



# Improving Fan System Performance

Four (4) Continuing Education Hours  
Course #ME1270

Approved Continuing Education for Licensed Professional Engineers

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### **Course Description:**

The Improving Fan System Performance course satisfies four (4) hours of professional development.

The course is designed as a distance learning course that overviews fan system performance and practical guidelines for increasing system efficiency.

### **Objectives:**

The primary objective of this course is to enable the student to understand fan systems, their components and operation, and various methods and guidelines to improve the performance for new or existing systems.

### **Grading:**

Students must achieve a minimum score of 70% on the online quiz to pass this course. The quiz may be taken as many times as necessary to successfully pass and complete the course.

A copy of the quiz questions are attached to last pages of this document.

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## Introduction to Fan Systems

Fans are widely used in industrial and commercial applications. From shop ventilation to material handling to boiler applications, fans are critical for process support and human health. In the manufacturing sector, fans use about 78.7 billion kilowatt-hours<sup>2</sup> of energy each year. This consumption represents 15 percent of the electricity used by motors.<sup>3</sup> Similarly, in the commercial sector, electricity needed to operate fan motors composes a large portion of the energy costs for space conditioning.

Performance may range from “free air” to several pounds per square inch gage (psig), with airflow from a few cubic feet per minute (cfm) to more than 1 million cfm. Pressures above 15 psig generally require air compressors.

In manufacturing, fan reliability is critical to plant operation. For example, where fans serve material handling applications, fan failure will immediately create a process stoppage. In industrial ventilation applications, fan failure will often force a process to be shut down (although there is often enough time to bring the process to an orderly stoppage). Even in heating and cooling applications, fan operation is essential to maintain a productive work environment. Fan failure leads to conditions in which worker productivity and product quality declines. This is especially true for some production applications in which air cleanliness is critical to minimizing production defects (for example, plastics injection molding and electronic component manufacturing).

In each case, fan operation has a significant impact on plant production. The importance of fan reliability

often causes system designers to design fan systems conservatively. Concerned about being responsible for under-performing systems, designers tend to compensate for uncertainties in the design process by adding capacity to fans. Unfortunately, oversizing fan systems creates problems that can increase system operating costs while decreasing fan reliability.

Fans that are oversized for their service requirements do not operate at their best efficiency points. In severe cases, these fans may operate in an unstable manner because of the point of operation on the fan airflow-pressure curve. Oversized fans generate excess flow energy, resulting in high airflow noise and increased stress on the fan and the system. Consequently, oversized fans not only cost more to purchase and to operate, they create avoidable system performance problems. The use of a “systems approach” in the fan selection process will typically yield a quieter, more efficient, and more reliable system.

### Fans

There are two primary types of fans: centrifugal and axial. These types are characterized by the path of the airflow through the fan. Centrifugal fans use a rotating impeller to increase the velocity of an airstream. As the air moves from the impeller hub to the blade tips, it gains kinetic energy. This kinetic energy is then converted to a static pressure increase as the air slows before entering the discharge. Centrifugal fans are capable of generating relatively high pressures. They are frequently used in “dirty” airstreams (high moisture and particulate content), in material handling applications, and in systems at higher temperatures.

Axial fans, as the name implies, move an airstream along the axis of the fan. The air is pressurized by the aerodynamic lift generated by the fan blades, much like a propeller and an airplane wing. Although they can sometimes be used interchangeably with centrifugal fans, axial fans are commonly used in “clean air,” low-pressure, high-volume applications. Axial fans have less rotating mass and are more compact than centrifugal fans of comparable capacity. Additionally, axial fans tend to have higher rotational speeds and are somewhat noisier than in-line centrifugal fans of the same capacity; however, this noise tends to be dominated by high frequencies, which tend to be easier to attenuate.

### ◆ Fan Selection

Fan selection is a complex process that starts with a basic knowledge of system operating requirements and conditions such as airflow rates, temperatures, pressures, airstream properties, and system layout. The variability of these factors and other considerations, such as cost, efficiency, operating life, maintenance, speed, material type, space constraints, drive arrangements, temperature, and range of operating conditions, complicate fan selection. However, knowledge of the important factors in the fan selection process can be helpful for the purposes of reducing energy consumption during system retrofits or expansions. Often, a fan type is chosen for nontechnical reasons, such as price, delivery, availability, or designer or operator familiarity with a fan model. If noise levels, energy costs, maintenance requirements, system reliability, or fan performance are worse than expected, then the issue of whether the appropriate fan type was initially selected should be revisited.

Fans are usually selected from a range of models and sizes, rather than designed specifically for a particular application. Fan selection is based on calculating the airflow and pressure requirements of a system, then finding a fan of the right design and materials to meet these requirements. Unfortunately, there is a high level of uncertainty associated with predicting system airflow and pressure requirements. This uncertainty, combined with fouling effects and anticipated capacity expansion, encourages the tendency to increase the specified size of a fan/motor assembly.

Designers tend to protect against being responsible for inadequate system performance by “over-specifying.” However, an oversized fan/motor assembly creates a different set of operating problems, including inefficient fan operation, excess airflow noise, poor reliability, and pipe/duct vibrations. By describing some of the problems and costs associated with poor fan selection, this course is intended to help designers and operators improve fan system performance through better fan selection and improved operating and maintenance practices.

**Noise.** In industrial ventilation applications, noise can be a significant concern. High acoustic levels promote worker fatigue. The noise generated by a fan depends on fan type, airflow rate, and pressure. Inefficient fan operation is often indicated by a comparatively high noise level for a particular fan type.

If high fan noise levels are unavoidable, then ways to attenuate the acoustic energy should be considered. Noise reduction can be accomplished by several methods: insulating the duct; mounting the fan on a soft material, such as rubber or suitable spring isolator as required to limit the amount of transmitted vibration energy; or installing sound damping material or baffles to absorb noise energy.

**Rotational Speed.** Fan rotational speed is typically measured in revolutions per minute (rpm). Fan rotational speed has a significant impact on fan performance, as shown by the following fan laws:

$$\text{Airflow}_{\text{final}} = \text{Airflow}_{\text{initial}} \left( \frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}} \right)$$

$$\text{Pressure}_{\text{final}} = \text{Pressure}_{\text{initial}} \left( \frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}} \right)^2$$

$$\text{Power}_{\text{final}} = \text{Power}_{\text{initial}} \left( \frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}} \right)^3$$

Rotational speed must be considered concurrently with other issues, such as variation in the fan load, airstream temperature, ambient noise, and mechanical strength of the fan.

Variations and uncertainties in system requirements are critical to fan type and fan rotational speed selection. Fans that generate high airflow at relatively low speeds (for example, forward-curved blade centrifugal fans) require a relatively accurate estimate of the system airflow and pressure demand. If, for some reason, system requirements are uncertain, then an improper guess at fan rotational speed can cause under-performance or excessive airflow and pressure.

Airstream temperature has an important impact on fan-speed limits because of the effect of heat on the mechanical strength of most materials. At high temperatures, all materials exhibit lower yield strengths. Because the forces on shafts, blades, and bearings are proportional to the square of the rotational speed, high-temperature applications are often served by fans that operate at relatively low speeds.

**Airstream Characteristics.** Moisture and particulate content are important considerations in selecting fan type. Contaminant build-up on fan blades can cause severe performance degradation and fan imbalance. Build-up problems are promoted by a shallow blade angle with surfaces that allow contaminants to collect. Fans with blade shapes that promote low-velocity air across the blades, such as backward inclined fans, are susceptible to contaminant build-up. In contrast, radial tip fans and radial blade fans operate so that airflow across the blade surfaces minimizes contaminant build-up. These fans are used in “dirty” airstreams and in material handling applications.

Corrosive airstreams present a different set of problems. The fan material, as well as the fan type, must be selected to withstand corrosive attack. Also, leakage into ambient spaces may be a concern, requiring the fan to be equipped with a shaft seal. Shaft seals prevent or limit leakage from around the region where the drive shaft penetrates the fan housing. For example, in corrosive environments fans can be constructed with expensive alloys that are strong and corrosion resistant, or they can

be less expensively constructed with fiberglass-reinforced plastic or coated with a corrosion-resistant material. Because coatings are often less expensive than superalloy metals, fan types that work well with coatings (for example, radial fan blades because of their simple shape) are widely used in corrosive applications; however, wear will reduce the reliability of coatings. Alternately, materials such as reinforced fiberglass plastics have been developed for fan applications and function effectively in many corrosive environments. However, there may be size and speed limitations for composite materials and plastic materials.

Airstreams with high particulate content levels can also be problematic for the fan drive train. In direct drive axial fans, the motor is exposed to the airstream. Sealed motors can be used in these applications but tend to be more expensive and, in the event of lost seal integrity, they are susceptible to expensive damage. In axial fans, belt drives offer an advantage by removing the motor from the airstream. In centrifugal fans, the particulate content is less of a factor because the motor or sheave can be located outside of the fan enclosure and connected to the impeller through a shaft seal. Gear drives are occasionally used in applications where speed reduction is required but the use of belt drives is unfeasible because of access or maintenance requirements.

In flammable environments, fans are usually constructed of nonferrous alloys to minimize the risk of sparks caused by metal-to-metal contact. In some applications, certain components of the fan can be fabricated out of spark-resistant materials. Fans that operate in flammable environments should be properly grounded, including rotating components, to minimize sparking because of static discharge.

**Temperature Range.** To a large degree, temperature range determines fan type and material selection. In high-temperature environments, many materials lose mechanical strength. The stresses on rotating components increase as the fan’s operating speed increases. Consequently, for high-temperature applications, the fan type that requires the lowest operating speed for a particular service is often recommended. Radial blade fans can be ruggedly constructed and are frequently used in

high-temperature environments. Component materials also significantly influence a fan's ability to serve in high-temperature applications, and different alloys can be selected to provide the necessary mechanical properties at elevated temperatures.

**Variations in Operating Conditions.** Applications that have widely fluctuating operating requirements should not be served by fans that have unstable operating regions near any of the expected operating conditions. Because axial, backward-inclined airfoil, and forward-curved fans tend to have unstable regions, these fans are not recommended for this type of service unless there is a means of avoiding operation in the unstable region, such as a recirculation line, a bleed feature, or some type of anti-stall device.

**Space Constraints.** Space and structural constraints can have a significant impact on fan selection. In addition to dimensional constraints on the space available for the fan itself, issues such as maintenance access, foundation and structural support requirements, and ductwork must be considered. Maintenance access addresses the need to inspect, repair, or replace fan components. Because downtime is often costly, quick access to a fan can provide future cost savings. Foundation and structural requirements depend on the size and weight of a fan. Selecting a compact fan can free up valuable floorspace. Fan weight, speed, and size usually determine the foundation requirements, which, in turn, affect installation cost.

If the available space requires a fan to be located in a difficult configuration (for example, with an elbow just upstream or downstream of a fan), then some version of a flow straightener should be considered to improve the operating efficiency. Because non-uniform airflow can increase the pressure drop across a duct fitting and will degrade fan performance, straightening the airflow will lower operating costs.

An important tradeoff regarding space and fan systems is that the cost of floor space often motivates designers and architects to configure a fan system within a tight space envelope. One way to accomplish this is to use small-radius elbows,

small ducts, and very compact fan assemblies. Although this design practice may free up floor space, the effect on fan system performance can be severe in terms of maintenance costs. The use of multiple elbows close to a fan inlet or outlet can create a costly system effect, and the added pressure drops caused by small duct size or a cramped duct configuration can significantly increase fan operating costs. System designers should include fan system operating costs as a consideration in configuring fan assemblies and ductwork.

## Fan Performance Curves

Fan performance is typically defined by a plot of developed pressure and power required over a range of fan-generated airflow. Understanding this relationship is essential to designing, sourcing, and operating a fan system and is the key to optimum fan selection.

**Best Efficiency Point.** Fan efficiency is the ratio of the power imparted to the airstream to the power delivered by the motor. The power of the airflow is the product of the pressure and the flow, corrected for units consistency. [The equation for total efficiency is:](#)

$$\text{Total Efficiency} = \frac{\text{Total Pressure} \times \text{Airflow}}{\text{bhp} \times 6,362}$$

Where: Total Pressure is in inches of water  
Airflow is in cubic feet per minute (cfm)  
bhp is brake horsepower

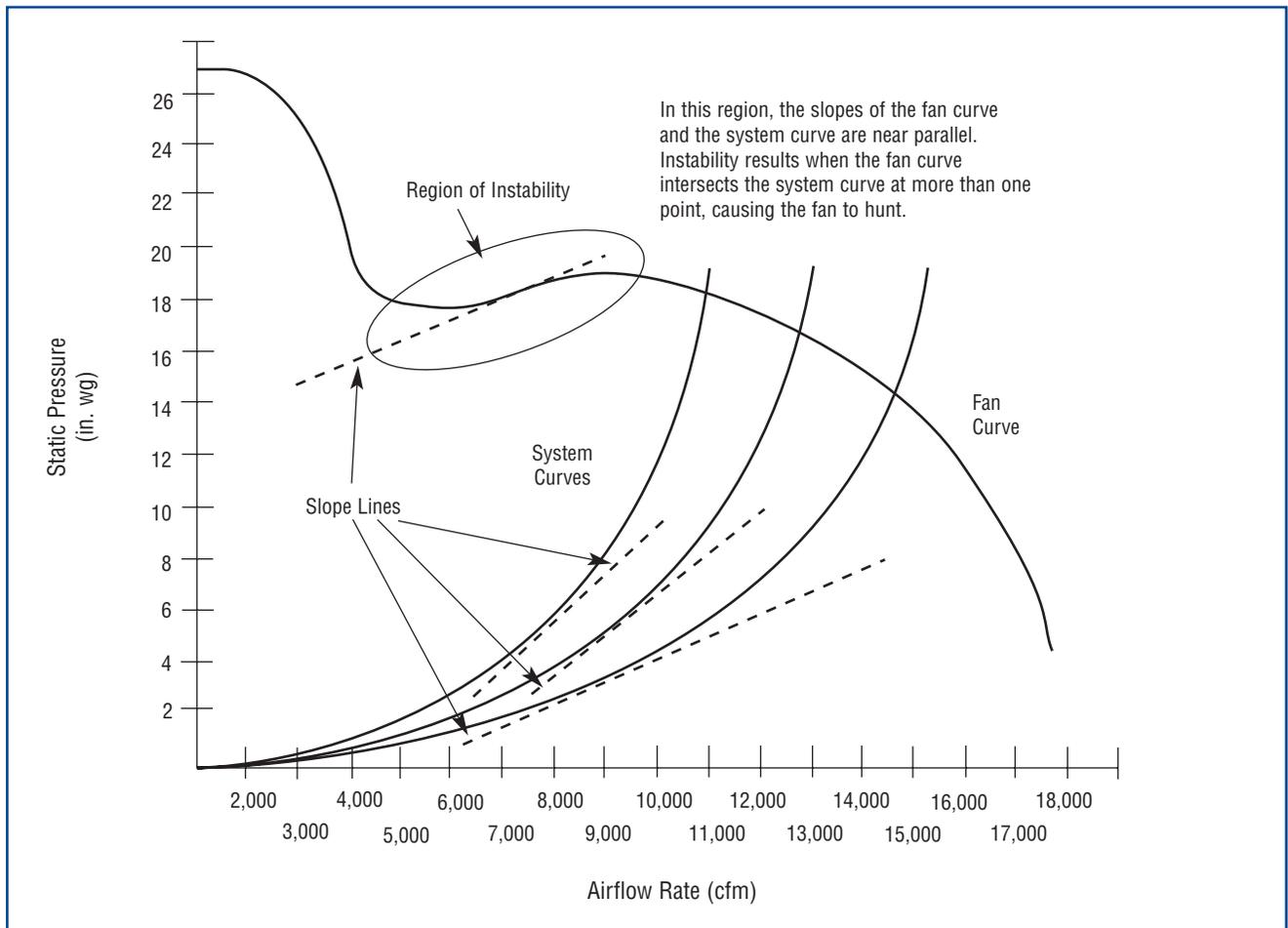
An important aspect of a fan performance curve is the best efficiency point (BEP), where a fan operates most cost-effectively in terms of both energy efficiency and maintenance considerations. Operating a fan near its BEP improves its performance and reduces wear, allowing longer intervals between repairs. Moving a fan's operating point away from its BEP increases bearing loads and noise.

Another term for efficiency that is often used with fans is static efficiency, which uses static pressure instead of total pressure in the above equation. When evaluating fan performance, it is important to know which efficiency term is being used.

**Region of Instability.** In general, fan curves arc downward from the zero flow condition—that is, as the backpressure on the fan decreases, the air-flow increases. Most fans have an operating region in which their fan performance curve slopes in the same direction as the system resistance curve. A fan operating in this region can have unstable operation. (See Figure 1-1.) Instability results from the fan's interaction with the system; the fan attempts to generate more airflow, which causes the system pressure to increase, reducing the generated airflow. As airflow decreases, the system pressure also decreases, and the fan responds by generating more airflow. This cyclic behavior results in a searching action that creates a sound similar to breathing. This operating instability promotes poor fan efficiency and increases wear on the fan components.

**Fan Start-Up.** Start-up refers to two different issues in the fan industry. Initial fan start-up is the commissioning of the fan, the process of ensuring proper installation. This event is important for several reasons. Poor fan installation can cause early failure, which can be costly both in terms of the fan itself and in production losses. Like other rotating machinery, proper fan operation usually requires correct drive alignment, adequate foundation characteristics, and true fit-up to connecting ductwork.

Fan start-up is also the acceleration of a fan from rest to normal operating speed. Many fans, particularly centrifugal types, have a large rotational inertia (often referred to as  $WR^2$ ), meaning they require significant torque to reach operating speed.



**Figure 1-1. Region of Instability<sup>5</sup>**

<sup>5</sup> Although fan system curves can have a static component, for the purposes of this course system curves pass through (0,0).

In addition to the  $WR^2$  load, the air mass moved by the fan also adds to the start-up torque requirements on the fan motor. Although rotational inertia is not typically a problem in heating, ventilation, and air conditioning (HVAC) applications, it may be a design consideration in large industrial applications. Proper motor selection is essential in ensuring that the fan can be brought to its operating speed and that, once there, the motor operates efficiently.

Because the start-up current for most motors is 2 to 5 times the running current, the stress on the motor can be significantly reduced by starting a fan under its minimum mechanical load and allowing the motor to achieve normal operating speed more quickly than when under full load. In many applications, system dampers can be positioned to reduce the load on the fan motor during start-up. For example, the power required by a centrifugal fan tends to increase with increasing flow (although in “non-overloading” fan types, the power drops off after reaching a peak). In axial fans, the power tends to decrease with increasing flow. Consequently, for most centrifugal fan types, large fan start-ups should be performed with downstream dampers closed, while for most axial fan types, start-ups should be performed with these dampers open. However, there are exceptions to these guidelines, and the actual power curve for the fan should be evaluated to determine how to soften the impact of a large fan start-up.

The power surges that accompany the starting of large motors can create problems. Among the effects of a large start-up current are power quality problems and increased wear on the electrical system. In response to increasing demand for equipment that minimizes the problems associated with large motor starts, electrical equipment manufacturers are offering many different technologies, including special devices known as soft starters, to allow gradual motor speed acceleration. A key advantage of variable frequency drives (VFDs) is that they are often equipped with soft starting features that decrease motor starting current to about 1.5 to 2 times the operating current. Although VFDs are primarily used to reduce operating costs, they can significantly reduce the impact of fan starts on an electrical system.

In axial fan applications, controllable pitch fans offer a similar advantage with respect to reducing start-up current. Shifting the blades to a low angle of attack reduces the required start-up torque of the fan, which allows the motor to reach operating speed more quickly.

**System Effect.** The system effect is the change in system performance that results from the interaction of system components. Typically, during the design process, the system curve is calculated by adding the losses of each system component (dampers, ducts, baffles, filters, tees, wyes, elbows, grills, louvers, etc.). The governing equation for pressure loss across any particular component is:

$$\Delta p = C \left( \frac{V}{1,097} \right)^2 \rho$$

Where:  $\Delta p$  = pressure loss in inches of water gage (in. wg)  
 $C$  = loss coefficient for the component  
 $V$  = velocity in feet per minute  
 $\rho$  = density of the airstream (0.075 pounds per cubic foot at standard conditions)

The result of this equation is a parabolic line, as shown by the system curve in Figure 1-2. This system curve assumes all components display pressure loss characteristics according to their loss coefficients. However, in reality, non-uniform airflow profiles that are created as the airstream develops swirls and vortices cause system components to exhibit losses that are higher than their loss coefficients. The overall effect of these added losses is to move the system curve up, as shown by the corrected system curve in Figure 1-2.

The system effect can be minimized by configuring the system so that the flow profile remains as uniform as possible. However, if space constraints prevent an ideal system layout, then system effect consequences should be incorporated into the fan selection process.

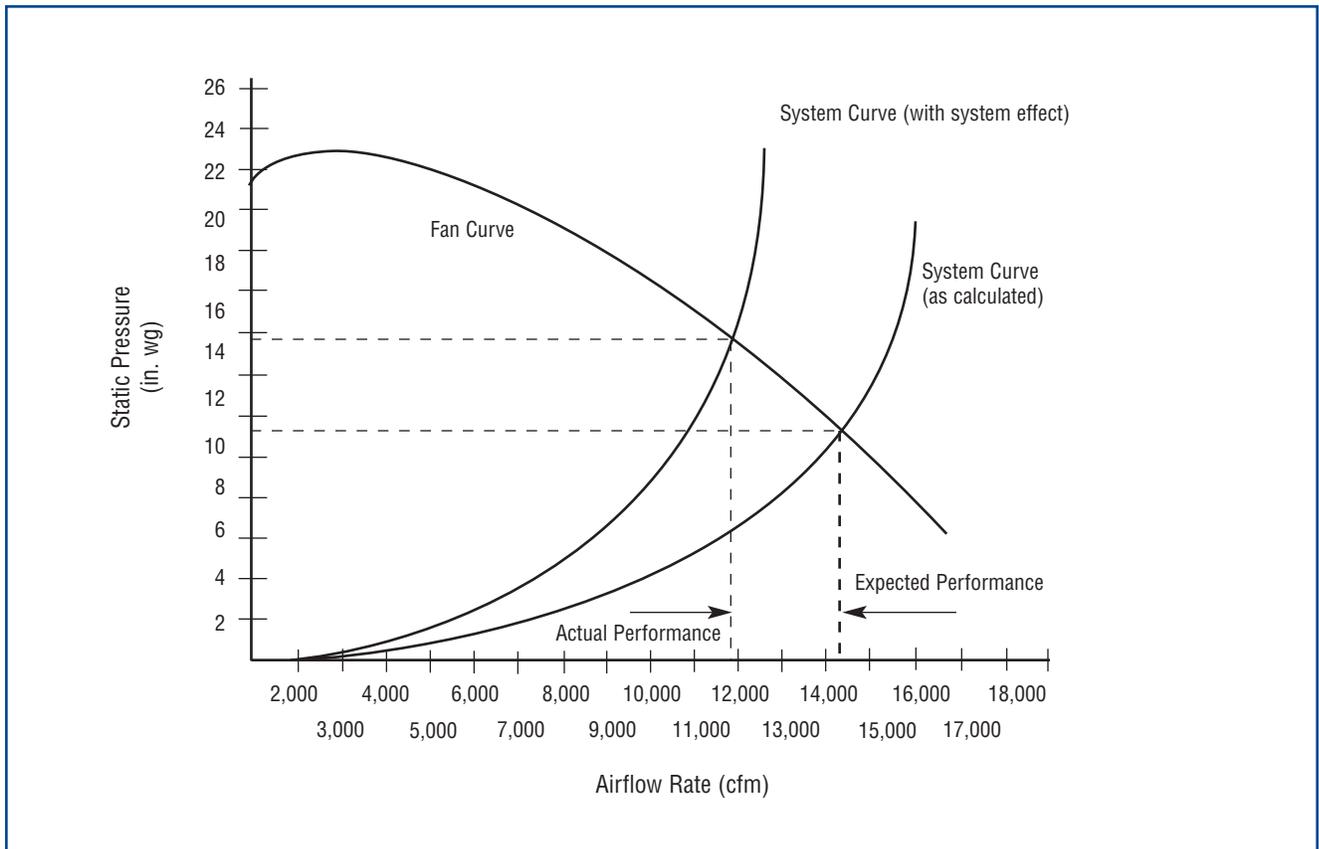


Figure 1-2. System Effect for a Typical Fan and System

The system effect can be particularly problematic when the airflow into or out of a fan is disrupted into a highly non-uniform pattern. Poor configuration of ductwork leading to or from a fan can severely interfere with a fan's ability to efficiently impart energy to an airstream. For example, placing an elbow close to the fan outlet can create a system effect that decreases the delivered flow by up to 30 percent. This can require an increase in fan speed, which in turn results in an increase in power and a decrease in system efficiency.

