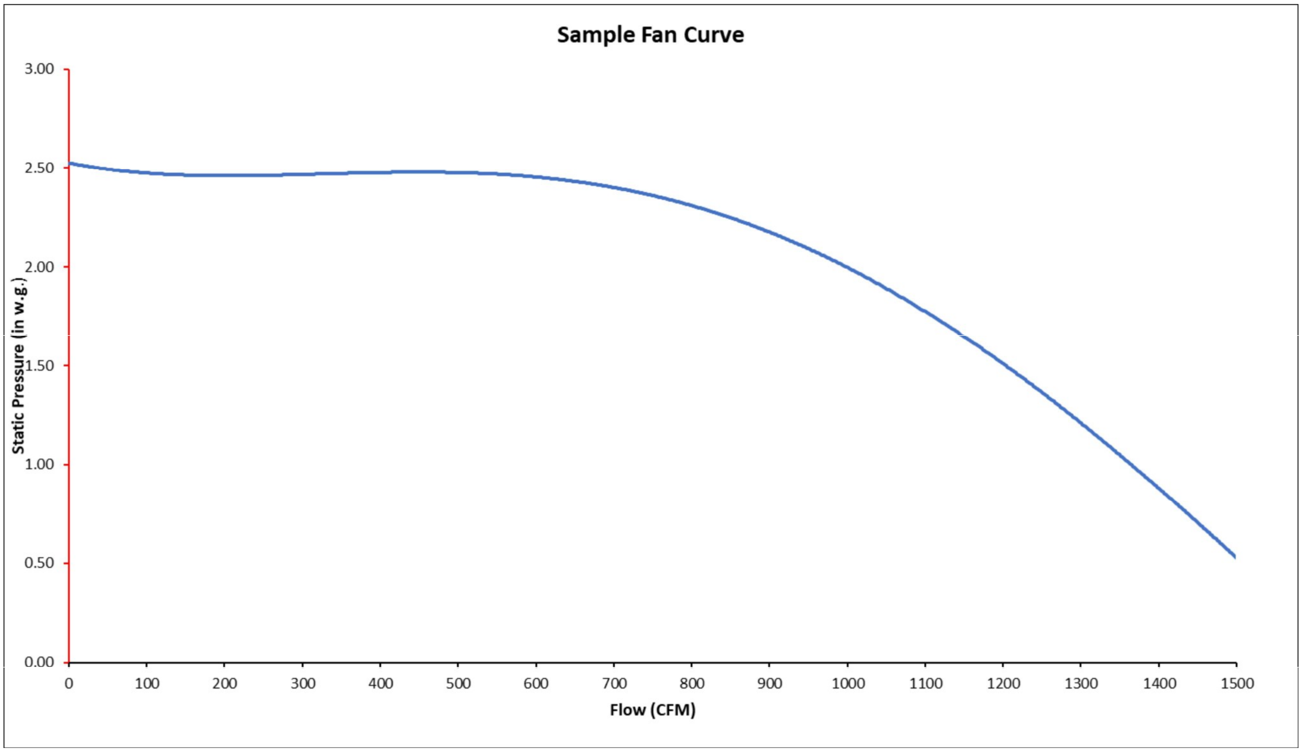

Figure 1

One important item to note is that the pressures used to generate the fan curve are always the differential pressure across the fan (discharge pressure at the fan outlet minus suction pressure at the fan inlet), which can be a source of confusion for the inexperienced. The differential pressure (ΔP) across the fan is exactly equal to the losses of the duct system at the operating point flow rate. When taking a field measurement, many meters can display the measured differential pressure as well as both the suction and discharge pressures. A good exercise is to pay attention to the sign of the suction pressure measurement.

Example Problem 1

A fan discharge pressure was measured to be 3.5 inches w.g., and the suction pressure was measured to be slightly below atmospheric pressure at -0.5 inches w.g. What is the differential pressure across the fan?

