Learn to Effectively Operate and Maintain Pumps

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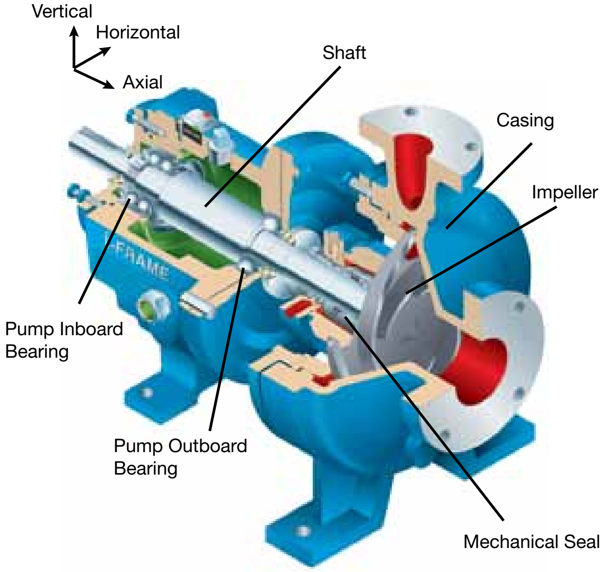
Centrifugal pumps play a central role in chemical processing. Proper pump operation and maintenance can improve a facility's productivity, reduce downtime, and trim costs.

For transporting fluids ranging from water to crude oil and pigments to pesticides, pumps serve an important function in the chemical process industries (CPI). Pumps are the second most widely used industrial machine (after motors), and are found in all CPI plants. Despite such prevalence and significance, however, pumps are often overlooked as a potential source of improved productivity and cost reductions.



▲ **Figure 1.** The main parts of a centrifugal pump are the impeller, casing, bearings, bearing frame, shaft, and mechanical seal.

Realizing this potential requires not only selecting the right pump, which is the subject of a previous *CEP* article *(1)*, but also properly operating and maintaining the pump — the focus of this article. In addition to discussing best practices for centrifugal pump operation and maintenance, this article also describes continuous monitoring systems and presents two case studies that show how they can be applied to improve system performance and reduce maintenance costs.

Pump basics

Although enhancements to pump designs and materials and the expanding use of digital monitoring technology have improved pump performance, the operating principle and basic structure of centrifugal pumps (the most commonly used pump in the CPI) have changed little in decades.

A centrifugal pump (Figure 1) is a rotating machine comprised of six main parts: an impeller, a pump casing, bearings, a bearing frame, a shaft, and a mechanical seal. These parts work together to convert mechanical energy into pressure: The rotating impeller accelerates the incoming liquid, and as the fluid travels through the pump casing, its velocity is converted to pressure. The pressurized liquid then exits the pump discharge.

Efficient pump operation

A key factor to assess whether a pump is operating properly is the best efficiency point (BEP), which is the flowrate at which a pump's efficiency is highest. Although few pumps operate at their BEP all of the time because of process variability, a pump that is properly sized for its application will maintain a flow near peak efficiency. Maintaining a flowrate of 80–110% of BEP is a good range to maximize efficiency and minimize the risk of excessive wear or pump failure.

Unfortunately, many pumps do not operate within this range. A study by the Finnish Technical Research Center that evaluated nearly 1,700 pumps at 20 process plants across multiple industries found that the average pumping efficiency was below 40% of BEP and that more than 10% of the pumps were running below 10% efficiency.

When the flowrate is higher than the pump was designed to handle, the pump is operating above its BEP, a condition known as runout. The high flow increases the exit velocity of the fluid leaving the pump, which in turn creates a low-pressure area inside the pump. Operating below the BEP occurs when the discharge flow is restricted, causing fluid to recirculate inside the pump. This also creates a low-pressure area within the pump.

In either case, the pressure imbalance inside the pump increases the radial load on the impeller and causes the shaft to bend, which increases vibration of the pump. The increased vibration and imbalanced forces create stress on the pump's internal components. This usually manifests itself first in the bearings and/or mechanical seals — the two parts of a centrifugal pump that fail most often.

Cavitation is another possible outcome of inefficient pump operation. Cavitation happens when the net positive suction head (NPSH) — the difference between the suction pressure and the vapor pressure of the fluid — is too low. If the fluid pressure on the trailing side of the impeller blade (opposite the pump intake) falls below the vaporization point of the fluid, the fluid will begin to boil, creating vapor bubbles. Cavitation occurs when these vapor bubbles reach an area of high pressure inside the pump and collapse violently — causing pitting damage to the impeller, along with sudden, uneven axial and radial loading on the impeller. This, in turn, can cause shaft deflection that is random in direction and often severe in magnitude.