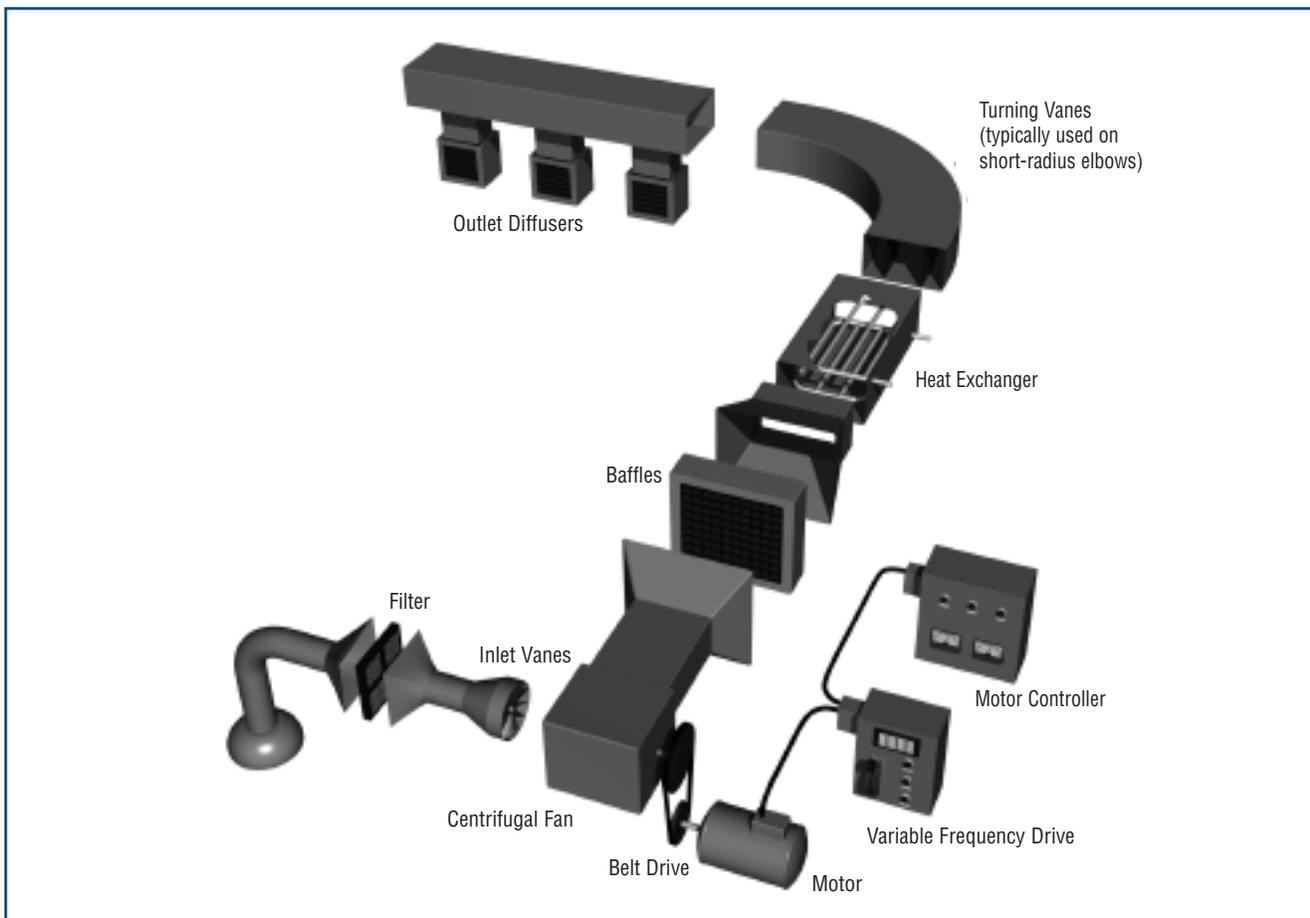
Although underestimating the system effect causes insufficient air delivery, many designers overcompensate for it and other uncertainties by selecting oversized fans. This practice creates problems such as high energy costs, high maintenance, and reduced system reliability. A more reasonable approach is to combine proper system layout practices with an accurate estimate of the system effect to determine an appropriate fan size.

## Fan System Components

A typical fan system consists of a fan, an electric motor, a drive system, ducts or piping, flow control devices, and air conditioning equipment (filters, cooling coils, heat exchangers, etc.). An example system is illustrated in a diagram on page 8.

To effectively improve the performance of fan systems, designers and operators must understand how other system components function as well. The "systems approach" requires knowing the interaction between fans, the equipment that supports fan operation, and the components that are served by fans.

**Prime Movers.** Most industrial fans are driven by alternating current (AC) electric motors. Most are induction motors supplied with three-phase, 240- or 480-volt power. Because power supplies are typically rated at slightly higher voltages than motors because of anticipated voltage drops in the



**Figure 1-3. Example Fan System Components**

distribution system, motors are typically rated at 230 or 460 volts. In recent years, because of efforts by the National Electrical Manufacturers Association (NEMA) and motor manufacturers, the efficiency of general-purpose motors has significantly improved. These improvements are also attributable to the Energy Policy Act (EPAAct), which for most motors went into effect in October 1997. To improve motor efficiency, motor manufacturers have modified motor designs and incorporated better materials, resulting in slight changes in motor operating characteristics. Although initial costs of the motors have increased 10 to 20 percent, for high run-time applications, improvements in motor efficiency create very attractive paybacks through lower operating costs.

A characteristic of induction motors is that their torque is directly related to slip, or the difference between the speed of the magnetic field and the speed of the motor shaft. Consequently, in many

fans, actual operating speeds are usually around 2 percent less than their nominal speeds. For example, a theoretical four-pole induction motor with no slip would rotate at 1,800 rpm with a 60-hertz power supply; however, rated operating speeds for this motor are usually around 1,750 rpm, indicating that slip rates are a little over 2.7 percent at rated load. Fans that are driven by older motors are probably operating at much lower efficiencies and at higher levels of slip than what is available from new motors.

Upgrading to a new motor can reduce operating costs, because of improved motor efficiency, while offering slightly improved fan performance. EPAAct-efficiency motors operate with less slip, which means fans rotate at slightly higher speeds. For applications that can effectively use this additional output, this high efficiency can be attractive. However, if the additional output is not useful, the added power consumption increases operating costs.

Another component of the prime mover is the motor controller. The controller is the switch mechanism that receives a signal from a low power circuit, such as an on/off switch, and energizes or de-energizes the motor by connecting or disconnecting the motor windings to the power line voltage. Soft starters are electrical devices that are often installed with a motor controller to reduce the electrical stresses associated with the start-up of large motors. In conventional systems, the high in-rush and starting currents associated with most AC motors creates power quality problems, such as voltage sag. Soft starters gradually ramp up the voltage applied to the motor, reducing the magnitude of the start-up current. As industrial facilities increase the use of computer-based equipment and control systems, soft starters are becoming important parts of many motor control systems. In fact, a major advantage associated with most VFDs is that they often have built-in, soft-start capabilities.

Another common characteristic of motors used in fan applications is multiple speed capability. Because ventilation and air-moving requirements often vary significantly, the ability to adjust fan speed is useful. Motors can be built to operate at different speeds in two principal ways: as a single set of windings equipped with a switch that energizes or de-energizes an additional set of poles, or with the use of multiple windings, each of which energizes a different number of poles. The first type of motor is known as a consequent pole motor and usually allows two operating speeds, one twice that of the other. The second type of motor can have two, three, or four speeds, depending on application. In general, multiple-speed motors are more costly and less efficient than single-speed motors. However, the flow control benefit of different motor speeds makes them attractive for many fan applications.

**Drive System.** The drive system often offers substantial opportunities to improve energy efficiency and to lower overall system operating costs. There are two principal types of drive systems: direct drive and belt drive. Gear drives are also used but are less common. In direct drive systems, the fan is attached to the motor shaft. This is a simple, efficient system but has less flexibility with respect to speed adjustments.

Because most fans are operated with induction motors, the operating rotational speeds of direct-drive fans are limited to within a few percent of the synchronous motor speeds (most commonly 1,200, 1,800, and 3,600 rpm). The sensitivity of fan output to its operating rotational speed means that errors in estimating the performance requirements can make a direct-drive system operate inefficiently (unlike belt drives, which allow fan rotational speed adjustments by altering pulley diameters). One way to add rotational speed flexibility to a direct-drive system is to use an adjustable speed drive (ASD). ASDs allow a range of shaft speeds and are quite practical for systems that have varying demand. Although ASDs are generally not a practical option for fans that are only required to operate at one speed, ASDs can provide a highly efficient system for fans that operate over a range of conditions.

In axial fans, direct drives have some important advantages. Applications with low temperatures and clean system air are well-suited for direct drives because the motor mounts directly behind the fan and can be cooled by the airstream. This space-saving configuration allows the motor to operate at higher-than-rated loads because of added cooling. However, accessibility to the motor is somewhat restricted.

Belt drives offer a key advantage to fan systems by providing flexibility in fan speed selection. If the initial estimates are incorrect or if the system requirements change, belt drives allow flexibility in changing fan speed. In axial fans, belt drives keep the motor out of the airstream, which can be an advantage in high temperature applications, or in dirty or corrosive environments.

There are several different types of belt drives, including standard belts, V-belts, cogged V-belts, and synchronous belts. There are different cost and operating advantages to each type. In general, synchronous belts are the most efficient, while V-belts are the most commonly used. Synchronous belts are highly efficient because they use a mesh-type contact that limits slippage and can lower operating costs. However, switching to synchronous belts must be done with caution. Synchronous belts usually generate much more noise than other belts. They also transfer shock loads through the

drivetrain without allowing slip. These sudden load changes can be problematic for both motors and fans. Another problem with synchronous belts is the limited availability of pulley sizes. Because the pulleys have a mesh pattern, machining them alters the pitch diameter, which interferes with engagement. Consequently, pulleys are available in discrete sizes, which precludes an important advantage of belt drives: the ability to alter operating rotational speeds by adjusting sheave diameters. Because of these factors, synchronous belts are not as widely used as V-belts in fan applications.

In contrast, V-belts are widely used because of their efficiency, flexibility, and robust operation. V-belts have a long history in industrial applications, which means there is a lot of industry knowledge about them. An important advantage to V-belts is their protection of the drivetrain during sudden load changes. Service conditions that experience sudden drivetrain accelerations cause accelerated wear or sudden failure. While synchronous belts tend to transfer these shock loads directly to the shafts and motors, V-belts can slip, affording some protection. Although they are less efficient than synchronous belts, V-belts offer many advantages such as low cost, reliable operation, and operating flexibility. In applications that use standard belts, upgrades to V-belts should be considered.

Although they are not commonly used, gear systems offer some advantages to belt systems. Gear systems tend to be much more expensive than belt drive alternatives; however, gears tend to require less frequent inspection and maintenance than belts and are preferable in applications with severely limited access. Gears also offer several motor/fan configurations, including in-line drives, parallel-offset drives, and 90-degree drives, each of which may provide an attractive advantage in some applications. Gear-system efficiency depends largely on speed ratio. In general, gear efficiencies range from 70 to 98 percent. In large horsepower (hp) applications (greater than 100 hp), gear systems tend to be designed for greater efficiency because of the costs, heat, and noise problems that result from efficiency losses. Because gears require lubrication, gearbox lubricant must be periodically inspected and changed. Also, because gears—like synchronous belts—do not allow slip, shock loads are transferred directly across the drivetrain.

**Ductwork or Piping.** For most fan systems, air is directed through ducts or pipes. In general, ducts are made of sheet metal and used in low-pressure systems, while pipes are sturdier and used in higher-pressure applications. Because ducts are used for most air-moving applications, “duct” will be the common reference for this course; however, most of the same principles can be applied to pipes.

In ventilation applications in which a fan pulls directly from a ventilated space on one side and discharges directly to an external space (like a wall-mounted propeller fan), duct losses are not a significant factor. However, in most applications, ducts are used on one or both sides of a fan and have a critical impact on fan performance. Friction between the airstream and the duct surface is usually a significant portion of the overall load on a fan.

As a rule, larger ducts create lower airflow resistance than smaller ducts. Although larger ducts have higher initial costs in terms of material and installation, the reduced cost of energy because of lower friction offsets some of these costs and should be included during the initial design process and during system modification efforts.

Other considerations with ducts are their shape and leakage class. Round ducts have less surface area per unit cross sectional area than rectangular ducts and, as a result, have less leakage. In hot or cool airstreams, this surface area also influences the amount of heat transferred to the environment.

Duct leakage class, typically identified by the factor  $C_L$  (which has units of cfm/linear foot) is an indicator of duct integrity. Variables that determine  $C_L$  include the type of joints used in construction, the number of joints per unit length of duct, and the shape of the duct. Depending on the length of the duct system, leakage can account for a significant portion of a fan’s capacity. This is especially applicable to systems with rectangular ducts that have unsealed joints. In many cases, the system designer can improve the performance of the ventilation system by specifying ducts that have low  $C_L$ s.

**Airflow Control Devices.** Flow control devices include inlet dampers on the box, inlet vanes at the inlet to the fan, and outlet dampers at the outlet of the fan. Inlet box dampers are usually parallel blade dampers. Inlet vanes adjust fan output in two principal ways: by creating a swirl in the airflow that affects the way in which the air hits the fan blades, or by throttling the air altogether, which restricts the amount of air entering the fan. The inlet vanes and dampers must be designed for proper fan rotation and are to be installed in such a way that these inlet vanes and dampers open in the same direction as the fan rotation. The pre-rotation or swirl of the air helps reduce the brake horsepower of the fan. If the inlet dampers on the inlet box are located too far away from the inlet of the fan, the effect of pre-rotation may be lost or reduced, and horsepower savings may be negligible.

The outlet damper, when used for controlling airflow, is usually of opposed-blade design for better flow distribution on the discharge side of the fan. If the outlet damper is going to be used for open/close service or for isolating the fan, a parallel-blade discharge damper may be used. Typically, fans with inlet vanes provide better power savings while operating the fan at part load conditions, as opposed to fans with inlet box dampers operating in a similar situation. Inlet vanes provide better controllability with optimum power savings compared to other dampers. Outlet dampers adjust resistance to airflow and move the operating point along the fan's performance curve. Because they do not change air entry conditions, outlet dampers do not offer energy savings other than shifting the operating point along the fan horsepower curve.

Dampers can be used to throttle the air entering or leaving a fan and to control airflow in branches of a system or at points of delivery. Dampers control airflow by changing the amount of restriction in an airstream. Increasing the restriction creates a larger pressure drop across the damper and dissipates some flow energy, while decreasing the restriction reduces the pressure differential and allows more airflow.

From a system perspective, proper use of dampers can improve energy efficiency over traditional system designs, especially in HVAC systems. In variable-air volume (VAV) systems, dampers are effective at rerouting airflow and at controlling the amount of air

delivered to a particular workspace. Because VAV systems are much more energy efficient than their precursors (constant-volume or dual-supply systems), dampers can be used to lower system operating costs.

However, in many applications, dampers can decrease fan efficiency. Dampers decrease total fan output by increasing backpressure, which forces the operating point of a fan to shift to the left along its performance curve. Often, as the fan operating point moves to the left along its curve, it operates less efficiently and, in some cases, may perform in an unstable manner. Unstable fan operation is the result of an aerodynamic phenomenon in which there is insufficient air moving across the fan blades. The airflow rate surges back and forth resulting in inefficient performance, annoying noise characteristics, and accelerated wear on the fan drive system.

Another airflow control method that is available for axial fan applications is the use of variable pitch blades. Variable pitch fans control fan output by adjusting the fan blade angle of attack with respect to the incoming airstream. This allows the fan to increase or decrease its load in response to system demand. In effect, this method is similar to that provided by inlet vanes, which adjust the angle of attack of the entering airstream by creating a swirl in the airflow pattern. Variable pitch fans provide a highly efficient means of matching fan output to system demand.

Another method of airflow control is fan speed adjustment. Recalling the fan laws, speed has a linear relationship with airflow, a second-order relationship with pressure, and a third-order relationship with power. By slowing or speeding up a fan, its output can be adjusted to match system demand. In general, fan speed adjustment is the most efficient method of airflow control.

There are two primary speed control options: multiple-speed motors and ASDs. Multiple-speed motors have discrete speeds, such as "high," "medium," and "low." Although these motors tend to be somewhat less efficient than single speed motors, they offer simplicity, operating flexibility, a relatively compact space envelope, and significant energy savings for fan systems with highly variable loads. ASDs include several different types of mechanical and electrical equipment. The most common type

of ASD is a VFD. VFDs control the frequency of the power supplied to a motor to establish its operating speed. Unlike multiple speed motors that operate at discrete speeds, VFDs allow motors to operate over a continuous range of speed. This flexibility provides accurate matching between fan output and the flow and pressure requirements of the system.

**Air Conditioning and Process Equipment (Filters, Heat Exchangers, etc.).** Other equipment commonly found in air-moving systems includes devices used to condition the airstream to obtain certain properties. Heat exchangers are used to heat or cool an airstream to achieve a particular temperature or to remove moisture. Filters are used to remove unwanted particles or gases. Conditioning equipment influences fan performance by providing flow resistance and, in some cases, by changing air density. Filters, including cyclone types or mesh types, inherently create pressure drops, which are often significant components of the overall system pressure drop. Mesh-type filters create increasingly large pressure drops as they accumulate particles. In many systems, poor performance is a direct result of inadequate attention to filter cleanliness.

Cyclone filters remove particulates by rapidly altering the direction of the airflow so that heavy particulates, unable to change direction quickly, get trapped. Although cyclone filters are less effective than mesh filters, they tend to require less maintenance and have more stable pressure-drop characteristics.

The effects of heating and cooling coils on fan system performance depend largely on where in the system the heat exchangers are located, the extent of the temperature change, and how the heat exchangers are constructed. Where there are large changes in airstream temperature, fan performance can change as the air density changes. Heat exchangers that have closely spaced fins can accumulate particulates and moisture that not only impact heat transfer properties, but also increase pressure losses.

## Assessing Fan System Needs

There are three principal opportunities in the life cycle of a system that can be used to improve fan system performance:

- During initial system design and fan selection
- During troubleshooting to solve a system problem
- During a system capacity modification.

### ◆ Initial Fan Selection

Fan selection starts with a basic knowledge of system operating conditions: air properties (moisture content, temperature, density, contaminant level, etc.), airflow rate, pressure, and system layout. These conditions determine which type of fan—centrifugal or axial—is required to meet service needs.

Axial fans move air along the direction of the fan's rotating axis, much like a propeller. Axial fans tend to be light and compact. Centrifugal fans accelerate air radially, changing the direction of the airflow. They are sturdy, quiet, reliable, and capable of operating over a wide range of conditions. Many factors are used to determine whether axial or centrifugal fans are more appropriate for certain applications.

After deciding which fan type is appropriate, the right size must be determined. Fans are usually selected on a "best-fit" basis rather than designed specifically for a particular application. A fan is chosen from a wide range of models based on its ability to meet the anticipated demands of a system. Fans have two mutually dependent outputs: airflow and pressure. The variability of these outputs and other factors, such as efficiency, operating life, and maintenance, complicate the fan selection process.

**Tendency to Oversize.** A conservative design tendency is to source a fan/motor assembly that will be large enough to accommodate uncertainties in system design, fouling effects, or future capacity increases. Designers also tend to oversize fans to protect against being responsible for inadequate system performance.

However, purchasing an oversized fan/motor assembly creates operating problems such as excess airflow noise and inefficient fan operation. The incremental energy costs of operating oversized fans can be significant.

### ◆ Troubleshooting a System Problem

Some fan system problems, such as abnormally high operating and maintenance costs and ineffective airflow control, are sufficiently troublesome to justify a system assessment. If the system problems are significant, then a change to the fan, its drive system, or the airflow control devices may be justifiable.

**High Operating and Maintenance Costs.** Unusually high operating costs are often caused by inefficient fan operation that, in turn, can be the result of improper fan selection, poor system design, or wasteful airflow control practices. Improper fan selection often means the fan is oversized for the application, resulting in high energy costs, high airflow noise, and high maintenance requirements.

Poor system design can lead to high operating and maintenance costs by promoting poor airflow conditions. For example, duct configurations that create large system effect factors can cause significant efficiency and airflow losses.

An effective way of minimizing maintenance and operating costs is to keep a fan operating within a reasonable range of its best efficiency point (BEP). However, this practice is often difficult in systems that have changing demands.

**Poor Airflow Control.** Poor airflow control refers to a wide range of causes and problems, including inadequate delivery to a system branch, surging operation, and high airflow noise.

Inadequate delivery may be the result of poor system balancing or leakage. If a branch has a damper that is stuck open or a duct develops a large leak, then this branch may provide a low resistance flow path that robs airflow from other delivery points. Fans typically react to this loss of

backpressure by generating high airflow rates. In severe cases, many centrifugal fan motors will overload if operated against little or no backpressure. If not corrected, an overloaded motor will typically shut itself down with thermal or current safety switches.

Several situations can cause surging. Fans in a parallel configuration may be shifting load between each other. A single fan may be operating in a stall condition or hunting for the right operating point along an unstable part of its performance curve. In these cases, the system resistance is too high.

**Electrical System Wear.** Frequent start-ups of large loads can add significant stress to an electrical system. The in-rush current and the starting current for motors can create voltage sags in the electrical system and cause the motor to run hot for several minutes. In fan applications where sensitive loads can be affected by fan start-ups, the use of soft starters should be considered. Soft starters are electrical devices that gradually ramp up the voltage to the fan motor, limiting the in-rush and starting current. Soft starters can extend fan motor life by keeping the motor temperature low.

Variable frequency drives (VFDs) are also commonly used to soft start fans. By gradually bringing fan speed up to operating conditions, VFDs reduce stress on the electrical system.

### ◆ System Capacity Change

For a system that is to be modified or upgraded, an assessment of the available fan capacity should be performed. Unless the existing fan is considerably oversized, added capacity requires the installation of a larger fan or an additional fan. Conversely, a system with excess fan capacity can often be accommodated by operating the fan at a slower speed. In these applications, the effects of operating a motor at less than half its rated load should be considered. Recall that motor efficiency and power factor fall significantly when the motor is operated below half its rating.

**Higher Fan Rotational Speed.** One option to accommodate the increased demand is to operate the fan at a higher speed. In belt driven applications, the sheave diameters can be changed to increase fan speed. The relationship between fan speed and airflow rate is linear; however, the relationship between fan speed and power consumption is cubed.

Consequently, increasing the airflow rate of the fan by increasing its speed requires significantly more power and may require a larger motor. The structural integrity of the rotating elements, bearings, shafts, and support structure needs to be evaluated for the higher speeds.

**Lower Fan Rotational Speed.** If the fan is oversized for normal operating conditions, the feasibility of operating it at lower rotational speeds should be considered. Reducing fan speed can significantly reduce energy consumption. For example, according to the fan laws, reducing fan rotational speed by 20 percent decreases fan power by 50 percent. Unfortunately, this speed reduction may cause motor efficiency and power factor to drop to low levels. The costs of inefficient operation and low power factor may justify motor replacement or the installation of a variable frequency drive.

$$\text{Power}_{\text{final}} = \text{Power}_{\text{initial}} \left( \frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}} \right)^3$$

**Multiple Fans.** Airflow rate can also be increased by installing a separate fan next to an existing one. Multiple-fan configurations have many advantages, including flexibility in meeting widely varying system demands and redundancy in case of equipment failure. When adding a fan to an existing system, the system can be configured so that both fans operate concurrently or either fan operates independently. The concurrent operation of two fans creates a combined performance curve that may be more appropriate for the system requirements than that of a single fan.

**Fan Replacement.** Replacing an existing fan with a different model is also an option. Selecting a new, larger fan requires consideration of the same factors that are involved in any initial fan selection. A new fan may be more feasible if the existing one has degraded or requires extensive refurbishment. In high run-time applications, the purchase of a new fan with an energy-efficient motor may provide an attractive payback.

## Fan Types

### ◆ Basic Principle

Fans can be classified primarily into two different types: axial and centrifugal. Axial fans act like propellers, generating airflow along the direction of the fan's axis. Centrifugal fans generate airflow by accelerating the airstream radially and converting the kinetic energy into pressure. Axial and centrifugal fans have overlapping capabilities in terms of pressure, airflow, and efficiency; however, usually they are not interchangeable.

Key impacts that determine which fan type is the most appropriate include technical and non-technical attributes. Technical considerations include pressure, airflow rate, efficiency, space constraints, noise generation, drive configuration, temperature range, variations in operating conditions, and tolerance to corrosive or particulate-laden airstreams. Nontechnical reasons include cost, delivery time, availability, and designer/operator familiarity with a fan model.

Understanding the principles of fan selection can be helpful in correcting poor system performance, especially during retrofit or upgrade opportunities. If noise levels, energy costs, maintenance requirements, or fan performance do not meet expectations, then a different type of fan may need to be considered.

### ◆ Centrifugal Fans

Centrifugal fans are the most commonly used type of industrial fan. Centrifugal fans are capable of generating high pressures with high efficiencies, and they can be constructed to accommodate harsh operating conditions. Centrifugal fans have several types of blade shapes, including forward-curved, radial-blade, radial-tip, backward-inclined, backward-curved, and airfoil. Some centrifugal fan types are capable of serving widely varying operating conditions, which can be a significant advantage.