Solution

$$dp = [3.5 - (-0.5)]in\,w.g. = 4.0\ in\,w.g.$$

A fan curve with a specific operating point will show the fan curve, which is a manufacturer-published curve generated under laboratory conditions, and another curve called the system curve.

System Curve

In addition to the fan curve, Figure 2 adds the system ... rve and operating point. In this example, the design operating point is 1000 CFM at 2 inches w ... system cur ... f parabola with positive x and y values, vertex at (0,0), and th ...

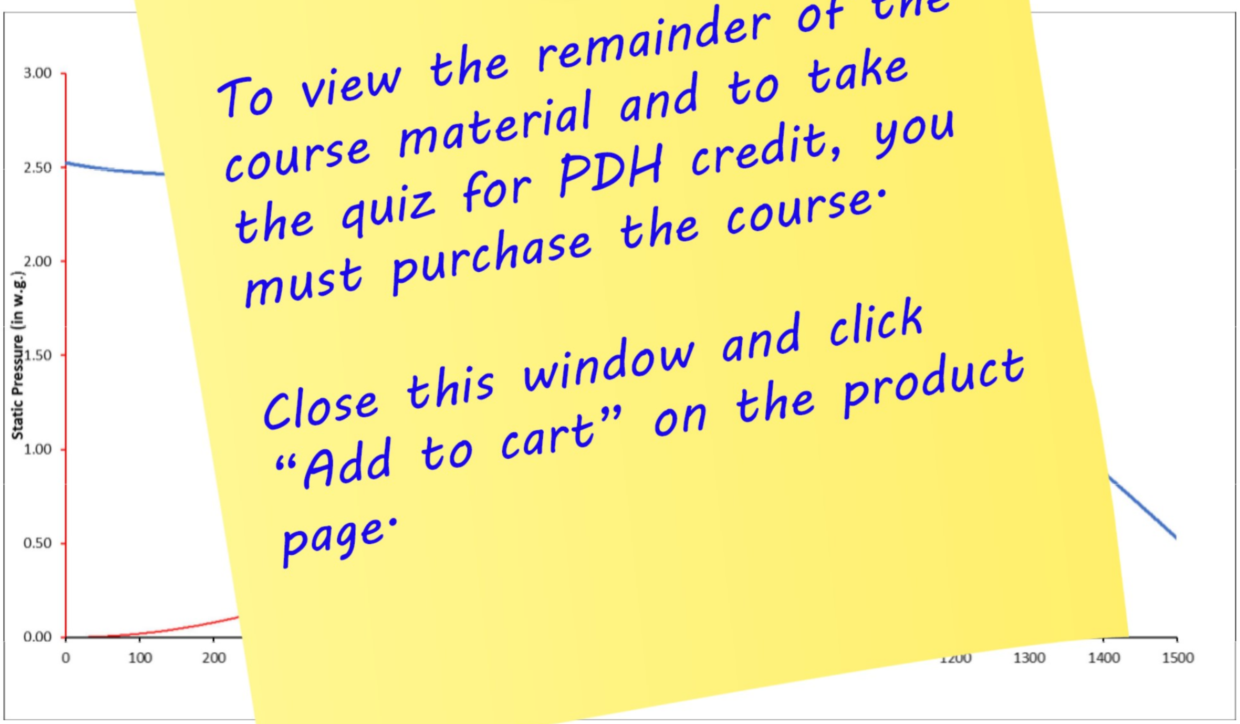

Figure 2

The system curve represents everything else connected to and, therefore, affects the fan, such as discharge and suction side ductwork, cooling and heating coils, filters, dampers, diffusers, bird screens, etc. The operating point is ***always*** the intersection of the two curves. More system resistance shifts the system curve and fan operating point to the left along the fan curve, and less resistance shifts the system curve and fan operating point to the right along the fan curve. The system pressure drop must be calculated for a new design but can be measured for an existing installation. Notice how the system