7. Pumps and Motors

The focus of this publication is to identify best practices in energy efficiency for the chemical industry. While there are some standard approaches that are almost universally beneficial in pumping systems, it is vital to emphasize from the outset that rules of thumb provided in this document should not be used solely to determine the implementation of best practices; rather they should help identify best practices that have potential energy savings. Resources shall be provided with these rules of thumb to offer more in-depth information and suggestions on proceeding with the implementation of a best practice.

7.1 Explanation of Use

Pumping systems are the single largest type of industrial end-user of motor-driven electricity in the United States, accounting for 25% of industrial motor energy usage. [36] Also, pumping systems account for nearly 20% of the world's demand for electric energy.[37] While pumps typically operate to serve various chemical process support equipments such as chillers, cooling towers, material transfer, etc., pumping is considered an individual process separate from the processes of the aforementioned equipment.

A pump is a device used to raise, compress, or transfer fluids. The motors that power most pumps can be the focus of many best practices. It is common to model the operation of pumps via pump and system curves. Pump curves offer the horsepower, head, and flow rate figures for a specific pump at a constant rpm. System curves describe the capacity and head required by a pump system. An example of both of these curves may be seen in Figure 7.1.

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[36] United States Industrial Motor Systems Market Opportunities Assessment, report by Xenergy for Oak Ridge National Laboratory and the U.S. Department of Energy, 1998, available for free download at http://www.oit.doe.gov/bestpractices/pdfs/mtrmkt.pdf

[37] Pump Lifecycle Costs: A Guide to LCC Analysis for Pumping Systems, Europump and Hydraulic Institute, 2001. An executive summary can be downloaded free from the U.S. Department of Energy at: http://www.oit.doe.gov/bestpractices/pdfs/pumplcc_1001.pdf

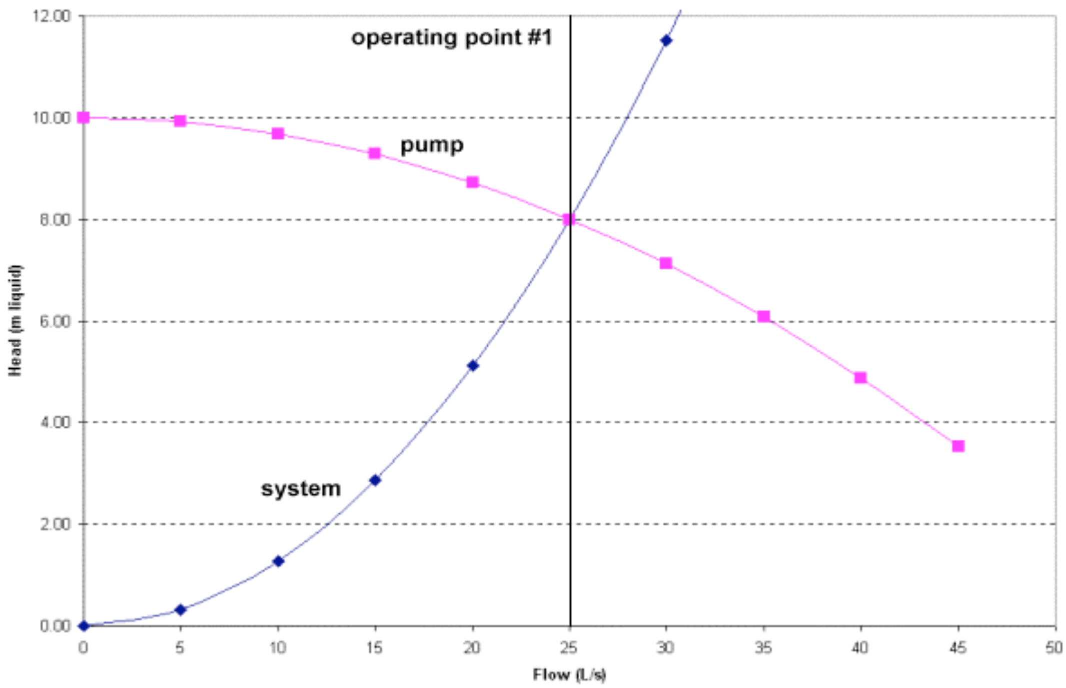


Figure 7.1 [www.cheresources.com/ vpumpzz.shtml](www.cheresources.com/vpumpzz.shtml) **(example of pump and system curve, there may be better graphics available)**

Pump operation may be modeled by a system of affinity laws that show a relationship between rpm, flow rate, and power. Understanding these basic relationships, shown below, is very important in considering the performance of a pumping system.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad Q = Flowrate$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \qquad N = Speed$$

$$H = Head$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \qquad P = Power$$

7.1.1 Pump Types

Various types of pumps are used in the chemical industry, including centrifugal, reciprocating, and helical rotor pumps.

Centrifugal pumps operate by applying a centrifugal force to fluids, many times with the assistance of impellers. These pumps are typically used in moderate to high flow applications with low-pressure head, and are very common in chemical process industries. There are three types of centrifugal pumps—radial, mixed, and axial flow pumps. In the radial pumps, pressure is developed completely through a centrifugal force, while in axial pumps pressure is developed by lift generated by the impeller. Mixed flow pumps develop flow through a centrifugal force and the impeller.

Reciprocating pumps compress liquid in small chambers via pistons or diaphragms. These pumps are typically used in low-flow and high-head applications. Piston pumps may have single or multiple stages and are generally not suitable for transferring toxic or explosive material. Diaphragm pumps are more commonly used for toxic or explosive materials.

Helical rotor pumps use a rotor within a helical cavity to develop pressure. These pumps are useful for submersible and waste applications.

7.1.2 A Pump Lifecycle Analysis

Energy usage is a critical factor in determining the lifecycle costs of pumps and their motors. As an illustration of how significant the energy cost can be, Figure 7.2 shows the 10-year lifecycle distribution of costs for a 250-hp motor driven pump used in a relatively benign service (e.g., clean water) and operated about 80% of the time: Energy accounts for over 85% of the ownership cost for the pump and motor. But even if the equipment is operated only half of the time and is exposed to a more severe service (therefore increased purchase and maintenance costs), energy is still the dominant lifecycle element, as shown in Figure 7.3. Assumptions used in developing the Fig. 7.2 and 7.3 pie charts are listed below the figures.

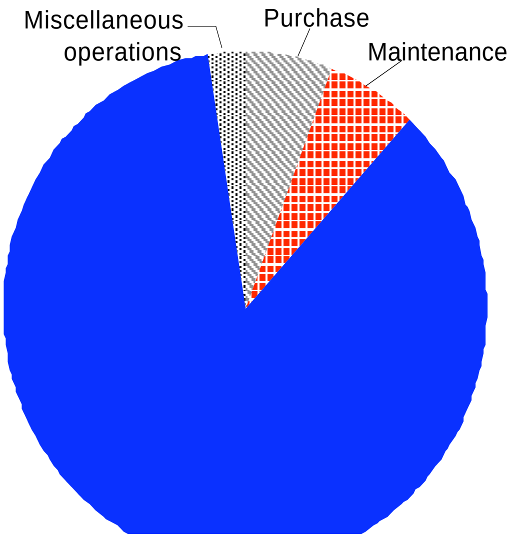


Figure 7.2 Moderate cost, benign service, high use 250-hp pump lifecycle cost distribution

Bases for Figure 7.2

- 250 hp motor, 95% efficient, operated at rated load
- 7,000 hours/year operation (80% of the time)
- 5 ¢/kWh electricity cost rate
- Purchase and installation cost = $40,000
- 10-year service life
- Maintenance cost = $5,000/year
- Miscellaneous operations cost = $2,000/year
- Discount rate = 8%
- Inflation rate for all recurring costs = 5%

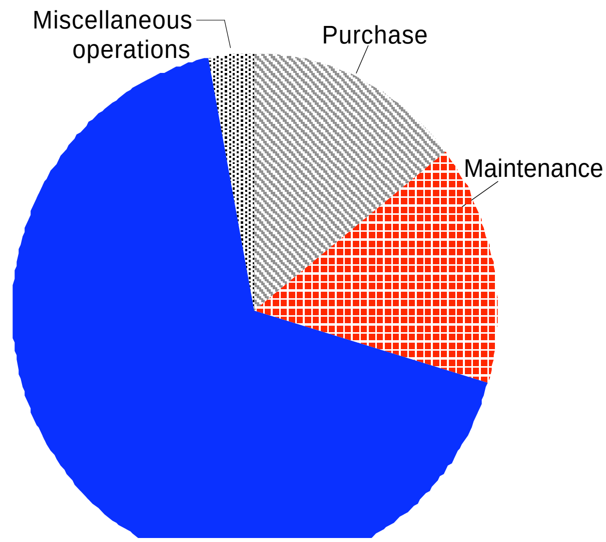


Figure 7.3 Higher cost, harsher service, moderate use 250-hp pump lifecycle cost distribution

Bases for Figure 7.3

- 250 hp motor, 95% efficient, operated at rated load
- 4,380 hours/year operation (50% of the time)
- 5 ¢/kWh electricity cost rate
- Purchase and installation cost = $80,000
- 10-year service life
- Maintenance cost = $10,000/year
- Miscellaneous operations cost = $2,000/year
- Discount rate = 8%
- Inflation rate for all recurring costs = 5%

Figure 7.2 and 7.3

It might be noted that the energy costs of the *first year of operation* for the Figure 7.2 data would be over $68,000, or 170% of the purchase and installation cost.