**Forward-Curved Blades.** This fan type, shown in Figure 2-1, has blades that curve in the direction of rotation. This fan type is typically used in applications that require low to medium air volumes at low pressure. It is characterized by relatively low efficiency (between 55 and 65 percent). This fan type can operate at relatively low speeds, which translates to low levels of noise. Forward-curved fans are commonly selected because of their small size relative to other fan types.

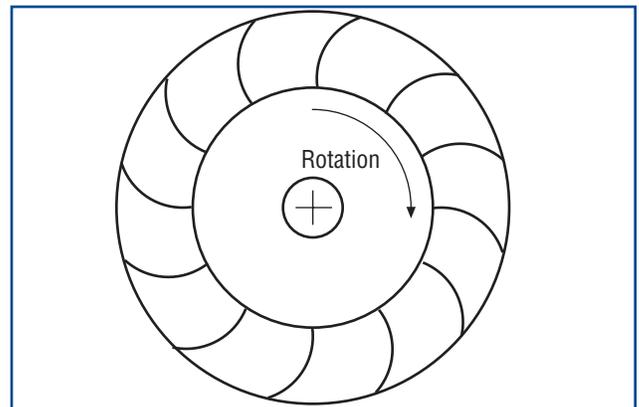
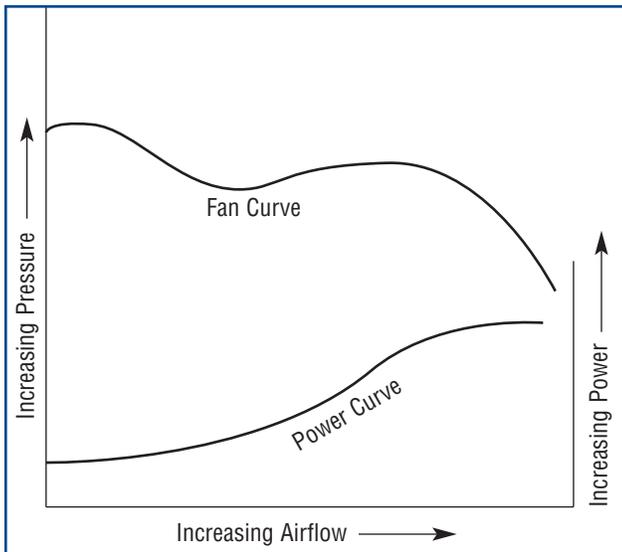


Figure 2-1. Forward-Curved Blade Fan

Stress levels in fans are closely related to operating speed; consequently, forward-curved fans do not require high-strength design attributes. Their low operating speed also makes them quiet and well-suited for residential heating, ventilation, and air conditioning (HVAC) applications. A typical performance curve is shown in Figure 2-2. The dip in the performance curve represents a stall region that can create operating problems at low airflow rates.

Forward-curved fans are usually limited to clean service applications. These fans are typically not constructed for high pressures or harsh service. Also, fan output is difficult to adjust accurately (note how the fan curve is somewhat horizontal), and these fans are not used where airflow must be

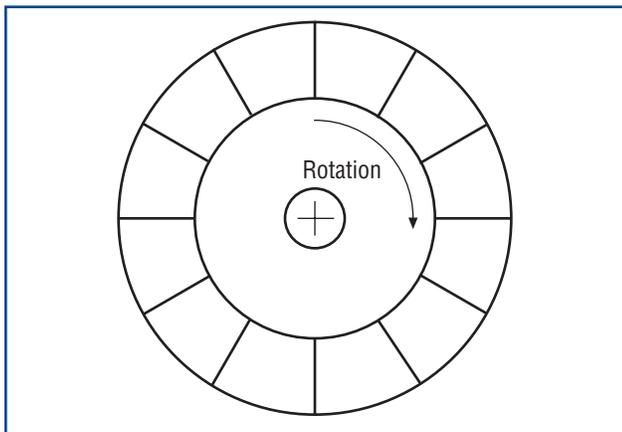


**Figure 2-2. Forward-Curved Centrifugal Fan Performance Curve**

closely controlled. Forward-curved fans have a power curve that increases steadily with airflow toward free delivery; consequently, careful driver selection is required to avoid overloading the fan motor.

**Radial-Blade.** Shown in Figure 2-3, this type is commonly used in applications with low to medium airflow rates at high pressures. The flat blade shape limits material build-up; consequently, these fans are capable of handling high-particulate airstreams, including dust, wood chips, and metal scrap.

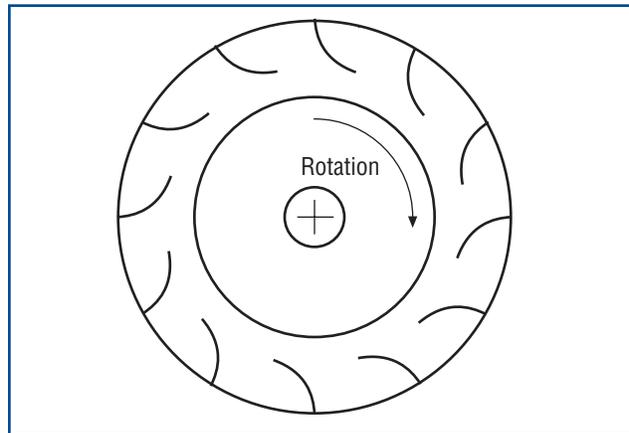
This fan type is characteristically rugged. The simple design of these fans allows many small metalworking shops to custom build units for special



**Figure 2-3. Radial-Blade Centrifugal Fan**

applications. In many cases, the blades can be inexpensively coated with protective compounds to improve erosion and corrosion resistance. The large clearances between the blades also allow this fan to operate at low airflows without the vibration problems that usually accompany operating in stall. The characteristic durability of this fan type is a key reason why it is considered an industry workhorse.

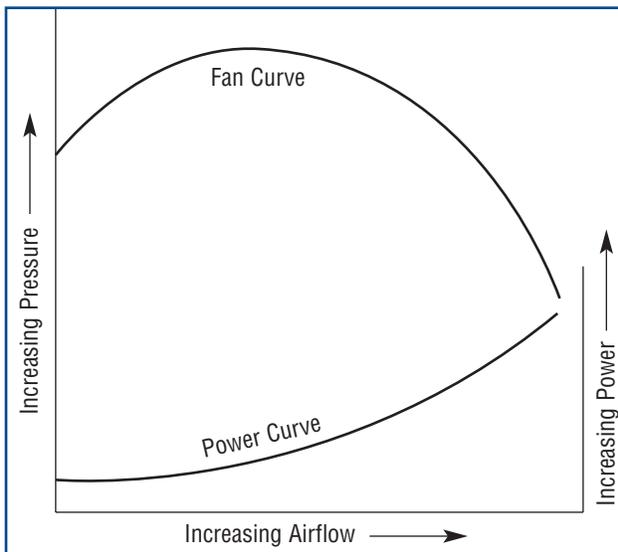
**Radial-Tip.** This fan type fills the gap between clean-air fans and the more rugged radial-blade fans. Radial-tip fans are characterized by a low angle of attack between the blades and the incoming air, which promotes low turbulence. A radial tip fan is shown in Figure 2-4.



**Figure 2-4. Radial-Tip Centrifugal Fan**

Radial-tip fans have many of the characteristics of radial-blade fans and are well-suited for use with airstreams that have small particulates at moderate concentrations and airstreams with high moisture contents. Radial-tip fans can have efficiencies up to 75 percent. These fans are commonly used in airborne-solids handling services because they have large running clearances. A typical fan curve for radial fans is shown in Figure 2-5.

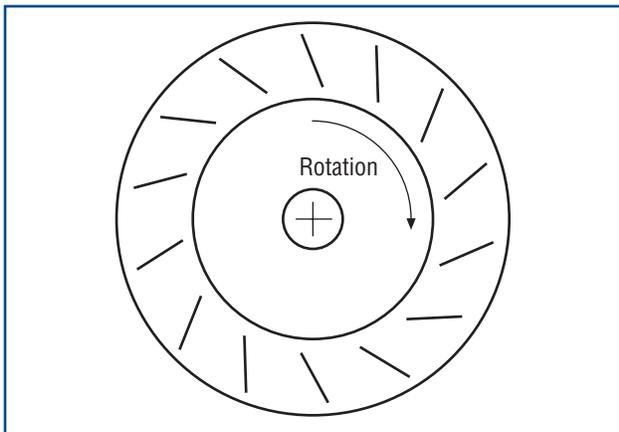
**Backward-Inclined Fans.** This fan type is characterized by blades that tilt away from the direction of rotation. Within backward-inclined fans are three different blade shapes: flat, curved, and airfoil. Flat blade types, shown in Figure 2-6, are more robust. Curved-blade fans tend to be more efficient. Airfoil blades, shown in Figure 2-7, are the most efficient of all, capable of achieving efficiencies exceeding



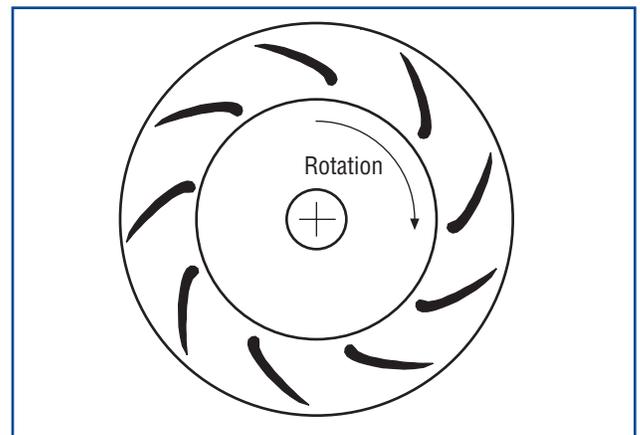
**Figure 2-5. Radial-Blade Fan Curve**

85 percent. Because airfoil blades rely on the lift created by each blade, this fan type is highly susceptible to unstable operation because of stall.

A consequence of backward-incline blade orientation is a low angle of impingement with the airstream. This promotes the accumulation of particulates on the fan blades, which can create performance problems. Thin airfoil blades are more efficient than the other blade types because of their lower rotating mass. However, this thin-walled characteristic makes this fan type highly susceptible to erosion problems. Loss of blade wall thickness can lead to cavity formation in the blades, which can severely interfere with fan performance.



**Figure 2-6. Backward-Inclined Fan**



**Figure 2-7. Backward-Inclined Centrifugal Airfoil Fan**

A common application for backward-inclined fans is forced-draft service. In these applications, the fan is exposed to the relatively clean airstream on the upstream side of the process. The high operating efficiencies available from this fan type can provide low system life-cycle costs. A typical performance curve is shown in Figure 2-8. The motor brake horsepower increases with airflow for most of the performance curve but drops off at high airflow rates. Because of this non-overloading motor characteristic, this fan type is often selected when system behavior at high airflow rates is uncertain.

#### ◆ Axial Fans

The key advantages of axial airflow fans are compactness, low cost, and light weight. Axial fans are frequently used in exhaust applications where airborne particulate size is small, such as dust streams, smoke, and steam. Axial fans are also useful in ventilation applications that require the ability to generate reverse airflow. Although the fans are typically designed to generate flow in one direction, they can operate in the reverse direction. This characteristic is useful when a space may require contaminated air to be exhausted or fresh air to be supplied.

Axial fans have a severe stall region that makes them particularly unsuitable for systems with widely varying operating conditions. In this stall region, airflow is insufficient to fill the blades, causing the fan to operate unstably. The consequences of unstable operation include annoying noise patterns, inefficient performance,

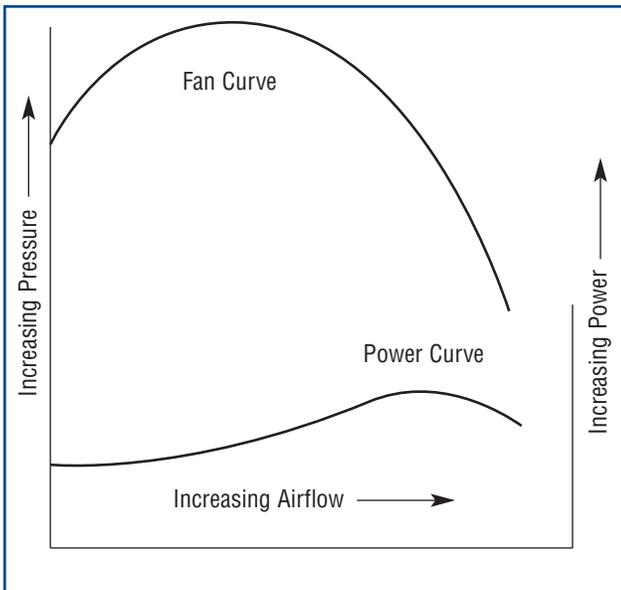


Figure 2-8. Backward-Inclined Fan Curve

and accelerated drivetrain wear. This problem of stall can be solved in many axial fans by selecting a fan with an anti-stall device. These devices alter the airflow patterns around the fan blades, allowing stable fan operation over the entire range of airflow and pressure.

Axial fans must rotate faster than comparable centrifugal fans to achieve the same airflow capacity. This characteristic makes them noisier than comparable centrifugal fans; however, the noise signature is dominated by higher frequencies, which are easier to attenuate.

**Propeller Fans.** The simplest version of an axial fan is the propeller type, shown in Figure 2-9.

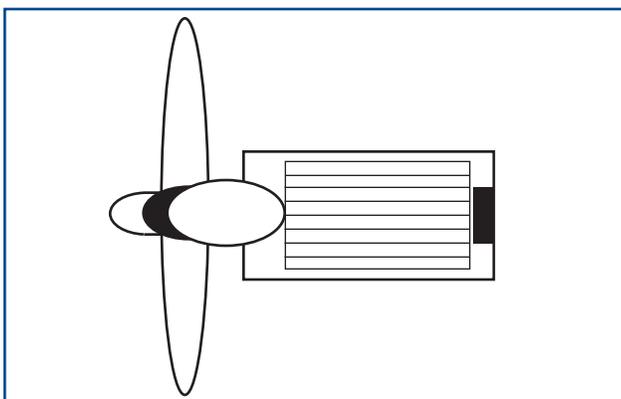


Figure 2-9. Propeller Fan

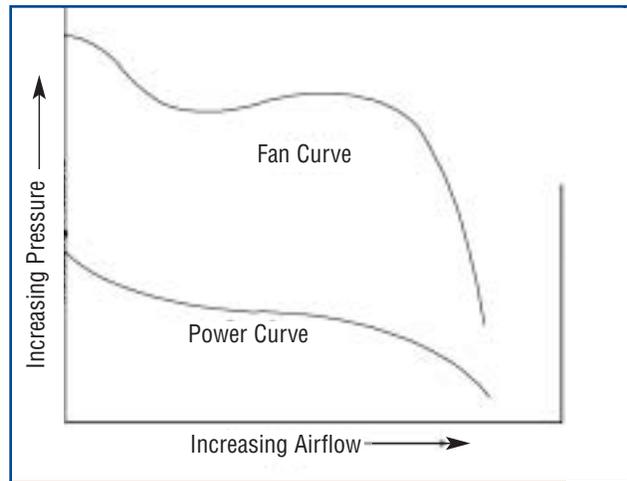


Figure 2-10. Propeller Fan Curve

Propeller fans generate high airflow rates at low pressures. Because propeller fans do not generate much pressure, they are usually not combined with extensive ductwork. Propeller fans tend to have relatively low efficiencies, but they are inexpensive because of their simple construction. Propeller fans tend to be comparatively noisy, reflecting their inefficient operation.

As shown in Figure 2-10, the power requirements of propeller fans decrease with increases in airflow. They achieve maximum efficiency, near-free delivery, and are often used in rooftop ventilation applications.

**Tubeaxial Fans.** A more complex version of a propeller fan is the tubeaxial fan. This type, shown in Figure 2-11, is essentially a propeller fan placed inside a cylinder. By improving the airflow

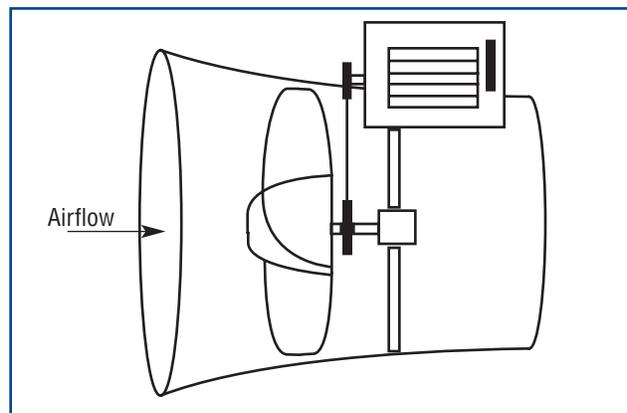


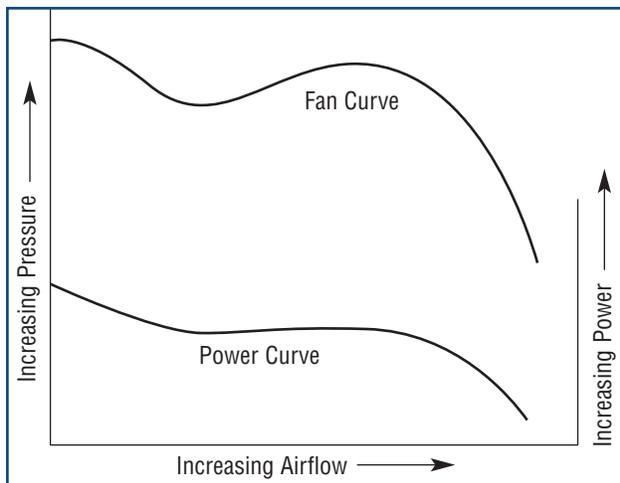
Figure 2-11. Tubeaxial Fan

characteristics, tubeaxial fans achieve higher pressures and better operating efficiencies than propeller fans.

Tubeaxial fans are used in medium-pressure, high-airflow rate applications and are well-suited for ducted HVAC installations. The airflow profile downstream of the fan is uneven, with a large rotational component. This airflow characteristic is accompanied by moderate airflow noise.

Tubeaxial fans are frequently used in exhaust applications because they create sufficient pressure to overcome duct losses and are relatively space efficient. Also, because of their low rotating mass, they can quickly accelerate to rated speed, which is useful in many ventilation applications.

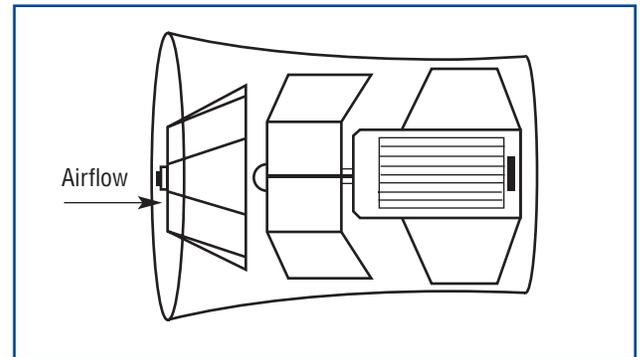
The performance curve for tubeaxial fans is shown in Figure 2-12. Much like propeller fans, tubeaxial fans have a pronounced instability region that should be avoided.



**Figure 2-12. Tubeaxial Fan Curve**

Tubeaxial fans can be either connected directly to a motor or driven through a belt configuration. Because of the high operating speeds of 2-, 4-, and 6-pole motors, most tubeaxial fans use belt drives to achieve fan speeds below 1,100 revolutions per minute.

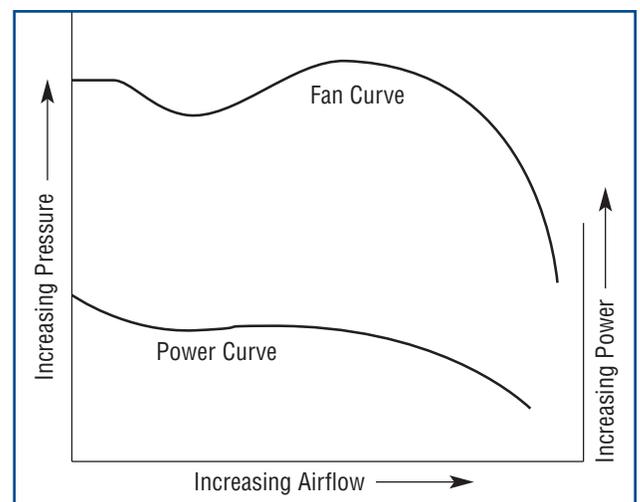
**Vaneaxial Fans.** A further refinement of the axial fan is the vaneaxial fan. As shown in Figure 2-13, a vaneaxial fan is essentially a tubeaxial fan with



**Figure 2-13. Vaneaxial Fan**

outlet vanes that improve the airflow pattern, converting the airstream's kinetic energy to pressure. These vanes create an airflow profile that is comparatively uniform.

Vaneaxial fans are typically used in medium- to high-pressure applications, such as induced draft service for a boiler exhaust. Like tubeaxial fans, vaneaxial fans tend to have a low rotating mass, which allows them to achieve operating speed relatively quickly. This characteristic is useful in emergency ventilation applications where quick air removal or supply is required. Also, like other axial fans, vaneaxial fans can generate flow in reverse direction, which is also helpful in ventilation applications. Depending on the circumstances, these applications may require the supply of fresh air or the removal of contaminated air.



**Figure 2-14. Vaneaxial Fan Curve**

Vaneaxial fans are often equipped with variable-pitch blades, which can be adjusted to change the angle of attack to the incoming airstream. Variable-pitch blades can change the load on the fan, providing an effective and efficient method of air-flow control.

As shown in Figure 2-14, vaneaxial fans have performance curves that have unstable regions to the left of the peak pressure. These fans are highly efficient. When equipped with airfoil blades and built with small clearances, they can achieve efficiencies up to 85 percent. Vaneaxial fans are frequently connected directly to a motor shaft.

## Basic Maintenance

### ◆ Maintenance Items

Common maintenance tasks on fan systems include:

- Periodic inspection of all system components
- Bearing lubrication and replacement
- Belt tightening and replacement
- Motor repair or replacement
- Fan cleaning.

The most costly consequence of improper maintenance is unscheduled downtime. Causes of this downtime vary according to the demands of the application. Because each system places particular demands on its air-moving equipment, maintenance requirements vary widely.

### ◆ Maintenance Schedules

To minimize the amount of unscheduled downtime, basic system maintenance should be performed at reasonable intervals, the length of which should be determined by either hours of operation or calendar periods. The maintenance interval should be based on manufacturer recommendations and experience with fans in similar applications.

Factors that should weigh into this schedule include the cost of downtime, the cost and the risk of catastrophic failure, and the availability of back-up equipment. In systems that do not have abnormally severe operating demands, a typical maintenance schedule would include the items on the checklist.

**Belt Inspection.** In belt-driven fans, belts are usually the most maintenance-intensive part of the fan assembly. As belts wear, they tend to lose tension, reducing their power transmission efficiency. Even new, properly adjusted belts suffer losses of 5 to 10 percent. As belt conditions degrade, these losses increase. Because noise is one of the ways

### Basic Maintenance Checklist

- ❑ **Belts.** Check belt condition, tightness, and alignment. Also check sheave condition.
- ❑ **Bearings.** Determine bearing condition by listening for noises that indicate excessive wear, measuring bearing operating temperature, or by using a predictive maintenance technique, such as vibration analysis or oil analysis. Lubricate bearings in accordance with fan manufacturer instructions. Replace bearings, if necessary.
- ❑ **System Cleaning.** Fans and system components that are susceptible to contaminant build-up should be cleaned regularly.
- ❑ **Leaks.** Check for ductwork leakage that can lead to energy losses and poor system performance.
- ❑ **Motor Condition.** Check the integrity of motor winding insulation. Generally, these tests measure insulation resistance at a certain voltage or measure the rate at which an applied voltage decays across the insulation. Also, vibration analysis can indicate certain conditions within the motor windings, which can lead to early detection of developing problems.

in which the energy loss of belts is manifested, poor belt condition can add significantly to the ambient noise level.

Belt inspection is particularly important to the operation of large fans because of the size of the power losses. For example, in a 200-horsepower (hp) fan, a 5 percent decrease in power transmission efficiency results in a 10-hp loss, translating to \$3,270 annually for a continuously operating system.<sup>1</sup>

<sup>1</sup> Using \$0.05/kilowatt-hour.

Although belt inspection and tightening is usually a routine task for any mechanic, increased awareness of the costs associated with poorly adjusted belts can improve the attention devoted to this maintenance effort.

In multiple-belt arrangements, whenever one belt degrades to the point of requiring replacement, all the belts should be replaced at the same time. As belts wear and age, they exhibit different properties; consequently, replacing only one or two belts in a multiple-belt arrangement creates a risk of overloading one or more of the belts. Exposing all the belts to roughly the same operating time minimizes the risk of uneven loading.

Establishing proper belt tightness is essential to minimizing the energy losses associated with belt drives. However, care should be taken to prevent overtightening the belts. This leads to high radial bearing loads, accelerated wear, and shorter bearing replacement intervals.

**Fan Cleaning.** In many fans, performance decline is largely because of contaminant build-up on fan blades and other system surfaces. Contaminant build-up is often not uniform, resulting in imbalance problems that can result in performance problems and drivetrain wear. Because fans are often used in ventilation applications to remove airborne contaminants, this problem can be particularly acute. Fans that operate in particulate-laden or high-moisture airstreams should be cleaned regularly.

