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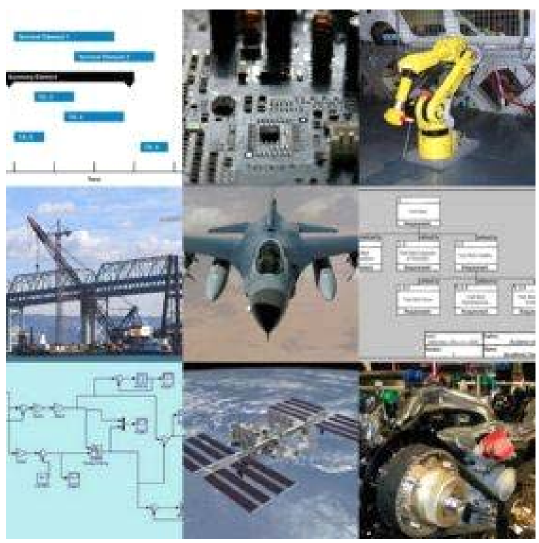
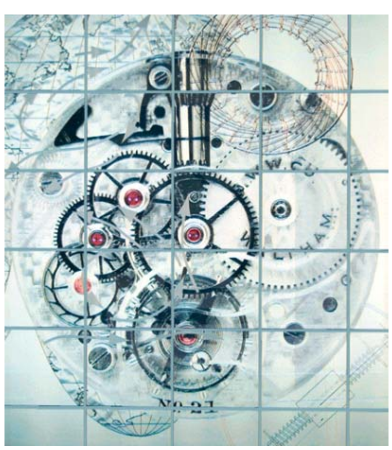
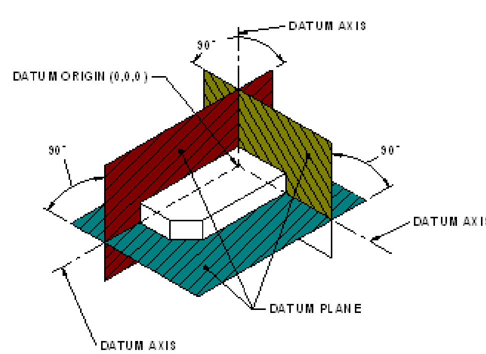




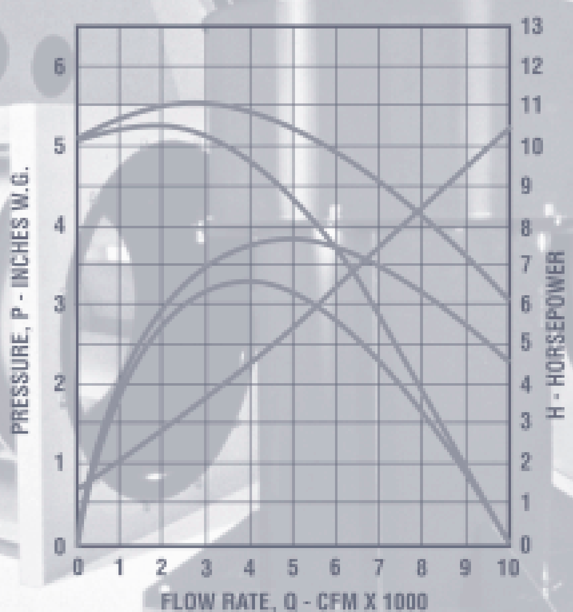


PDH Storm, by Engineers Edge, LLC

One of a series of industrial energy efficiency sourcebooks

Improving Fan System Performance

a sourcebook for industry



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Acknowledgments

Improving Fan System Performance: A Sourcebook for Industry has been developed by the U.S. Department of Energy's (DOE) Industrial Technologies Program and the Air Movement and Control Association International, Inc. (AMCA), a DOE Allied Partner. Industrial Technologies and AMCA International undertook this project as part of a series of sourcebook publications on motor-driven equipment under the BestPractices effort. Other topics in this series include compressed air systems, pumping systems, and motors and drives. For more information about the Industrial Technologies' BestPractices effort and AMCA International, see Section 3.