Europump and the Hydraulic Institute, two industry trade associations, collaborated to produce a lifecycle cost (LCC) analysis document that provides some detailed discussion on both technical and economic factors involved in doing a lifecycle cost analysis.[38] The executive summary of the LCC document can be downloaded from either the U.S. Department of Energy or the Hydraulic Institute at no cost.[39]

[38] Pump Lifecycle Costs: A Guide to LCC Analysis for Pumping Systems, Europump and Hydraulic Institute, 2001. An executive summary can be downloaded free from the U.S. Department of Energy at: http://www.oit.doe.gov/bestpractices/pdfs/pumplcc_1001.pdf

[39] The full document can be purchased from Hydraulic Institute at www.pumps.org; an executive summary (and other useful documents) can be requested free of charge from Hydraulic Institute at http://www.pumps.org/public/pump_resources/energy/index.html.

7.2 Control Strategy Best Practices

There is no single control strategy that is optimal for all pumping systems. In one case, on/off control is clearly preferred while in another, pump speed control is the obvious choice. However, there are many systems for which the choice is not so clear or in which two or more different control schemes would work equally well. And there are some systems that merit a combination of controls, such as multiple parallel pumps with adjustable speed drives for each pump.

Each system must be evaluated on its own terms. The nature of the system curve, the performance characteristics of the installed pumps, the nature of the load variability, and other factors influence the decision process. It is important to note that all of these best practices are likelihoods, not necessarily guarantees.

The following best practices will be discussed in the context of control strategies:

- Understand the fundamental nature of the system head requirements
- Understand the variability of the required flow rate and head
- Systems with essentially constant requirements and/or large storage inventories
- Systems with continuously varying requirements (and lacking stored inventory)
- Systems that operate in two or three principal operating zones
- Minimize the use of throttling valves or bypass operation for flow regulation
- Demand charge minimization

The most commonly selected control strategies for regulation of pumping systems are:

- Control valve throttling
- Bypass (pump recirculation) valve operation
- Multiple parallel pump operation
- On/off control
- Pump speed control
- Combinations of the above
- No control – the pumps just run

7.2.1 Understand the Fundamental Nature of System Head Requirements

This is absolutely a critical best practice. Note that it is not an equipment choice or simple rule of thumb. It is recognized that knowledge and understanding are essential to proper equipment selection.

Nature of System Head Requirements: An illustrative example

Assume that the system designer indicates that 5,000 gpm and 200 feet of head should be the pump design point, and that the flow rate is not expected to remain very constant. That would seem to indicate that a pump that operates at its best efficiency point at 5000 gpm and 200 feet of head would be a straightforward, lowest capital and operating cost choice.

Of course, some might note that even in this simplest of situations, equipment redundancy and potential protection from transients such as water hammer, (sudden changes in fluid velocity which cause catastrophic component failure) are control issues that would need to be considered. The addition of a parallel pump for redundancy, use of a soft starter, application of air release and/or vacuum breaker, and check valves with carefully selected closing response to address startup and shutdown hydraulic transients might be needed in all of these systems.

But what if the flow requirements are expected to vary between 1,000 and 5,000 gpm, and the 5,000 gpm at 200 feet head is simply the maximum design basis condition? Three different system curves that share one common point—5,000 gpm and 200 feet of head—are shown in Figure 7.4. These three hypothetical systems have static head requirements that range from 0 to 180 feet. But they also have different levels of frictional resistance to fluid flow.

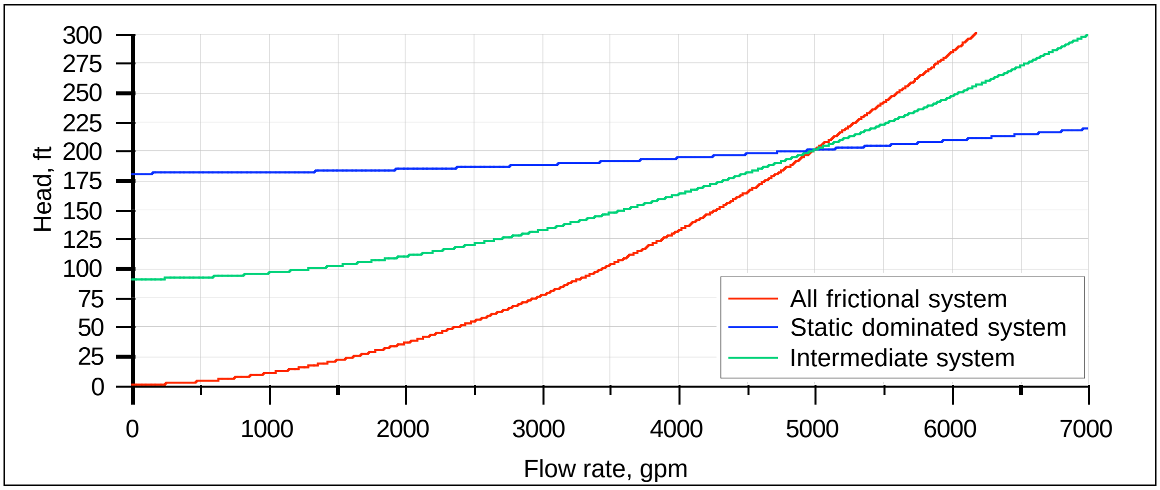


Figure 7.4 Three different system curves with a single common flow rate/head point (5000 gpm/200 ft)

While the three systems do share the same head requirement at 5,000 gpm, at 1,000 gpm the required head varies from 9 to 181 feet. This divergence should affect the choice of not only the control system but the pump itself. Some general tendencies will be discussed below, but the point to be made here are that the nature of the static and frictional head distributions absolutely should be considered in selecting a control strategy. It is, therefore, an essential best practice that the control designer must understand the system curve characteristic.

It might also be noted that the transient protection considerations mentioned above would need to factor into the nature of the system, including the static head as well as the general piping distribution—even when the system only operates at a single flow rate. So even in the simplest of control arenas, the nature of the system curve must be considered.

Best Practice—Consider and Apply the Best Control System and Pump

- Consider the divergence of system curves based on the frictional and static head distributions of the pumping system in order to select/modify pumps and their control systems.
- Adjust the control system to fit the most appropriate system curve.

7.2.2 Understand the Variability of the Required Flow Rate and Head

Integrally linked with the fundamental nature of the system curve is the need to understand the variability of the flow and head requirements. This is also a knowledge-and-understanding-based best practice.

Nature of System Head Requirements: An illustrative example (continued)

For the three systems represented in Figure 3, the control strategy decision would is affected by the head-flow curve shape as well as the variation in flow requirements. The optimal control strategy for a situation where the flow requirements vary between 1,000 and 5,000 gpm in any of the three systems would almost certainly be different than the strategy chosen if the range of variability was between 4,500 and 5,000 gpm (particularly for the static dominated system).

For existing systems, an excellent way of capturing the variability is by monitoring flow rate (and/or head) over time and creating a histogram such as those shown in Figures 7.5 and 7.6 to help clarify the time distribution requirements.