Certain fan types, such as backward-inclined airfoil, are highly susceptible to build-up of particulates or moisture. These build-ups disturb the airflow over the blades, resulting in decreased fan efficiency and higher operating costs.

In high-particulate or moisture-content applications, radial-blade, radial-tip, and forward-curved blade type fans are commonly used because of their resistance to contaminant build-up. If, for some other reason, a different type of fan is used in a high-particulate or high-moisture service, then fan inspection and cleaning should be performed more frequently than normal.

**Leakage.** System leaks degrade system performance and increase operating costs. Leaks tend to develop

in flexible connections and in areas of a system that experience high vibration levels. Leakage decreases the amount of air delivered to the point of service; consequently, one of the first steps in troubleshooting a system that has experienced declining performance is to check the integrity of the ductwork.

Sources of leaks can be identified visually by inspecting for poorly fitting joints, and tears or cracks in ductwork and flexible joints. In systems with inaccessible ductwork, the use of temporary pressurization equipment can determine if the integrity of the system is adequate.

**Bearing Lubrication.** Worn bearings can create unsatisfactory noise levels and risk seizure. Bearings should be monitored frequently. Bearing lubrication should be performed in accordance with the manufacturer's instructions. For example, for high-speed fans in severe environments, lubrication intervals can be necessary weekly or more often.

- For oil-lubricated bearings, check the oil quality and, if necessary, replace the oil.
- For grease-lubricated bearings, check the grease quality and, if necessary, repack the bearings. Be careful not to over-grease bearings as this interferes with ball or roller motion and may cause overheating.
- Ensure the bearings are adequately protected from contamination.

In axial fans, anti-friction bearings (ball, roller-type) are predominantly used because of the need for a robust thrust bearing to handle the axial thrust load.

**Motor Replacement.** Even properly maintained motors have a finite life. Over time, winding insulation inevitably breaks down. Motors in which the winding temperatures exceed rated values for long periods tend to suffer accelerated insulation breakdown. When faced with the decision to repair or replace a motor, several factors must be considered, including motor size, motor type, operating hours, and cost of electricity. For example, in a motor application where the

cost of electricity is \$0.05/kilowatt-hour, the motor operates 4,000 hours each year at 75 percent rated load, and the rebuild cost is 60 percent of the price of a new motor, the calculated breakeven point between repair and replacement is 50 hp.<sup>2</sup> Under these circumstances, in applications requiring less than 50 hp, replacement motors meeting Energy Policy Act (EPA) efficiency requirements should be selected, while larger motors should be rebuilt.

Of course, each facility must establish its own repair/replace strategy. There are several resources that provide guidance in developing such a strategy.

For motor rewinds, ensure that the repair facility has a proper quality assurance program, because poor quality motor rewinds can compromise motor efficiency. Although motor rewinds are often cost-effective, motors that have been previously rewound can suffer additional efficiency losses during subsequent rewinds.

For motor replacements, high-efficiency motors should be considered. High-efficiency motors are generally 3 to 8 percent more efficient than standard motors. In high-use applications, this efficiency advantage often provides an attractive payback period. EPA, which went into effect in October 1997, set minimum efficiency standards for most general-purpose motors from 1 to 200 hp.

The MotorMaster+ software program can be a valuable tool in selecting energy-efficient motors. The program allows users to compare motors and estimate energy costs and savings along with life-cycle costs. Because MotorMaster+ contains motor rotational speed data, it is useful in finding replacement motors that operate at the same speed

as the existing motor. This can help avoid the problem of installing a motor that, because of its higher operating speed, causes the fan to generate more airflow and consume more energy than the previous motor/fan combination. MotorMaster+ is available through the Industrial Technologies Information Clearinghouse and can be downloaded from the BestPractices Web site at [www.oit.doe.gov/bestpractices](http://www.oit.doe.gov/bestpractices).

**Fan Replacement.** Under most conditions, fan blades should last the life of the impeller. However, in harsh operating environments, erosion and corrosion can reduce fan-blade thickness, weakening the blades and creating an impeller imbalance. In these cases, either the impeller should be replaced or an entirely new fan should be installed.

#### ◆ Predictive Maintenance

In many applications, fan maintenance is reactive rather than proactive. For example, bearing lubrication is performed in response to audible bearing noises. Fan cleaning is performed to correct an indication of poor fan performance or vibration because of dust build-up. Unfortunately, many fan system problems remain unaddressed until they become a nuisance, by which time they may have resulted in significantly higher operating costs.

Vibration analysis equipment is essentially a refined extension of the human ear. By “listening” to the vibrations of a motor or similar piece of machinery, the instrumentation can detect the early symptoms of a bearing problem, motor winding problem, or dynamic imbalance. By identifying problems before they become worse, repairs can be effectively scheduled, reducing the risk of catastrophic failure.

Fortunately, recent improvements in instrumentation and signal analysis software have increased the availability of vibration monitoring and testing equipment. These devices can be permanently installed with a fan and incorporated into an alarm or safety shutdown system. Vibration monitors offer relatively inexpensive insurance for avoiding costly failures and can improve the effectiveness with which fan maintenance is planned.

<sup>2</sup> *HorsePower Bulletin*, Advanced Energy (in cooperation with the U.S. Department of Energy).

Portable vibration instruments can also be used as part of a facility's preventive maintenance system. Vibrations measured during operation can be compared against a baseline set of data, usually taken when the machinery was first commissioned. Vibration signatures taken at different points in a fan's operating life can be evaluated to determine whether a problem is developing and, if so, how fast.

### ◆ **Records**

A written log or record documenting observations and inspection results is a useful supplement to a maintenance schedule. Often a machinery problem will develop over time. A history of the repairs, adjustments, or operator observations regarding the conditions under which the problem becomes noticeable improves the ability to effectively schedule a repair. The MotorMaster+ software contains an inventory module that allows the user to record maintenance and inspection results.

# Common Fan System Problems

## ◆ Basic Principle

Like most other rotating machinery, fans experience wear and require periodic maintenance and repairs. Dynamic surfaces in bearings and belt drives degrade over time. Fan blade surfaces may erode from abrasive particles in the airstream, and motors eventually require replacement or rewinding.

Although some degree of wear is unavoidable, operating the system at efficient levels reduces the risk of sudden equipment failure and can lower the cost and frequency of maintenance.

Fan system problems can be grouped into two principal categories: problems that are related to the fan/motor assembly and problems associated with the system. A systems approach is important to help understand the total costs and performance impacts of these problems.

## ◆ Fan/Motor Assembly Problems

Problems with the fan/motor assemblies can result from improper component selection, poor installation, or poor maintenance.

**Belt Drives.** Belt drives are frequently the most maintenance-intensive component of a fan/motor assembly. Common problems include belt wear, noise, and rupture. Belt wear can lead to efficiency and performance problems. As belt slippage increases, it can translate directly into lower fan output. Insufficient belt tension can also cause high noise levels through belt slap or slippage. In some cases, belts will develop one or more smooth spots that lead to vibrations during fan operation.

In contrast, belt tension that is too high increases the wear rate, increases load on the bearings, and can create an increased risk of unexpected downtime.

In multiple-belt drive assemblies, uneven loading of the belts causes uneven wear, which can affect

the life and reliability of the whole drive unit.

Poor belt drive maintenance also promotes costly system operation. Contaminant build-up on the belts often results in increased slippage and noisy operation. The presence of abrasive particles tends to accelerate belt wear.

Belts are not the only item in a belt drive assembly that develop problems. The sheaves themselves are subject to wear and should be periodically inspected. Because sheave diameter has a significant effect on fan speed, the relative wear between the driven and the driving sheave can affect fan performance.

**Bearings.** As with most rotating machinery, the bearings in a fan/motor assembly wear and, over time, can create operating problems. To prevent such problems from causing unplanned downtime, bearings should be a principal maintenance item. There are two primary bearing types in fan/motor combinations: radial and thrust. In general, radial bearings tend to be less expensive than thrust bearings in terms of material cost and installation requirements. Because of the nature of the airflow, axial fans typically require heavier thrust bearings. These bearings tend to be comparatively expensive, making proper fan operation and effective maintenance important.

Common bearing problems include noise, excessive clearance, and, in severe cases, seizure. Because operating conditions vary widely, the history of other fans in similar applications should be used to schedule bearing replacement. Vibration analysis tools can improve confidence in determining bearing condition and planning bearing work. In oil-lubricated bearings, oil analysis methods can help evaluate bearing condition.

**Motors.** Even properly maintained motors have a finite life. Over time, winding insulation inevitably breaks down. Motors in which the winding temperatures exceed rated values for long periods tend to suffer accelerated insulation breakdown. In motor applications below 50 horsepower, the

common repair choice is simply to replace a motor with a new one; however, in larger applications, rewinding an existing motor is often more economically feasible. Although motor rewinds are typically a cost-effective alternative, motors that have been previously rewound can suffer additional efficiency losses during subsequent rewinds.

For motor rewinds, ensure that the repair facility has a proper quality assurance program, because poor-quality motor rewinds can compromise motor efficiency.

For motor replacements, energy-efficient motors should be considered. A section of the national Energy Policy Act (EPAAct) setting minimum efficiency standards for most common types of industrial motors went into effect in October 1997. EPAAct should provide industrial end users with increased selection and availability of energy efficient motors. EPAAct-efficient motors can be 3 to 8 percent more efficient than standard motors. In high run-time applications, this efficiency advantage often provides an attractive payback period.

The MotorMaster+ software program can be a valuable tool in selecting energy-efficient motors. The program allows users to compare motors and estimate energy costs and savings along with life cycle costs. It is available through the Information Clearinghouse and can be downloaded from the Web site at [www.oit.doe.gov/bestpractices](http://www.oit.doe.gov/bestpractices).

**Contaminant Build-Up.** Some fan types are susceptible to contaminant build-up. The tendency to suffer build-up is related to the velocity and angle of attack of the airflow with respect to the blades. In many cases, especially with backward-inclined blades, this build-up can significantly affect fan performance. Fan types that have blade shapes that discourage material accumulation (for example, radial and radial-tip types) are usually selected for applications in which the airstreams have high particulate or moisture content. However, even in relatively clean air applications, over time, particulate build-up can be a problem. Consequently, fan cleaning should be a part of the routine maintenance program.

In many heating and cooling system applications, highly efficient fan types, such as backward-inclined fans, are increasingly used to lower system energy consumption. An important component in this trend is the use of filters upstream of the fans to lessen material build-up. While these filters can help maintain efficient fan performance, additional attention to filter cleaning and replacement is required to avoid the pressure drops and energy losses that result from clogged filters.

**Fan Degradation.** In airstreams that have corrosive gases or abrasive particles, fan blade degradation can present a threat to reliable operation. As fan blades degrade, the airflow over the surfaces becomes disrupted and the fan imparts energy less efficiently to the airstream. Certain blade types are particularly susceptible to erosion because of the angle of attack with the airstream. In applications where higher-than-expected blade degradation has occurred, different fan types or fan materials should be considered. Many fan manufacturers have developed materials and coatings that solve this problem.

### ◆ System Problems

Poor system performance can be caused by several factors, including improper system design and component selection, incorrect installation practices, and inadequate maintenance. Improper system design usually means the system is configured so that it has high system effect factors (SEFs) that result in high operating costs, system leakage, and noisy system operation. Poor component selection includes oversizing fans or using ineffective or wasteful flow control devices.

Improper installation practices include on-site modifications to the duct system that result in high SEFs, improper fan rotational speed selection, and incorrect fan rotation.

Inadequate maintenance often means a lack of bearing lubrication and fan cleaning. Contaminant accumulation on fan blades, duct surfaces, and in filters results in decreased system efficiency and inadequate airflow.

**High Operating Costs.** Many fan systems are designed to support the highest expected operating loads. Because systems are frequently not re-adjusted during periods of low demand, fans often generate higher-than-necessary airflows and incur

higher-than-necessary operating costs. Awareness of the costs of inefficient system operation can lead to efforts that reduce these costs and increase system reliability. An important part of evaluating whether operating costs can be significantly reduced is to measure the amount of variability in delivery requirements and determine operating configurations that meet—but do not exceed—these requirements.

**Fouling.** The accumulation of contaminants in parts of a system can disrupt airflow profiles and create high-pressure drops. Finned heat exchangers and filters are particularly susceptible to contaminant accumulation that can severely impair airflow. In heat exchangers, fouling interferes with heat transfer, which can compound an airflow problem by requiring more airflow to compensate for the reduction in heat exchanger effectiveness. Consequently, fouling can have a compounding impact on energy use.

Another aspect of fouling that can affect fan performance is interference with inlet-guide vane operation or blade-angle adjustment in variable-pitch fans. Inlet-guide vanes are used to change the load on a fan according to system airflow requirements, thus allowing lower energy consumption during periods of low demand. However, because these devices are typically controlled with a mechanical linkage, contaminant build-up on the linkage components can impair proper operation. Similarly, the linkages controlling the position of variable-pitch blades can become fouled with contaminant build-up, limiting blade-angle adjustability.

Where contaminant build-up on mechanical linkages is a problem, it can defeat the energy savings and performance benefits that were intended when the fan system was specified. Consequently, either a greater maintenance effort should be made to keep the linkage action free, or an alternative airflow control solution should be considered. In many dirty air fan applications, adjustable-speed drives are attractive because of the avoided fouling problems.

**Airflow Noise.** In many systems, airflow noise is a large component of ambient noise levels. Improper fan selection or operating a fan at higher speeds than necessary can create avoidable noise levels that impair worker comfort and productivity.

**Insufficient Delivery.** Poor system configuration can lead to insufficient delivery. In many systems, designers have improperly calculated the system effect or have attempted to overpower it with additional fan capacity. The system effect stems from poor airflow conditions, and it can cause a fan to operate much less efficiently. This causes a system component to exhibit a higher-than-expected pressure drop. Frequently, a key consequence of the system effect is inadequate airflow.

There are many alternatives to compensate for this problem. A common solution is to increase fan speed, which increases airflow. Although this option is sometimes unavoidable, it results in higher operating costs and increased airflow noise.

Often, a more effective solution to inadequate airflow can be obtained by addressing the fundamental cause of the problem. By configuring the system to improve airflow and by using flow straighteners where appropriate, the performance problems caused by the system effect can be minimized.

**Leakage.** Some systems are constructed with little attention to joint integrity. In these systems, leakage can have a significant impact on operating cost and system performance. Some system leakage is unavoidable; however, minimizing the amount of airflow and pressure loss can provide key savings.

Over time, system leakage tends to increase. This is particularly true for systems with oversized fans. Higher-than-expected system pressure and high vibration levels cause joint integrity to suffer. As joints loosen, the amount of leakage increases. In systems with extensive ductwork, increases in joint leakage can have a direct impact on airflow delivery and can dramatically increase operating costs.

**Unstable Operation.** Unstable operation can result from operating certain types of fans at low airflow rates and from the interaction of multiple fans operating in parallel. In single fan configurations, an aerodynamic phenomenon known as “stall” occurs at low airflow rates. The severity of this stall varies according to fan type, but is most severe in axial fans, forward-curved centrifugal fans, and backward-inclined centrifugal fans.

The hunting phenomenon associated with fan stall occurs as the fan searches for a stable operating point.

Stall occurs when there is insufficient air moving across the fan blades. As the air “separates” from the fan blade, the force on the blade changes, causing the airflow to change as well. Stall happens largely because of air separation from the fan blades. When this separation starts on one blade, it often initiates an effect that carries over to the next blade, resulting in a cascading effect.

The shape and distance between the fan blades significantly affect how the stall affects fan performance. Some centrifugal fans, such as those with radial blades, show little change in output. This fact is largely because of the way radial-blade fans operate—they do not rely on air slipping across the blade surfaces and tend to have relatively large distances between the blades. As a result, stall problems are not as common in radial-blade fan as they are in other fans.

Axial fans are particularly vulnerable to stall. Because axial fans rely on the lift generated by blade surfaces, stall can create a significant performance problem. In general, axial fans are not recommended for use in systems with widely varying flow requirements, unless a means of keeping airflow rates above the stall point, such as a bleed line or a recirculation path, is available.

A solution to this problem is commercially available. A proprietary design feature, known as an anti-stall device, automatically modifies the flow patterns around the fan blades to provide stable operation at all combinations of flow and pressure. In applications where stall is a risk, this fan design can be considered.

Even in systems in which operating conditions are not expected to create stall problems, fan degradation or a significant increase in system pressure (filter clogging or system fouling) can cause a fan to develop an instability problem. In multiple-fan configurations, fans alternately shifting loads between each other can cause instability. This effect occurs at low-flow rates that are typically to the left of the peak pressure on the combined fan curve. Avoiding this problem requires de-energizing one of the fans or decreasing the

system resistance to allow greater airflow.

## Indications of Oversized Fans

### ◆ Tendency to Oversize Fans

Conservative engineering practices often result in the specification, purchase, and installation of fans that exceed system requirements. Engineers often include a margin of safety in sizing fans to compensate for uncertainties in the design process. Anticipated system capacity expansions and potential fouling effects add to the tendency to specify fans that are one size greater than those that meet the system requirements.

A recent U.S. Environmental Protection Agency (EPA) study revealed that within building fan systems, almost 60 percent of the fans were oversized, and almost 10 percent of the fans were oversized by 60 percent.

Unfortunately, many of the costs and operating problems that result from oversized fans are overlooked during the equipment specification process. The problems that accompany the selection of oversized fans are outlined below.

**High Capital Costs.** Large fans typically cost more than small ones, and large fans also require larger and more costly motors. Consequently, specifying oversized fans results in higher-than-necessary initial system costs.

**High Energy Costs.** Oversized fans increase system operating costs both in terms of energy and maintenance requirements. Higher energy costs can be attributed to two basic causes. The fan may operate inefficiently because the system curve intersects the fan curve at a point that is not near the fan's best efficiency point (BEP). Alternately, even if an oversized fan operates near its BEP, by generating more airflow than necessary, it uses more energy and increases stress on the system.

**Poor Performance.** Oversized fans tend to operate with one or more of the indications of poor performance including noisy, inefficient, or unstable fan operation. High airflow noise often results from

the excess flow energy imparted to the airstream. In addition, oversized fans are more likely to operate in their stall regions, which can result in surging flow and vibrations that damage the fans and degrade fan systems. Indications of stall include pulsing airflow noise, system ducts that seem to "breathe" in response to the pressure variations, and vibrating fan and duct supports.

**Frequent Maintenance.** When oversized fans operate away from their BEP, they may experience cyclic bearing and drivetrain stresses. This is particularly applicable when a fan operates in its stall region, which is typically on the left side of the fan performance curve. Also, cyclic bearing loads tend to increase the stress on other drivetrain components such as belts and motors. Oversized fans also tend to create high system pressures, which increase stress on the ductwork and promote leakage.

**High Noise/Vibration Levels.** Fans that operate inefficiently tend to create high airborne and structure-borne vibration levels. Airborne vibrations are often perceptible as noise, while structure-borne vibrations are felt by the system equipment, ductwork, and duct supports. Oversized fans often create high airflow noise. Workers acclimate to ambient acoustic levels and do not express discomfort. However, high noise levels promote fatigue, which reduces worker productivity.

High levels of structure-borne vibrations can create problems in welds and mechanical joints over time. High vibration levels create fatigue loads that eventually crack welds and loosen fittings. In severe cases, the integrity of the system suffers and leaks occur, further degrading system efficiency.

### ◆ Typical Indications of Oversized Fans

There are several indications of oversized fans. A few of these indications can be discerned by quick checks of system airflow control device settings.

Systems in which airflow demand varies widely inevitably require control devices to restrict airflow for certain periods. However, in some systems, inlet vanes and dampers remain closed so often that they can be found rusted or locked in a restrictive position. This indicates that the system continually operates against an unnecessary load and that fan operation is unnecessarily costly.

Other indications of oversized fans require more detailed measurements. For example, the location of the operating point on the fan curve can provide an indication of how appropriately the fan is sized.

If possible, compare the pressure required by the end uses to the pressure generated by the fan. If the fan is oversized, it will generate more total pressure for the same airflow than a correctly sized fan.

**Fan Load Factor.** As with any measured data, the data's usefulness is limited by how representative it is of the average system operating conditions. In systems with widely varying operating conditions, simply taking data once will probably not provide a true indication of system energy consumption.

To account for the fact that a fan does not operate at a single condition all the time, an estimate of its average load factor—the percentage of the fan's full capacity at which it operates—must be made. Unfortunately, unless operators maintain comprehensive records or are highly familiar with fan operating data, the average load factor may be difficult to determine.

**Direct Measurement.** An accurate way to determine motor power consumption requires directly measuring amps and volts. Kilowatt use is the product of amps and line volts, corrected by the power factor. Power factor is the ratio of real work performed to the product of volts and amps. Motors usually have power factors between 0.8 and 1, because of the reactive power that they draw. Reactive power is essentially the power stored in the magnetic field of the motor. The power factor data for most motors can be obtained from the manufacturers.

When conditions permit, hot readings (readings taken while the system is in operation) are relatively simple to take. Using a clamp-type ammeter, the current on each of the three power cables running to the motor (most industrial motors are three-phase) can be measured. Sometimes the motor controller

is a convenient point to take these readings, while at other sites, the connection box on the motor is more accessible. Line voltage is usually measured at the motor controller and should be measured around the same time as the current reading. In some facilities, line voltage varies over time because of changes in plant power consumption.

Alternately, for better accuracy, a power meter can be used instead of separately reading volts and amps. Most power meters measure real-time power, obviating the need to estimate power factor. Direct measurement of motor power is not always practical. "Hot" measurement of a motor current exposes workers to risk and may not be feasible in some industrial environments because of high voltage or exposure of the power connections to moisture or contaminants. Such readings should only be taken by properly trained personnel.

**Use of Fan Curves.** Another method of determining fan power consumption is to measure the static pressure generated by the fan and to determine the corresponding brake horsepower as shown in Figure 2-15. To determine electrical power, the brake horsepower value must be divided by motor efficiency. Also, the static pressure measurement must be corrected for any difference between the density of the airstream and the density used to define the performance curve. Most fan performance curves assume air density of 0.075 pounds per cubic foot, which is the density of air at standard conditions. Also, because fan performance is highly sensitive to operating speed, fan rotational speed should be measured and the affinity law

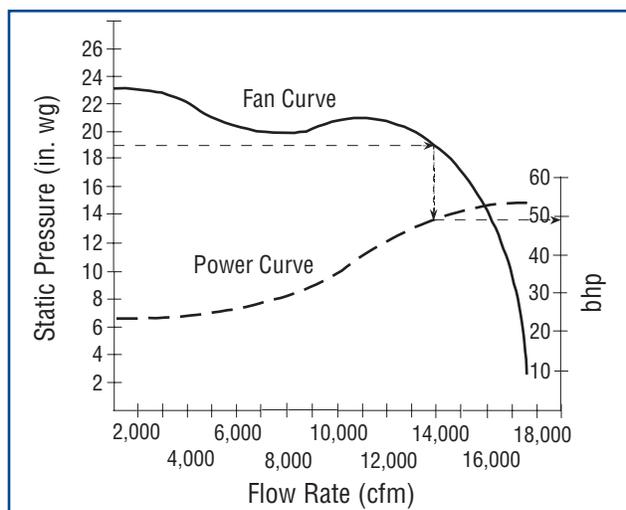


Figure 2-15. Use of Fan Curve to Determine Power Consumption

relationships should be used to find the equivalent operating point on the performance curve.

Unfortunately, this method is the least accurate and not usable on fans with relatively flat pressure curves.

### ◆ Corrective Measures

In systems served by oversized fans, several corrective measures can lower system operating costs and extend equipment maintenance intervals. Obviously, the entire fan/motor assembly could be replaced by a smaller version or, if necessary, with a more appropriate fan type; however, this option may be too costly.

Other alternatives include:

- Decreasing fan speed using different motor and fan sheave sizes (may require downsizing the motor)
- Installing an adjustable speed drive (ASD) or multiple-speed motor
- Using an axial fan with controllable pitch blades.

The choice among these measures depends on the system and on the particular indicator that points to the oversized fan problem.

**Decreasing Fan Speed.** Applications with an oversized, belt-driven fan may be suitable for decreasing fan speed. Fan power consumption is highly sensitive to fan speed, as shown by the following equation:

$$\text{Power}_{\text{final}} = \text{Power}_{\text{initial}} \left( \frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}} \right)^3$$

Consequently, significant energy savings are available if the fan can adequately serve the system at a lower speed. One method of reducing fan speed is to adjust the ratio of the pulley diameters for the motor and the fan.

A consideration in the fan-speed adjustment is the effect on the motor. Most motors operate at relatively consistent efficiencies above 50 percent of full load capacity. There is some efficiency loss above full load rating. However, below 40 percent of the motor load, efficiency begins to decline. This efficiency loss should be included in any economic

analysis. If fan power is to be reduced significantly, a smaller motor should be considered.

Another consideration is the effect on the motor's power factor. At relatively low loads, the power factor for a motor tends to decrease. Low power factors are detrimental to a motor and its power supply. Utilities often assess a charge against industrial facilities that have low power factors. The costs of reducing the motor's power factor should be included in the economic analysis and may provide an incentive to switch to a smaller motor.