A common reason for inefficiency is improper pump size. In an ideal world, all pumps would be properly sized to run constantly at their best efficiency points.

In the real world of an industrial plant, however, this is impractical. Many process pumps are oversized for the needs of the application, often because pumps need to be specified before all of the process parameters have been defined and engineers tend to err on the side of overestimating pump needs. Furthermore, a pump might be perfectly suited to an application but changing process demands render it unsuitable. Processes are fluid — literally and figuratively.

Formulations change and production rates vary, but typically the hundreds or thousands of pumps supporting the processes do not change with them. Thus, continued reliable pump operation requires a robust maintenance program centered around monitoring basic machine health data and pump operating conditions.

A pump maintenance and monitoring program contains three main elements:

- pump performance monitoring and pump system analysis
- vibration and bearing temperature monitoring
- visual inspections.

Individually, each of these elements is an important indicator of pump health. Collectively, they provide a complete picture of the actual condition of the pump.

Performance monitoring

Ideally, five parameters should be monitored to understand how a pump is performing: suction pressure, discharge pressure, power, pump speed, and flowrate. At a minimum, suction and discharge pressures are essential for determining the total dynamic head (TDH), which is critical to understanding the pump's operation with respect to BEP, and the available net positive suction head ($NPSH_A$).

Suction and discharge pressures. The suction and discharge pressures are measured either by pressure tranducers that can transmit real-time data or by pressure gages. If pressure gages will be used, the gage taps should be installed in a straight section of pipe, ideally one whose length is 10 times the diameter, adjacent to the pipe wall and on the horizontal centerline of the pipe. Taps in elbows or reducers will not accurately measure the true static pressure due to the velocity head component of the pressure reading. Also avoid putting taps in the top or bottom of the pipe, where they can become air-bound or clogged with solids.

Using only suction and discharge pressure measurements to assess pump operation has limitations. For instance, when a pump is operated by a variable-speed drive, the speed of the pump must be factored into the evaluation using the affinity laws, which state that the change in TDH is proportional to the square of the speed. It is also difficult to determine pump wear based on only suction and discharge pressure data. As the pump wears, internal clearances increase (*i.e.*, the area through which the fluid passes gets larger) and the pump's ability to generate pressure decreases. Without additional information, this decrease in pressure could be interpreted as a change in the process conditions and not necessarily a worn pump.

Power. An accurate power measurement, in combination with suction and discharge pressure readings, can be a powerful tool to assess pump performance. Although transducers that measure current are the most basic and cost-effective power-monitoring solution, their readings should be applied judiciously. The motor's current reading is not directly proportional to load. Factors such as input voltage, power factor, and motor efficiency should be considered to accurately determine the actual shaft horsepower being transmitted to the pump.

Low-voltage pump load monitors are available for fixed-speed pumping applications. For a typical investment of less than $1,000, these devices offer protection against underload and overload conditions that could result in mechanical seal damage or pump failure.