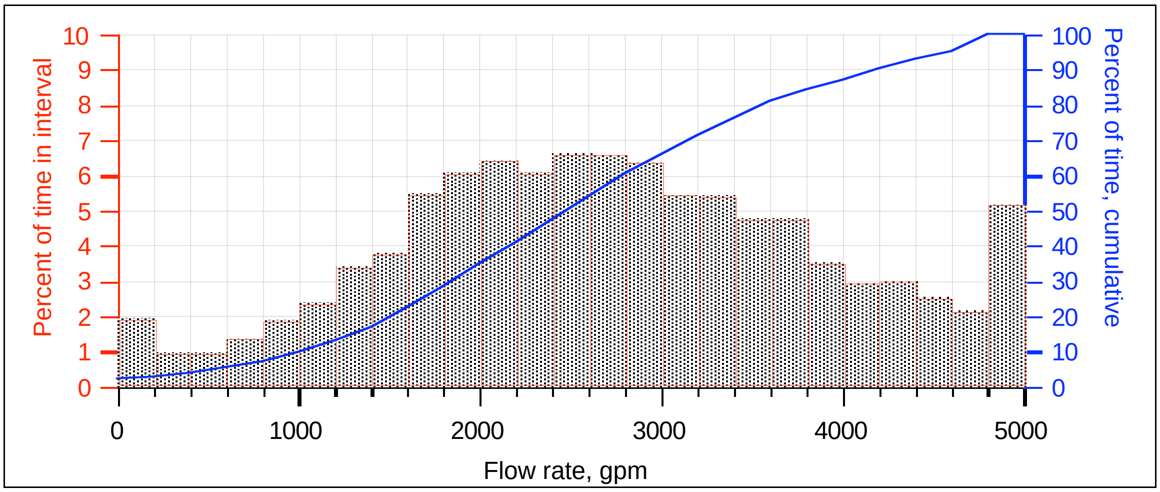


Figure 7.5 Flow histogram for a system with continuously variable flow requirements

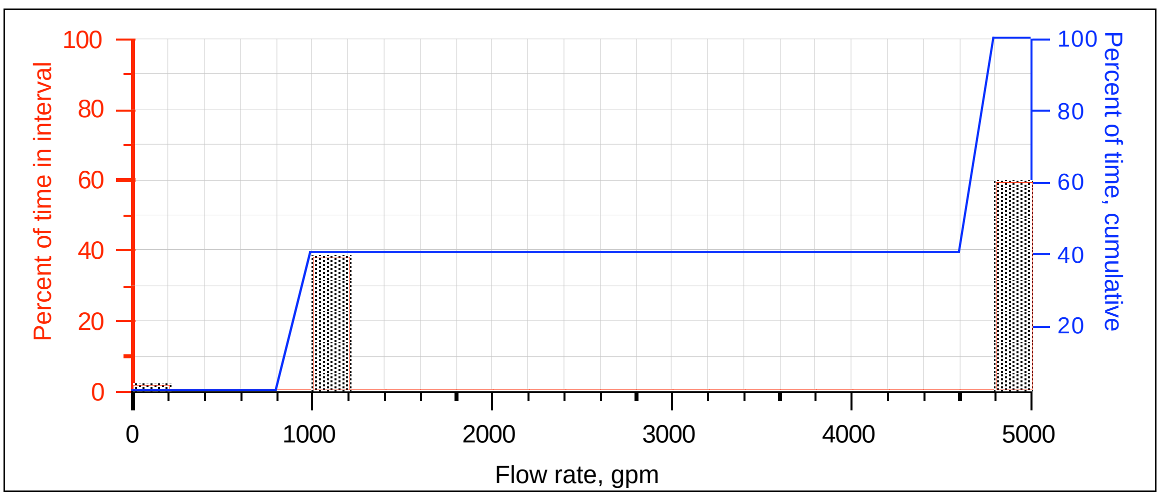


Figure 7.6 Flow histogram for a system with two basic operating regimes

Best Practice—Monitor System Variability

- Monitor the flow rate over time to help clarify time distribution requirements.
- Select a flow system that is in concordance with observations of the flow rate.

7.2.3 ON/OFF Controls

Systems in which neither the flow rate nor head need to be regulated (under normal, steady-state conditions) are prime candidates for on/off control. This is a general rule of thumb and does not apply to all systems.

An excellent example of this type of system is the municipal water system, where filtered and treated water is pumped from the clear well of a chemical plant to elevated storage tanks. Although customer demands vary with the time of day and weather conditions, the system storage in most municipal operations provides a sufficient buffer to meet these demand fluctuations. The elevated tanks, of course, also provide a relative constant source of pressure.

Some municipalities do use adjustable speed drives to both regulate flow and minimize the effect of start and stop transients, and some even employ them to minimize demand charges (Section 7.2.7). However, for many applications, a properly selected pump and motor will provide the lowest capital and operating cost for systems with constant requirements and/or large storage capacity.

Best Practice—Select an ON/OFF Control System for Systems with no Flow Rate or Head Regulations

- If a study of the variability and regulations of the system (Sections 7.1.1, 7.1.2) shows that flow rate and head do not need regulating, investigate an ON/OFF system, which will likely provide the lowest capital and operating costs.

7.2.4 Adjustable Capacity Controls

Generally speaking, systems that experience continuously variable demand are good candidates for adjustable speed drive consideration. The phrase "continuously variable" is intended to portray a load profile similar to that shown in Figure 7.5, where the flow requirements vary across a broad range.

But it is also important to note that the nature of the system curve becomes very important here. If the Figure 7.5 flow profile was applied to the all-frictional system curve of Figure 7.4, a single adjustable speed driven pump would likely be suitable to the entire flow range (with the possible exception of extremely low flow rates). However, if the Figure 4 flow profile was applied to the static-dominated system curve of Figure 7.4, it is a virtual certainty that an adjustable speed driven pump would not only become inefficient, but also be problematic from a control standpoint as the required flow rate dropped below 1000 gpm or so.

The use of either multiple parallel pumps might well be a preferred alternative in a high static head case, where the optimal set of pumps might not all be the same size. Or it may be that using a combination of parallel pumps with adjustable speed drives would be the preferred choice.

Best Practices—Adjustable Speed Drive or Multiple Parallel Pump Controls

- Installing a variable speed drive on the motor will adjust the pump operation to meet a variable demand system.
- In cases with high static head, parallel pumps may be a more effective alternative.

7.2.5 Multiple Flow Regime (Parallel Pump) Controls

Systems with varying flow requirements that operate in discrete regimes can generally be well served by a parallel pump operation, where pumps are properly sized and selected for the individual flow regimes. The histogram shown in Figure 5 might be a good candidate for parallel pump control.

It should be noted that the two different flow regimes in Figure 7.6 could have similar or quite different head requirements. If the all-frictional system of Figure 7.1 applied, the head at 1000 gpm would be about 9 feet while the head at 5000 gpm would be 200 feet. Clearly, two entirely different pumps would be needed. It might be noted that an adjustable speed-driven pump would also work reasonably well under this system and load profile type, but the inherent drive losses and the much higher capital cost for a drive for the larger pump would certainly favor the dual pump design configuration.

In the case of the static-dominated system, two options would merit consideration. Two pumps could be chosen to operate solo under the two flow regimes. Or, one pump could be used for the lower flow regime (1000 gpm) and a second pump turned on to run in parallel with the smaller pump to meet the 5000 gpm requirement.

One important note regarding distinct regime operation: In some cases, the intervals for these flow regimes are long and in others, they're short. The parallel pump operation is most readily applied to the longer intervals (such as once per shift). Where the cycles occur in relatively quick fashion (minutes), special care is needed. Frequent direct across-the-line motor starting is hard on switchgear, motors, pumps, and systems. If frequent starting is needed, the use of electronic soft starters or other alternatives (such as adjustable speed drives) should definitely be considered.

Best Practice —Parallel Pump Control

- If there are multiple obvious flow regimes noticed from the system, investigate the option of parallel pumps to handle the different regimes.

7.2.6 Minimize the Use of Throttling Valves or Bypass Operation

One generic best practice is to minimize the use of valve throttling and bypass losses in system control. Throttled valves convert hydraulic energy that the pump has imparted to the fluid into frictional heat, thus wasting a portion of the pump's energy. Bypass control simply routes some of the fluid that the pump has energized right back where it came from (dissipating the energy into heat in the process).

Even this best practice, which is about as close as one can get to simplistic rules of thumb in pumping systems, has its exceptions. And those exceptions are strongly influenced by the two previously mentioned knowledge-and-understanding best practices (Sections 7.2.1 and 7.2.2). Two examples of the exceptions are provided here.

- For pumping systems with very high static head requirements, such as boiler feed water applications, the fundamental nature of the pump and system curves often dictates that some level of adjustable friction (i.e., control valve) be injected into the system in order for it to be controllable across the entire operating range. It is simply not practical to use an adjustable speed drive (for example) to provide all of the flow regulation, particularly at reduced load conditions.

- For systems that operate in a very narrow window of flow rate and head but do not require relatively tight regulation, the use of a control valve may, almost paradoxically, be the lowest energy cost alternative. For example, consider the pump and system curves shown in Figure 7.7 below. The pump was selected based on flow and head requirements at 5000 gpm. While an adjustable speed drive could be used to slow the pump down to achieve the 4700 gpm instead of regulating with the control valve, the end result would be additional cost.