Another method of decreasing fan rotational speed is to use a motor that has multiple speeds and to select a lower rotational speed during low airflow requirements. However, many of the same advantages available from a multiple-speed motor are also available from ASDs. ASDs, particularly variable frequency drives (VFDs) are commonly used as retrofit solutions because of their ability to work with existing motors. Multiple-speed motors are usually selected during the initial design process rather than retrofitted into an existing system.

**Variable Frequency Drives.** Fans that operate over a wide range of their performance curves are often attractive candidates for ASDs. The most popular type of ASD is the VFD. VFDs use electronic controls to regulate motor speed which, in turn, adjusts the fan output more effectively than changing pulley diameters. The principal advantage offered by VFDs is a closer match between the fluid energy required by the system and the energy delivered to the system by the fan. As the system demand changes, the VFD adjusts fan speed to meet this demand, reducing the energy lost across dampers or in excess airflow.

Also, VFDs tend to operate at unity power factors, which can reduce problems and costs associated with reactive power loads. Because VFDs do not expose mechanical linkages to potential fouling from contaminants in the airflow, they can also lead to reduced maintenance costs. The energy and maintenance cost savings provide a return that often justifies the VFD investment.

However, VFDs are not practical for all applications. Fans with severe instability regions should not be operated at rotational speeds that expose the fan to inefficient operating conditions. Additionally, many

fans have resonant frequencies at speeds below their normal operating speeds. Operating at these resonant speeds can cause high vibration levels that, if uncorrected, will cause damaging vibrations. Because slowing a fan increases the risk of encountering one of these conditions, a VFD, if used, should be programmed to avoid operating at these frequencies.

Also, for a belt-driven application where the fan load is relatively constant, using a VFD simply to slow the fan is probably less cost-effective than using a sheave change-out.

**Controllable Pitch Fans.** Where the use of an axial fan is practical, the selection of one with variable-pitch fan blades can provide several advantages. Controllable-pitch fans allow adjustment of the fan blade angle of attack according to airflow requirements. Adjusting this angle of attack changes both the load on the motor and the amount of energy delivered to the airstream. The average operating efficiencies of controllable pitch fans can equal or exceed those achieved by VFD-powered fans. Consequently, an application that requires an axial fan to meet a peak load while normally operating under much smaller load conditions may be an attractive opportunity to use controllable-pitch blades.

Advantages of controllable-pitch fans include allowing the fan to operate over a wide range of airflow requirements, reducing the start-up load on the motor, and providing constant motor speed operation. The disadvantages of controllable-pitch blades include higher initial cost, exposure of the pitch angle linkage to fouling, and the potential efficiency and power factor effects that accompany operating a motor below one-half of its rated capacity.

## System Leaks

### ◆ Basic Principle

Leakage is a common characteristic of most duct systems. Because system leakage can be a significant operating cost, it should be a consideration during the design of a system and the selection of a fan. The type of duct, the tightness and quality of the fittings, joint assembly techniques, and the sealing requirements for duct installation are all factors that designers should consider during the development of engineering drawings that guide system installation. Failure to account for leakage can result in an under-performing system. Also, designers who focus on initial costs without considering the costs due to leakage can specify a system that uses far more energy than necessary.

Leakage decreases the amount of delivered airflow. Often, the costs of compensating for leakage in an under-performing system far exceed the incremental costs of installing a “tight” system or locating and repairing a system leak.

System leakage tends to increase as the systems age. Gaskets dry and lose their sealing properties, and joints loosen from vibrations or inadequate support (for example, sagging ductwork).

System leakage is also largely dependent upon the pressure in the duct. One of the principal operating consequences of installing an oversized fan is higher duct pressure, which increases the airflow losses through leaks. The higher pressure in the duct system is because of the damper throttling that is required to achieve the proper flow rate. As the dampers are throttled to create a higher pressure loss, the system curve becomes steeper. The higher pressure upstream of the dampers leads to increases in leakage.

**Costs of Leakage.** The cost of leakage includes the additional fan power required to generate more airflow to compensate for leakage and, in some applications, the power applied to cool, heat, or filter that air. Much of the leakage cost is attributable

to the relationship between fan speed, fan power, and the system curve. Under an assumption that the system curve does not change because of the leaks, a 5 percent increase in airflow would require a 5 percent increase in fan speed and a 16 percent increase in power because of the fan law relationship between fan speed and power. In reality, the actual power required to generate this airflow is somewhat lower because the leakage changes the system curve, allowing the fan to operate against a lower backpressure. Consequently, calculating the effect of leakage on fan power requires analysis of the fan curve, the system curve, and how the leaks affect the system curve.

However, the costs of leakage can include more than just the fan power. In many industrial facilities, particularly those that require precise environmental control, the airflow delivered to the end uses is often extensively conditioned. Relative humidity, particulate content, and temperature must often be kept within close tolerances. The leakage of air that has been cleaned and conditioned generally results in an increased load on heating, ventilation, and air conditioning (HVAC) equipment, such as chillers, dehumidifiers, etc.

**Leakage Class.** Leakage classes are denoted by the term  $C_L$ , which represents leakage in cubic feet per minute (cfm) per 100 square feet of duct surface area.  $C_L$  factors range from 48 for unsealed rectangular ducts to 3 for sealed, round ducts.

Different duct types have different leakage rates. For example, because rectangular ducts have corners, the joints do not seal as well as those in round ducts. Rectangular ducts also have more surface area than round ducts with an equivalent cross-section. The combined result of these factors is that rectangular ducts tend to have higher leakage rates than round ducts.

To determine the correct leakage class in a duct system, one must know how the ducts were

assembled. A  $C_L$  of 48 is considered average for unsealed rectangular ducts. Lower leakage classes can be achieved depending on the pressure rating and the construction techniques specified in the assembly drawings. For example, if the transverse joints in rectangular ducts are sealed, then the estimated  $C_L$  is reduced to 24 (12 for round ducts). If all joints, seams, and wall penetrations are sealed, then the leakage classes drop to 6 for rectangular ducts (3 for round ducts).

The following equation forms the basis for the leakage classes:

$$C_L = \frac{Q}{p^{0.65}}$$

Where:  $Q$  = the leakage rate in cubic feet per minute (cfm) per 100 square feet of duct surface area

$p$  = average of upstream and downstream static pressure in inches of water gage (in. wg) in the duct

A useful resource for evaluating construction techniques and leakage considerations of ventilation ductwork is the Sheet Metal and Air Conditioning Contractors' National Association, Inc. (SMACNA). Further information can be found in the *HVAC Air Duct Leakage Test Manual*, which is referenced in the Resources and Tools section on page 68.

Another useful resource is a standard maintained by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) titled, *ASHRAE 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings*, also referenced on page 68. In an effort to promote energy-efficient building design and construction practices, this standard provides guidelines for sealing ducts and test requirements for checking leakage.

**Fittings and Equipment.** The tightness of system fittings and equipment, such as access doors, dampers, and terminal boxes, is also an important consideration. Poorly constructed dampers or improper sourcing of fittings promotes system leakage. Designers should specify mating ductwork and system equipment, so that joints fit tightly. Also, where practical, designers should set

maximum allowable leakage rates for systems and equipment, requiring integrity tests to verify that the equipment is properly constructed and installed.

**Installation Practices.** In addition to designing systems to minimize leakage, installation personnel should follow proper installation practices. Systems should be sealed with the right type of sealant for the application. Sealants that are compatible with the service conditions, such as temperature and moisture, should be selected. In general, because there are essentially no adequate industry performance standards for cloth and vinyl pressure-sensitive tape, the tape is not recommended for use on metal ducts. However, for flexible ducts, the use of pressure-sensitive tape on metal duct collars may be prescribed for the connection of flexible duct materials to metal duct collars. This is largely because of the ability of the tape to hold well on clean, galvanized steel ducts and fittings. Additionally, aluminum foil pressure-sensitive tape may be specified for the connection of fibrous glass duct to metal fittings (sleeves, terminals, and other equipment), particularly where operating pressures are 1 in. wg or less.

**Tightness Tests.** To ensure proper installation of duct systems, tightness tests should be performed, especially in systems where pressures exceed 2 or 3 in. wg. Although tightness checks are often not feasible on every part of the system, as much of the system as practical should be evaluated. In general, tightness tests pressurize the duct up to its pressure class rating and measure the airflow required to sustain this pressure.

## Configurations to Improve Fan System Efficiency

### ◆ Basic Principle

Flow patterns have a substantial impact on fan output and system resistance. Fans and system components are sensitive to the profile of an entering airstream. Non-uniform air patterns cause fans and system components to display flow/pressure-drop characteristics that are different from the manufacturer-supplied data. These differences are attributable to the conditions under which the manufacturer or an independent testing facility tests their products. Lab conditions tend to create uniform airflows. Consequently, performance data that is gathered under ideal conditions will probably not be repeated in an industrial environment. This difference is the fundamental reason for including the system effect.

The pressure drop across a component is calculated by the equation:

$$\Delta p = C \left( \frac{V}{1,097} \right)^2 \rho$$

Where:  $\Delta p$  = pressure drop in inches of water gage (in. wg)

$C$  = local loss coefficient

$V$  = velocity of the airstream in feet per minute (ft./min.)

$\rho$  = density of the airstream in pounds per cubic foot (lbs./ft.<sup>3</sup>)

The loss coefficient,  $C$ , is a dimensionless indicator of flow resistance. The loss coefficient is based on uniform flow into and out of the component. However, under non-uniform flow conditions, the coefficient becomes less accurate as an indicator.

Loss coefficients for system components such as ducts, fittings, and components are typically listed in tables provided by manufacturers. During the system design phase, designers calculate system resistance curves based on the published loss coefficients for each component. However, system configurations that promote non-uniform flow conditions will create flow resistances that are

higher than anticipated, leading to under-performing systems.

Unfortunately, a common approach to handling uncertainties in system design is to increase the size of the air movers, essentially overpowering the problems associated with a system effect. The consequences of this approach include high equipment costs, high operating costs, increased energy use, and noisy system operation.

### ◆ Design Practices

Many fan performance problems can be avoided by designing the system so that the inlet and outlet ducts to and from the fan are as straight as possible within the physical constraints of the available space. Inadequate attention to duct conditions during the design phase increases operating costs. Designers developing new systems and operators seeking to upgrade or retrofit existing systems can minimize system effect problems by recognizing and avoiding common configurations that aggravate them.

**Fan Inlet.** Poor airflow conditions at the inlet of a fan decrease the effectiveness and efficiency with which a fan imparts energy to an airstream. In fact, this sensitivity is used to control fan output in many types of fans. Devices such as variable inlet guide vanes adjust an airflow pattern entering a fan to change the amount of flow energy transferred by the fan.

A pre-rotational swirl in the airflow rotates in the same direction as a fan impeller. This phenomenon reduces the load on the fan and shifts its performance curve down and to the left. As shown in Figure 2-16, these swirls can result from locating elbows too close to a fan inlet. If possible, the fan should be configured so that there is enough distance from the closest bend for the airflow to straighten out. Because space constraints often do not allow ideal configuration, an airflow straightener, such as turning vanes, also shown in Figure 2-16, can improve fan performance.

A counter-rotating swirl rotates in the opposite direction of an impeller. This swirl creates an additional load on the impeller. Although it tends

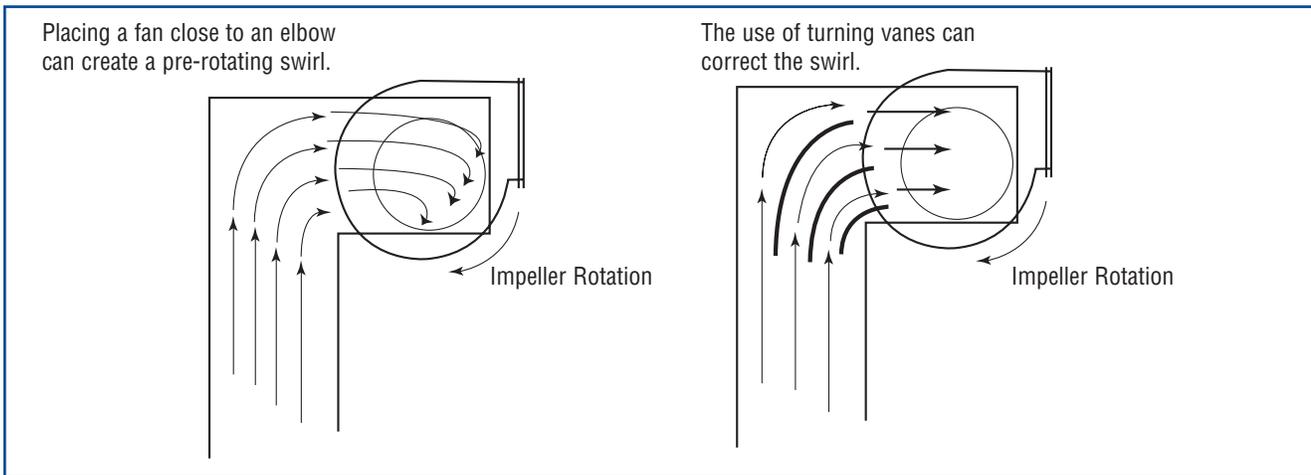


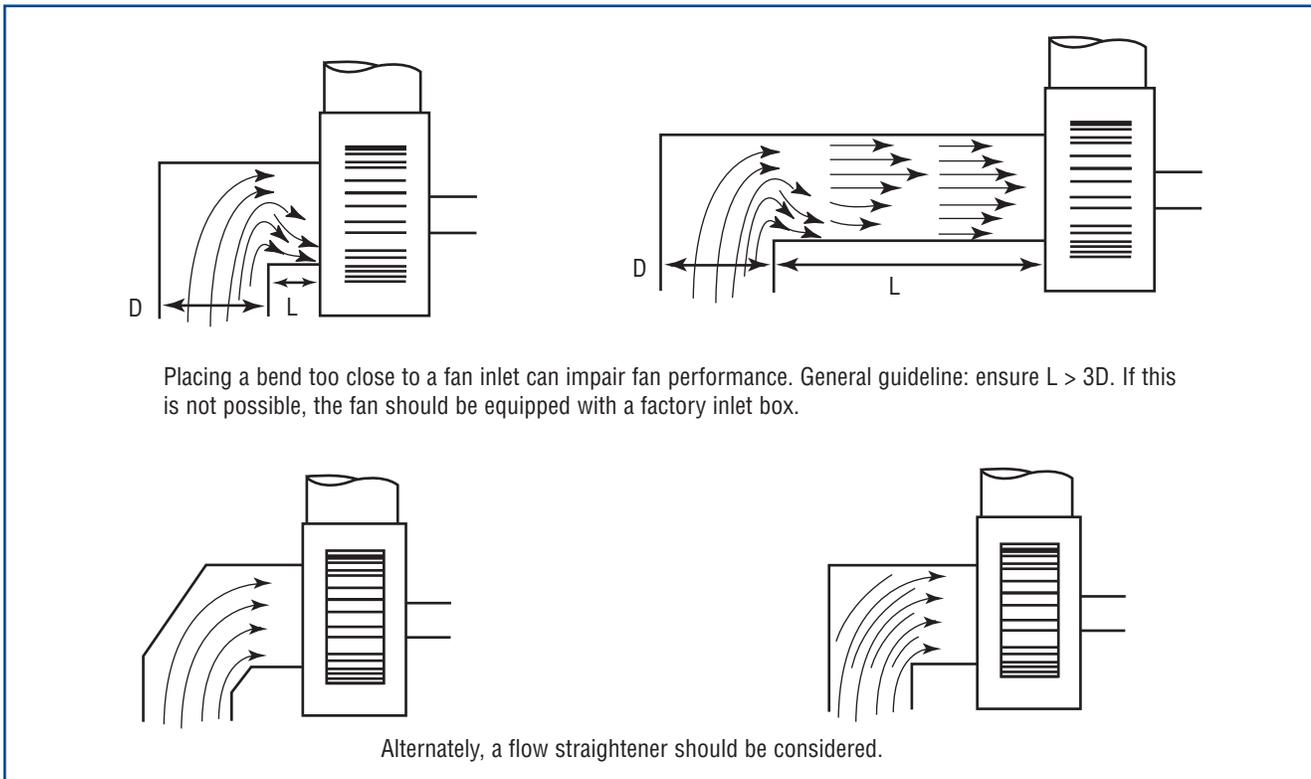
Figure 2-16. Pre-Rotational Swirl

to shift a fan’s performance curve upwards, a counter-rotating swirl is an inefficient method of increasing fan pressure.

Another inlet condition that can interfere with fan performance is highly non-uniform flow. As shown in Figure 2-17, placing a bend too close to a fan inlet can cause the airflow to enter the fan unevenly,

which leads to inefficient energy transfer and fan vibrations. One general guideline is to provide a straight duct length of at least 3 times the duct diameter just prior to the fan inlet.

**Fan Outlet.** Poor outlet conditions also contribute to under-performance in fan systems. Swirls and vortices increase the pressure drops of elbows and



Placing a bend too close to a fan inlet can impair fan performance. General guideline: ensure  $L > 3D$ . If this is not possible, the fan should be equipped with a factory inlet box.

Alternately, a flow straightener should be considered.

Figure 2-17. Effect of Elbow Placement Close to a Fan Inlet

other duct fittings and can lead to inadequate service to one or more system branches. As shown in Figure 2-18, tees and other fittings should be placed far enough downstream of a fan for the airflow to become more uniform. Similarly, where possible, fans should be oriented so that the airflow profile out of a fan matches the airflow behavior created by fittings such as an elbow.

Also as shown in Figure 2-18, the outer radius of an elbow requires higher velocity airflow than the inside edge (because the airflow has farther to travel), which is consistent with the airflow profile leaving a centrifugal fan.

**Airflow Straighteners and Splitters.** Many problems can be corrected with devices such as turning vanes or airflow straighteners. For example, as shown in Figure 2-19, flow splitters can prevent highly

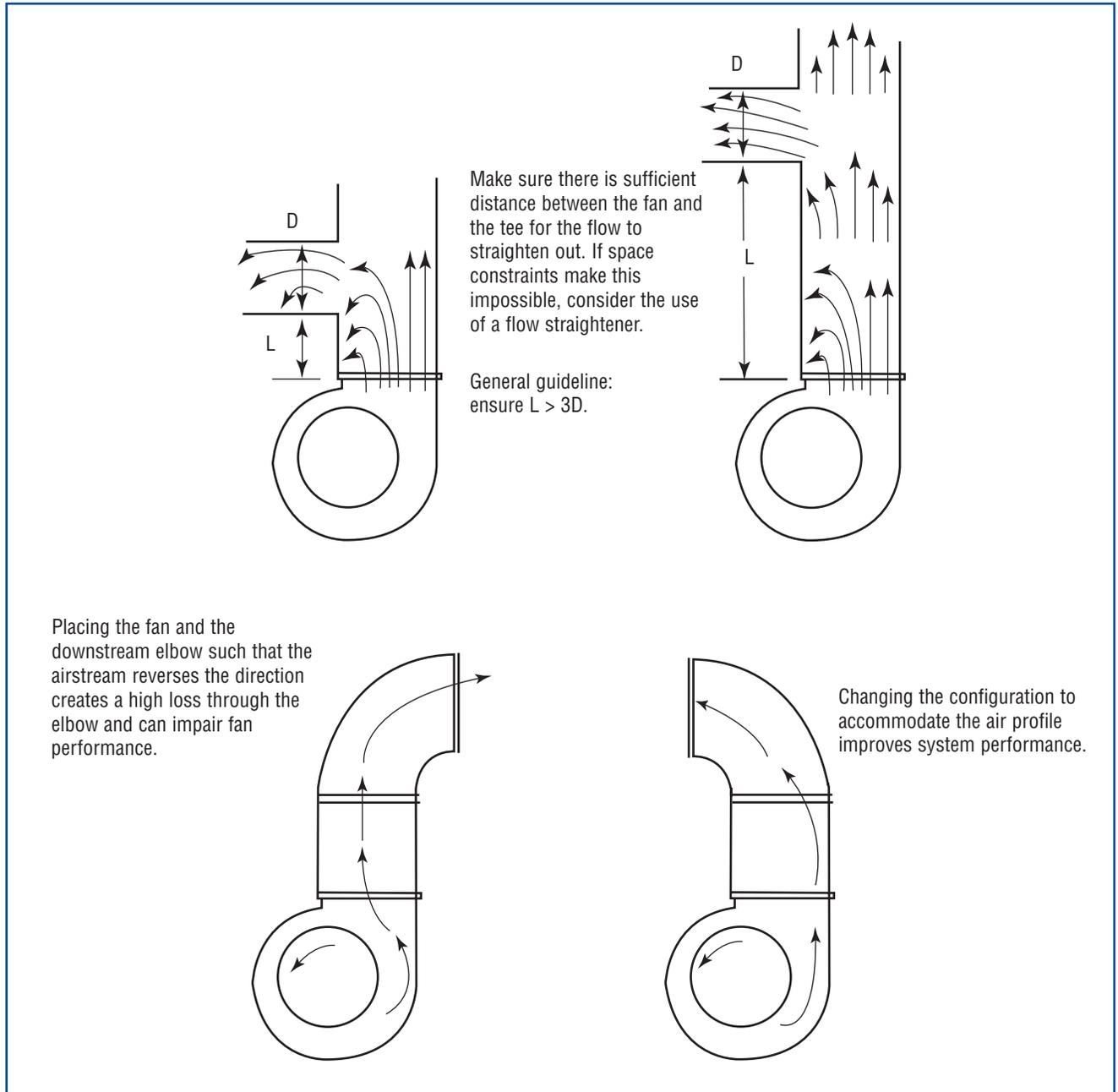
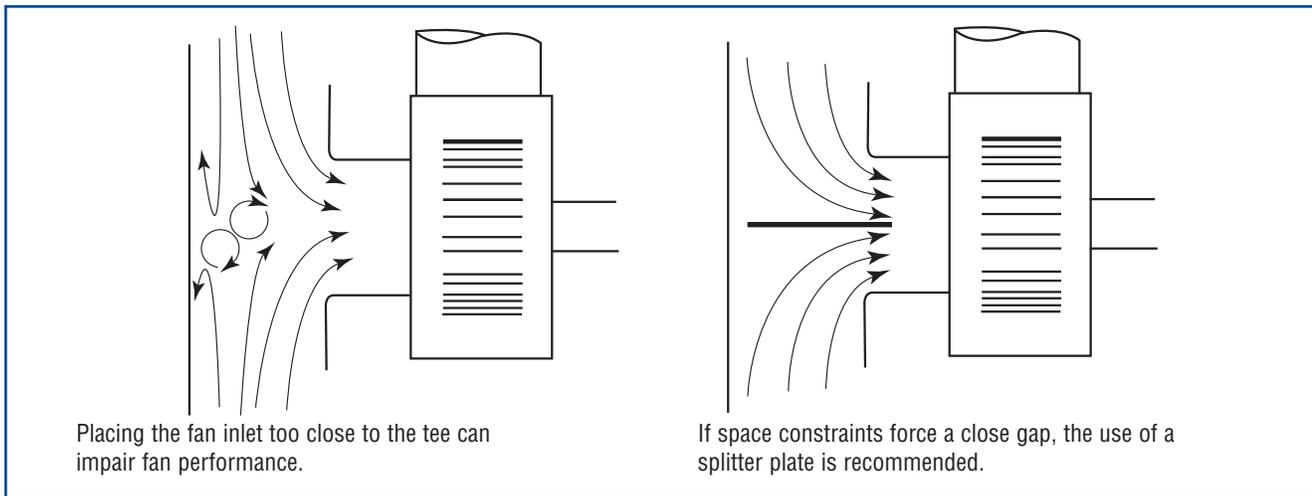


Figure 2-18. Fan Outlet Conditions



**Figure 2-19. Effect of Placing a Tee Close to a Fan Inlet**

disturbed airflow from forming in a tee. By properly guiding the airstream into an adjoining duct, the splitter avoids a highly disrupted airflow profile.

However, such devices should be used with caution. For example, a non-uniform profile emerging downstream of a tee can correct itself within several diameter lengths of a straight duct. The use of flow straighteners in this case may keep this imbalance from correcting itself before the flow encounters another component, thereby creating a problem where one did not previously exist.

**Duct Sizing.** In most fan systems, friction between the airstream and the duct surfaces accounts for most of the energy consumed by the fan. The resistance of airflow through a duct is a function of the square of the velocity, as shown in the following equation:

$$\Delta p = f \frac{L}{D} \left( \frac{V}{1,097} \right)^2 \rho$$

- Where:  $\Delta p$  = pressure drop (in. wg)  
 $f$  = non-dimensional friction coefficient  
 $L$  = duct length in feet (ft.)  
 $D$  = duct diameter (ft.)  
 $V$  = velocity of the air stream (ft./min.)  
 $\rho$  = density of the airstream (lbs./ft.<sup>3</sup>)

The friction coefficient ( $f$ ) depends on the duct surface finish, duct diameter, and the level of turbulence in the airstream. Although accurately calculating the pressure drop requires detailed knowledge of the duct and airstream characteristics, the relationship between pressure drop and duct size is readily apparent. For a given delivery volume, increasing duct diameter decreases both the velocity

and the friction loss per duct length. Consequently, larger ducts create lower friction losses and lower operating costs. For example, in a round duct, doubling the duct diameter reduces frictional head loss by a factor of 32. Although doubling the size of a duct is often not realistic, increasing the diameter of a round duct from 10 inches to 12 inches can reduce friction head loss by 60 percent.