AMCA International is a not-for-profit association of the world's manufacturers of related air system equipment—primarily, but not limited to fans, louvers, dampers, air curtains, airflow measurement stations, acoustic attenuators, and other air system components—for industrial, commercial, and residential markets. The association's mission is to promote the health and growth of industries covered by its scope and the members of the association consistent with the interests of the public.

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Section 1: Introduction to Fan Systems

Fans[1] 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[2] of energy each year. This consumption represents 15 percent of the electricity used by motors.[3] 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)[4], with airflow from a few cubic feet per minute (cfm) to more than 1 million cfm. Pressures above 15 psig generally require air compressors, which are addressed in a separate sourcebook titled *Improving Compressed Air System Performance, A Sourcebook for Industry*.

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.

[1] For the purposes of this sourcebook, the term "fan" will be used for all air-moving machines other than compressors.
[2] *United States Industrial Electric Motor Systems Market Opportunities Assessment,* U. S. Department of Energy, December 1998.
[3] Ibid.
[4] At standard conditions, a column of water 27.68 inches high exerts 1 psig of pressure. Equivalently, 1 inch of water gage = 0.036 psig.

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 sourcebook 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. For more information, see the fact sheet titled *Configurations to Improve Fan System Efficiency* on page 39.

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:

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

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 airflow 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.