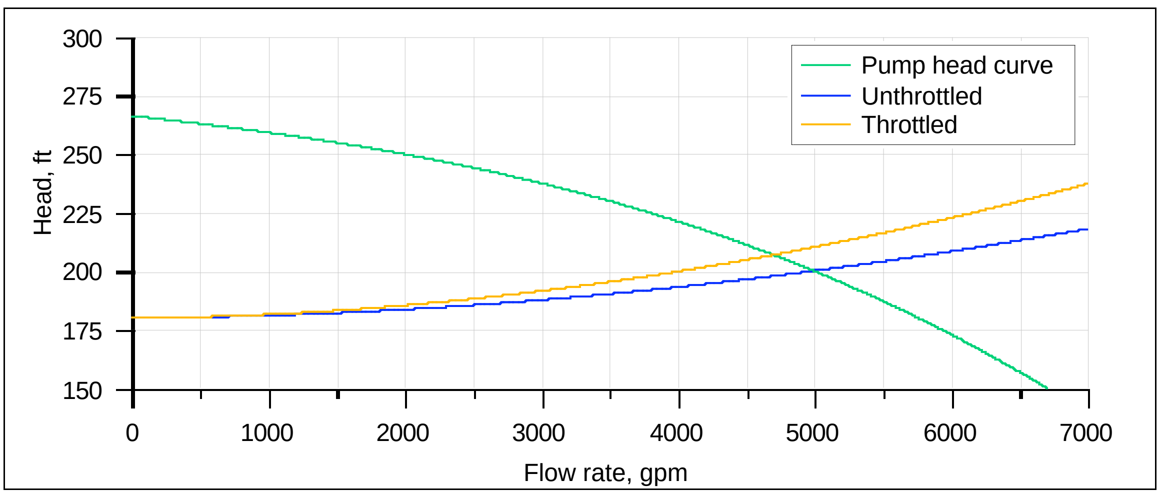


Figure 7.7 System curves to vary flow rate between 4700 and 5000 gpm

The reason for this is that the drive is not a perfectly efficient device. When operated near full-speed conditions, the drive would consume 3-4% of the input energy (converting electrical energy into heat). The drive itself would consume as much electrical energy at all flow conditions between 4700 and 5000 gpm as the maximum electrical energy that would be required to overcome the valve frictional losses at 4700 gpm. Thus, the use of the control valve – lightly throttled – would be the lowest energy cost alternative.

It should also be noted that while the use of bypass controls on centrifugal pump systems as a part of overall system process regulation is almost always a poor idea from an energy standpoint, not all bypass or re-circulation flow is a bad thing. In fact, it is essential in some cases. Minimum flow lines are designed to protect the pump against deadhead or no flow operation. Particularly for high-energy pumps, operation at no flow can result in nearly immediate equipment damage.

However, minimum flow protection and bypass operation for process control are two different things. It is when considerable flow is being diverted through a bypass line (and for a sizable portion of the time) that the wasted energy flag needs to be raised.

Best Practice—Minimize the Use of Throttling and Bypass Controls

- Use only the optimum number of throttling and bypass valves to reduce frictional losses in the system.
- Be aware that installing a control valve or bypass valve may be a better alternative to other control methods, such as using adjustable speed drives.

7.2.7 Demand Charge Minimization

Control systems can also be an integral part of reducing electrical demand charges. Demand charges are common electric rate elements for industrial plants. The precise billing structure and magnitude varies significantly. Some utilities impose relatively mild demand charges, while for others the demand cost can be in the same ballpark as the energy charge component.

One very common misconception about demand charge is that motor starting is a critical component, since the motor inrush current (and power) are much higher than normal full load conditions during startup. However, the startup transient only lasts a few seconds, and the demand interval is typically 15 to 30 minutes in duration. It is the average power over that period that establishes the interval demand value. Either soft starters or adjustable speed drives can, in fact, reduce the inrush current, and be quite helpful in minimizing the mechanical and electromagnetic transient. But the associated reduced current inrush impact on the demand charge will not be measurable.

There are two best practices that do apply to demand charge reduction. These are simple rules of thumb, but unlike those noted above, they are both straightforward and essentially without exception.

Low-use equipment

Some equipment operates a relatively small portion of the time; for example, a pump might only run for a few minutes a day or maybe for an hour once a week. Coordinating these run times with the overall plant load —when possible—can pay healthy dividends.

Power factor penalty

In many cases, electric utilities include a power factor charge in the rate structure. Perhaps the most common way of including a power factor charge (or "penalty") is to specify a demand charge that is based on kVA (apparent power) rather than kW (true power). In many cases, the demand will be the greater of two values:

- the peak interval true power (kW), or
- 0.85 times the peak interval kVA (note: 0.85 is an common threshold, but values in excess of 0.9 are also found)

The effect of this structure is that if the plant's overall power factor is greater than 0.85 (or whatever the threshold value is), they will not be penalized. But if the power factor is less than 0.85, the demand charge will be multiplied by 0.85 and then divided by the actual power factor.

There are several things that can be done to improve power factor. First, motors that are severely under loaded will contribute to an overall lower power factor. Ensuring that motors are reasonably well sized to the load will help.

Second, power factor correcting capacitors can be used. These capacitors are individually coupled to specific motors. In some cases, capacitor banks are connected to the main bus instead of individual motors.

It might be noted that adjustable frequency drives (AFDs)—especially when accompanied by input line reactors—also tend to have relatively high power factors. There are some caveats here, since the true rms power factor and the displacement power factor are different for AFDs. The displacement power factor will usually be at 0.95 or greater, and the true rms power factor somewhat below that. But it is also important to mention that adjustable frequency drives and capacitor banks are not good companions.

An excellent third choice is to use synchronous motors to assist in power factor correction. Generally synchronous motors are quite large, such as the compressor motor shown in Figure 7.8. The power factor for synchronous motors can be adjusted to be leading, thereby compensating for the lagging power factor of induction motors and other inductive loads. Since synchronous motors are generally large (the one in Figure 7.8 is rated at 3850 hp), they can cancel the effects of numerous smaller inductive motors.

Figure 7.8 Synchronous 3850-hp Motor

Best Practices—Demand Charge Minimization

- Coordinate equipment operation times to level out demand peaks.
- Install capacitors on motors to improve the power factor.
- Use synchronous motors to increase the power factor.

7.3 Equipment Selection and Installation Best Practices

In most cases, the selection and installation of pumping system equipment in new applications involves significant conservatism. There are a host of factors involved, including uncertainties in component losses and equipment performance. The fundamental driving force, however, is that design engineers want to ensure that plant requirements are met.

Conservatism in component selection and system design inherently leads to excess energy consumption. Given the significance of energy in the overall lifecycle cost of ownership, it is important that personnel responsible for designing, installing, and operating pumping systems be aware of the potential effects of excessive conservatism. The following example is derived from actual experience.

System and pump design An example of conservatism

An example is used here to illustrate the impact of conservatism in design. The process —and end result—is representative of a considerable portion of existing process systems.

Step 1: Identify the system design flow rate and head
Flow rate basis: Plant production specification
Head basis: Calculations based on assumed pipe and pipe fitting loss characteristics at the design basis flow rate. Note that approximately 70% of the system frictional head is for control valve allowance.

Step 2: Add system flow margin
Add 10% to the Step 1 design flow rate basis

Step 3: Add pump wear margin
Add 10% to the Step 1 design head basis

Figure 7.9 shows the static head and the flow/head points corresponding to Steps 1 and 3.

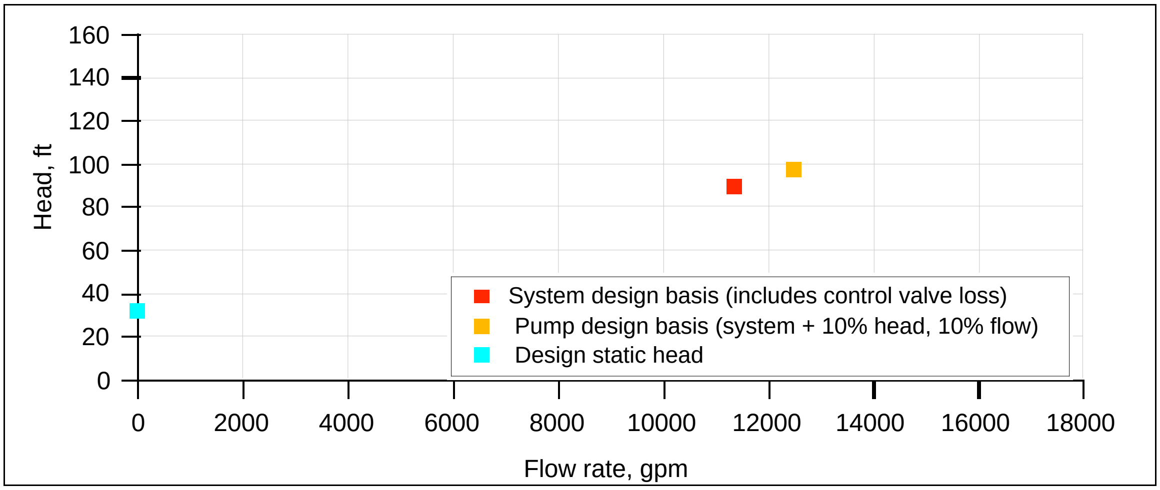


Figure 7.9 Design points (correspond to after Step 1 and Step 3 above)

Step 4: Margin included in the pump selection process (independent of above margins)
The last step in pump procurement is to use the Step 3 design point (12,500 gpm and 97 feet) to select a pump. The pump supplier will help with the selection of the right pump since they want to be sure that the equipment meets customers' needs. As part of the procurement process, which often includes a factory witness test requirement, the factory test encourages additional conservatism in pump selection.