Offsetting the lower operating costs associated with large ducts are higher initial costs, both in terms of duct material and the added structural requirements. Additionally, larger ducts take up more space, which may be a problem for certain facilities. Also, some material handling applications require a certain air velocity to ensure proper entrainment, making frictional head loss less important than system performance. Striking the right balance between these competing costs requires effort; however, using a systems approach during the design phase can minimize system life-cycle costs.

### ◆ Installation Practices

Frequently, installation of a fan system is performed with inadequate regard to the effect of flow profile on fan performance. Ductwork is often bent, shifted, and dented on site to align connections and to make room for other equipment.

When done far upstream or downstream of a fan, these installation practices may have only a minor impact on system performance; however, when they create non-uniform flow into or out of a fan, the effect can be costly. In fact, one of the first checks typically performed on an under-performing fan system is to examine the ductwork around the fan to determine if it is creating the problem.

## Controlling Fans with Variable Loads

### ◆ Basic Principle

Fans often serve over a wide range of operating conditions. For example, many industrial ventilation systems see variable loads because of changes in ambient conditions, occupancy, and production demands. To accommodate demand changes, flow is controlled by three principal methods: inlet vanes, outlet dampers, and fan speed control.

Each method has a set of advantages and drawbacks in terms of initial cost, flow control effectiveness, and energy efficiency. In fan systems that are used relatively infrequently (for example, less than 500 hours annually), initial cost may be the dominant factor. In high run-time applications, flow control effectiveness and energy efficiency may be the key determinants.

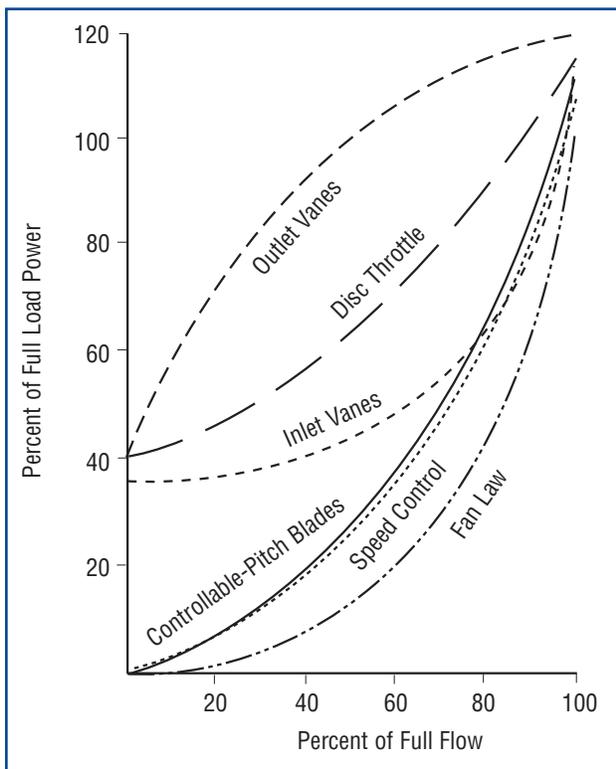


Figure 2-20. Relative Power Consumption Among Flow Control Options

In many industrial applications, fans must operate for extended periods. They are often used directly to support production (material handling) or to maintain safe working conditions (ventilation). In either case, fan system operating efficiency is high priority. The relative efficiencies of the flow control options are shown in Figure 2-20. Although these flow control options are available for new fan selection, not all of them can be retrofit into existing fans. For example, controllable-pitch blades are typically not considered for retrofits.

Many fans are sized to handle the largest expected operating or peak condition. Because normal operating conditions are often well below these design conditions, air-moving equipment is often oversized, operating below its most efficient point and creating several types of problems. Among these problems are high energy costs, high system pressures and flow noise, and, in systems with high particulate contents, erosion of impeller and casing surfaces.

Consequently, the combination of extended operating times and the tendency to oversize the air-moving equipment creates a need for efficient flow control. Often, the existing flow control devices are inefficient, yet the costs associated with their performance are not recognized.

**Dampers.** Dampers provide flow control by changing the restriction in the path of an airstream. As dampers close, they reduce the amount of flow and increase pressure on their upstream side.

By increasing system resistance, dampers force fans to operate against higher backpressure, which reduces their output. As a fan works against higher backpressure, its operating point shifts to the left along its performance curve. Fans operating away from their best efficiency points suffer increased operating and maintenance costs.

**Inlet Vanes.** Inlet vanes are more commonly used with centrifugal fans than axial fans. Inlet vanes

change the profile of an airstream entering a fan. Inlet vanes create swirls that rotate in the same direction as a fan impeller. These pre-rotating swirls lessen the angle of attack between the incoming air and the fan blades, which lowers the load on the fan and reduces fan pressure and airflow. By changing the severity of the inlet swirl, inlet vanes essentially change the fan curve. Because they can reduce both delivered airflow and fan load, inlet vanes can improve fan efficiency. Inlet vanes are particularly cost effective when the airflow demand varies between 80 and 100 percent of full flow; however, at lower airflow rates, inlet vanes become less efficient.

**Disc Throttle.** In some centrifugal fan designs, the generated airflow can be controlled by changing the effective width of the impeller using a sliding throttle plate. As the plate moves, it changes the amount of impeller width that is exposed to the airstream. Although this fan design characteristic is not common, its simple design may be feasible in some applications.

**Variable-Pitch Fans.** An option with some types of axial fans is the incorporation of a variable-pitch feature for the fan blades. Variable-pitch fans allow the fan blades to tilt, changing the angle of attack between the incoming airflow and the blade. Reducing the angle of attack reduces both the airflow and the load on the motor. Consequently, variable-pitch fans can keep fan efficiency high over a range of operating conditions.

Variable-pitch fans can be a very efficient flow control option and offer several performance advantages. Because variable-pitch fans maintain their normal operating speed, they avoid resonance problems that can be problematic for certain fan types. Additionally, variable-pitch blades can operate from a no-flow to a full-flow condition without stall problems. During start-up, the fan blades can be shifted to a low angle of attack, reducing the torque required to accelerate the fan to normal operating speed.

Disadvantages of this flow-control option include potential fouling problems because of contaminant accumulation in the mechanical actuator that controls the blades. Also, because motor efficiency and power factor degrade significantly at loads

below 50 percent of rated capacity, operating at low loads for long periods may not provide efficiency advantages and can incur a low power factor charge from the utility.

**Fan Rotational Speed Adjustments.** Fan rotational speed adjustments provide the most efficient means of controlling fan flow. By reducing fan rotational speed, less energy is imparted to the airstream, which means less energy must be dissipated by the system airflow-control devices. There are two primary devices used to control fan rotational speed: multiple-speed motors and adjustable speed drives (ASDs). Although both directly control fan output, multiple-speed motors and ASDs typically serve separate applications.

Multiple-speed motors contain a different set of windings for each motor speed. For example, a motor controller may have high, medium, and low settings. Depending on the application, switching from one discrete setting to another may provide a sufficient level of speed control. Although they are more expensive than single-speed motors, multiple-speed motors provide a wide range of fan output within a single unit, avoiding the need for multiple fans.

ASDs allow fan rotational speed adjustments over a continuous range, avoiding the need to jump from speed to speed as required by multiple-speed fans. ASDs include several different types of mechanical and electrical systems. Mechanical ASDs include hydraulic clutches, fluid couplings, and adjustable belts and pulleys. Electrical ASDs include eddy current clutches, wound rotor motor controllers, and variable frequency drives (VFDs). VFDs are by far the most popular type of ASD, largely because of their proven effectiveness in reducing energy costs.

### ◆ Advantages of VFDs

For many systems, VFDs offer a way to improve fan operating efficiency over a wide range of operating conditions. VFDs also provide an effective and easy method of controlling airflow. Among the primary reasons for selecting VFDs are improved flow control, ability to retrofit to existing motors, their compact space advantages, and elimination of the fouling problems associated with mechanical control devices.

VFDs decrease energy losses by lowering overall system flow. By slowing the fan and lessening the amount of unnecessary energy imparted to the airstream, VFDs offer substantial savings with respect to the cost-per-unit volume of air moved. When fan speed decreases, the curves for fan performance and brake horsepower move toward the origin. Fan efficiency shifts to the left, providing an essential cost advantage during periods of low system demand. Keeping fan efficiency as high as possible across variations in the system's flow requirements reduces fan operating costs.

VFDs eliminate the reliance on mechanical components, providing an attractive operational advantage, especially in "dirty" airstreams.

**Noise.** Other benefits of VFDs include lower airflow noise. Excess fluid energy is primarily dissipated in the form of noise; consequently, operating a fan at high capacity and then throttling the airflow tends to generate high noise levels. Airflow noise can be a significant component of the overall ambient noise in a workplace. In fact, in many fan systems, airflow noise is high enough to require ear protection. Because VFDs decrease airflow noise during low system demand, they can improve worker comfort.

**Other System Benefits.** VFDs offer operating improvements by allowing higher fan operating efficiency and by increasing system efficiency as well. Using a system perspective to identify areas in which fluid energy is dissipated in non-useful work often reveals opportunities for operating cost reductions. For example, in many systems, venting flow does not noticeably affect the backpressure on a fan. Consequently, in these applications, fan efficiency does not necessarily decline during periods of low flow demand. However, by analyzing the entire system, the energy lost in venting excess pressure or dissipating it across dampers can be identified.

Another system benefit of VFDs is their soft-start capability. During start-up, most motors experience in-rush currents that are 5 to 6 times higher than normal operating currents. In contrast, VFDs allow the motor to be started with a lower start-up current (usually about 1.5 times the normal operating current), thus reducing wear on the motor windings

and the controller. Soft starting a fan motor also provides a benefit to the electrical distribution system. Large start-up currents can create voltage sags that affect the performance of sensitive equipment, such as controllers. By limiting start-up current, VFDs can reduce these power quality problems.

#### ◆ Disadvantages of VFDs

Although VFDs offer a number of benefits in terms of lower operating and maintenance costs, they are not appropriate for all applications.

Decreasing the rotational speed of a fan too much often risks unstable operation, especially with axial fans and some centrifugal fans, such as backward-inclined airfoil and forward-curved types. With these fans, careful review of the performance curves should precede the selection of a VFD.

**Resonance.** Fans, like most rotating machinery, are susceptible to resonance problems. Resonance is an operating condition in which the natural frequency of some component coincides with the frequency set up by the rotation. Fans are usually designed so that their normal operating speeds are not near one of these resonant speeds. However, decreasing the rotational speed of a fan increases the chances of hitting a resonant speed.

The effects of operating at resonant speeds can be damaging. Depending on which component of the assembly is in resonance with the fan rotational speed, the vibrations can cause a wide range of problems, from annoying noise to destructive failure. Shafts, bearings, and foundations are particularly susceptible to problems with resonance.

To avoid resonance problems, VFDs should be programmed to avoid operating near resonant speeds. This requires knowing what these resonant speeds are, which, in turn, requires input from the fan manufacturers. Similarly, programming the VFDs accordingly often requires input from the VFD manufacturers.

**High Static Pressure.** Another concern is the effect of reducing fan speed in a system with high static pressure. When a fan's rotational speed is reduced,

the fan generates less pressure, and some fans, like many types of turbomachinery, operate poorly against shut-off conditions. For example, in many fan systems, duct outlets are equipped with normally closed dampers that require a certain amount of static pressure to open them. If a VFD slows the fan so that this static pressure requirement exceeds the pressure generated by the fan, no airflow will be generated and the fan may operate poorly.

**Power Quality.** In some VFD applications, power quality can also be a concern. VFDs operate by varying the frequency of the electric power supplied to the motor. The solid-state switching that accompanies inverter operation can create voltage spikes that increase motor winding temperatures, accelerating the rate of insulation degradation. To account for the added winding heat, conventional motors usually must be de-rated by 5 to 10 percent when used with VFDs. A classification of motors known as “inverter-duty” has been developed to improve the matching of VFDs to motors.

VFDs can also generate electrical noise that interferes with the power quality of the supporting electrical supply. These problems are typically correctable with the installation of coils or electrical filters. Systems that are sensitive to minor power supply disturbances should be served separately from the VFD power supply.

**VFD Efficiency.** Finally, in some applications, anticipated energy savings from VFDs are not realized because of incomplete consideration of all the losses associated with a VFD installation. Although at full capacity VFDs can achieve efficiencies of 98 percent, their efficiency at part-loads is often much lower. When considering VFDs, test data from the manufacturer should be evaluated for the efficiencies at the actual load of the application.

Although VFDs offer an attractive opportunity to reduce energy consumption in many applications, all of these considerations should be included in any feasibility study or system analysis.

## Fan Drive Options

Fans are typically driven by alternating current (AC) motors. In industrial fan applications, the most common motor type is the squirrel-cage induction motor. This motor type is commonly used because of its characteristic durability, low cost, reliability, and low maintenance. These motors usually have 2 or 4 poles which, on a 60-hertz system, translates to nominal operating speeds of 3,600 revolutions per minute (rpm) and 1,800 rpm, respectively. Although motors with 6 poles or more are used in some fan systems, they are relatively expensive. The most common class of motors for fan applications is NEMA Design B. Service factors range from 1.1 to 1.15, meaning that the motors can safely operate at loads between 110 to 115 percent of their horsepower (hp) ratings.

Motors are connected to fans either directly, through a gearbox, or, more commonly, by a belt system. There are advantages and drawbacks to each drive option. Understanding how drives are selected can be helpful in correcting problems that are the result of poor design.

### ◆ Direct Drives

Direct drives have several advantages over belt drives, including higher efficiency, compact space requirements, and lower maintenance. The absence of a belt removes a key maintenance element, allowing a fan to operate more reliably and more quietly. Although belt drives are occasionally used in fan applications over 300 hp, they are rarely found in fan applications over 500 hp. At these power levels, the efficiency advantages of direct drives are very attractive. However, direct-drive fans must rotate at the speed of the motor (typically 3,600 rpm, 1,800 rpm, or 1,200 rpm). This limits the applications for which they can be used.

Direct drives may be used in applications where space is an important consideration. For example, vaneaxial fans are well-suited for direct-drive applications because the motor often fits conveniently behind the fan hub.

### ◆ Gear Drives

Gear drives are not as common as belt or direct drives, but are useful in a few applications that require special configurations between the fan and motor. Gear systems have a wide range of efficiencies that depend on gear design and speed ratio. Gear systems can be very robust, affording high reliability—a characteristic that is very important in applications with restricted access to the drive system. However, gears, unlike belt systems, do not allow much flexibility in changing fan speed.

### ◆ Belt Drives

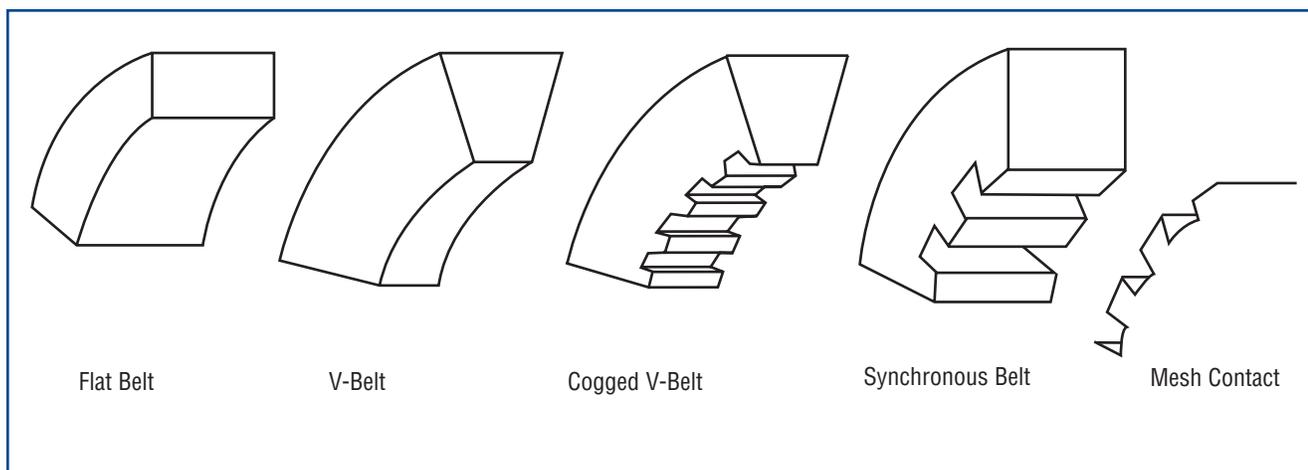
Because the required rotational speed of a fan is usually less than 1,800 rpm, belts are used to transfer power from a motor pulley (sheave) to a fan pulley with a larger diameter. The desired fan rotational speed can be achieved using various pulley sizes according to [the following relationship](#):

$$\text{RPM}_{\text{driven}} = \text{RPM}_{\text{driver}} \times \frac{D_{\text{driver}}}{D_{\text{driven}}}$$

In small horsepower applications (typically less than 5 brake horsepower), adjustable pitch sheaves can be used. Because the diameter ratio is variable, these configurations can provide speed control advantages. However, most large industrial fan applications use fixed diameter sheaves.

**Types of Belt Drives.** The four principal types of belts are flat, V-belts, cogged V-belts, and synchronous, each shown in Figure 2-21. Flat belts have a uniform cross-section and transmit power through friction contact with flat pulley surfaces. V-belts are an improvement over the flat belt, using a wedging action to supplement friction-based power transfer.

Cogged V-belts offer the same advantages as V-belts; however, their notched design provides additional flexibility that allows the use of smaller pulleys. Cogged V-belts are slightly more efficient than conventional V-belts, because of their added



**Figure 2-21. Different Types of Belts**

flexibility and the fact that the notched surface transfers force more effectively.

Synchronous belts offer many advantages over standard flat belts and V-belts. By using a mesh engagement, synchronous belts are the most efficient type of belt drive because they do not suffer efficiency losses through slip. Synchronous belts have teeth that engage with grooves in the sheave. Synchronous belts can allow lower belt tension than conventional belts, reducing the radial loads on motor and fan bearings and extending their operating lives. Further, synchronous belts do not lose efficiency as they wear.

Despite their advantages, synchronous belts must be used with caution. Synchronous belts are very noisy, which often discourages their use. Synchronous belts transfer torque very quickly and, in applications with rapid load changes, the cumulative effects of sudden acceleration and deceleration increases wear on the driven machinery and the risk of catastrophic failure. Synchronous belts also require precise alignment, which is difficult to achieve in some fan applications. Before selecting or switching to synchronous drives, one should contact the belt drive vendor and review the history of similar equipment in similar service conditions.

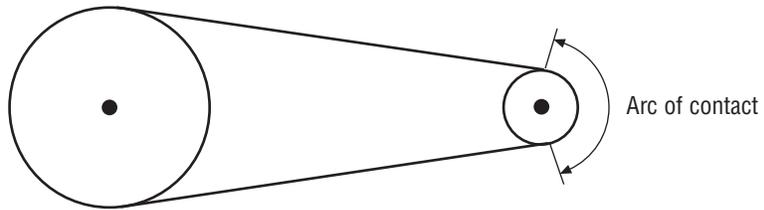
**Belt Sizing Considerations.** The required belt capacity must not only include the horsepower required by the driven load; it must also account for site-specific factors, such as temperature,

service factor, and arc of contact. The effect of temperature varies according to the belt material. Rubber contracts at higher temperatures. Consequently, in belts that have high rubber content, tension and stress increase as the drive system temperature increases. Because temperature also affects the mechanical strength of a belt, belts should be sized to meet the torque requirements at the highest normal operating temperature.

Ignoring the belt service factor and arc of contact (see Table 2-1) can lead to undersizing the belts, which may lead to frequent servicing or belt failure. The belt service factor accounts for acceleration loads during start-up and under load changes. For most fans, the belt service factor is between 1.2 and 1.4. The arc of contact correction factor accounts for the loss in power that results when the belt runs over by less than 180° of the pulley circumference. As shown in Table 2-1, the horsepower rating drops off as the arc of contact decreases. In applications where a small arc of contact is unavoidable, the use of cogged V-belts is recommended.

**Belt Speed.** The sensitivity of fan power to speed makes belt-drive sizing an important issue. Although flow rate is linearly related to fan speed, power is related to the cube of fan speed. Even changes in the slip of an induction motor can create noticeable changes in the power transferred to the airstream. Consequently, establishing the right fan speed is critical to operating the system efficiently. In general, fan-belt speed should not exceed

Correction factor for horsepower rating for a V-belt according to arc of contact	
180°	1
170°	.98
160°	.95
150°	.92
140°	.89
130°	.86
120°	.83
110°	.79
100°	.74
90°	.69



**Table 2-1. Effect of Arc of Contact on V-Belt Horsepower Rating**

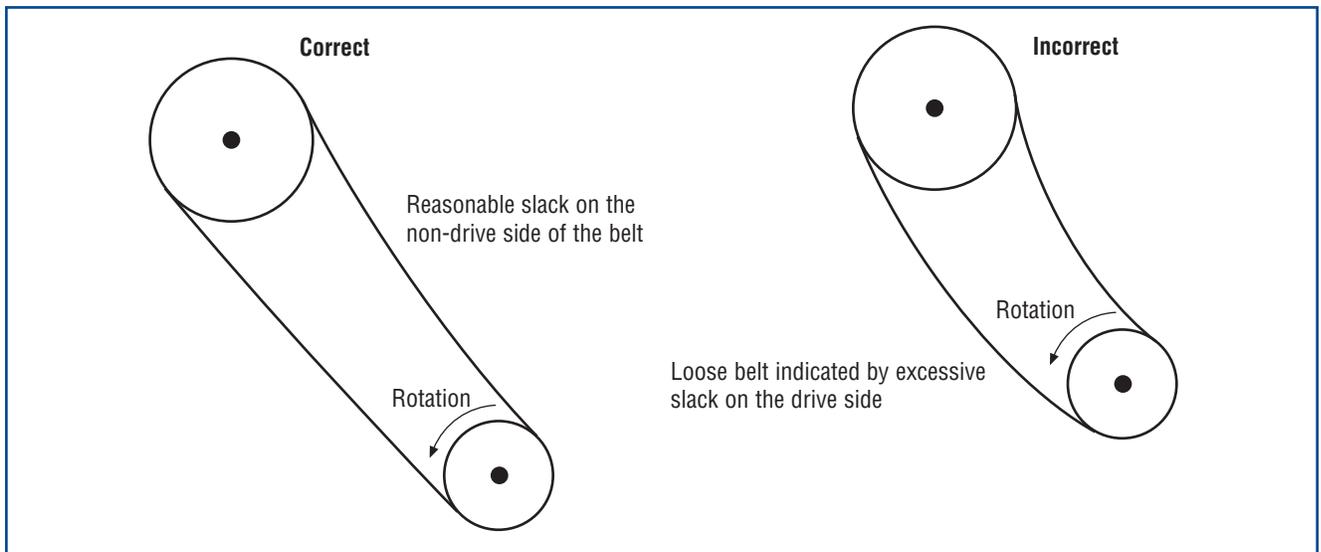
6,500 feet per minute (ft./min.). Many manufacturers suggest that to minimize bearing loads and to increase reliability, up to but no more than 6,500 ft./min is a good speed value for belt system design.

**Maintenance Practices.** Belt tension and alignment should be checked periodically (see Figure 2-22). Proper belt tension is typically the lowest that prevents a belt from slipping at peak load. An important maintenance practice to avoid is the use of belt dressing. Belt dressing is a surface treatment that increases the level of friction between a belt and pulley. Because it masks the fundamental cause of slippage, belt dressing only provides a

temporary means of reducing noise. Belt slippage should be corrected by either cleaning the drive system or adjusting belt tension.

When installing or replacing belts, ensure they are oriented correctly in accordance with the directions of the manufacturer. Belts are often tagged to show the preferred direction of rotation. Although some belts can be operated in either direction, belt manufacturers often test their belts in one direction and package them with an indication of this direction.

In high-temperature applications, new belts should be operated under low-load conditions and at normal

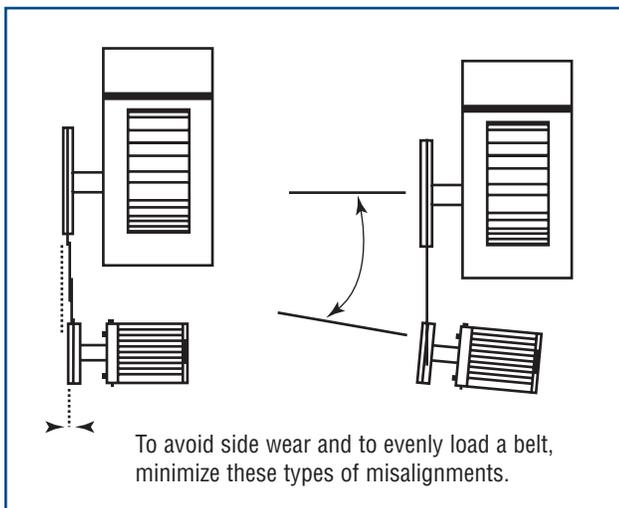


**Figure 2-22. Proper Belt Tension**

operating temperature for a reasonable period. This run-in time increases the creep strength of the belt.