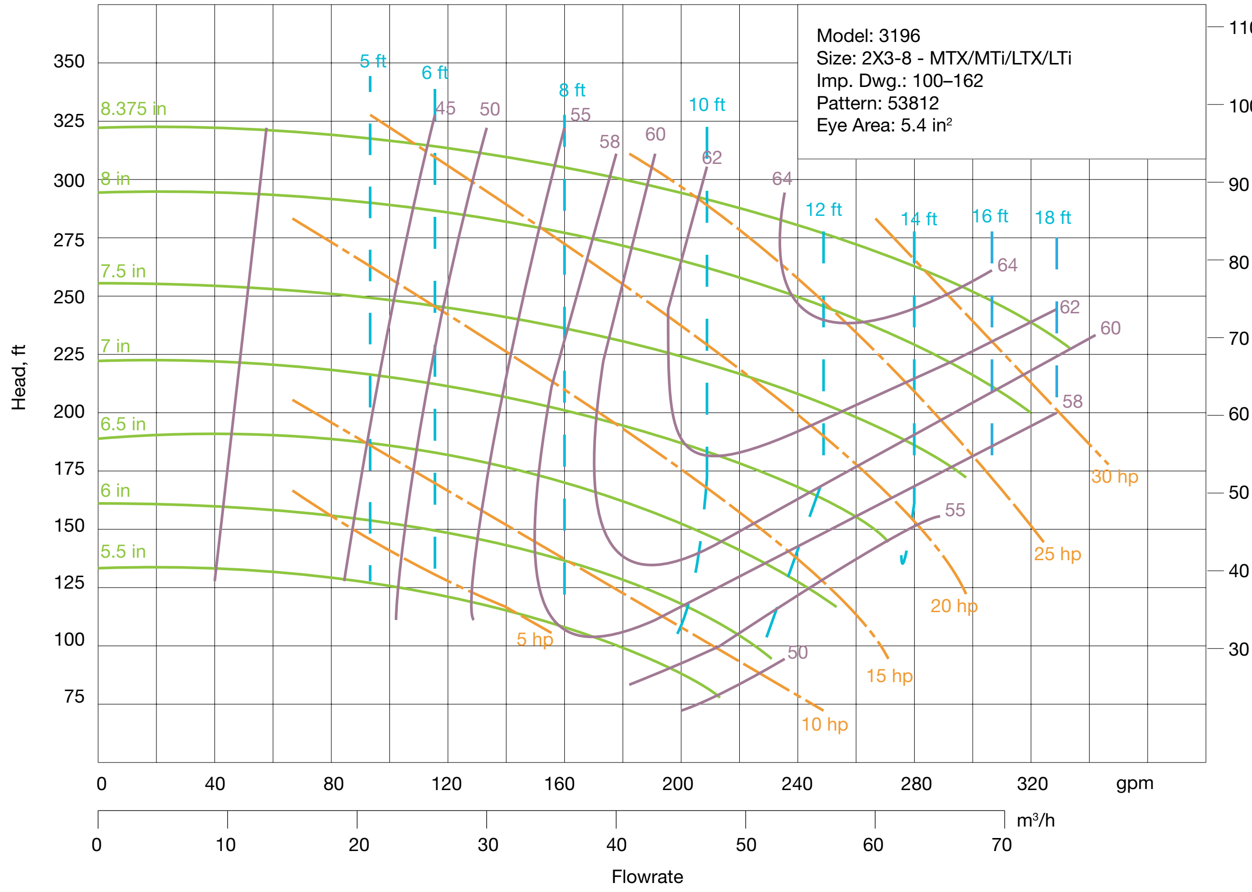
Pump speed. Pump speed also plays a role in centrifugal pump load monitoring because of its relationship to power utilization. While a pump's output varies in direct proportion to the speed of the motor, the horsepower required to operate centrifugal pumps varies with the cube of the speed. This means that if the speed of the pump motor is reduced to one-half of the base speed, the required horsepower is only one-eighth of the rated horsepower. Changes in fluid properties such as specific gravity and viscosity can impact pump speed and power requirements and thus should also be considered.

Flowrate. In an ideal world, it would be possible to obtain flow measurements on all pumps. Although this is often impractical, flowrate data are vital for understanding the overall efficiency of the pump.

Some facilities have installed permanent flowmeters to make the job of monitoring easier. If your plant uses such flowmeters, make sure they are working properly and are calibrated on a regular schedule. A clamp-on ultrasonic flowmeter can provide a non-intrusive, temporary solution. These devices can be used on a range of pipe diameters and have an accuracy of approximately 1%. The challenge is finding a straight run of pipe, typically 10 times longer than the diameter upstream of the meter and five times longer than the diameter downstream, on which to attach the flowmeter.

In some cases, it will be very difficult (or impossible) to determine all of these parameters in the field. In such cases, you will need to combine the known measurements with your engineering experience to assess whether a particular pump is properly sized and performing the job adequately.

The key document for a pump is the pump performance curve. Pump curves (which are covered in more detail in Ref. 1) depict the total dynamic head, brake horsepower, efficiency, and NPSH, all plotted over the capacity range of the pump (Figure 2).



▲ **Figure 2.** A pump curve shows, at a glance, how the pump will operate at a given speed as a function of impeller diameter. Constant horsepower, efficiency, and NPSH lines are superimposed over the head curves.