The pump head-capacity curve of the selected model is added to the design points and shown in Figure 7.10. The actual pump includes roughly an additional 10% margin for both the head and capacity.

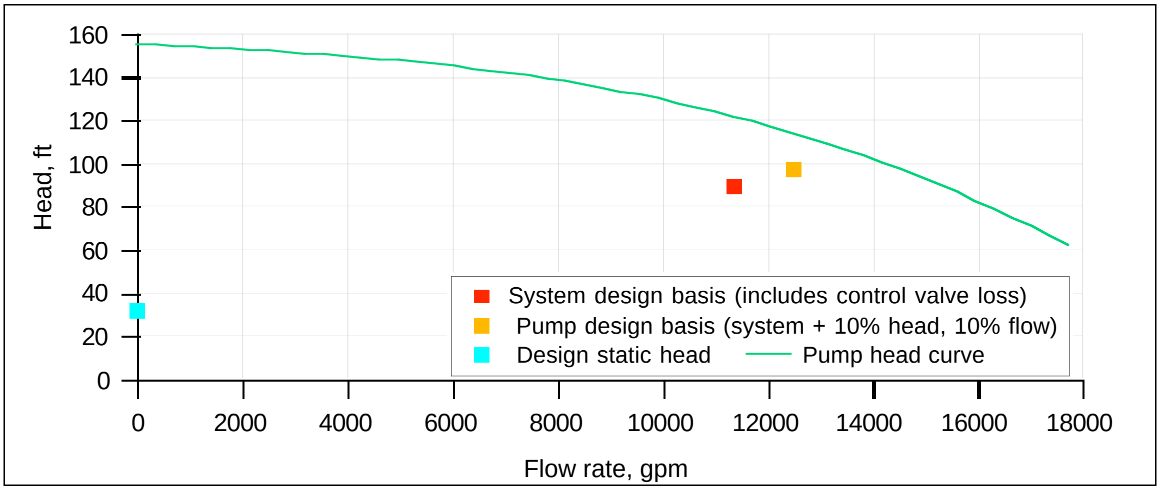


Figure 7.10 Design points and manufacturer's curve for the selected and installed pump

Typical performance points were measured in the field (flow rate and head), and are plotted in Figure 7.11. Note that the measured data fall above the pump curve, indicating that the pump is performing better than the generic pump manufacturer's performance curve. An estimated actual system curve, based on the field data (including significant losses across the system control valve) is included.

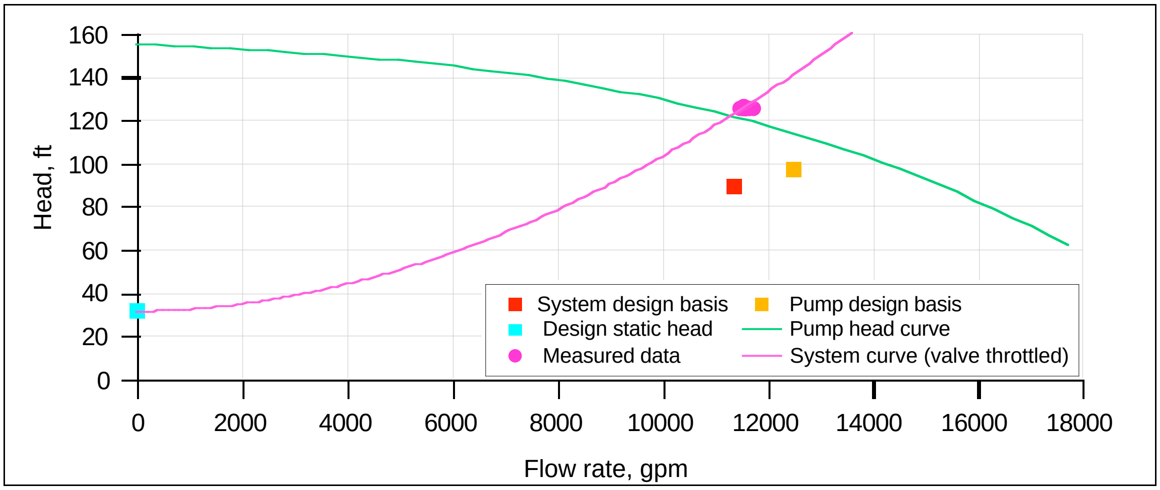


Figure 7.11 Design and observed performance data

There were clearly significant valve losses in this system. In order to determine how an un-throttled system curve would look, a special test was conducted to run the pumps with the control valve fully open for a few minutes (overflowing the receiving tank). The measured data and the unthrottled system curve are added to the above data and shown in Figure 7.12. The difference between the normal operating head (125.5 feet) and the unthrottled system head curve at the same flow rate (47 feet) is 78.5 feet.

The effect is that the pump adds 125.5 feet of head to the fluid, and the control valve then dissipates over 60% of the energy imparted by the pump.

Conservative design, at many levels, was responsible for creating this situation. At each step along the path, the conservatism assigned generally seemed reasonable (with the possible exception of a 40-foot allowance for control valve loss). But the conservatism at each of the steps accumulated until the actual installed equipment was vastly oversized for the true needs of the system.

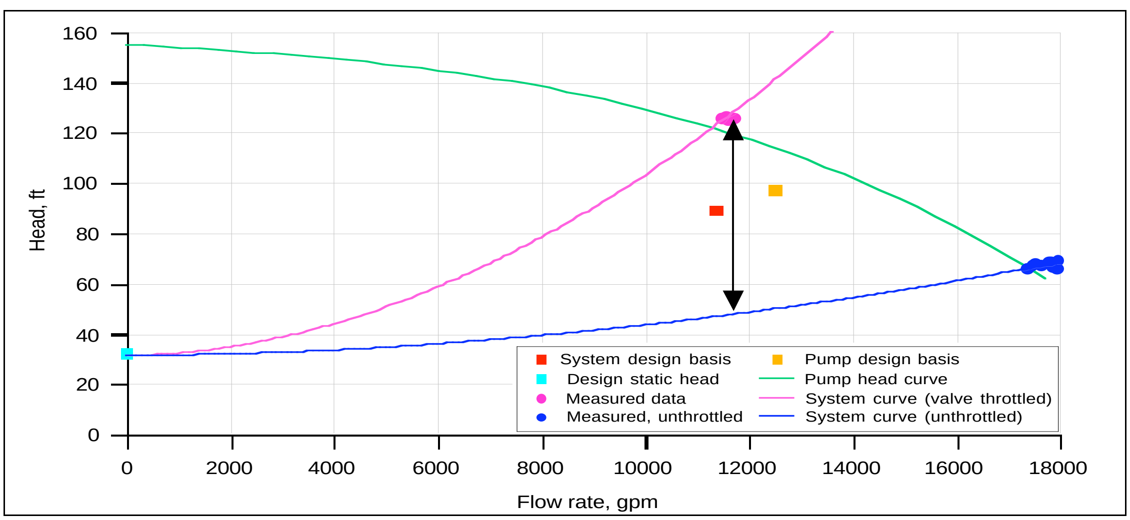


Figure 7.12 Design and observed field data, including unthrottled operation and related system curve

The preceding example illustrates perhaps the most fundamental and important reason that there are significant energy-reduction opportunities in some pumping systems. While it may not possible or even desirable to eliminate all of the conservatism, there are a few practices that may be helpful in minimizing its consequences.

Best Practice—Prevent Excessive Conservatism in Design

- Base purchase and design decisions on lowest lifecycle costs.
- Match true system requirements.
- Select the pump that is closest to the BEP (Best Efficiency Point on pump diagram).
- Select equipment with future changes in mind
- Ensure that installation follows standard recommended practices (particularly for suction)

7.3.1 Purchase and Design Decisions

The importance of energy in the lifecycle costs of pumping systems was discussed in section 7.1.2. One way to minimize the effects of excessive conservatism is to ensure that lifecycle costs are recognized and included throughout the design specification and equipment selection processes.

Consider control valves, for example. The fluid power associated with 12,500 gpm and 40 feet of head is 126 hp. Assuming a combined pump and motor efficiency of 80% (which would be excellent), the electric power attributable to the valve loss would be 117 kW. Over the course of a year, more than 1 million kWh of energy will be dissipated by the valve. At a cost of 5 cents/kWh, the annual cost of the valve design allowance would exceed $51,000.

The same sort of process could be applied to other conservative approaches, such as the 10% wear allowance for pumps. By tabulating and segregating costs in this fashion, there will be at least an element of feedback to counter the excessive conservatism in the design and procurement process.

Non-energy costs, such as the increased capital expenditure associated with significantly larger-than-necessary equipment, the purchase and maintenance costs for the control valve, etc., should also be factored in.