**Maximum Practical Speed Ratio.** Most industrial fan-belt drive applications are limited to speed ratios below 4:1 (the motor speed is 4 times faster than the fan speed); however, for small horsepower applications (less than 1 hp), this ratio can be as high as 10:1. The limiting factors on speed ratios are the practical size of the pulleys, the arc of contact between the belt and the drive pulley, and belt speed.

**Alignment.** Proper belt installation requires careful alignment and tensioning to ensure that belts wear correctly. Belt alignment is important to minimize side wear on the belt and to keep the stress on the belt distributed evenly (see Figure 2-23). Side wear on a belt will shorten its life; insufficient tension promotes belt slippage, which can “polish” the sheave surface as well as the contact surface of the belt. A polished sheave surface has a low friction constant, which reduces the belt’s ability to transfer power. This loss is especially problematic after a belt stretches, releasing tension and decreasing the force holding the belt against the sheave.



**Figure 2-23. Improper Alignment**

### ◆ Other Considerations

Service conditions, such as high-temperature, contaminants, erosive or corrosive properties, and moisture, can preclude the exposure of motors to the airstream. Motors can be sealed for protection against the harmful effects of some airstreams; however, these motors are more expensive and sometimes require external cooling services.

Motor performance is closely linked to operating temperature and, in high-temperature applications, less heat from the motor windings is rejected to the ambient air. High winding temperatures decrease motor efficiency and accelerate the degradation of winding insulation, shortening motor life. In most severe system environments, belt drives are used to allow the motor to operate outside of the harmful service conditions.

**Access.** Access to a motor for maintenance and repairs in a direct-drive fan assembly can also be problematic. Because many direct-drive applications are selected for space-saving reasons, these motors are often located in tight spaces, complicating tasks such as lubricating and replacing bearings.

## Multiple-Fan Arrangements

### ◆ Basic Principle

Fans can be combined in series or in parallel as an alternative to using single, large fans. In many cases, two smaller fans are less expensive and offer better performance than one relatively large one. Fans configured in series tend to be appropriate for systems that have long ducts or large pressure drops across system components. Fans used in an induced-draft/forced-draft configuration can minimize the amount of pressurization in a duct or an enclosure. Advantages of fans in series include:

- Lower average duct pressure
- Lower noise generation
- Lower structural and electrical support requirements.

Fans placed in parallel can provide several advantages including:

- High efficiencies across wide variations in system demand
- Redundancy to mitigate the risk of downtime because of failure or unexpected maintenance.

Parallel configurations may be feasible for systems with large changes in air-moving requirements. Wide variations in system demand preclude a single fan from consistently operating close to its best efficiency point (BEP). Operating a fan away from its BEP can result in higher operating and maintenance costs. Multiple fans placed in parallel allow units to be energized incrementally to meet the demands of the system. By energizing or de-energizing individual fans to meet demand changes, each fan can be operated more efficiently. To allow operation of individual fans in a multiple-fan arrangement, each fan must have a back-draft damper installed to prevent recirculation through the fan when it is idle.

Parallel fan configurations may also be a safety requirement in case of a single fan failure. In mining and other hazardous work environments, ventilation is critical to worker safety. The

existence of backup fans can help avoid production stoppages and may be a safety requirement.

### ◆ Advantages of Multiple-Fan Arrangements

**Lower Average Duct Pressure.** As shown in Figure 2-24, the series-configurations fans along different points in a system minimize the average static pressure in a duct. Because leakage in a duct system depends largely on the pressure difference between inside and outside the system, reducing the maximum system pressure can minimize energy losses attributable to system leaks.

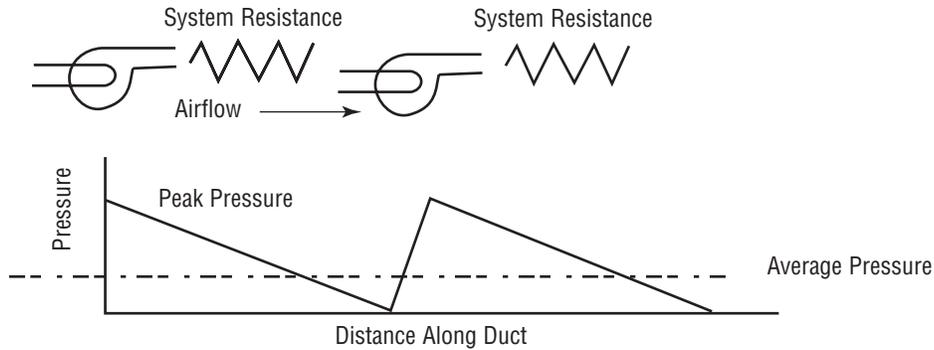
**Lower Noise Generation.** Lower pressure requirements can decrease the noise generated by fan operation.

**Redundancy.** Failure of one unit does not force a system shutdown. In a single-fan application, a repair task on that fan requires a system shutdown. With a multiple-fan arrangement, one can be repaired while the others serve the system. In some facilities, fan failure can cause the interruption of production work. With redundant fan configurations, failure of one fan does not necessarily cause the whole process to halt. Although total fan output falls if one of the parallel units fails, the capacity of the remaining fan or fans may be sufficient for limited production.

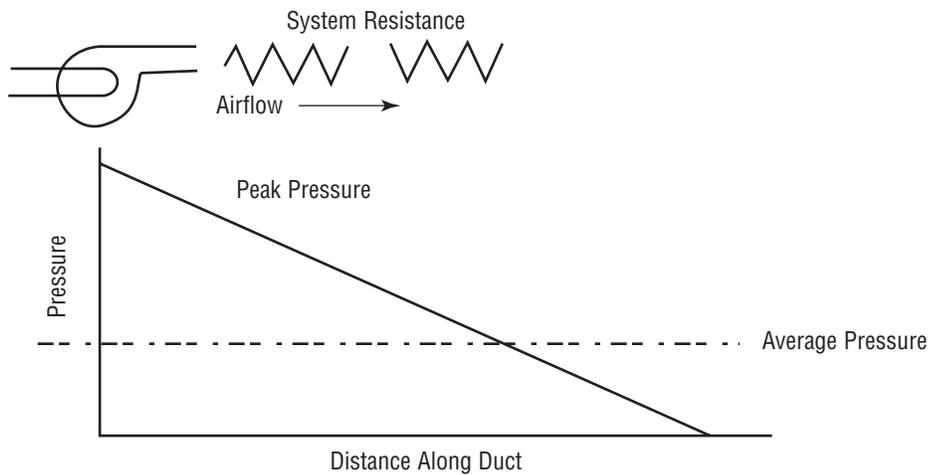
**Efficiency.** Allowing each fan to operate close to its BEP can provide substantial energy savings. In addition, a potential advantage of multiple fans is a higher overall efficiency level. Although larger motors tend to be more efficient than smaller ones, operating smaller, higher-speed fans close to their BEPs can often achieve a net efficiency advantage over a single, low-speed fan.

**Structural and Electrical Constraints.** Two smaller fans in series may be more suitable in terms of structural and electrical requirements than a single one. Large motors have large starting currents that can affect the power supply to other parts of the facility. This concern is particularly acute if the service requires the fan to energize and de-energize

**Two Fans in Series**



**Single Fan**



**Figure 2-24. Lower Duct Pressure Because of Fans Placed in Series**

relatively often. Frequent power surges that often accompany the start-up of large motors can create power quality variations that are problematic for numeric controlled machinery and other sensitive equipment.

Also, the use of multiple fans in parallel may be necessary because of space considerations. A single fan with an impeller large enough to move the proper amount of air may not fit into the available space or may encounter structural constraints.

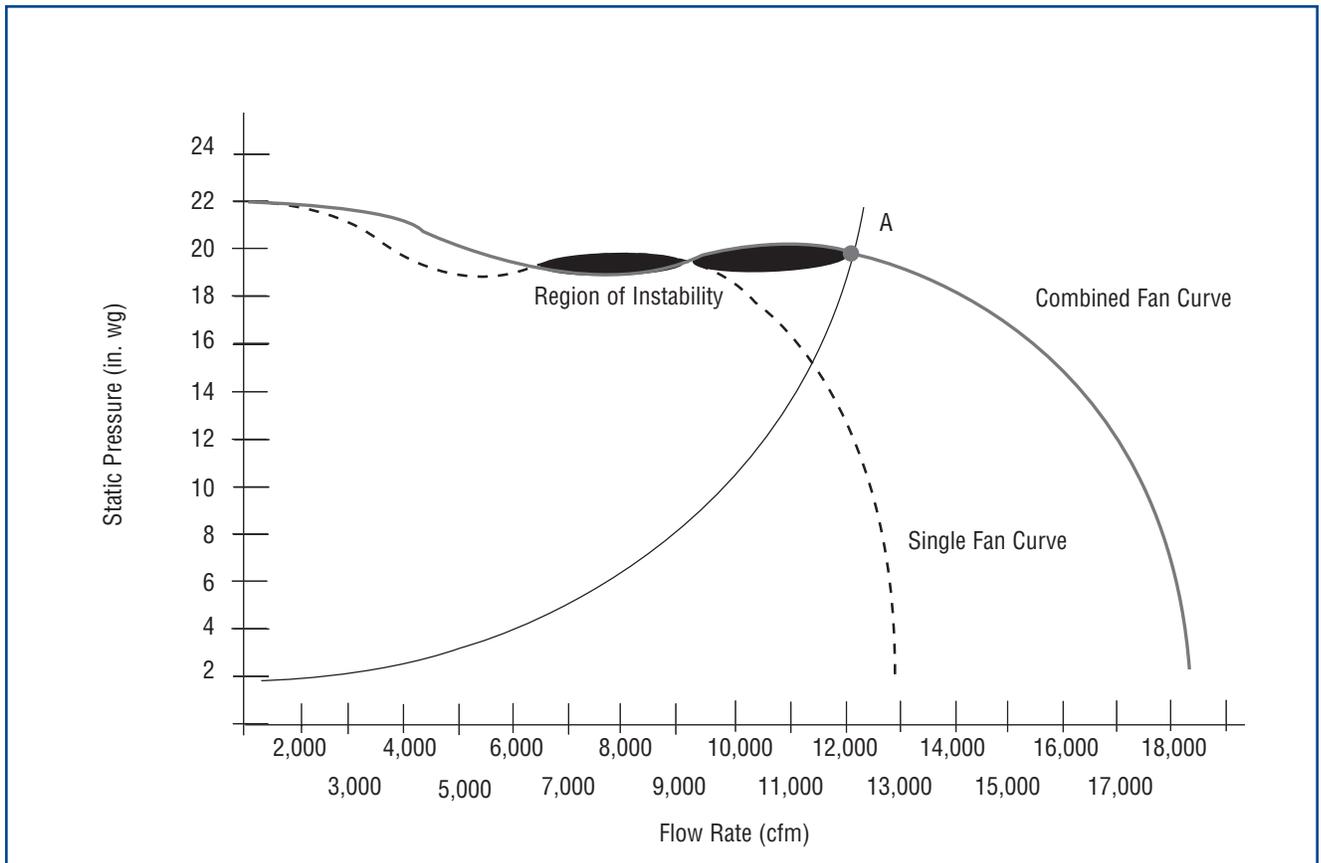
**◆ Potential Disadvantages of Multiple-Fan Arrangements**

When placing centrifugal fans in parallel, caution should be used to ensure that one fan does not dominate another. Ideally, all fans should be the same type and size; however, differences in the duct configuration can cause one fan to operate

against a higher backpressure. In severe cases, one fan will force another fan to operate far away from its BEP. Often, fans placed in parallel are the same model so that there is balanced load sharing during periods when all the fans are operating.

Another problem that accompanies parallel operation of fans is instability. This problem is especially applicable to fans with unstable operating regions (axial fans, forward-curved centrifugal fans, and airfoil fans). Instability results from alternate load sharing that can occur below certain airflow rates, as shown by the shaded region in Figure 2-25. This can occur despite the fact that each fan alone is operating outside of its stall region.

However, the combined performance curve of both fans has a region in which there are multiple combinations of airflow from each fan that can



**Figure 2-25. Instability Region Because of Parallel Operation of Identical Fans**

meet the system needs. The instability results from the fans' shifting between these multiple combinations (known as "hunting"), as the fans tend to load and unload. In addition to creating an annoying noise pattern, this continued hunting increases the wear on the fan drives because of repeated acceleration and deceleration. To avoid this problem, the system airflow should be kept to the right of Point A, shown in Figure 2-25.

#### ◆ Other Options

Other alternatives that can handle widely varying operating conditions include multiple-speed fans, variable frequency drives (VFDs), inlet vanes, and, in the case of axial fans, controllable-pitch fan blades. In each of these options, the airflow generated by the fan is adjusted to meet the needs of the system.

Multispeed motors have separate windings for each speed. Operators can select different speeds, such as high, medium, and low, according to the system requirement. VFDs adjust fan speed by changing the frequency of the power supplied to

the motor. VFDs allow speed control over a continuous range, which allows relatively accurate matching between the system requirements and fan operating speed.

Inlet vanes control fan output by creating a swirl in the airflow before it reaches the fan blades, thus changing the angle of attack. This affects how much energy is added to the airflow. Although this option is generally less efficient than speed adjustment, it is a relatively simple and inexpensive option that is widely used.

In applications that use axial fans, controllable-pitch fans should be considered to handle varying airflow conditions. This fan type allows the fan blades to tilt away from the incoming airflow. By changing the angle of attack to the incoming air, the amount of airflow generated and the load on the motor can be controlled.

## Fan System Economics

Fan systems are often critical in supporting plant operations. A significant portion of all energy consumed by motor-driven equipment in manufacturing facilities is for process fans and air distribution. In many industrial applications, fans help maintain environmental conditions that ensure worker safety and productivity by keeping machinery spaces cool. Because they often directly support production processes, many fans operate continuously. These long run times translate into significant energy consumption and substantial annual operating costs.

The operating costs of large fans are often high enough that improving fan system efficiency can offer a quick payback. In spite of this, facility personnel often do not know the annual operating costs of an industrial fan, or how much money they could save by improving fan system performance.

Fan system operating costs primarily include electricity and maintenance costs. Of these two components, electricity costs can be determined with simple measurements. In contrast, maintenance costs are highly dependent on service conditions and need to be evaluated case-by-case. A particularly useful method of estimating these costs is to review the maintenance histories of similar equipment in similar applications.

### ◆ Load Factor

Fan economic analyses are primarily affected by the amount of time and the percentage of full capacity at which a fan operates. Because the fan usually does not operate at rated full load all the time, an estimate of its average load factor—the average percentage of full load that a fan operates over a period of time—must be made. Unfortunately, unless operators maintain comprehensive records or are highly familiar with fan operating data, the average load factor may be difficult to determine.

A more accurate analysis of equipment operation is the load-duty cycle. Load-duty cycle refers to the amount of time that equipment operates at various loads relative to its rated capacity and is often used during the system design process. An example of a load-duty cycle is shown in Figure 2-26. Load factor can be determined from the load-duty cycle.

### ◆ Calculating Electricity Consumption

Electricity consumption can be determined by several methods, including:

- Direct measurement of motor current or power
- Use of motor nameplate data
- Use of performance curve data.

With any of these methods, the data's usefulness is limited by how representative it is of the average system operating conditions.

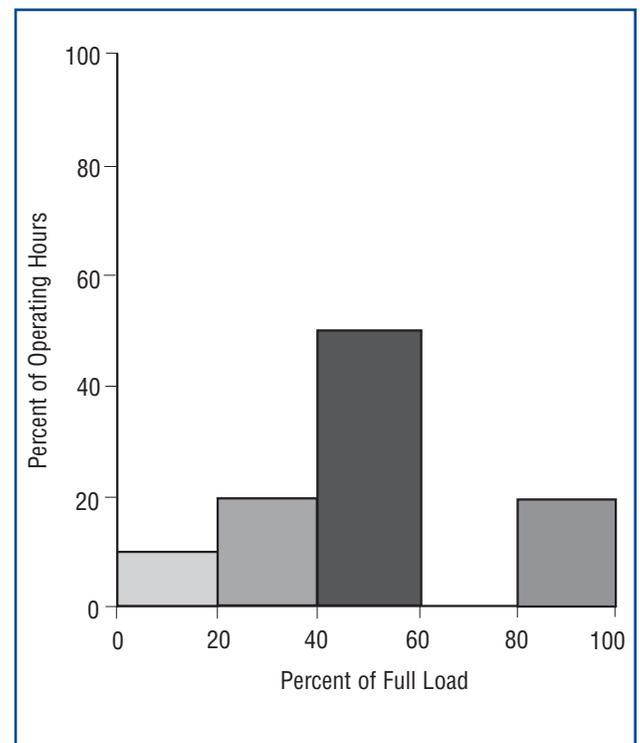


Figure 2-26. Load-Duty Cycle

In systems with widely varying operating conditions, simply taking data once will probably not provide a true indication of fan energy consumption.

**Nameplate Data.** A quick way to determine energy costs is to use the fan motor nameplate data. In many applications, the fan/motor assembly is oversized, which means the motor operates well below its full-load nameplate data. However, by using the nameplate data in combination with load factor and power factor estimates, the fan’s annual operating costs can be calculated. Other necessary data include the annual hours of operation (hours/year) and the average annual unit cost of electricity (\$/kilowatt-hour [kWh]).

Annual electricity costs can be calculated by inserting this information into the equation found in the [Simple Calculation](#) sidebar. This equation assumes the electric motor driving the fan is 95 percent efficient (the 0.95 in the 1/0.95 factor), which is a reasonable estimate for a fan motor larger than 50 horsepower (hp). Newer motors may have even higher efficiencies, thanks to the Energy Policy Act, which has been in effect since October 1997. If the fan uses an older motor that has been rewound several times or has a smaller motor, then a lower motor efficiency should be used.

### Simple Calculation

Annual electricity costs =  
 (motor full-load bhp) x (0.746 kW/hp) x  
 (1/efficiency) x (annual hours of operation) x (electricity  
 cost in \$/kWh) x (load factor)

Assumptions:

- Cost of electricity = \$0.05/kWh
- Load factor = 65 percent
- Motor efficiency = 95 percent

For example:

- Motor full-load bhp = 100 hp
- Annual hours of operation = 8,760 hours (3-shift, continuous operation)

Annual electricity costs =  
 (100 hp) x (0.746 kW/hp) x (1/0.95) x (8,760 hours)  
 x (\$0.05/kWh) x (0.65) = \$22,356

The motors used on most fans have a 1.15 continuous service factor. This means that a motor with a nominal nameplate rating of 100 brake horsepower (bhp) may be operated continuously up to 115 bhp, although motor efficiency drops slightly above the rated load. Using nameplate data to calculate energy costs on motors that operate above their rated loads will understate actual costs.

**Direct Measurement.** A more accurate way to determine electricity consumption requires taking electrical measurements of both full-load amps and volts. Motor full-load bhp and efficiency are not required for this calculation. However, the power factor over a range of operating conditions is required. If practical, the power factor should be measured with a power meter; however, if this measurement is not feasible, then it can be obtained from the motor manufacturer.

Using a clamp-type ammeter, the current on each of the three power cables running to the motor should be measured. The average of these three readings should be used as the current value. This is also an opportunity to determine if there are phase imbalances.

Sometimes the motor controller is a convenient point to take these readings while, at other sites, the connection box on the motor itself is more accessible. Line voltage is usually measured at the motor controller and should be measured around the same time as the current reading. In some facilities, line voltage drops with increased power usage.

Wattmeters, in general, are more difficult to use because they require two simultaneous inputs, voltage and current; many motor installations do not offer convenient access to both. However, if the use of a wattmeter is practical, then it would provide a more accurate indication of actual power consumption. Wattmeters provide a direct reading of real power, obviating the need to estimate power factor. Note that the direct measurement of motor current is not always practical. “Hot” measurement of motor voltage exposes workers to risk and may not be feasible in some industrial environments because of exposure of the power connections to moisture or contaminants. Such readings should only be taken by properly trained personnel.

### Direct Measurement Calculation

Case I. Separately using a voltmeter and an ammeter  
 Annual electricity costs =  
 (full-load amps) x (volts) x (1.732) x (power factor) ÷ (1000)  
 x (annual hours of operation) x (electricity cost in  
 \$/kWh) x (load factor)

Case II. Use of a Wattmeter  
 Annual electricity costs =  
 Wattmeter reading (using a 3-phase setting) x (annual  
 hours of operation) x (electricity cost in \$/kWh) x (load  
 factor)

Assumptions:

- Cost of electricity = \$0.05/kWh
- Load factor = 65 percent
- Motor efficiency = 95 percent
- Power factor = 0.85

For example:

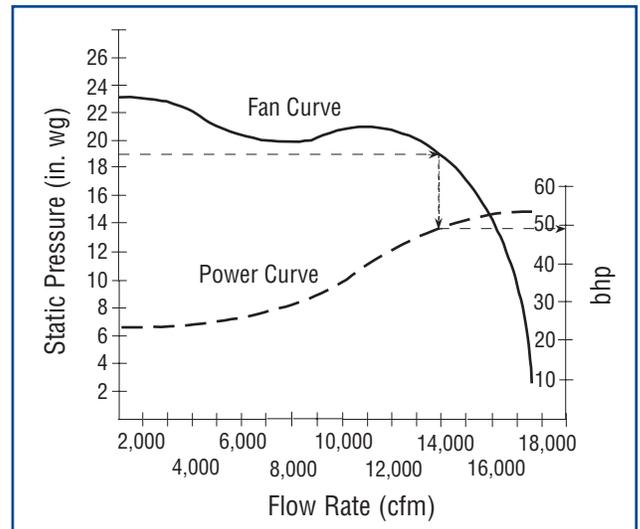
- Full-load amps = 115 amps
- Voltage = 460 volts
- Annual hours of operation = 8,760 hours (3-shift, continuous operation)

Annual electricity costs =  
 (115 amps) x (460 volts) x (1.732) x (0.85) ÷ (1000) x  
 (8,760 hours) x (\$0.05/kWh) x (0.65) = \$22,172

The **Direct Measurement** sidebar shows an example calculation of energy costs. By taking full-load amps and volts, converting them to full-load kilowatt (kW), multiplying by hours of operation and electricity price, annual energy costs can be determined.

**Use of Fan Curves.** Another method of determining fan power consumption is to take pressure measurements of the airstream and use the fan's performance curve to determine the corresponding bhp. Refer to Figure 2-27. The correct method of measuring fan pressure depends on how the fan is configured in the system.

Figure 2-28 shows different methods of measuring fan pressure. Once the fan operating pressure is known, the corresponding horsepower reading can be found. The **Calculation with Fan Curves** sidebar shows how to estimate annual energy cost.