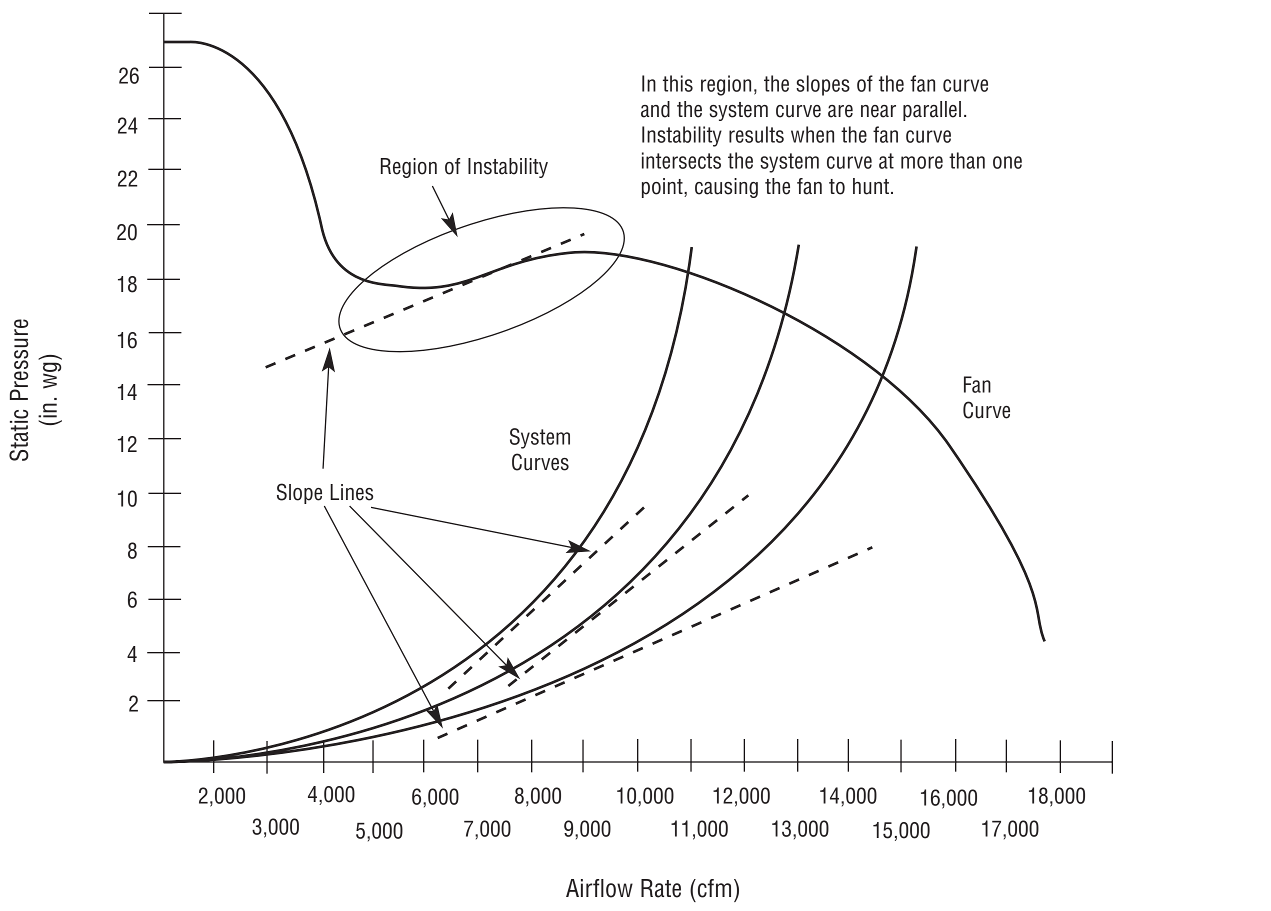

Figure 1-1. Region of Instability[5]

[5] Although fan system curves can have a static component, for the purposes of this sourcebook, 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. For more information on VFDs and controllable pitch fans, see the fact sheet titled *Controlling Fans with Variable Loads* on page 43.

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: Δp = pressure loss in inches of water gage (in. wg)
C = loss coefficient for the component
V = velocity in feet per minute
ρ = 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. For more information on how to minimize losses, see the fact sheet titled *Configurations to Improve Fan System Efficiency* on page 39.

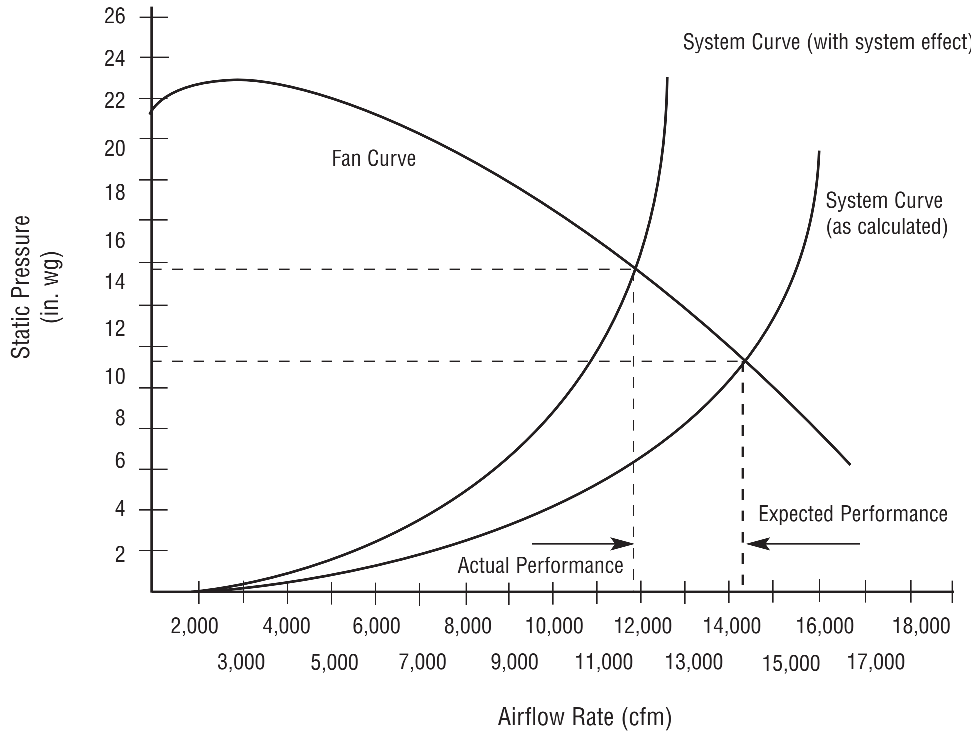

Figure 1-2. System Effect for a Typical Fan and System

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 10.