Table 1. Cavitation can be eliminated by increasing the suction pressure, lowering the fluid temperature, or reducing the required NPSH.	
Boost suction pressure	Elevate the feed tank, or increase the suction pressure available to the pump.
Lower operating temperature	Lowering the operating temperature reduces the fluid's vapor pressure, which increases the available NPSH.
Reduce flowrate	Reduce the flowrate to reduce the NPSH required; this can be done by installing several smaller pumps.
Reduce speed	Pumps running at lower speeds have lower NPSH requirements. In many cases, however, this will require a larger pump.
Install a larger impeller and reduce pump speed	If a pump has a relatively small impeller (which is ideal from a hydraulic viewpoint), installing a larger impeller will reduce the $NPSH_R$.

Pump system analysis

Pump system analysis is more comprehensive than monitoring the performance of an individual pump. It is the discipline of assessing pumping requirements in the context of an overall system designed to move fluids as part of an industrial process.

It is often overlooked because operators assume that the system was constructed with the installed pumps in mind, and that the pumps are operating according to design specifications. This often is not the case, however.

Many pumps are purchased as individual pieces of equipment to meet specific process needs (or estimated needs), rather than as part of a comprehensive system design. Ensuring that the pump is right-sized for the application, has good suction piping design, and has adequate suction pressure are essential to reliable operation.

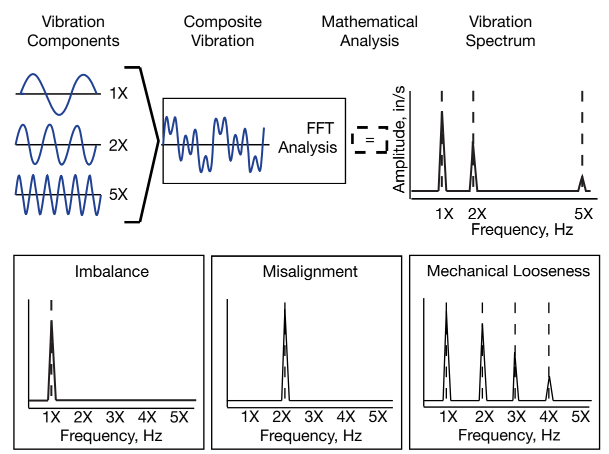
An oversized pump is typically operated with its discharge valve throttled back to limit flow. This has the effect of applying a mechanical brake to the pump, forcing it to operate outside its optimal flow range, away from its BEP. As discussed previously, running a pump away from the BEP causes the internal hydraulic forces to become imbalanced, which puts stress on the pump shaft, seals, and bearings, which in turn can lead to premature failure.

When monitoring a pump, it is important to note the discharge valve position. A valve that is throttled more than 50% can indicate that the pump is oversized for the application. The simplest and most cost-effective way to right-size the pump is to trim the impeller. A more-flexible option is to add a variable-frequency drive to ramp the pump speed up or down. If the pump is drastically oversized, it may have to be hydraulically re-rated or a new pump may need to be installed. Many factors go into this decision, such as demand variability, static head requirements, and flexibility for future capacity changes. The energy savings and reduced maintenance costs will often offset the initial investment to right-size the pump.

The design of a piping system, especially the pump suction piping, can have a significant impact on pump operation. Many centrifugal pump problems are caused by poor suction conditions. Suction piping should never be smaller than the pump intake, and, in most cases, it should be one size larger. An eccentric reducer, which has a flat top to prevent the buildup of air bubbles, should be used rather than a concentric reducer.

Suction pipes should be as short and straight as possible. If an elbow or tee is located adjacent to the pump suction nozzle, install a straight run of pipe, three to five times longer than the pipe diameter, between it and the pump suction. A general rule of thumb is to keep suction pipe velocities within the range of 5–8 ft/s. Higher velocities will increase the friction loss and can cause air/vapor separation from the fluid and uneven flow patterns. This can prevent the liquid from evenly filling the impeller and lead to hydraulic imbalance, excessive shaft deflection, vibration, and cavitation.

The Hydraulic Institute, a nonprofit trade association of pump manufacturers and suppliers, defines NPSH as the total suction head in feet absolute, determined at the suction nozzle and corrected to datum, minus the vapor pressure of the liquid. The energy conditions on the suction side of a pump determine whether the liquid will vaporize at the lowest pressure in the pump. If the pressure falls below the vapor pressure of the liquid, the liquid will vaporize and cavitation can occur. To prevent cavitation, pump manufacturers publish the net positive suction head requirement



▲ **Figure 3.** By dissecting the vibration signal and analyzing the individual components of the fast Fourier transform (FFT) spectrum, the specific machine defects can be identified. For example, high vibration at the running speed typically indicates machine imbalance.