Best Practice—Conduct a Lifecycle Cost Analysis

- Conduct a lifecycle cost analysis to improve the accuracy of design and equipment selections. (Section 7.1.2)

7.3.2 Ensure that True System Requirements are Met

This practice is intended to reinforce the very basic idea of doing what needs to be done, but no more. Designs will continue to be conservative, even when lifecycle costs are fully considered during the design and procurement process.

A good practice to implement for new systems follows:

1. Design with a reasonable amount of conservatism to ensure that the system meets plant needs, being sure to consider lifecycle costs in the process.

2. Complete the installation, startup testing and early operational phases.
3. When stable operation has been achieved (typically, within a few months), review the actual system performance to determine the cost of the differences between actual operation and an operating environment with a reasonable chunk of the excess losses eliminated (by equipment resizing, for example). The goal is to size pumping equipment as close to true system requirements as possible.

Including lifecycle costs in the design and procurement stages will help ensure that the equipment that is chosen will operate near its BEP. But, in conjunction with the previous practice of reviewing the system operation to make sure that the pumping system equipment is as closely matched to the true system requirements as practical, reconsideration of the actual operating pump efficiency is a useful practice.

Not only does this help verify that the equipment is operating near its BEP, it also provides a baseline reference for establishing trends over time.

Best Practice——Test the System After It Is Installed

- After installation, startup testing, early operational phases, and stable operation have been achieved, review actual system performance to determine the cost of the differences between actual operation and an operating environment.
- Resize equipment to eliminate losses.
- Select the pump to operate close to the Best Efficiency Point (BEP).

7.3.3 Plan for Future Capacity Increases

In the design example above, margin was included for both pump wear and for "flow margin." The intent was to ensure that the installed equipment not only met today's requirements, but also had the capability of supporting increased production.

Considering future requirements is a very important part of the design process. However, installing equipment that is capable of doing more than is currently needed creates considerable energy-related cost burdens. A more intelligent process is to select equipment that can easily be upgraded by, for example, installing a larger impeller in the same pump casing. In other words, select the equipment with future modifications in mind, but don't install the modifications until they are actually needed.

It should be noted that the cost of oversized motors and switchgear is significantly lower than the cost of oversized pumps. While extreme over sizing of the motor is certainly to be discouraged, it is important that future pump modifications not be made excessively costly by upgrades to the motor and switchgear. In a case where the motor, cabling, and switchgear have to be upgraded to accommodate a larger impeller or a new pump, the modification costs can go up by almost an order of magnitude.

The absence of margin in motor sizes is also often a limiting factor in the ability to change existing operations to reduce energy costs. Take, for example, the case of a system that has two pumps, where the original design intent was to provide redundancy. If production increases change things to where a single pump is not quite capable of meeting the flow needs, the pump that was originally intended to be redundant will be used to provide supplemental capability. It may be that with a slightly larger impeller, a single pump could meet the system needs and require only 70% of the power required by the two existing pumps. While cost of a new impeller would be easy to justify, the option will be unattractive if the motor, starter, and cables must also be upgraded.

There is no single best approach in this area—each situation must be considered on its own merits. But it is certainly a best practice to consider the future, but to do so from a lifecycle cost perspective.

Best Practice—Consider the Future when Selecting New Equipment

- Install a pump model that efficiently meets current needs but can be easily and cost effectively upgraded (or downgraded) in the future by adding stages or changing impellers.
- Install a pump with an adjustable speed drive, and adjust pump speed to meet both current and future needs.
- Provide sufficient space for equipment replacement or augmentation, as needs change.

7.3.4 Follow Standard Installation Practices

Recommended best practices for pump installation, including foundation size and preparation, base plate installation and grouting, equipment alignment, intake design, and other important installation factors are included in the Hydraulic Institute standards[40,41].

One particular area that the author has commonly observed to be out of bounds involves suction piping. The suction piping configuration establishes the flow profile for fluid approaching the pump impeller. Two examples of poor suction configuration are shown in Figures 7.13 and 7.14.

The horizontal split case pumps shown in Figure 7.13 include short radius elbows in a horizontal plane connected to the pump suction flange. This creates an unbalanced distribution of flow between the two sides of the impeller (which has a double suction). As a consequence, the pumps cavitate, operate inefficiently, and create a higher thrust load for the thrust bearing (which runs hot). In Figure 7.14, the eccentric reducer is turned upside down. As a result, air present in the pumped fluid, which comes out of a solution, tends to accumulate in the upper side of the pipe. Occasional slugs of air are pulled into the pump, resulting in a frothy discharge.

The suction configuration shown in Figure 7.15 is a much better design. The eccentric reducer's flat side is on top, and there are several pipe diameters of straight pipe upstream of the suction.

Best Practice—Avoid Pump Geometries that Cause Unbalanced Flow Distribution

- Ensure that the flow maintains a balanced distribution entering the pump inlet to prevent cavitations.

[40] ANSI/HI 1.4, American National Standard for Centrifugal Pumps for Installation, Operation and Maintenance, Hydraulic Institute, 9 Sylvan Way, Parsippany, New Jersey, http://www.pumps.org/

[41] ANSI/HI 9.8, American National Standard for Pump Intake Design, Hydraulic Institute, 9 Sylvan Way, Parsippany, New Jersey, http://www.pumps.org/

Figure 7.13 Pumping system layout with poor suction geometry (and little opportunity for improvement)

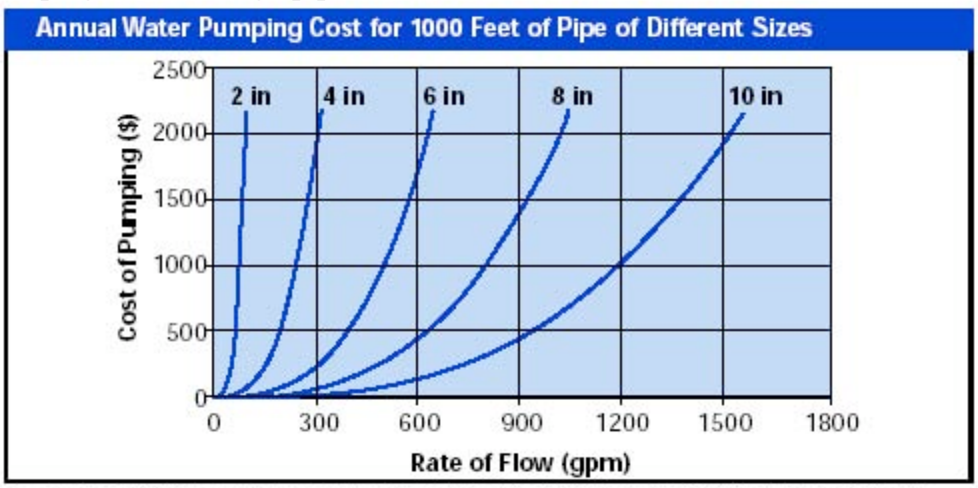
Figure 7.14 Inverted eccentric reducer allows air accumulation

Figure 7.15 Pump suction with properly oriented eccentric reducer, well-developed suction flow profile

7.3.4 Optimize Pipe Sizes

The power required to overcome static head varies linearly with flow, and there isn't much that can be done to minimize the static component of the system requirements. However, there are many energy- and money-saving opportunities to reduce the head required to overcome frictional losses in a pumping system.

There are several parameters that affect friction, such as flow rate, pipe diameter, pipe length, pipe characteristics (i.e. surface roughness, etc.), and properties of the liquid being pumped. The diagram in Figure 7.16., taken from a fact sheet provided by the DOE,[42] shows estimates of the costs for pumping water through pipes of various diameters.



Based on 1000 ft. for clean iron and steel pipes (schedule 40) for pumping 70°F water. Electricity rate—0.05 \$/kWh and 8,760 operating hours annually. Combined pump and motor efficiency—70%.

Figure 7.16 Annual Water Pumping Cost

[42] Obtained from DOE website http://www.oit.doe.gov/bestpractices/pdfs/motor1.pdf

Best Practice—Optimize Pipe Sizes

- Compute annual and lifecycle costs for the system before making an engineering decision.
- In systems dominated by frictional head, consider multiple options when trying to accommodate pipe size with lowest overall lifecycle cost.
- Search for ways to reduce the friction factor of the system. Certain piping materials, (if applicable), may reduce the friction factor by as much as 40%, proportionally reducing pumping costs.

7.4 Equipment Maintenance and Monitoring Best Practices

Equipment reliability is critical in any production environment, especially the chemical plant environment when it comes to using pumps. Chemical processes rely on the movement of fluids through process equipment and pumps are the main method of fluid transfer. There are several diagnostic methods that are very helpful in monitoring equipment health. Well-implemented programs can often recognize degradation in the incipient stage. In some cases, the root cause of the problem can be identified and mitigated before further damage is done. In others, developing problems can be monitored carefully and trended, allowing preventive or corrective actions to be initiated in a planned environment instead of having to address failures that cause unplanned outages.