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

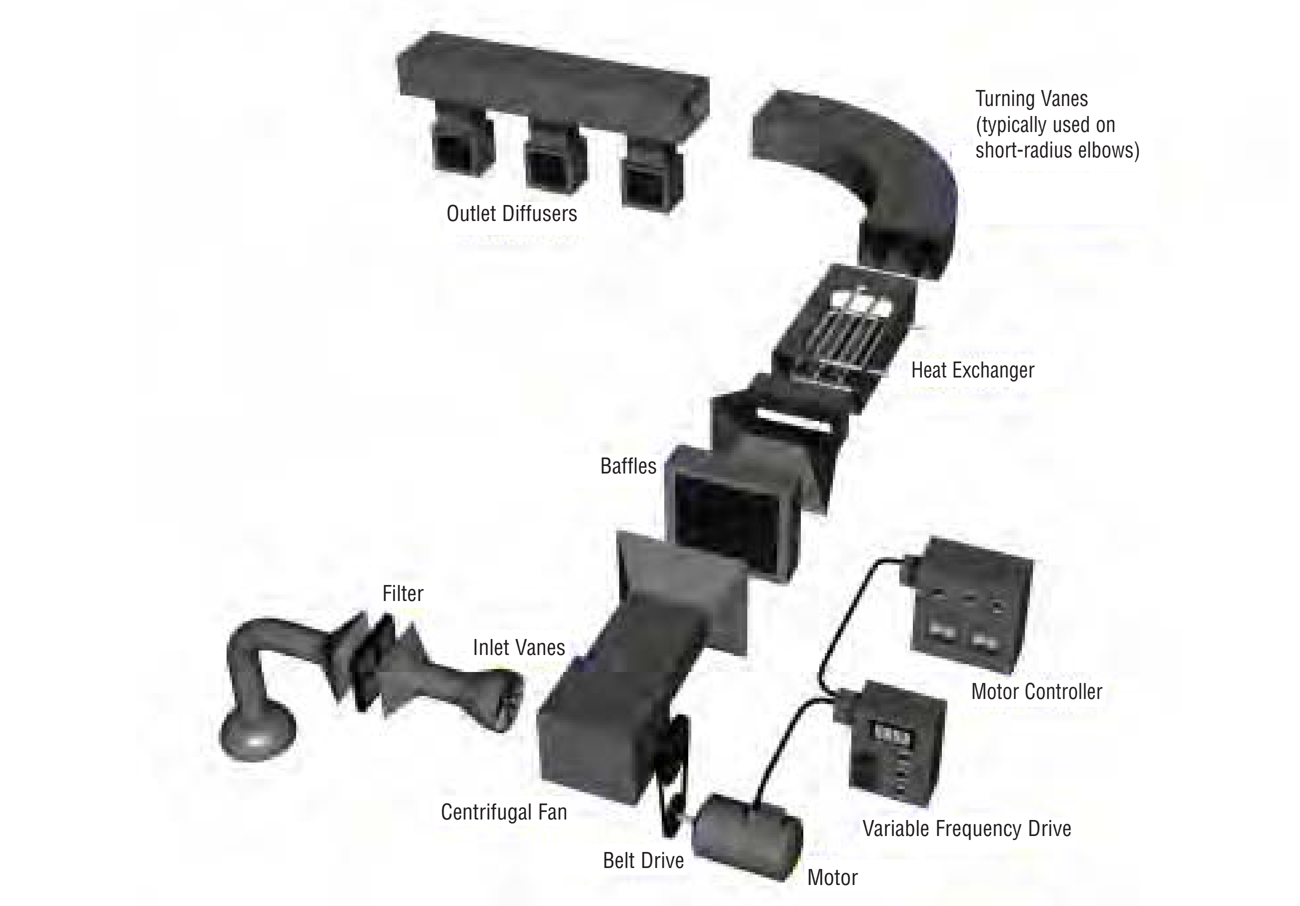

Figure 1-3. Example Fan System Components

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 (EPAct), 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. EPAct-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. A

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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.

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Ductwork or Piping. For most fan systems, air is directed through ducts or pipes. In general, ducts

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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_Ls. For more information see the fact sheet titled *System Leaks* on page 37.