**Figure 2-27. Use of Fan Curve to Determine Power Consumption**

### ◆ Energy and Demand Charges— Understanding Your Electricity Bill

The calculations shown previously use electricity rates that are stated in terms of average dollars per kWh (\$/kWh). However, electric utilities bill industrial customers using more complicated rate structures. These typically include both energy (\$/kWh) and demand charges (\$/kW), and have different rates depending on the level of consumption or seasons. Demand charges are

#### Calculation with Fan Curves

Annual electricity costs =  
 Fan bhp/motor efficiency x (annual hours of operation)  
 x (electricity cost in \$/kWh) x (load factor)

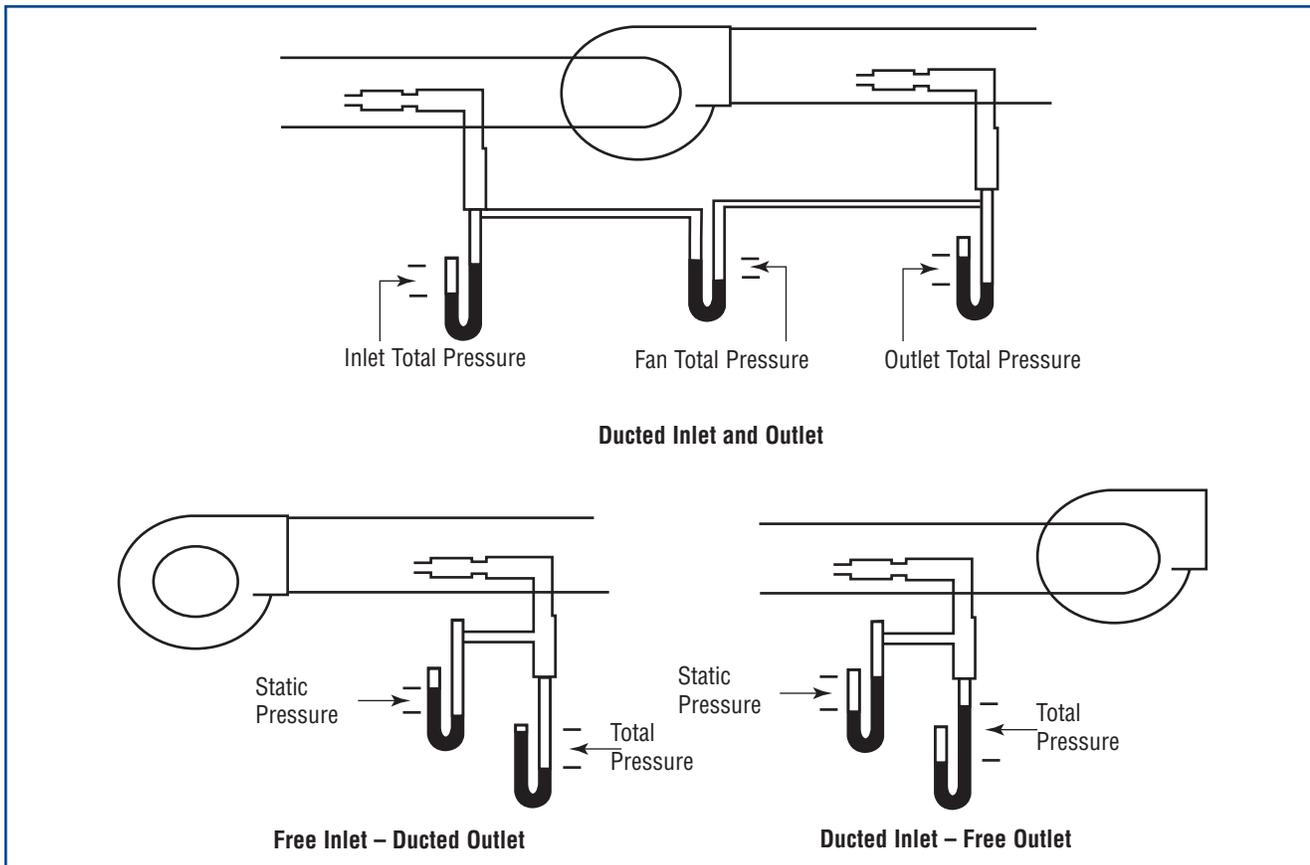
Assumptions:

- Fan discharge pressure is known
- Motor efficiency = 90 percent
- Load factor = 65 percent
- \$0.05/kWh unit electricity cost

For example:

- Fan discharge pressure = 19 in. wg
- Reading from the bhp line, fan bhp = 49

Annual electricity costs =  
 (49 bhp) x (0.746 kW/hp) x (1/0.9) x (8,760 hours)  
 x (\$0.05/kWh) x (0.65) = \$11,563



**Figure 2-28. Alternative Methods of Measuring Fan Pressure**

based on the peak demand for a given month or season and can have significant impacts on electricity costs for some customers. When the economic impacts of efficiency measures are calculated, the actual cost of the electricity needs to be considered, taking into account energy and demand charges, seasonal rates, and different rates for different levels of consumption.

#### ◆ Maintenance Considerations and Life-Cycle Costs

In addition to the cost of energy consumption, maintenance costs can be a significant portion of a fan system's total operating costs. There are two principal types of maintenance: preventive and predictive. Both are intended to improve system reliability, reduce the risk of unplanned downtime, and avoid expensive failures. Preventive maintenance generally refers to the use of a schedule to perform inspections and replacement tasks. Predictive maintenance uses diagnostic tools to evaluate machinery condition, allowing effective planning of repair or replacement tasks.

In much the same way that preventive and predictive maintenance schedules minimize expensive repairs, a well-designed system can avoid higher-than-necessary operating costs. Using a life-cycle cost perspective during initial system design or during the planning of system upgrades and modifications can provide both lower operating costs and improved system reliability. For fan applications, the dominant components of life-cycle cost include initial equipment cost, energy consumption, maintenance, and decommissioning. A highly efficient fan system is not merely a system with an energy-efficient motor. Overall system efficiency is the key to maximum cost savings. Often, users are only concerned with initial cost, accepting the lowest bid for a component, while ignoring system efficiency. To achieve optimum fan system economics, users should select equipment based on life-cycle economics and operate and maintain the equipment for peak performance.

## Fan System Terminology

This appendix is a collection of terms used in fans and fan systems. It is based primarily on *Engineering Letter G*, written by The New York Blower Company, and is used here with permission.

**acceleration loss**—the energy required to induce air to move at the entry to a system

**acfm**—actual cubic feet per minute; the quantity or volume of a gas flowing at any point in a system. Fans are rated and selected on the basis of ACFM, as a fan handles the same volume of air regardless of density.

**air conditioning**—treating air to meet the requirements of a conditioned space by controlling its temperature, humidity, cleanliness, and distribution.

**air curtain**—mechanical air-moving device designed to limit the influx of unwanted air at a building opening

**air handling unit**—factory-made encased assembly consisting of a fan or fans and other equipment to circulate, clean, heat, cool, humidify, dehumidify, or mix air

**ambient**—immediate surroundings or vicinity

**AMCA**—Air Movement and Control Association International, Inc.

**anemometer**—a device that reads air velocity, such as a wind vane. In fan applications, it is usually a spinning-vane-type instrument used to read low velocities at registers or grills.

**anneal**—the process of relieving stress and brittleness in metals by controlled heating and cooling

**ANSI**—American National Standards Institute

**API**—American Petroleum Institute

**ARI**—Air Conditioning and Refrigeration Institute

**ASHRAE**—American Society of Heating, Refrigerating, and Air Conditioning Engineers

**ASME**—American Society of Mechanical Engineers

**aspect ratio**—the ratio of width to length

**ASTM**—American Society for Testing and Materials

**atmospheric pressure**—one atmosphere is approximately 14.7 psi, 408" water gauge at sea level. Airflow is the result of a difference in pressure (above or below atmospheric) between two points.

**attenuation**—absorption of sound pressure. Attenuation reduces the amplitude of a sound wave while leaving the frequency unchanged.

**axial fan**—fan where the airflow through the impeller is predominantly parallel to the axis of rotation. The impeller is contained in a cylindrical housing.

**axial flow**—in-line air movement parallel to the fan or motor shaft

**backdraft damper**—damper used in a system to relieve air pressure in one direction and to prevent airflow in the opposite direction

**backward-inclined fan**—a group of centrifugal fans with blades that angle back from the direction of fan rotation. These fans can have curved and airfoil blade shapes. Airfoil blades are among the most efficient fan types.

**balancing**—the process of adding (or removing) weight on a rotor in order to move the center of gravity toward the axis of rotation

**barometric pressure**—a measurement of the pressure of the atmosphere; standard atmospheric pressure is 29.92" Hg at sea level

**bearing losses**—power losses resulting from friction in the main bearings

**Bernoulli's Theorem**—the principle that the total energy per unit of mass in the streamline flow of a moving fluid is constant, being the sum of the potential energy, the kinetic energy, and the energy because of pressure. In terms of air movement, the theorem states that static pressure plus velocity pressure as measured at a point upstream in the direction of airflow is equal to the static pressure plus velocity pressure as measured at a point downstream in the direction of airflow plus the friction and dynamic losses between the points.

**best efficiency point (BEP)**—the operating condition at which a fan transfers energy to an airstream most efficiently. In general, this is a point on a fan curve to the right of peak pressure.

**blade liners**—pieces of material added over the impeller blades to reduce abrasion of the blades

**blade-pass frequency**—the tone generated by the blades passing a fixed object

**blast area**—the fan outlet area less the projected area of the cut-off

**brake horsepower (bhp)**—a measure of the rate of energy expended. One bhp is equivalent to mechanical energy consumed at a rate of 33,000-ft. lbs. per minute.

**breakdown torque**—maximum torque a motor will produce without a sudden decrease in speed. Often referred to as pullout torque or maximum torque.

**Btu**—British thermal unit; heat required to raise the temperature of 1 pound of water by 1°F

**capture velocity**—air velocity necessary to overcome opposing air currents or natural flow and cause contaminated air, fumes, or material to flow in a desired direction

**Celsius**—a thermometric scale in which water boils at 100° and freezes at 0°

**centrifugal fan**—a fan design in which air is discharged perpendicular to the impeller's rotational axis

**cfm**—cubic feet per minute; the volume of flow for a given fan or system

**coatings**—specialty coverings, typically referred to as paints, with varying degrees of resistance to atmospheric or chemical corrosion

**coefficient of conductivity**—the rate of heat transfer through a material, expressed in Btu, transmitted per hour through one square foot of surface per degree difference in temperature across the material.

**compressibility**—a factor used by fan manufacturers to correct performance ratings in higher pressure ranges to account for the fact that air is a compressible gas

**compression**—a phenomenon related to positive pressure. When air is forced into a system it is compressed and becomes more dense. Depending on the volume or weight of air required downstream in the positive-pressure portion of the system, the volume of air at the inlet of a fan may have to be adjusted by the ratio of absolute pressure at the entrance of the fan versus the design requirements in the system.

**conveying velocity**—the air velocity required in a duct system to maintain entrainment of a specific material

**corrosion**—the deterioration of a material by chemical or electrochemical reaction resulting from exposure to weathering, moisture, chemical, or other agents in the environment in which it is placed

**curve, fan performance**—a graphic representation of static or total pressure and fan bhp requirements over an airflow volume range

**curve, system**—a graphic representation of the pressure versus flow characteristics of a given system

**damper**—an accessory to be installed at the fan inlet or outlet for air-volume modulation

**density**—the measure of unit mass equal to its weight divided by its volume (lbs./ft.<sup>3</sup>); standard air is 0.075 lbs./ft.<sup>3</sup>

**dew point**—the temperature at which condensation begins to form as air is cooled

**dust**—air suspension of particles [aerosol] of any solid material, usually with a particle size smaller than 100 micrometers

**dust collector**—an air-cleaning device used to remove heavy-particulate loadings from exhaust systems prior to discharge

**DWDI**—double-width, double-inlet fans

**dynamic balance**—the mechanical balancing of a rotating part or assembly in motion

**efficiency, mechanical total**—the ratio of fan output to the power applied to the fan; can be helpful in selecting fan size, type, or manufacturer for the same application

**elevation**—the distance of the subject site above or below sea level

**entry loss**—the loss in pressure caused by air flowing into a system; normally expressed in fractions of velocity pressure

**equivalent duct diameter**—for rectangular duct with sides a and b is:

$$D_{\text{eff}} = \sqrt{\frac{4ab}{\pi}}$$

**evase**—a diffuser at the fan outlet that gradually increases in area to decrease velocity and to convert kinetic energy to static pressure at the fan outlet and inlet

**Fahrenheit**—a thermometric scale in which water boils at 212°F and freezes at 32°F

**fan**—a power-driven machine that moves a continuous volume of air by converting rotational mechanical energy to an increase in the total pressure of the moving air

**fan capacity**—performance requirement for which a fan is selected to meet specific system calculations given in terms of ACFM at the fan inlet

**fan class**—operating limits at which a fan must be physically capable of operating safely

**fan laws**—theoretical constant relationships between cfm, rpm, static pressure (sp), and bhp for a given fan used in a given fixed system:

$$\begin{aligned} \text{cfm} &\sim \text{rpm} \\ \text{sp} &\sim (\text{rpm})^2 \\ \text{bhp} &\sim (\text{rpm})^3 \end{aligned}$$

**foot-pound (ft.-lb.)**—torque rating or requirement; equivalent to the force required to move a 1-pound weight 1 foot in distance, equal to 12 in.-lb.

**forced draft**—how air is provided in a process, such as a combustion process; when air is blown or forced into a process, it is known as a “forced draft” system. Also see **Induced Draft**.

**forward-curved blade fan**—a fan type with blades that angle toward the direction of rotation. This fan type generates relatively high pressure at low operating speeds and is used frequently in residential furnace applications

**fpm**—feet per minute; commonly defines air velocity (to determine velocity pressure or suitability for material conveying), shaft/bearing speeds (used to determine lubrication requirements), and impeller tip speeds

**frame size**—a set of physical dimensions of motors as established by National Electrical Manufacturers Association (NEMA) for interchangeability between manufacturers. Dimensions include shaft diameter, shaft height, and motor-mounting footprint.

**frequency**—any cyclic event, whether vibration, alternating current, or rotational speed. Usually expressed in cycles per second (cps) or just “cycles.”

**friction loss**—resistance to airflow through any duct or fitting, given in terms of static pressure

**FRP**—abbreviation for fiberglass-reinforced-plastic

**full-load speed**—the speed at which the rated horsepower is developed. This speed is less than synchronous speed and varies with motor type and manufacturer.

**full-load torque**—the torque required to produce the rated horsepower at full-load speed

**fumes**—airborne particles, usually less than 1 micrometer in size, formed by condensation of vapors, sublimation, distillation, or chemical reaction

**gauge (gage)**—metal manufacturers' standard measure of thickness for sheet stock

**gauge pressure**—the pressure differential between atmospheric and that measured in the system

**heat exchanger**—a device, such as a coil or radiator, which is used to transfer heat between two physically separated fluids

**HEPA filter**—high-efficiency particulate air filters, commonly called absolute filters

**hertz**—frequency measured in cycles per second

**Hg**—symbol for mercury. Pressure is often measured in inches of mercury (1 inch Hg = 13.64 inches wg).

**horsepower (hp)**—(as applied to motors) an index of the amount of work the machine can perform in a period of time. One hp equals 33,000-ft. lbs. of work per minute, also equal to 0.746 kilowatts. Horsepower can be calculated by:

$$\text{horsepower} = \frac{\text{Torque} \times \text{RPM}}{5,250}$$

**housing**—the casing or shroud of a centrifugal fan

**HVAC**—heating, ventilating, and air conditioning

**impeller**—another term for fan “wheel.” The rotating portion of the fan designed to increase the energy level of the gas stream.

**impeller diameter**—the maximum diameter measured over the impeller blades

**impingement**—striking or impacting, such as material impingement on a fan impeller

**inch of water**—unit of pressure equal to the pressure exerted by a column of water 1 inch high at a standard density (1 inch of water = 0.036 psig)

**inch-pound (in.-lb.)**—torque equal to one-twelfth foot-pound

**inclined manometer**—a metering device used to obtain pressure measurements

**induced draft**—how air is provided in a process, such as a combustion process, where air is drawn or pulled through a process. **Also see forced draft.**

**induction**—the production of an electric current in a conductor in a changing magnetic field

**inertia**—tendency of an object to remain in the state it is in. **Also see WR<sup>2</sup>.**

**inlet-vane damper**—round multiblade damper mounted to the inlet of a fan to vary the airflow

**instability**—the point of operation at which a fan or system will “hunt” or pulse; common in forward-curved fans and some axial fan types where the point of operation is left of the peak of the static-pressure curve

**kilowatt**—measure of power equal to 1.34 horsepower

**L-10 bearing life**—the theoretical number of hours after which 90 percent of the bearings subjected to a given set of conditions will still be in operation

**laminar flow**—gas or fluid in parallel layers with some sliding motion between the layers, characteristic of airstreams with Reynolds numbers less than 2,000

**load factor**—ratio of the average capacity to the rated full capacity, determined by the following relationship:

$$\text{Load Factor} = \frac{\sum (\text{Actual Load} \times \text{Number of operating hours at this load})}{\text{Rated Full Load} \times \text{Number of hours in the period}}$$

**louver**—a device composed of multiple blades which, when mounted in an opening, permits the flow of air but inhibits the entrance of undesirable elements

**make-up air**—a ventilating term which refers to the replacement of air lost because of exhaust air requirements

**manometer**—instrument for measuring pressure; u-shaped, and partially filled with liquid, either water, light oil, or mercury

**maximum continuous rating**—the point at which the fan is expected to operate

**natural frequency**—the frequency at which a component or system resonates

**NEMA**—the National Electrical Manufacturers Association; the trade association establishing standards of dimensions, ratings, enclosures, insulation, and other design criteria for electric motors and other devices

**noise criteria**—a way for a designer to specify the maximum permissible sound-power level in each of the eight-octave bands. Noise criteria curves give maximum permissible intensity per octave-band in a graphical form.

**opposed-blade damper**—a type of damper where adjacent blades rotate in the opposite direction

**parallel-blade damper**—a type of damper where the blades rotate in the same direction

**parallel fans**—two or more fans that draw air from a common source and exhaust into a common duct or plenum. A parallel fan arrangement is generally used to meet volume requirements beyond that of single fans. Two identical fans in parallel will effectively deliver twice the rated flow of any one fan at the same static pressure.

**pitch diameter**—the mean diameter or point at which V-belts ride within a sheave. This dimension is necessary for accurate drive calculations.

**pitot tube**—a metering device consisting of a double-walled tube with a short right-angle bend; the periphery of the tube has several holes through which static pressure is measured; the bent end of the tube has a hole through which total pressure is measured when pointed upstream in a moving gas stream

**plenum**—a chamber or enclosure within an air-handling system in which two or more branches converge or where system components such as fans, coils, filters, or dampers are located

**poles**—the number of magnetic poles established inside an electric motor by the placement and connection of the windings

**propeller fan**—an axial fan type that is compact, inexpensive, but relatively inefficient

**psia**—pounds per square inch absolute, represents total pressure above a perfect vacuum

**psig**—pounds per square inch measured in gauge pressure, represents the difference between psia and atmospheric pressure

**radial blade**—fan impeller design with blades positioned in straight radial direction from the hub

**radial-tip fan**—a fan type with short blades and large clearances between the blades and the impeller hub

**rarefaction**—a phenomenon related to negative pressure. When air is drawn through resistance into a fan inlet, the air is stretched out, or rarefied, and becomes less dense than at the entry to the system. While negligible at low pressures and volumes, high-pressure fan selection must be based on rarefied inlet density.

**relative humidity**—the ratio of existing water vapor to that of saturated air at the same dry-bulb temperature

**Reynolds number**—a mathematical factor used to express the relation between velocity, viscosity, density, and dimensions in a system of flow; used to define fan proportionality

**rotor**—the rotating part of most alternating current motors

**rpm**—revolutions per minute

**radial tip**—fan impeller design with shallow blades in which the trailing edge points radially from the axis of rotation

**saturated air**—air containing the maximum amount of water vapor for a given temperature and pressure

**scfm**—standard cubic feet per minute; a volume of air at 0.075 lbs./ft.<sup>3</sup> density; used as an equivalent weight

**scroll**—the general shape of a centrifugal fan housing; the formed piece to which housing sides are welded

**sensible heat**—any portion of heat which affects a change in a substance's temperature but does not alter that substance's state

**series fans**—a combination of fans connected so that the outlet of one fan exhausts into the inlet of another. Fans connected in this manner are capable of higher pressures than a single fan and are used to meet greater pressure requirements than single fans.

**service factor**—the number by which the horsepower rating is multiplied to determine the maximum safe load that a motor may be expected to carry continuously

**shaft seal**—a device to limit gas leakage between the shaft and fan housing

**slip**—the percentage difference between synchronous speed and actual speed

**sound**—produced by the vibration of matter. The vibration causes sound waves to spread through the surrounding medium.

**surge limit**—that point near the peak of the pressure curve that corresponds to the minimum flow at which the fan medium can be operated without instability

**sound-power level**—acoustic power radiating from a sound source; expressed in watts or in decibels

**sound-pressure level**—the acoustic pressure at a point in space where the microphone or listener's ear is situated; expressed in units of pressure or in decibels

**specific gravity**—the ratio of the weight or mass of a given volume of any substance to that of an equal volume of some other substance taken as a standard. The ratio of the density of any gas to the

density of dry air at the same temperature and pressure is the specific gravity of the gas.

**specific heat**—the ratio of the quantity of heat required to raise the temperature of a certain volume by one degree to that required to raise an equal volume of water by one degree

**squirrel-cage winding**—a permanently short-circuited winding, usually uninsulated and chiefly used in induction motors, with its conductors uniformly distributed around the periphery of the machine and joined by continuous end rings

**standard air density**—0.075 lbs./ft.<sup>3</sup>, corresponds approximately to dry air at 70°F and 29.92 in. Hg

**stator**—the stationary parts of a magnetic circuit with operating speeds associated windings

**synchronous speed**—rated motor speed expressed in rpm:

$$\text{Synchronous speed} = \frac{120 \times \text{Frequency}}{\text{Number of poles}}$$

**system curve**—graphic presentation of the pressure versus volume flow-rate characteristics of a particular system

**system effect**—the difference between the actual flow-pressure characteristics of a fan or a fan system component and the flow-pressure characteristics determined in laboratory tests to obtain performance ratings

**tachometer**—an instrument which measures the speed of rotation; usually in rpm

**tensile strength**—the maximum stress a material can withstand before it breaks; expressed in pounds per square inch

**tip speed**—fan impeller velocity at a point corresponding to the outside diameter of the impeller blades; normally expressed in feet per minute (circumference times rpm)

**torque**—a force that produces rotation; commonly measured in ft.-lbs. or in.-lbs.

**tubeaxial fan**—axial fan without guide vanes

**tubular centrifugal fan**—fan with a centrifugal impeller within a cylindrical housing that discharges the gas in an axial direction.

**turbulent flow**—airflow in which true velocities at a given point vary erratically in speed and direction

**uniform flow**—airflow in which velocities between any two given points remain fairly constant

**vaneaxial fan**—axial fan with either inlet or discharge guide vanes or both

**ventilation**—supplying and removing air by natural or mechanical means to and from any space

**vibration**—alternating mechanical motion of an elastic system, components of which are amplitude, frequency, and phase

**viscosity**—the characteristic of all fluids to resist flow

**watt**—a unit of power. In electrical terms, the product of voltage and amperage; 746 watts are equal to 1 horsepower

**wg**—water gage. Also see “inch of water.”

**WR<sup>2</sup>**—the unit designation of fan-impeller rotational inertia in lb.-ft.<sup>2</sup>, also known as WK<sup>2</sup>

1. **How many primary types of fans are there?**
  - Two
  - Four
  - Eight
  - Eighteen
  
2. **Contaminant build-up problems are promoted by fans with?**
  - High velocity airflow
  - Shallow blade angles
  - Steep blade angles
  - Any blade angle - effects all surfaces
  
3. **When the fan performance curve slopes in the same direction as the system resistance curve it decreases fan efficiency, what is it called?**
  - Region of Instability
  - Efficiency point
  - System effect
  - Fan start-up
  
4. **Which of the following is the most reasonable method to address system effect?**
  - Combine proper system layout practices with an accurate estimate of the system effect
  - Always oversize fans to compensate for system effect
  - Configure system as non-uniform as possible
  - All of the above
  
5. **Which of the following is an air control device?**
  - Electric Dampers
  - Power factor
  - Limiter
  - Soft starters
  
6. **What type of centrifugal fan is well-suited for HVAC applications?**
  - Radial-blade
  - Radial-tip
  - Forward-curved blades
  - Backward-inclined

7. **Axial fans must rotate \_\_\_\_\_ comparable centrifugal fans to achieve the same airflow capacity?**
- Faster than
  - Slower than
  - Roughly the same to
  - Slightly less than
8. **Which fan type has the greatest susceptibility for contaminant build-up?**
- Forward-curved blades
  - Radial-tip
  - Radial-blade
  - Backward-inclined
9. **Which of the following are common maintenance tasks on fan systems?**
- Periodic inspection of all system components
  - Bearing lubrication and replacement
  - Belt tightening and replacement
  - Motor repair or replacement
  - Fan cleaning
  - All of the above
10. **True or False? Belt drives are frequently the most maintenance-intensive component of a fan/motor assembly.**
- True
  - False
11. **A system which is found to have inlet vanes or dampers closed so often they are rusted or locked in is a good indication the fan is?**
- Undersized
  - Oversized
  - Operating at peak efficiency
  - None of the above
12. **What is the approximate leakage class (CL) for an unsealed rectangular duct system?**
- 6
  - 12
  - 24
  - 48

- 13. The general guideline to correct inefficiencies in fan inlets such as pre-rotational swirls or non-uniform flow, is to provide straight duct lengths of at least \_\_\_\_\_ times the duct diameter prior to fan inlet?**
- 10
  - 3
  - 1
  - ½
- 14. True or False? Inlet vanes cause a higher power consumption than outlet vanes.**
- True
  - False
- 15. Which type of adjustable speed drive is by far the most popular due to proven effectiveness in reducing energy costs?**
- Fluid couplings
  - Eddy current clutches
  - Variable Frequency Drive (VFD)
  - Hydraulic clutches
- 16. In industrial fan applications, which is the most common type of motor used as it offers low cost, durability, reliability, and low maintenance?**
- Slip Ring Induction motor
  - Wound rotor motor
  - Squirrel-cage induction motor
  - Shunt DC motor
- 17. Which type of fan belt is recommended in applications with a small arc of contact?**
- Flat belt
  - V-belt
  - Cogged V-belt
  - Synchronous belt
- 18. For a system with long ducts or large pressure drops across components, what type of fan system should be employed?**
- Multiple Fans in series
  - Multiple Fans in parallel
  - Large axial fan
  - Any of the above

**19. Which of the following methods can be used to determine fan electrical consumption?**

- Direct measurement of motor current or power
- Use of motor nameplate data
- Use of performance curve data
- All of the above

**20. What are the electrical devices that gradually ramp up the voltage to the fan motor, limiting the in-rush and starting current and can extend fan motor life by keeping the motor temperature low.**

- Power factor
- Limiter
- Soft starters
- Electric Dampers