Rotating equipment can fail in any number of ways. With pumps, seals and bearings represent the most common areas where failures and, subsequently, repairs occur. For motors, it's bearings and motor windings. As a consequence of advances in digital processing capability, machinery diagnostic monitoring has reached a state of relative maturity in the last 20 years.

In addition to the now commonly implemented predictive techniques, a complementary method that is often overlooked—performance monitoring —can provide important insights into areas of pumps that are not well monitored by the diagnostic techniques.

7.4.1 Predictive or Diagnostic Monitoring

Vibration monitoring is an excellent technique for measuring and trending rotating equipment balance, alignment, and bearing conditions. Analysis and trending software programs have automated detection and alarming of many of the critical degradation mechanisms that vibration measurements can detect, such as characteristic bearing flaw frequencies. Human analysis is still required, however.

Some equipment is so essential that dedicated, full-time monitoring with remote indication and alarm is merited. The use of routine routes with portable analyzers (see Figure 20) to acquire and store data for subsequent analysis is the best way to monitor other equipment. The frequency of monitoring is commonly dictated by both the criticality and previous measurement results. For example, if a pump bearing shows early indications of wear, the monitoring interval might be dropped from quarterly to monthly.

Other predictive methods that are effective in equipment health monitoring include lubricant analysis, infrared thermography, and various motor diagnostics (e.g., meggering, inductive and impedance unbalance measurements, and motor current signature analysis).

Equipment scope
An important best practice related to any predictive monitoring effort is the scope and breadth of equipment that is included in the program. As noted above, certain equipment merits continuous diagnostic monitoring while other equipment can be effectively managed by periodic checks. And it is important to point out that some equipment simply does not warrant the time and expense associated with diagnostic monitoring. It is often the case that a relatively small part of the overall equipment population merits a large share of attention. (It should be noted that this is also true with respect to energy reduction opportunities).

When selecting equipment to be monitored and establishing the priority it receives, several factors must be considered, including safety, reliability and downtime, potential environmental release, cost of repair, and redundancy. Similarly, recognizing that each diagnostic technique has its own strengths and weaknesses, it is important to establish a program that matches the primary failure modes and mechanisms of concern for each piece of equipment with a monitoring protocol that is effective at detecting developing problems.

Who should be involved?
There are different schools of thought regarding who is best suited to perform diagnostic testing, and it is beyond the scope of this report to discuss all of the pros and cons of different approaches. However, when the chemical plant organizational structure permits it, diagnostic monitoring by the same maintenance staff responsible for equipment repairs is excellent. This is not always practical, but it is strongly encouraged.

7.4.2 Performance Monitoring

Although equipment performance monitoring is normally considered a diagnostic tool, the fact is that, at least with pumps, it is an excellent preventative technique. In fact, most pump hydraulic degradation is essentially not detectable by any of the standard predictive tools (such as vibration monitoring), but can be detected by flow, head, and power measurements.

Very few facilities have well-developed performance monitoring programs. This is, in part, due to the fact that many fluid systems lack adequate instrumentation. However, portable instruments, such as the portable ultrasonic flow meter, can be used for field testing.

The Pumping System Assessment Tool[43], which, as previously noted, is available as a free download from the U.S. DOE, can be effective in not only assessing the opportunity for energy savings, but in periodic performance monitoring as well. One of the reported values from the PSAT analysis is an "optimization rating," which is akin to an exam grade, with a value of 100 indicating that the equipment measured is not only very well suited to the fluid conditions, but is in excellent health. The DOE and several other organizations host one-day end-user training workshops several times a year; two-day qualified specialist workshops are also available.[44]

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[43] Pumping System Assessment Tool, developed by Diagnostic Solutions, LLC for Oak Ridge National Laboratory and the U.S. Department of Energy. Available for free download at: http://www.oit.doe.gov/bestpractices/software_tools.shtml#psat
[44] Pumping System Assessment Tool Specialist Qualification workshop, developed by Diagnostic Solutions, LLC for Oak Ridge National Laboratory and the U.S. Department of Energy. Information available at: http://www.oit.doe.gov/bestpractices/software/psat_cert.shtml

PSAT input data and results for two pumps are shown in Figures 7.17 and 7.18. The "Condition A" data in Figure 7.17 represents field data for a newly installed vertical turbine pump at a water treatment facility. Note that the Optimization rating (bottom right, green background) is 97.8, indicating an excellent pump. On the other hand, the "Condition B" data of Figure 7.18 applies to a cooling tower vertical turbine pump. A few months after this measurement, the "Condition B" pump failed catastrophically (see pictures in Figure 7.19).

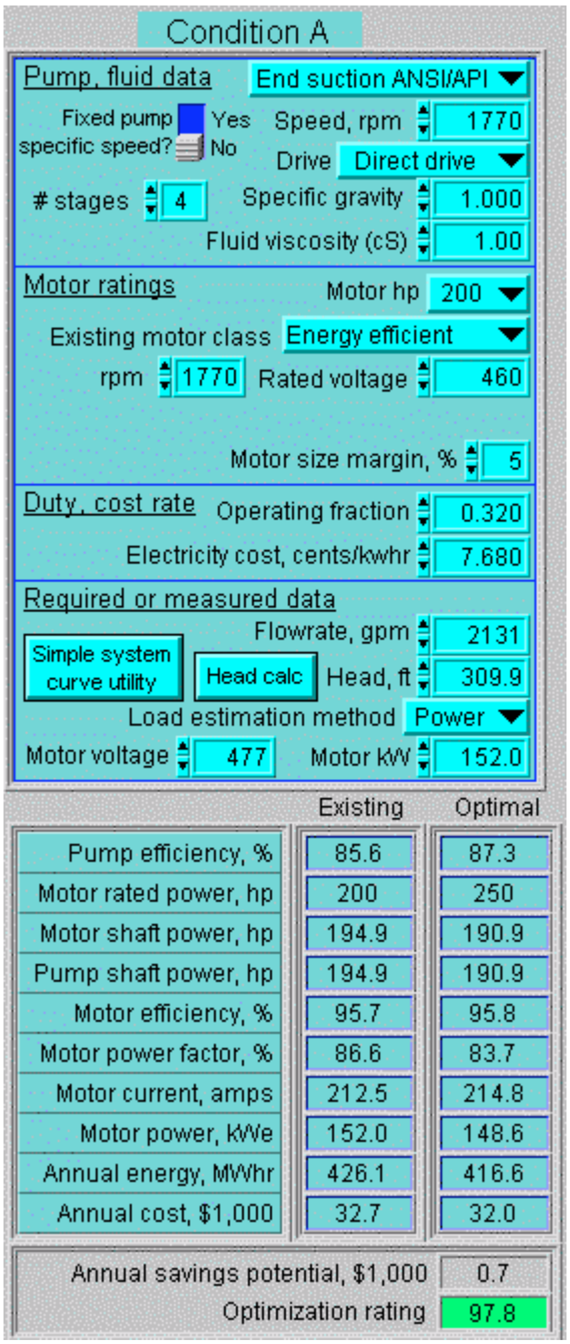

Figure 7.17 Newly installed pump, water treatment plant

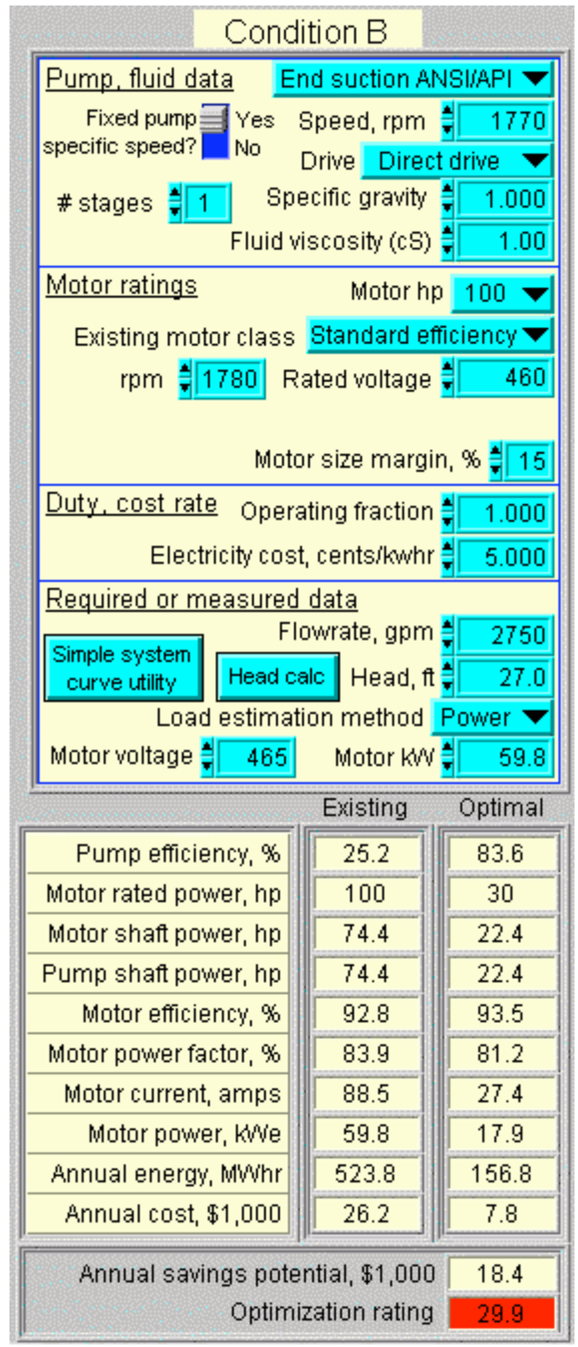

Figure 7.18 Significantly degraded tower water pump

Figure 7.19 Impeller and bowl bolts from the tower water pump evaluated by PSAT in Figure 7.18