($NPSH_R$) for each pump. $NPSH_R$ is the minimum suction pressure required by the pump to prevent cavitation. Table 1 lists some remedies for cavitation.

A typical pump system analysis includes analysis of the suction pressure requirements, evaluation of the pump's operation, and a thorough review of the piping configuration and valving. The more complete understanding the engineer has of the pumping system, the more effective the maintenance program will be.

Vibration analysis

Vibration analysis is the cornerstone of all pump-performance monitoring programs. Vibration is directly related to the pump's operation relative to its BEP — the higher the vibration level, the further away from the BEP.

Organizations such as the Hydraulic Institute and the Vibration Institute have developed criteria for normal, acceptable vibration levels. However, exercise caution when applying these published values, because the allowable vibration level for a specific pump depends on the application, and there is no absolute vibration level that indicates a pump in distress.

Since every installation is unique, each plant should develop its own site-specific criteria. When a pump is initially started up, take vibration readings on the outboard and inboard bearing housings of both the pump and motor, in the vertical and horizontal directions, and record the pump's operating point. Compare these data to published values for the specific pump, and use this information to set alarm levels. These setpoints can be programmed into a digital monitoring system or checked during walkaround inspections.

Evaluate the frequency and the amplitude of the vibrations. Frequency identifies the type of defect that is causing the problem, and amplitude indicates the problem's severity. The total vibration is comprised of multiple smaller vibrations, each due to a specific condition, such as pressure imbalance, shaft misalignment, looseness of parts, or vane pass — the varying frequencies created by the rotation of multi-vane impellers. The measured vibration signal can be mathematically dissected using fast Fourier transform (FFT) analysis to reveal the individual contributing components (Figure 3). A plot of amplitude vs. frequency can then be evaluated to identify the source of vibration and the conditions that may ultimately cause machine failure.

Bearing defect analysis is another useful condition-monitoring tool. Each component of a pump's roller bearing has its own unique defect frequency. Vibration monitors enable the engineer to isolate bearing defects and determine whether the bearing is in distress. This allows the user to shut down the machine prior to a catastrophic failure. Several methods of bearing defect analysis are available.

The most practical defect analysis technique is bearing enveloping. In this method, filters built into the vibration analyzer amplify repetitive frequencies produced by the bearings. Bearing manufacturers publish charts of defect frequency as a function of running speed, which can be used to identify and monitor the defect frequency. As noted earlier, a baseline must be established and then trends monitored.

Another good practice is to monitor bearing temperature. Higher-than-normal temperatures provide an early indication of lubrication breakdown or lack of lubricant. In most CPI applications, a temperature sensor mounted on the outside

Pump Failure Cited as the Cause of Catastrophes

Case study 1: Failed pump causes a refinery shutdown. A catastrophic failure occurred at a refinery that produces about 70,000 bbl/d of oil. A fire broke out at the bottom of a vacuum tower, forcing a three-day shutdown that cost $1.5 million in damages and lost production time. An investigation quickly identified a failed vertical inline pump as the cause.

A root-cause analysis traced the origin of the fire to the pump's mechanical seal, and a review of maintenance records revealed numerous repairs and parts replacements consistent with off-BEP pump operation in the weeks and months leading up to the fire. After the fire, the refinery installed a continuous monitoring system. In the two years since the system was installed, the refinery has required no unplanned maintenance on its pumps.

This is a more common occurrence than one might think among pumps that are not operated and maintained properly. On average, one of every 1,000 pumps with a failed mechanical seal leads to a fire.

Case study 2: Corn processor employs predictive condition monitoring. A large corn processor operates three manufacturing plants that run 24 hours a day, seven days a week. The processing equipment refines corn kernels into starches and syrups used by soft-drink makers, canners, confectioners, and bakers. The equipment operates at high speeds with extreme precision, creating safety issues if any piece malfunctions.

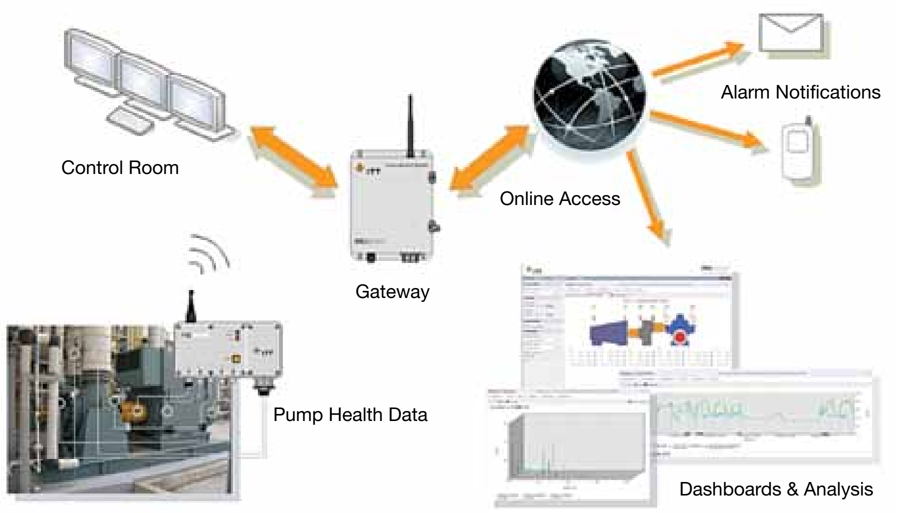
This plant uses a web-based condition monitoring approach to reduce the risk of equipment trouble. Sensors in three different areas of the plant collect data on variables such as bearing vibrations, temperature, speed, oil level, liquid leaks, and pump cavitation. The data are fed continually via a wireless transmitter to a monitoring system server, and displayed through a standard web browser. If any measured data are higher than the alarm setpoint, operations personnel are notified via email or telephone. Managers can go online at any time from any computer to check pump readings. The system has improved plant safety and equipment uptime.

of the bearing housing is sufficient to measure bearing temperature. Alternatively, an infrared (IR) sensor *(2)* can be used. Note that an IR temperature detector measures the outside surface of the bearing housing and not the actual bearing temperature — a distinction that should be taken into consideration when using this technique.

Continuous condition monitoring

The most rudimentary form of condition monitoring is visual inspection by experienced engineers, operators, and maintenance personnel. Walkarounds are part of any preventive maintenance program, and are useful for detecting failure modes such as cracking, leaking, or corrosion before pump failure is likely to occur.

The central concept of the walkaround is something children learn at an early age: stop, look, and listen. Noise, visible vibration, visual corrosion, and leaks are easily detectable signs of trouble. The earlier these problems can be caught, the lower the cost of repair and risk of downtime.



▲ **Figure 4.** The monitoring data from a digital condition-monitoring system can be sent to both the control room and to a web-based monitoring platform. Key performance indicators (KPIs), such as $NPSH_A$, flowrate relative to BEP, and vibration data, allow operators (with no special training) to monitor pump operations. When more-advanced diagnostics are necessary, such as vibration spectrums and time-wave forms, the reliability and maintenance teams can access the system via the web. Integrating maintenance and operational data improves operational efficiency and reduces the need for onsite manual monitoring.

Another way to spot developing problems before they lead to pump failure — the essence of predictive maintenance — is the use of continuous vibration analysis. In its simplest form, this technique involves installing a simple mechanical vibration switch or digital warning light that will indicate excessive vibration on individual pumps.

To achieve the full benefits of a predictive maintenance program, plants can employ digital monitoring systems (Figure 4) that gather more comprehensive data on pump performance. Options include:

- wired systems — the equipment sensors are hardwired to rack-based computer servers, and data are accessed and analyzed over an internal network
- wireless systems — sensors transmit data to a central hub, and data are accessed and analyzed over secure Internet connections
- integrated systems — hardwired and wireless sensors feed data to an internal server-based network.

All of these systems provide continuous monitoring of key machine health indicators — including performance (efficiency), vibration, temperature, flowrate, pressure, and power — and provide advance warning of impending trouble. In general, wired systems are more costly to implement and provide more comprehensive process-related information. Wireless systems are simpler to install and provide greater accessibility to information. Data from wired and/or wireless systems can be fed to automated process-control systems to provide a fully integrated program.

Wrapping up

Proper pump operation and maintenance involves ensuring that pumps are operating near the BEP and closely monitoring key performance parameters — suction pressure, discharge pressure, flowrate, pump speed, and power. Predictive maintenance uses condition-monitoring systems that collect machine status and process data to identify pumps that are about to fail and the underlying problems. By implementing the best practices described in this article, you can run your pumps efficiently, while reducing risk of equipment failure and downtime. CEP

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