Selecting equipment for performance monitoring

Quantifying the effective operation of a particular system requires detailed measurements of pressures, flow rates, and electrical input power. In some cases, these measurements are readily available but in others, there is little or no reliable process instrumentation. Particularly in the latter case, considerable time may be needed to install temporary instruments to acquire the necessary data. Furthermore, in many industrial facilities, there are literally hundreds of pumping systems. It is neither practical nor cost-effective to attempt to characterize each system.

In support of the PSAT software program and associated training, the U.S. Department of Energy's Best Practices program has developed prescreening guidance that is largely symptom-based. It has been found to be quite effective in identifying pumping systems that are most likely to yield cost-effective energy reduction potential. Several of the symptoms in the prescreening guide are directly linked to the existing control scheme.

It should be noted that the prescreening guide was specifically developed to flag systems that are *most likely* to yield energy reduction opportunities. There is no guarantee that energy reductions will, in fact, be realized. There is also no guarantee that systems without any of these symptoms could not be improved significantly. However, this symptoms-based approach has been demonstrated in a broad variety of process facilities, including steel, aluminum, mining, chemical and petroleum processing, paper, and others.

The first step in the prescreening process is to focus on the larger equipment that runs most of the time, for obvious reasons. Centrifugal pumping systems that do not use adjustable speed controls are selected in the second step. The third step involves identifying the presence of one or more of the following symptoms. The potential for savings increases with an increase in symptoms.

- Throttle valve-controlled systems
- Bypass (re-circulation) line normally open
- Multiple parallel pump system with same number of pumps always operating
- Constant pump operation in a batch environment or frequent cycle batch operation in a continuous process
- Cavitation noise (at pump or elsewhere in the system)
- High system maintenance
- Systems that have undergone a change in function

It should be noted that this prescreening process is strictly qualitative—it does not quantify opportunities. But it is an extremely valuable approach to identifying those systems for which a PSAT-based analysis (which *does* quantify the energy reduction opportunities), should be applied.

Best Practice—Use Prescreening Processes to Identify Systems with Energy Savings Potential

- Use PSAT-based analysis to identify potential energy saving opportunities.

7.4.3 Corrective Maintenance

Although predictive maintenance and performance monitoring approaches are important to maximizing reliability and minimizing energy consumption, failures are inevitable. There are some recommended practices for both pump and motor failures that not only help to restore equipment to like-new condition, but also have the potential to improve reliability and reduce energy costs.

Repair/replace policy

An important element for both motor and pump maintenance is the establishment of a repair/replacement program.

Establishing a repair/replace policy for motors is a reasonably straightforward process. The cost of repair is weighed against the cost of replacement; the potential for reducing energy costs by installing a more efficient motor is also considered. Many users have a defined motor horsepower threshold below which a major motor failure automatically triggers a replacement. But above that threshold, the motor is sent to a repair shop.

An integral best practice connected with the repair part of the program is the selection of a shop that follows motor repair guidelines set by the Electrical Apparatus Service Association (EASA).[45] This ensures that work will be done in a manner that not only returns the motor to service, but avoids a reduction in efficiency.

A repair/replace policy is one part of a motor management program. The Motor Decisions Matter organization, which was developed from collaborative efforts of manufacturers, trade associations, utilities, and the U.S. Department of Energy, has additional information and guidance on recommended motor management activities.

There currently is not an equivalent organization for pumps. However, it is equally important for users to recognize that similar types of decision-making processes are appropriate for pumps. In many cases, the potential savings from either replacing or modifying an existing pump can be an order of magnitude greater than those available from a motor upgrade. Although it is generally not practical to complete a detailed analysis on all equipment, it is possible to do so for major energy using pumps. Performance monitoring of pumps, as discussed above, provides a critical insight into which pumps need a contingency plan for modification or replacement in the event of failure.

To help clarify the need for a contingency maintenance upgrade program, consider an example where replacing or modifying an existing pump could reduce energy costs by $30,000 per year. But because of the critical nature of the pump, the cost of downtime associated with an outage to complete the modification or replacement is $100,000. While a lifecycle cost analysis might suggest that this is the right thing to do, the reality is that it won't happen. However, if preparations are made for the point in time when the pump is removed from service—either for periodic overhaul or as the result of a failure – the picture becomes entirely different. If removal from service is the result of a failure, the urgencies associated with getting the equipment back on line will take precedence *unless a contingency plan is already in place*.

The U.S. DOE's PSAT workshop series uses case studies to describe examples of contingency-based upgrades.[46] In one example, a repair effort was used as leverage to make a design change that is saving over $50,000 per year.

Best Practice—Implement a Motor/Pump Maintenance Program

- Develop and use a maintenance program

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[45] EASA AR100-1998 Recommended Practice for the Repair of Rotating Electrical Apparatus, Electrical Apparatus Service Association, Inc., 1331 Baur Blvd., St. Louis, Missouri 63132, www.easa.com.

[46] Pumping System Assessment Tool Specialist Qualification workshop, developed by Diagnostic Solutions, LLC for Oak Ridge National Laboratory and the U.S. Department of Energy. Information available at: http://www.oit.doe.gov/bestpractices/software/psat_cert.shtml

7.5 Motors

The U.S. Department of Energy (DOE) estimated in a 1994 study that electrical motors in industrial facilities use roughly 23% of the electricity sold in the country. Motors are widely used by industry and efficiencies have increased in recent years due to market pressure and regulations.

The following paragraphs describe various factors that can result in energy savings; if available, the accepted best practices associated with each factor is also given. Motor upgrades should be considered since, in large applications, energy savings will quickly offset the initial investment.

7.5.1 Motor Efficiency Upgrades

Always purchase the most efficient motor available when replacing an existing unit. Energy-efficient motors can cost 10-20% more than standard motors but energy savings normally offset this cost in less than two years. Often, motors are replaced by low-efficiency equipment because a fast work order is needed. To ensure the availability of energy-efficient equipment, make advanced purchases of replacement motors for equipment that tends to fail.

7.5.2 Motor Sizing and Loading

Most industrial motors are most efficient when running from 65% to 100% of the rated power. The maximum efficiency is normally 75% of the load. Most motors tend to dramatically lose efficiency at loads below 50%. Power factor also deteriorates as loads decrease. Motors are considered under loaded when running below 65% load. On the other hand, motors are considered overloaded when running for long periods of time above their rated power. Overloaded motors will overheat and lose efficiency. Consider replacing all motors operating constantly below 40% or at any point above the rated load.

In many cases, motors are oversized because of safety factors incorporated during the design stage. All systems, including pumps, fans, and compressors, are designed to accommodate changes in the system, but designers should size motors to run within the best efficiency band (65-100% of the load). Variable frequency drives (VFD) or variable speed motors can accommodate changes in the load as well. Following are some opportunities for reducing the load requirements on the system:

- Eliminate bypass loops and unnecessary flows
- Increase pipe diameter to reduce friction
- Use holding tanks to better match pumping flows and production requirements
- Reduce equipment (e.g., pump, fan, etc.) size to match load
- Install parallel systems for varying loads
- Reduce system pressure

7.5.3 Voltage Unbalance

Voltage unbalance occurs when there are different voltages on the lines of a polyphase motor. This leads to vibrations and stress on the motor as well as overheating and reductions in shaft power. It is recommended that the electrical distribution system be checked for voltage unbalances in excess of 1%. Polyphase motors with unequal voltage supplies lose efficiency and those losses are drastic for unbalances beyond 1%. According to the DOE, common causes of unbalances include:[47]

- faulty operation of power factor correction equipment
- unbalanced or unstable utility supply
- unbalanced transformer bank supplying a three-phase load that is too large for the bank
- unevenly distributed single-phase loads on the same power system
- unidentified single-phase to ground faults
- an open circuit on the distribution system primary

Pump and Motor References

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